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Clay Illuviation in Calcareous Vertisols of Peninsular India

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Abstract : *In view of diverse understanding on the movement and accumulation of clay particles in Vertisols, a study on seven benchmark calcareous Vertisols representing a climosequence from sub-humid moist to arid dry climate was undertaken. The Vertisols have clay enriched slickensided horizons (Bss) (≥8% absolute increase from the eluvial horizon). The study indicates that the clay enrichment in the Bss horizons due to illuviation of clay particles and their subsequent accumulation in the Bss horizons have been possible because of the dispersion of the clay particles caused by Mg^{2+} and Na^{+} ions when precipitation of soluble Ca^{2+} ions as calcium carbonate ($CaCO_3$) occurs. The formation of $CaCO_3$ and the illuviation of clay are two pedogenetic processes occurring simultaneously as comtemporary pedogenic events in drier climate since the late Holocene. Thus, the argilliturbation towards proisotropic pedoturbation has not been able to overtake the clay illuviation in Vertisols under study for thousands of years.*

Earlier studies on shrink-swell soils of Peninsular India in general and Vertisols in particular, indicate the distribution of clay is more or less uniform through depth upto 1 to 1.6 m and the uniformity substantiates the effect of the process of haploidisation within the pedon (Murthy *et al.*, 1982). A review by Ahmad (1983) also indicated a similar observation that one of the distinguishing features of Vertisols is the near absence of textural differentiation due to considerable mixing of the soil material through pedoturbation (Dudal and Eswaran, 1988; Eswaran *et al.*, 1988; Mermut *et al.*, 1996). In contrast, Dudal (1965) reported that in some cases there is a gradual increase with depth. However, Ahmad (1983) indicated from all available evidence, that variations in clay content with depth are not due to clay migration but rather inherited from the parent material.

Studies on shrink-swell soils in general and Vertisols in particular, by the Division of Soil Resource Studies at the National Bureau of Soil Survey and Land Use Planning, Nagpur, India during the

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last two and a half decades observed the presence of the Bss horizons from nil to substantially enriched with clay (~20% increase from the eluvial horizon) (Pacharne, 1992; Pillai, 1993; Balpande, 1993; Paranjape, 1995; Gabhane, 1996; Kadu, 1997; Vaidya, 2001; Pal *et al.*, 2003a). Morphological examination of these Vertisols did not indicate any sign of stratification in the parent material and also clay skins.

In Vertisols clay translocation is not phenomenal since pedoturbation processes tend to obliterate all evidence of the illuviation process except in lower horizons (Eswaran *et al.*, 1988). Hallsworth (1963) through an experimental study on artificial mixture of sand with montmorillonite found that there was no clay movement when the clay percentage was over 20. Thus, Blokhuis (1982) was of the opinion that clay illuviation in a Vertisol is unlikely and even if it did occur it would be difficult to ascertain, because pedoturbation would in most cases eliminate any textural horizon differentiation (Ahmad, 1983). However, Yaalon and Kalmar (1978) and Wilding and Tessier (1988) indicated pedoturbation in Vertisols is a dynamic, partially functional process. It is an incomplete genetic model and not rapid enough to preclude long-term pedogenic translocation processes.

In view of diversity in observations and understanding on the depth distribution of clay, the present study was undertaken to examine factors involved in and processes in the genesis of the Bss horizons with ≥ 8% clay increase than the eluvial horizons. It is hoped that despite the major gaps in understanding the clay illuviation and pedoturbation, the present work will be of value not only for Vertisols of Peninsular India but also for similar soils occurring elsewhere.

Materials and Methods

Soils

Seven benchmark Vertisols in the states of Maharashtra, Andhra Pradesh, Karnataka, Rajasthan and Gujarat were selected from sub-humid, semi-arid and arid climatic regions (Table 1).

