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Clay illuviation in calcareous soils of the semiarid part of the Indo-Gangetic Plains, India

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Abstract

In view of diverse understanding on the movement and accumulation of clay particles in calcareous parent material, a micromorphological study on 28 Alfisols of the semiarid part of the Indo-Gangetic Plains (IGP) was undertaken. The study indicates that the identified clay pedofeatures are typically of the type "impure clay pedofeatures" which have resulted from the impairment of the parallel orientation of the clay platelets induced by dispersion of both clay and silt size layer silicates in slightly to highly sodic environment. The study also indicates that the illuviation of clay particles and their subsequent accumulation in the Bt horizons have occurred in sodic environment caused by the precipitation of soluble Ca^{2+} ions as calcium carbonate ($CaCO_3$), thus discounting any role of soluble Ca^{2+} ions and the presence of $CaCO_3$ in preventing the movement and accumulation of clay particles. The study thus suggests that the formation of impure clay pedofeatures and pedogenic $CaCO_3$ are two pedogenic processes occurring simultaneously in soils of the IGP as contemporary pedogenic events in the semiarid climate since the last 4000 years B.P.

Keywords: $CaCO_3$; Sodic environment; Clay illuviation; Pedogenesis; Pedogenic threshold

1. Introduction

The clay particles move in a suspended state. When the water is absorbed by the dry peds, the ped faces or void walls act as a filter retaining the clay platelets that are deposited in the subsurface horizons. These platelets are oriented parallel to the surface of deposition

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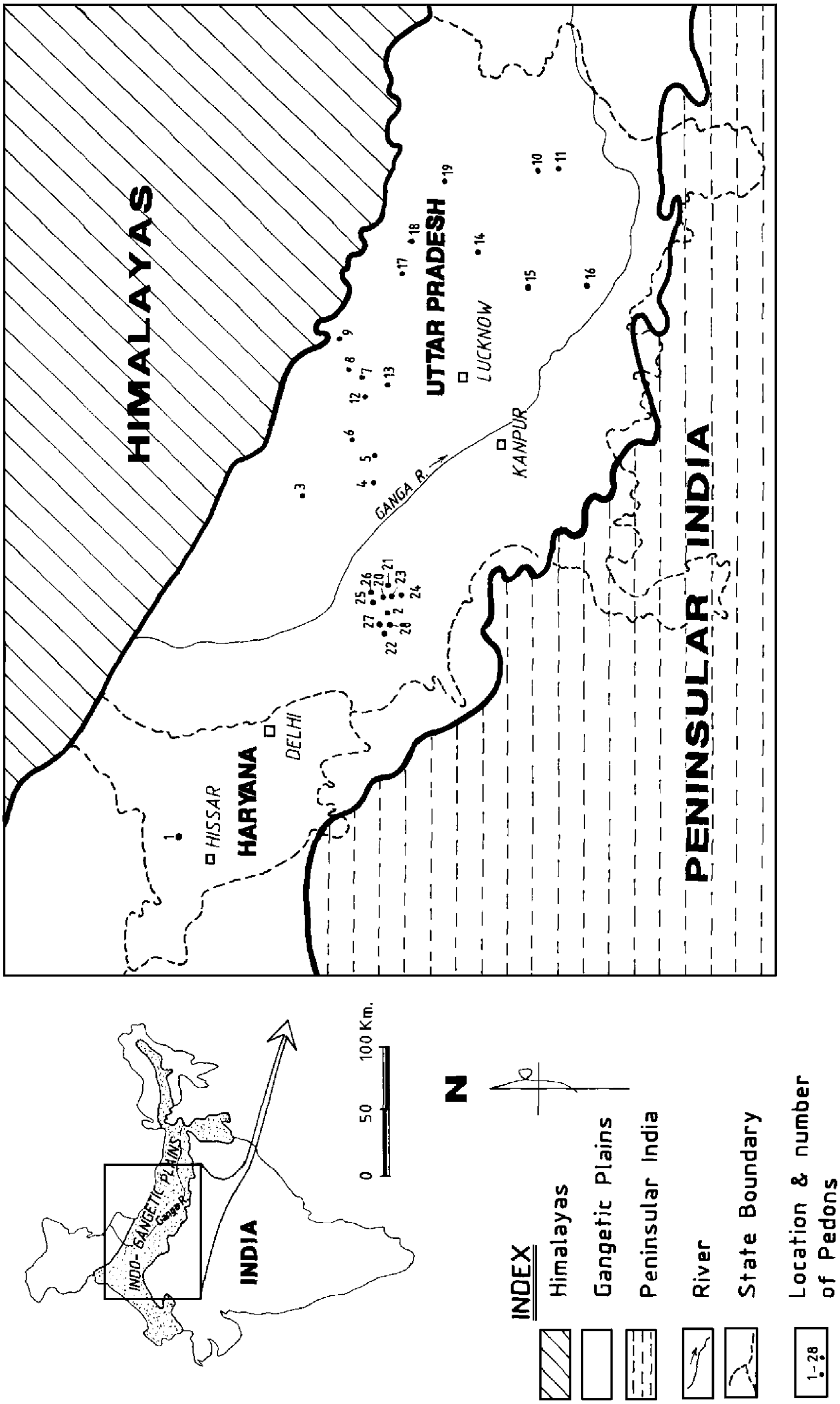
giving rise to optically oriented argillans through the process of clay illuviation (Soil Survey Staff, 1975). Illuviation of clay is considered to be an important pedogenetic process in soil formation. Clay accumulation through illuviation in soils is an established fact since the presence of illuvial clay horizon known as argillic horizon has been recognized as a subsurface diagnostic criterion to group soils at order level in *Soil Taxonomy* (Soil Survey Staff, 1975, 1999) which finds application in the preparation of the legend of *Soil Map of the World* (FAO/UNESCO, 1974).

The argillic (textural B) horizons of large number of calcareous non-sodic and sodic soils developed in loamy-textured parent material and in the semiarid part of Indo-Gangetic Plains of India (IGP) are developed due to illuviation of the fine clay under ustic soil moisture regime (Karale et al., 1974; Sehgal et al., 1975; Bhargava et al., 1981; Manchanda et al., 1983; Pal and Bhargava, 1985; Tomar, 1987; Pal et al., 1994; Srivastava et al., 1994; Kumar et al., 1996; Srivastava, 2001; Srivastava and Parkash, 2002). However, the illuviation of clay has not always resulted in the presence of distinct void argillans. Instead, the pedofeatures without distinct lamination, poorly oriented and with low birefringence (Karale et al., 1974; Kooistra, 1982; Pal et al., 1994) appear to be common in soils of the IGP and thus qualify to be impure clay pedofeatures (Pal et al., 1994) according to Bullock et al. (1985).

Presence of clay pedofeatures and calcium carbonate ($CaCO_3$) is common in soils of arid and semiarid climates not only in the IGP but also elsewhere (Gile, 1970, 1975; Reynders, 1972; Allen and Goss, 1974; Eswaran and Sys, 1979; El-Tezhani et al., 1984; Reheis, 1987). A calcic horizon containing translocated clay is commonly interpreted to represent a climate change (Reheis, 1987). Gile et al. (1966) and Reynders (1972) indicated that clay was translocated in a moister climate but was later engulfed by carbonate when climate became drier, and the clay orientation was also disturbed by accumulation of carbonate (Reynders, 1972). The opposite relation, argillans coating carbonate masses or nodules representing a climatic change from dry to wet, has been reported only rarely (Yarilova, 1964). Allan and Hole (1968) and Arnold (1965), however, implied that for soils developing in calcareous materials, the carbonate must be removed before the clay is mobilized. Like them, many researchers (Jenny, 1941; Smith et al., 1950; Culver and Gray, 1968; Dankert and Drew, 1970; Schaetzl, 1996; Timpson et al., 1996) have postulated carbonate removal as a criterion for illuviation of clay. Bartelli and Odell (1960) opined that the calcium ion enhances flocculation and immobilization of colloidal material. However, Brewer and Haldane (1957) indicated that calcium had no influence on the development of clay skins when produced artificially. Gile and Hawley (1972) concluded that abundant carbonate in alluvial parent materials can prevent the develop-

Fig. 1. Locations of Haplustalfs and Natrustalfs in the Gangetic Plains in the states of Haryana and Uttar Pradesh (UP): 1–28 Pedon numbers: 1—Zarifa Viran, Haryana; 2—Sakit, UP; 3—Bareilly, UP; 4—Kant, Shahajahanpur, UP; 5—Jalalpur, Shahajahanpur, UP; 6—Barwar, Sitapur, UP; 7—Nabinagar, Bahraich, UP; 8—Nanpara, Bahraich, UP; 9—Nawabganj, Bahraich, UP; 10—Azamgarh, UP; 11—Azamgarh 2, UP; 12—Hargaon, Sitapur, UP; 13—Khairabad, Sitapur, UP; 14—Bikapur, Sultanpur, UP; 15—Amethi, Sultanpur, UP; 16—Sheogarh, Allahabad, UP; 17—Jankipur, Gonda, UP; 18—Ranipur, Uturolla, UP; 19—Dudhara, Basti, UP; 20—Misa, Etah, UP; 21—Mihole, Etah, UP; 22—Nagla Bitch, Etah, UP; 23—Hasangarh, 1, Etah, UP; 24—Rajarampur, Etah, UP; 25—Hasangarh 2, Etah, UP; 26—Hasangarh 3, Etah, UP; 27—Daulatpur 1, Etah, UP; 28—Daulatpur 2, Etah, UP.


HIMALAYAS
UTTAR PRADESH
HARYANA
PENINSULAR INDIA
HISSAR
DELHI
LUCKNOW
KANPUR
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INDO-GANGETIC PLAINS
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Gangetic Plains
Peninsular India
River
State Boundary
Location & number of Pedons
1–28

ment of argillic horizons. Experimental studies by Goss et al. (1973) indicated that clay particles can be translocated in a calcareous soil, despite the tendency of clay to flocculate in the presence of Ca^{2+} ions, if channels or pores are available and if precipitation is adequate (Holliday, 1985).

In view of the diversity in the understanding of the genesis of clay pedofeatures in calcareous soils, the present study was undertaken to examine factors involved in and processes in their genesis in calcareous soils in general, and in calcareous non-sodic and sodic soils of the IGP in particular in the light of available data on micromorphological, mineralogical, physical and chemical properties of these soils (Murthy et al., 1982; Kooistra, 1982; Pal et al., 1994; Srivastava et al., 1994; Srivastava, 2001; Srivastava and Parkash, 2002), supplemented by newly acquired data in the Soil Resource Studies Division. It is hoped that despite the major gaps in understanding clay illuviation and the formation of argillic horizons (Eswaran and Sys, 1979; Bullock and Thompson, 1985), the present work will be of value not only for calcareous soils of the IGP but also for similar soils occurring elsewhere.

2. Materials and methods

The study area covers the semiarid parts of the northwestern and north–central IGP in the states of Haryana and Uttar Pradesh (Fig. 1). Twenty-eight Alfisols were selected for detailed micromorphological study of the clay pedofeatures. Details of their location, climate, parent material and classification are given in Table 1.