The characteristic of each pedon and its individual horizons were described following the procedure of Soil Survey Manual (Soil Survey Staff, 1951). The particle-size distribution was determined by the international pipette method after removal of organic matter, $CaCO_3$ and Fe oxides. Sand (2000-50 μm), silt (50-2 mm), coarse clay (2-0.6 μm), medium clay (0.6-0.2 μm) and fine clay (< 0.2 mm) fractions were separated according to size segregation procedure of Jackson (1979).

Table 1. *General properties of Benchmark Vertisols in different rainfall and temperature regions of India*

Pedon No.	Soil Series (Soil Taxonomy)[1] (District, State)	Parent material(s)	MAR[2] MRw MRd mm	MAT[3] MTw MTd °C	Structure/lime nodules[4]	Soil Reaction (pH 1:2) water	Cracks (width, depth) Slickensides (depth)[5] Values in cm Effervescence[6] (with dilute HCl)
				Subhumid moist			
6	Loni (Typic Haplusterts) (Yavatmal, Maharashtra)	Basaltic alluvium	1134 1007 127	26.9 27.3 26.7	Moderate medium subangular blocky in the Ap horizon and strong, coarse angular blocky in the Bss horizons/many very fine and common fine nodules	6.3-6.6	1-2, 65; 65 e-es
				Subhumid dry			
9	Nipani (Typic Haplusterts) (Adilabad, Andhra Pradesh)	Alluvia of basalt, limestone and gneiss	1071 916 155	27.0 27.9 26.6	Moderate medium subangular blocky in the Ap horizon and strong, medium angular blocky structure in the Bss horizons/ many very fine, fine and medium lime nodules	7.9-8.4	1-2, 25; 62 ev
				Semi-arid moist			
11	Bhatumbra (Udic Haplusterts) (Bidar, Karnataka)	Basaltic alluvium	977 861 116	25.9 25.6 26.1	Moderate medium subangular blocky in the Ap horizon and strong medium angular blocky in the Bss horizons/ few, very fine, fine and common medium lime nodules	7.7-8.2	1-2, 30; 37 e-es
				Semi-arid dry			
15	Jhalipura (Typic Haplusterts) (Kota, Rajasthan)	Alluvia of basalt and metamorphic rocks	842 709 133	27.0 29.1 26.3	Moderate medium subangular blocky in the Ap horizon and strong medium angular blocky in the Bss horizons/common very fine and few fine lime nodules	7.7-8.4	0.5-2, 50; 48 nil to es

Table 1. *General properties of Benchmark Vertisols in different rainfall and temperature regions of India (contd.)*

Pedon No.	Soil Series (Soil Taxonomy)[1] (District, State)	Parent material(s)	MAR[2] MRw MRd mm	MAT[3] MTw MTd °C	Structure/lime nodules[4]	Soil Reaction (pH 1:2) water	Cracks (width, depth) Slickensides (depth)5 Values in cm Effervescence[6] (with dilute HCl)
18	Kasireddipalli (Sodic Haplusterts) (Medak, Andhra Pradesh)	Alluvia of basalt & granite-gneiss	764 653 111	25.9 26.3 25.5	Moderate medium subangular blocky in the Ap horizon and strong coarse angular blocky in the Bss horizons/many very fine and few fine and medium lime nodules	7.8-8.3	3-4, 60; 30 ev
22	Semla (Aridic Haplusterts) (Rajkot, Gujarat)	Basaltic alluvium	635 486 149	26.7 28.2 26.2	Moderate medium subangular blocky in the Ap horizon and strong coarse angular blocky in the Bss horizons/ many very fine and few fine and medium lime nodules	7.8-8.0	1-2, 40; 57 es-ev
				Arid dry			
25	Sokhda (Calcic Haplusterts) (Rajkot, Gujarat)	Basaltic alluvium	533 382 197	26.7 28.2 26.2	Weak medium subangular blocky in the Ap horizon and strong medium angular blocky in the Bss horizons/ common very fine and fine lime nodules	8.2-8.8	2-3, 30; 63 ev