The characteristics of each pedon and its individual horizons were described following the procedure of the *Soil Survey Manual* (Soil Survey Staff, 1951). Most of the Natrustalfs

Table 1
Soil type, location, parent material, climate, classification and selected properties of soils

Pedon number	Benchmark soil/soil series	State	Parent material	Bioclimatic zone	Texture	Soil reaction pH (1:2)	Classification
1	Zarifa Viran[a]	Haryana	Indo-Gangetic alluvium	Semiarid	Fine-loamy	Alkaline	Typic Natrustalfs
2	Sakit[a,b]	Uttar Pradesh	Indo-Gangetic alluvium	Semiarid	Fine-loamy	Alkaline	Typic Natrustalfs
3–20	17 identified soils of Lucknow, Sultanpur and Faizabad districts[c]	Uttar Pradesh	Indo-Gangetic alluvium	Semiarid	Coarse-loamy to fine-loamy	Neutral to slightly alkaline	Typic Haplustalfs
21–28	9 identified soils of Etah district[d,e]	Uttar Pradesh	Indo-Gangetic alluvium	Semiarid	Loamy	Alkaline	Typic Natrustalfs

[a] Murthy et al. (1982).
[b] Pal et al. (1994).
[c] Srivastava et al. (1994).
[d] Verma et al. (1995).
[e] Sharma et al. (2000).

Table 2
Physical and chemical properties of representative soils

Horizon	Depth (cm)	Particle size distribution of <2 mm (g kg^{-1})			pH 1:2	$CaCO_3$ (g kg^{-1})	Exchangeable cations cmol (+) kg^{-1}				CEC cmol (+) kg^{-1}	ESP	ECP	ESP in SCS
		Sand (2000–50 μm)	Silt (50–2 μm)	Clay (<2 μm)			Ca	Mg	Na	K				
Typic Haplustalf														
Ap	0–11	444	383	173	8.3	10	6.0	4.0	0.2	0.3	10.0	2	60	4
Bt1	11–41	392	392	216	8.2	15	6.4	3.0	0.3	0.3	10.3	3	62	
Bt2	41–71	360	412	228	8.5	20	5.5	2.3	0.4	0.3	11.0	4	50	
Btk	71–108	337	405	258	8.9	40	4.2	3.8	0.6	0.1	12.0	5	35	
Typic Natrustalf														
An1	0–18	400	469	131	10.5	21	Nil	Nil	5.9	0.4	6.0	98	Nil	93
Btn1	18–40	260	470	270	10.4	25	0.1	0.1	16.0	0.4	16.4	97	0.6	
Btn2	40–70	220	480	300	10.5	25	0.1	0.1	20.0	0.6	20.6	97	Nil	
Btn3	70–102	222	450	328	10.3	32	0.5	0.5	17.5	0.5	20.1	87	2.5	
Btn4	102–150	199	500	301	10.3	121	0.8	0.7	12.5	0.5	15.2	82	5.2	
Btk	150–160	220	486	294	10.2	168	1.0	1.0	9.5	0.5	13.0	73	7.7	

are not cultivated because of their very high sodicity and therefore are barren at present. The soils belong to loamy-textural class, have strong structure and patchy clay skins. The soils are calcareous and have neutral to mildly alkaline reaction in Haplustalfs but they are highly alkaline in Natrustalfs (Tables 1 and 2). The exchangeable sodium percentage (ESP) in soil control section (SCS) is very high in Natrustalfs (>25–100) and low in Haplustalfs (< 15) (Murthy et al., 1982; Pal et al., 1994; Srivastava et al., 1994; Verma et

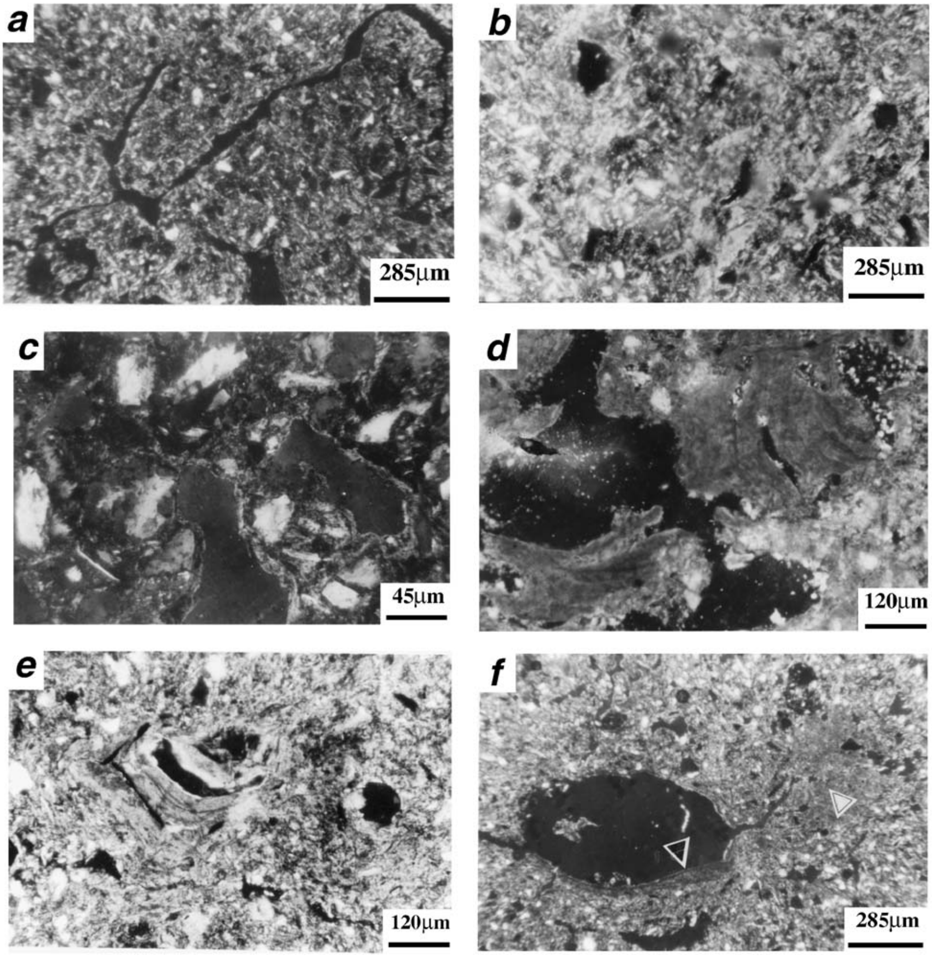


Fig. 2. Representative photomicrographs of the important pedogenic features of the soils (a) strongly developed subangular blocky structure, Pedon 21, Etah, 75–90 cm, (b) moderately to strongly developed cross- and reticulate-striated *b* fabric, Pedon 28, Etah, 78–103 cm, (c) thin continuous clay coating along the mineral grains, Pedon 16, 29–80 cm, (d) part of a large fragmented clay pedofeature, Pedon 20, Etah, 50–74 cm, (e) thick clay pedofeature along void, Pedon 13, Sitapur, 38–84 cm, (f) ferruginous clay pedofeature and diffused micritic nodule, Pedon 18, 50–66 cm. All photomicrographs between cross-polarized light. Black arrowhead indicates clay pedofeatures and the white arrowhead indicates $CaCO_3$ features.

al., 1995; Sharma et al., 2000). The soil temperature and moisture regimes are hyperthermic and ustic, respectively (Soil Survey Staff, 1999).

Undisturbed soil blocks 8 cm long, 6 cm wide and 5 cm thick were collected from soil horizons, and thin sections were prepared by the methods of Jongerius and Heintzberger (1975). They were described according to the nomenclature of Bullock et al. (1985).

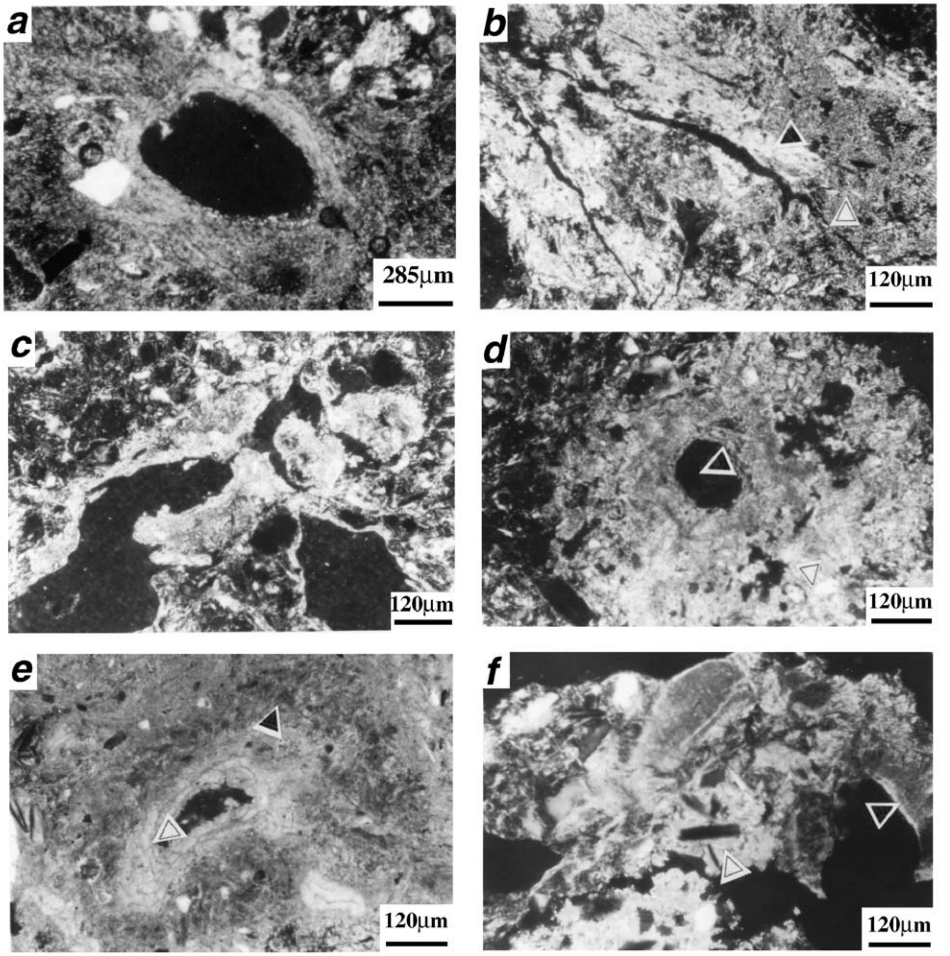


Fig. 3. Representative photomicrographs of clay pedofeatures associated with carbonates. (a) Calcareous silty clay coating along a void, Pedon 20, Etah, 50–74 cm, (b) alternate lamination of clay and calcium carbonate in the soil, Pedon 22, Etah, 51–77 cm, (c) thin clay coating over calcium carbonate coatings in voids, Pedon 13, Sitapur, 38–84 cm, (d) thin clay coating in a void within calcium carbonate nodule, Pedon 15, Sultanpur, 47–78 cm, (e) impure clay coating on a nodule of calcium carbonate, Pedon 18, Uturolla, 50–66 cm, (f) complex pedofeature with clay and calcium carbonate in a void, Pedon 26, Hasangarh 3, Etah, 50–68 cm. All photomicrographs between cross-polarized light. Black arrowhead indicates clay pedofeatures and the white arrowhead indicates $CaCO_3$ features.