1. Soil classification according to Soil Survey Staff (1999)
2. Mandal *et al.* (1999), MAR : mean annual rainfall; MRw = mean rainfall of wet months where rainfall exceeds half PET; MRd = mean rainfall of dry months where rainfall is less than half PET.
3. MAT = mean annual temperature; MTw = mean temperature wet months when rainfall exceeds half PET; MTd = mean temperature dry months when rainfall is less than half PET.
4. Described according to Soil Survey Staff (1951)
5. Indicates the depth of the first occurrence of slickensides
6. e = slight; es = strong; ev = violent effervescence

The $CaCO_3$, pH, cation exchange capacity (CEC) and exchangeable Na and K were determined on the fine earth (<2 µm) fractions by standard methods (Richards, 1954). Exchangeable Ca and Mg were determined following 1 *N* NaCl solution extraction method (Piper, 1966). Exchangeable sodium percentage (ESP), and exchangeable magnesium percentage (EMP) were computed from the values of CEC and exchangeable cations. For the estimation of water-dispersible clay (WDC), 10 g soil was added to distilled water in a bottle. The suspension was shaken for 8 hr, transferred to a cylinder, and the volume made up to 1000 ml. Aliquots were taken to determine the clay content following the international pipette method.

Results

Morphological properties of soils

The salient morphological features of Vertisols under study in terms of depth, colour, texture, structure, consistency, cracks, slickensides and calcareousness are detailed in Table 1.

Uniformity of the parent alluvium

The morphology of pedons as well as the depth distribution of sand and silt fractions and the sand to silt ratios on a clay free basis (Table 2) point toward parent material uniformity. Further, the thin sections (not reported here) indicated the presence of a similar group of major minerals within the solum depths, with minor variations in contents and the absence of distinct boundaries between the horizons. The homogeneity of the alluvium suggests that the clay enrichment of the Bss horizons was caused by some process other than sedimentation. In view of the uniformity of the parent alluvium, the clay distribution as a function of depth (Table 2) clearly indicates that these soil are fairly well developed as defined by Barshad (1964). In such soils, the clay content increases with depth to a maximum and then decreases until it remains constant or completely disappears.

Clay distribution as a function of depth

Depth distribution of coarse clay (<2-0.6 µm) and medium clay (0.6-0.2 µm) content does not show any trend with depth, whereas the fine clay (<0.2 µm) increases considerably (Table 2). The total clay content shows more than 8% clay in the Bss horizons than in the Ap and Bw horizons. Moreover, the ratio of fine clay to total clay in the Bss horizons is greater by 1.2 times than the ratio in the Ap and Bw horizons. Depth distribution of total and fine clays suggests the clay illuviation process for the enrichment of clays in the Bss horizons of the soils, indicating the presence of argillic horizon (Soil Survey