Peds of the Bt horizons of representative Haplustalf and Natrustalf of the study area and benchmark acidic (pH ~ 5.6) ferruginous soil of southern India (Vijayapura series, Oxic Haplustalf, Murthy et al., 1982) were broken to open the fresh surfaces and then fixed on aluminium stub with LEIT-C conductive cement. The samples were coated with gold, and examined in a Philips Scanning Electron Microscope (SEM) to study the orientation of clay platelets in the voids.

Particle size distribution was determined by the international pipette method after the removal of organic matter, $CaCO_3$ and free iron, aluminium oxides. Sand (2000–50 μm), silt (50–2 μm), total clay (< 2 μm) and fine clay (< 0.2 μm) fractions were separated by the procedure of Jackson (1979). Soil pH, electrical conductivity of the saturation extract (ECe) and soluble cations and anions in the saturation extracts were measured by standard methods (Richards, 1954). Cation exchange capacity (CEC) and exchangeable sodium and potassium were determined following the method of Richards (1954), substituting 1N $Mg(NO_3)_2$ of pH 8.6 for the NH_4OAc to eliminate the influence of zeolites and feldspathoid minerals (Gupta et al., 1985). Exchangeable calcium and magnesium were determined following the 1N NaCl solution extraction method of Piper (1966).

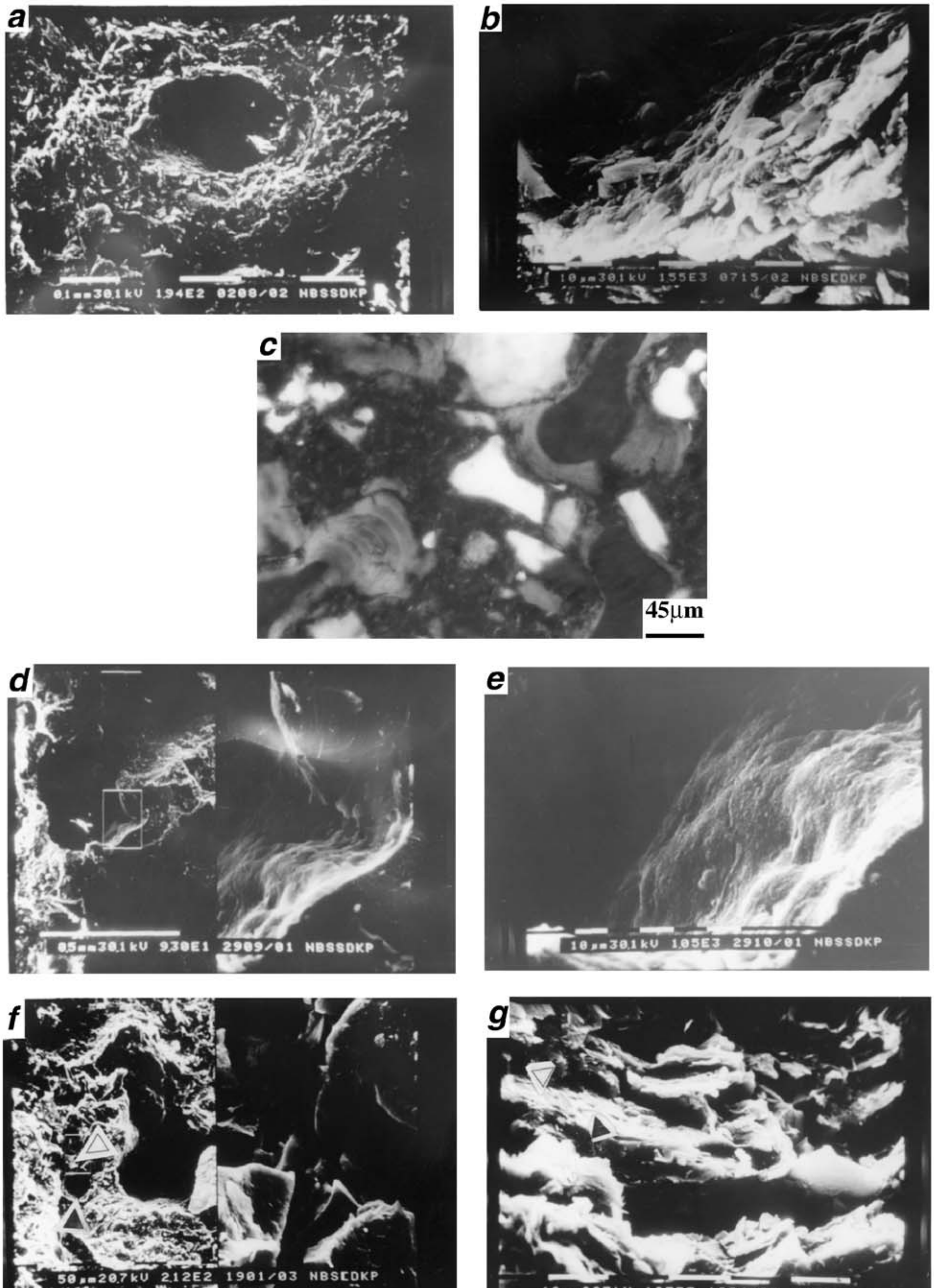
The silt and clay fractions were subjected to X-ray diffraction (XRD) analyses of parallel-oriented slide mounts after Ca- and K-saturation, Ca-glycolation using ethylene glycol and heat treatment of K-saturated samples at 25, 100, 300 and 550 °C, and also HCl treatment using a Philips diffractometer with Ni-filtered CuKα radiation and a scanning speed of 2° 2θ per minute. Semi-quantitative estimates of the clay minerals were made following the principles outlined by Gjems (1967) and Kapoor (1972).

3. Results

3.1. Micromorphological characteristics

The detailed micromorphology of soils with regard to clay pedofeatures were recorded, as this method is the best for identifying illuvial clay (Bullock and Thompson, 1985). Soils of the present study have developed subangular blocky microstructure with channel and vughs (Fig. 2a). In the B horizons, the percentage of coarse mineral grains decreases and that of fine fraction increases. The relative distribution pattern is open porphyric. The coarse fraction consists of quartz, biotite, muscovite, feldspars and heavy minerals. The fine fraction (< 20 μm) is micaceous with micrite crystals at places. The pores are

Fig. 4. Representative scanning electron microscopic features of illuvial clay in soils of the Gangetic Plains along with petrographic and SEM features of ferruginous soils of southern India. (a) Full view of illuvial clay pedofeature along a void, Pedon 13, Sitapur, 38–84 cm, (b) expanded part of the same showing poorly oriented clay platelets, (c) optical photomicrograph in cross-polarized light of strongly oriented void argillan from ferruginous soils showing microlaminations, Vijayapura, 21–46 cm, (d) the same under SEM showing strong orientation of fine clay coating in the void, (e) expanded part of the same showing strong parallel lamination of fine clay particles, (f) micritic to sparitic grains along with alluvial clay pedofeature, Pedon 13, Sitapur, 38–84 cm, (g) expanded view of (f) showing precipitation of $CaCO_3$ between the poorly oriented clay platelets. Black arrowhead indicates clay pedofeatures and the white arrowhead indicates $CaCO_3$ features.


a
0.1mm 30.1kV 1.94E2 0208/02 NBSSDKP
b
10μm 30.1kV 1.55E3 0715/02 NBSEDKP
c
45μm
d
0.5mm 30.1kV 9.30E1 2909/01 NBSSDKP
e
10μm 30.1kV 1.05E3 2910/01 NBSSDKP
f
50μm 20.7kV 2.12E2 1901/03 NBSEDKP
g
10μm 20.7kV 1.93E3 1904/03 NBSEDKP

comprised of randomly distributed, elongated and equant voids, vughs and channels. Carbonate and sesquioxide accumulations are observed throughout the soil depth. Plasma separation is moderate to strong. Cross- and reticulate-striated fabrics were observed in lower parts of the pedons (Fig. 2b).

There are four types of illuvial clay pedofeatures: (i) clay intercalations and thin clay coatings around mineral grains (Fig. 2c), (ii) disrupted clay pedofeatures occurring as remnant of earlier clay pedofeatures (Fig. 2d), (iii) clay pedofeatures occurring in voids (Fig. 2e) and (iv) clay coatings that are intimately associated with $CaCO_3$ coatings and nodules (Figs. 2f and 3a–f). The internal boundaries of these features are generally distinct. These pedofeatures under cross-polarized light are yellowish brown to dark yellowish red, mostly without distinct lamination, are poorly oriented and have low birefringence. Thus, they qualify as impure clay pedofeatures (Bullock et al., 1985). They occupy more than 1% area of the thin section. Impure clay pedofeatures are common in soils of the semiarid part of the IGP (Fedoroff and Courty, 1986; Pal et al., 1994). Disrupted clay pedofeatures were hitherto interpreted as features of paleoclimatic significance (Brewer, 1964; Bullock et al., 1985; Kemp, 1999). The presence of typical impure clay pedofeatures has so far been explained in terms of impairment of the parallel orientation of the clay platelets induced by the disruption of both clay and silt size layer silicates in sodic environment (Pal et al., 1994). Explanations so far proposed, however, do not resolve the prevailing diverse understanding in the genesis of void argillans in calcareous parent material (Jenny, 1941; Smith et al., 1950; Bartelli and Odell, 1960; Allan and Hole, 1968; Arnold, 1965; Culver and Gray, 1968; Dankert and Drew, 1970; Gile and Hawley, 1972; Goss et al., 1973), especially for clay pedofeatures alternating with $CaCO_3$ coatings (Fig. 3f) that have been understood to be an effect of climate change (Yarilova, 1964; Gile et al., 1966; Reynders, 1972; Reheis, 1987). This could be the reason why the development of void argillans and $CaCO_3$ formation are hitherto considered to be two independent pedogenic processes depicting two distinctly different set of climate (Eswaran and Sys, 1979).

Table 3
Chemical composition of the saturation of representative soils

Horizon	Depth (cm)	ECe dS m^{-1}	pH	Soluble cations			Soluble anions				
				Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	CO_3^{2-}
Typic Haplustalf											
Ap	0–11	0.9	8.3	3.2	1.9	10.7	0.4	12.5	1.7	2.0	Nil
Bt1	11–41	0.9	8.2	2.6	8.2	8.2	0.2	12.0	2.2	5.0	Nil
Bt2	41–71	1.3	8.5	4.4	8.1	10.0	0.2	11.9	4.3	6.5	Nil
Btk	71–108	0.1	8.9	4.5	4.2	13.5	0.2	11.5	1.1	9.8	Nil
Typic Natrustalf											
An1	0–18	2.9	10.5	2.6	0.7	1213.7	0.6	167.5	871.4	13.7	164.0
Btn1	18–40	9.0	10.4	2.0	0.6	696.3	0.3	137.9	471.7	25.6	64.0
Btn2	40–70	5.8	10.5	2.4	0.5	452.1	0.2	144.4	232.0	18.2	60.1
Btn3	70–102	4.9	10.3	2.0	0.3	195.6	0.4	80.0	84.2	6.8	27.3
Btn4	102–150	2.7	10.3	1.4	3.2	218.1	0.3	82.4	96.3	44.3	Nil
BtK	150–160	2.5	10.2	2.7	2.2	202.4	0.3	17.2	162.1	28.3	Nil