Table 2. *Physical and chemical properties of soils*

Hori-zon	Depth (cm)	Sand (2-0.05)	Silt (0.05-0.002)	Clay: Coarse (2-0.6 µm)	Clay: Medium (0.6-0.2 µm)	Clay: Fine (<0.2 µm)	Total clay (<2 µm)	Fine clay/total clay	Clay free Sand/Silt	WDC (%)	pH water (1:2)	$CaCO_3$ (%)	Extractable bases: Ca	Mg	Na	K	Sum	CEC	Exch. Ca/Mg	EMP	ESP
		←------ (%of <2mm) ------→											←-----cmol(p^+)/kg^{-1}------→								
Pedon 6 : LONI : Yavatmal : Sub-humid Moist (Non-Irrigated): *Typic Haplusterts*																					
Ap	0-14	4.2	32.0	11.1	24.4	28.3	63.8	0.44	0.13	7.5	6.3	6.0	43.3	18.0	0.5	1.2	63.0	60.9	2.4	29	0.80
Bw1	14-36	3.4	30.4	8.6	21.3	36.3	66.2	0.55	0.11	7.5	6.3	4.0	36.9	25.6	0.8	0.6	63.9	61.1	1.4	42	1.30
Bw2	36-65	1.9	29.8	4.6	16.8	46.9	68.3	0.69	0.06	15.2	6.4	6.5	27.8	35.3	2.3	0.6	66.0	63.0	0.8	56	3.60
Bss1	65-99	2.8	23.3	3.7	17.8	52.4	73.9	0.71	0.12	10.3	6.4	2.6	37.8	27.3	1.3	0.7	67.1	63.0	1.4	43	2.10
Bss2	99-144	2.5	27.7	7.5	14.5	47.8	69.8	0.68	0.09	14.4	6.5	4.0	23.8	42.9	3.0	0.5	70.2	66.6	0.6	64	4.50
Bss3	144-160	2.8	26.4	7.4	17.2	46.2	70.8	0.65	0.11	19.4	6.6	3.7	25.6	42.0	1.3	0.7	69.6	72.0	0.6	58	1.80
Pedon 9 : NIPANI : Adilabad : Sub-humid Dry : *Typic Haplusterts*																					
Ap	0-13	8.9	45.1	7.6	13.1	25.3	46.0	0.55	0.20	12.6	7.9	24.0	23.2	9.6	0.9	1.0	34.6	42.2	2.4	23	2.0
Bw1	13-35	6.8	41.4	3.8	8.6	39.4	51.8	0.76	0.16	14.5	8.0	26.3	19.1	17.9	0.9	0.3	38.2	40.4	1.6	44	2.1
Bw2	35-62	7.1	42.9	6.8	11.2	32.0	50.0	0.64	0.16	8.8	8.1	24.7	14.3	22.2	0.8	0.3	37.6	39.5	0.5	56	2.0
Bss1	62-88	6.3	43.1	3.3	6.6	40.7	50.6	0.80	0.15	10.1	8.3	25.0	9.8	27.8	0.9	0.2	38.7	43.2	0.3	64	2.0
Bss2	88-127	5.7	42.0	4.5	10.5	37.3	52.3	0.71	0.13	10.1	8.4	24.7	8.3	30.1	1.3	0.2	39.9	42.2	0.3	71	3.1
Bss3	127-155+	5.6	41.8	4.4	8.8	39.4	52.6	0.75	0.13	13.1	8.4	25.2	8.3	28.3	1.5	0.2	38.3	42.2	0.3	67	3.5
Pedon 11 : BHATUMBRA : Bidar : Semi-arid Moist: *Udic Haplusterts*																					
Ap	0-12	3.8	37.5	11.6	23.2	23.9	58.7	0.41	0.10	13.3	8.2	9.0	29.1	24.8	2.6	0.8	57.3	58.6	1.2	42.3	4.4
Bw	12—37	5.4	33.6	9.2	22.0	29.8	61.0	0.49	0.16	14.0	8.1	10.2	33.7	21.4	2.3	0.3	57.7	58.6	1.6	36.5	4.0
Bss1	37-79	6.9	31.4	6.5	17.1	38.1	61.7	0.62	0.22	12.3	7.7	10.0	20.6	24.4	2.0	0.3	47.3	49.8	0.8	49.0	4.0
Bss2	79-110	5.3	27.1	4.7	13.8	49.1	67.6	0.73	0.20	16.6	8.0	10.8	20.1	38.8	2.0	0.4	61.3	63.0	1.9	61.6	3.2
Pedon 15 : JHALIPURA : Kota : Semi-arid Dry : *Typic Haplusterts*																					
Ap	0-12	9.2	48.3	4.3	14.0	24.2	42.5	0.57	0.19	3.9	8.3	0.9	26.2	8.0	1.3	0.4	35.9	36.5	3.3	22	3.6
Bw1	12-31	7.4	47.9	4.3	9.3	31.1	44.7	0.70	0.15	3.7	8.3	5.7	30.9	7.3	0.9	0.4	39.5	36.5	4.2	20	2.5
Bw2	31-48	6.5	42.5	3.9	14.0	33.1	51.0	0.65	0.15	3.2	7.7	5.4	32.3	9.1	0.6	0.4	42.4	40.2	3.5	23	1.5
Bss1	48-74	8.6	43.7	2.6	9.9	35.2	47.7	0.74	0.20	3.3	8.1	5.9	32.0	7.9	0.6	0.4	40.9	37.0	4.1	21	1.6
Bss2	74-110	8.4	42.1	2.0	11.1	36.4	49.5	0.73	0.20	3.1	8.3	7.3	25.8	12.0	0.6	0.4	38.8	36.5	2.1	33	1.6