3.2. Examination of clay platelets under SEM

In order to confirm the impairment of the parallel orientation of the clay platelets as observed under petrographic microscope, voids of Haplustalf and Natrustalf under SEM indicated that both silt and clay size platelets are not oriented parallel to the surface of deposition (Fig. 4a and b). Due to lack of such orientation, they are not optically oriented argillans (Soil Survey Staff, 1975). To prove this point further, voids of a representative acid ferruginous soil (Oxic Haplustalf) indicated the presence of pure void argillans (Fig. 4c) and also strongly oriented clay platelets (Fig. 4d and e). The clay platelets remain in face-to-face or parallel, or oriented aggregation when the flocculation of the clay suspension is not induced by the presence of salts (van Olphen, 1966). The poor orientation of clay platelets suggests that even a mild environment of carbonate and bicarbonate of sodium (Table 3) would result in deflocculation, disengaging face-to-face association of clay platelets (van Olphen, 1966) which would impair the parallel orientation of clay platelets. Poorly oriented clay platelets are often found associated with $CaCO_3$ grains (Fig. 4f and g).

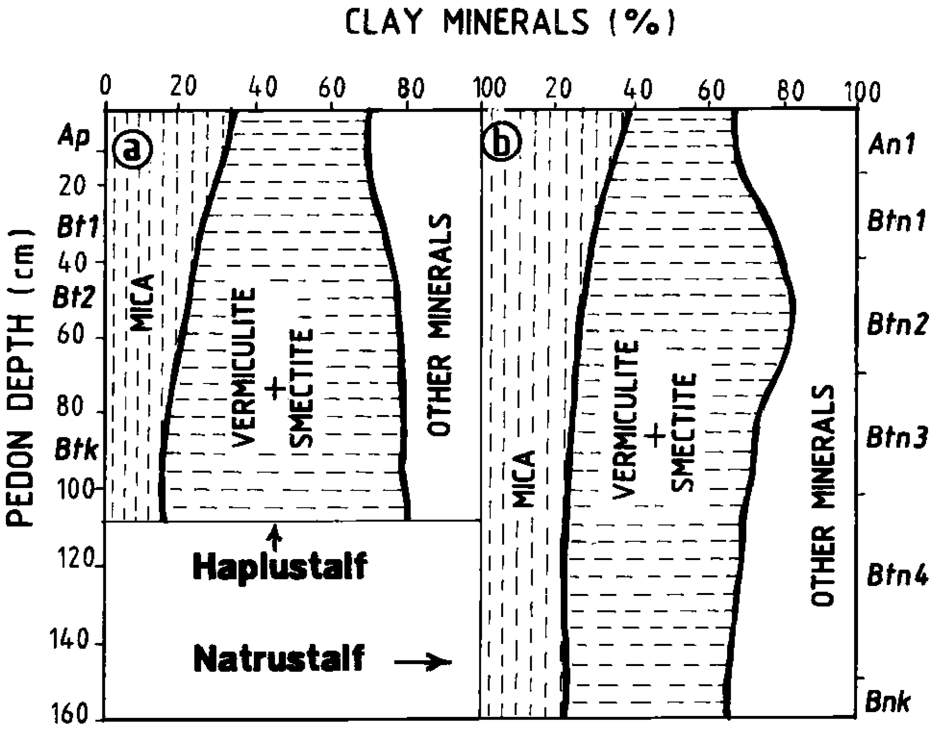


Fig. 5. Changes in clay size mica and vermiculite plus smectite with pedon depth in representative Haplustalf (a) and Natrustalf (b).

3.3. Depth distribution of clay minerals, CEC, exchangeable sodium and ESP

The presence of field-identifiable clay skins and impure clay pedofeatures confirm the illuviation of clay. As a result, clay increases considerably with depth. The ratio of clay content of the Bt horizon to that of the A horizon is >1.2. Like clay, the CEC and ES values increase with depth down to the Bt horizons and then decrease in both Haplustalf and Natrustalf (Table 2).

The illuviation of clay has also resulted in a typical depth distribution of mica and vermiculite plus smectite in the whole clay fraction of the soils (Fig. 5). This has been explained by preferential movement of vermiculite and smectite along with fine clay fractions into the B horizons resulting in an increase in the proportion of mica in the A horizon, and that of vermiculite and smectite in the B horizons (Pal and Bhargava, 1985; Pal et al., 1994). This suggests that movement of the finer clay particles in a deflocculated form can enrich B horizons with clay. Due to loss of clay in the A horizons and gain the Na-clay in the B horizons, both ES and CEC show an increase with depth in both Haplustalfs and Naturstalfs. However, due to low amount of soluble bicarbonate and carbonate of sodium (Table 3), Haplustalfs show an increase in ESP with depth. By contrast, Natrustalfs show decreasing trend in ESP with depth amidst very high amount of soluble sodium bicarbonate and carbonate (Table 3) and low amount of clay and CEC in the upper horizons (Table 2).

4. Discussion

The results of the study clearly indicate the illuviation of clay particles in calcareous soils with loamy-textured parent material under the ustic soil moisture regime. However, illuviation of clay has resulted only in "impure clay pedofeatures" because the parallel orientation of the clay platelets has been impaired by deflocculation of the clay colloids (Pal et al., 1994). This suggests that the removal of $CaCO_3$ is less important for the movement of clay as suggested earlier (Jenny, 1941; Smith et al., 1950; Bartelli and Odell, 1960; Culver and Gray, 1968; Dankert and Drew, 1970; Gile and Hawley, 1972). It was thought earlier that calcium ion enhances flocculation and immobilization of colloidal material (Bartelli and Odell, 1960). However, the pH of a system containing $CaCO_3$ in water in equilibrium with the atmosphere is 8.4 and the ionic strength is so low that correction for the difference of molality and activity is hardly worthwhile (Garrels and Christ, 1965). Marshall (1964) indicates that $CaCO_3$ maintains a concentration of Ca^{2+} ions in a solution of 0.25–5.00 meq/l, depending on the partial pressure of CO_2 in contact with it. Rimmer and Greenland (1976) also pointed out that at a calcium concentration of 5 meq/l, the swelling of Ca-montmorillonite is only 15% less than that in distilled water. The saturation extract of Haplustalfs and Natrustalfs under study indicates a very low amount of Ca^{2+} ions ($\ll$5 meq/l) as compared to Na^{+} ions ($\gg$10 meq/l) (Table 3). It thus suggests that the presence of $CaCO_3$ has minimal role to cause flocculation of clay particles or inhibition of swelling of expanding minerals in the clay fractions (Fig. 5) by contracting their diffuse double layers (Pal et al., 2000). This suggests that movement of deflocculated clay and its subsequent deposition on the void walls or ped faces is possible in calcareous soils. This fact has already been demonstrated experimentally by Goss et al. (1973). The $CaCO_3$ of the soils occur as irregular-shaped nodules as infillings, and coatings of micrite in voids and grains, and often occurs together with illuvial clay pedofeatures (Fig. 3a–f). The micromorphological properties of $CaCO_3$ of the soils are in accordance to their pedogenic origin (Pal et al., 2000) and pedogenic $CaCO_3$ is formed in the semiarid climate prevailing for the last 4000 years B.P. (Srivastava et al., 1994; Pal et al., 2000). During the same time, climate illuviation of clay has remained a major pedogenic process (Pal and Bhargava, 1985; Srivastava et al., 1994; Pal et al., 1994). It thus appears that the formation of $CaCO_3$ and illuviation of clay particles are occurring simultaneously as explained in the following.

The cationic and anionic compositions of the saturation extract of the soils indicate that Na^+ ions dominate among the cations and in the anions HCO_3^- and CO_3^{2-} ions constitute a substantial amount (Table 3). This indicates that the soils of the IGP in the presence of water are capable of releasing substantial amount of bicarbonates and carbonates of alkali (Kovda, 1964; Bhargava and Bhattacharjee, 1982) as the soils have considerable amount of slightly altered plagioclase feldspars (Srivastava et al., 1998; Srivastava and Parkash, 2002). This causes high sodium saturation and pH (≥ 8.4). At pH of ≥ 8.4, Ca^{2+} ions are precipitated as $CaCO_3$. Thus, the soils of the IGP in the semiarid climate are calcareous either in their subsoils or throughout the soil profile (Table 2). Thin sections indicate that its amount, however, increases with depth with its content as 1–2% in the upper horizons and 3–10% in the subsoils. The movement of water therefore resulted in the downward movement of soluble bicarbonates and their precipitation as $CaCO_3$ in the subsoils during the high evaporative demands for soil water. Due to the precipitation of $CaCO_3$, the maintenance of the higher Ca/Na ratio in the soil solution and on the exchange sites becomes difficult resulting in the higher amount of bicarbonate than carbonate ions in the saturation extract of the soils. This increases ESP and concomitantly decreases exchangeable calcium percentage (ECP) down the profile in Haplustalfs (Table 2). Due to accelerated rate of formation and accumulation of $CaCO_3$, the subsoils become sodic, impairing their hydraulic properties. The initial impairment of the percolative moisture regime in the subsoils results eventually in Natrustalfs where ESP decreases but ECP increases with depth (Table 2) (Pal et al., 2000; Srivastava et al., 2002). This suggests that the movement of clay during the formation of Alfisols in the semiarid climate was not prevented by the presence of $CaCO_3$. Rather, the precipitation $CaCO_3$ created an environment of carbonate and bicarbonate of sodium that facilitated the deflocculation of clay particles and their subsequent movement down the soil profile. The alkaline environment created by $NaHCO_3$ and Na_2CO_3 disengaged the face-to-face association of clay platelets (van Olphen, 1966) and consequently led to impairment of parallel orientation of the clay platelets. In this colloidal state, movement of the fine clay particles would result in “impure clay pedofeatures” (Pal et al., 1994). This fact is further corroborated from petrographic and SEM studies of the clay pedofeatures indicating that the impure clay pedofeatures consists of poorly oriented clay platelets (Fig. 4a and b) in contrast to the strongly oriented clay platelets in the pure void argillans of ferruginous soils (Fig. 4c–e).

The formation of clay pedofeatures and pedogenic $CaCO_3$ are, therefore, two simultaneously occurring pedogenic processes. The SEM observations (Fig. 4f and g) showing the presence of $CaCO_3$ grains along with illuvial clay pedofeature support this further. The formation of pedogenic $CaCO_3$, a basic process that initiates the development of sodicity (Pal et al., 2000) has been active in semiarid climate of IGP prevailing for the last 4000 years B.P. (Srivastava et al., 1994, 1998; Pal et al., 2000). Therefore, illuviation of clay and the formation of pedogenic $CaCO_3$ should not be considered as two different episodes representing two different climates; rather, they are two concurrent pedogenic events in soils of the IGP during the semiarid climate of the late Holocene.

5. Conclusions

The results of the present study indicate that the presence of $CaCO_3$ and the concentration of soluble Ca^{2+} ions have minimal role in preventing the illuviation and accumulation of clay particles preserved as clay pedofeatures in soils of the semiarid part of the IGP. The illuviation of clay and the formation of pedogenic $CaCO_3$ are two concurrent and active pedogenic processes. They are contemporary events during the semiarid climate and provide an example of pedogenic thresholds (Chadwick and Chorover, 2001) in soils of the IGP during the last 4000 years B.P.

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