Table 2. *Physical and chemical properties of soils (contd.)*

Horizon	Depth (cm)	Sand (2-0.05)	Silt (0.05-0.002)	Clay: Coarse (2-0.6 µm)	Clay: Medium (0.6-0.2 µm)	Clay: Fine (<0.2 µm)	Total clay (<2 µm)	Fine clay/total clay	Clay free Sand/Silt	WDC (%)	pH water (1:2)	$CaCO_3$ (%)	Extractable bases: Ca	Mg	Na	K	Sum	CEC	Exch. Ca/Mg	EMP	ESP
		←------ (%of <2mm) ------→											←-----cmol(p^+)/kg^{-1}-----→								
Bss3	110-148	8.2	41.4	4.0	9.5	36.9	50.4	0.73	0.20	3.1	8.1	7.1	30.0	9.1	0.7	0.4	40.2	37.0	3.4	24	1.9
Bss4	148-165	7.1	40.4	3.0	11.8	37.7	52.5	0.72	0.18	3.0	8.4	7.1	28.9	11.6	1.6	0.7	42.8	38.0	2.5	30	4.2
Pedon 18 : KASIREDDIPALLI : Medak : Semi-arid Dry : *Sodic Haplusterts*																					
Ap	0-12	25.3	32.0	3.0	13.7	26.0	42.7	0.60	0.79	6.3	7.8	5.9	34.2	10.7	0.9	0.4	46.2	48.7	3.2	22	2.0
Bw1	12—30	20.7	32.7	2.0	13.9	30.7	46.6	0.66	0.63	10.0	7.8	6.2	34.9	12.7	1.9	0.3	49.8	52.1	2.8	24	4.0
Bss1	30-59	19.7	31.0	2.9	12.1	34.3	49.3	0.70	0.64	11.6	8.1	6.0	29.3	14.0	3.7	0.3	47.3	52.2	2.1	27	7.1
Bss2	59-101	18.3	31.5	2.6	12.1	35.5	50.2	0.71	0.58	12.0	8.5	6.4	26.2	14.4	6.8	0.3	47.7	53.5	1.8	27	13.0
Bss3	101-130	8.6	37.1	2.6	13.1	38.6	54.3	0.71	0.23	15.0	8.5	6.5	35.8	11.5	8.6	0.5	56.4	57.8	3.1	20	14.8
BCK	130-160	12.9	32.5	1.2	13.5	39.9	54.6	0.73	0.40	11.3	8.2	9.1	25.1	16.2	11.1	0.5	48.9	49.5	1.5	33	22.4
Pedon 22 : SEMLA : Rajkot : Semi-arid Dry : *Aridic Haplusterts*																					
Ap	0-17	23.7	33.1	2.6	13.1	27.5	43.2	0.64	0.71	6.0	7.8	15.4	33.8	15.1	0.7	1.1	50.7	49.5	2.3	30	1.4
Bw1	17-42	11.8	28.1	5.4	7.2	47.5	60.1	0.79	0.42	8.8	7.8	18.2	36.4	17.3	1.1	0.5	55.3	50.1	2.1	34	2.2
Bw2	42-57	9.5	26.8	9.8	2.4	51.5	63.7	0.81	0.35	8.6	7.9	18.6	30.9	22.0	2.6	0.3	55.8	53.2	1.4	41	4.9
Bss1	57-86	7.5	32.0	6.2	7.8	46.5	60.5	0.77	0.23	9.1	7.9	14.5	33.8	15.6	2.2	0.8	52.4	48.3	2.2	32	4.5
Bss2	86-115	7.8	25.6	5.2	6.7	54.7	66.6	0.82	0.30	10.4	7.9	17.2	30.2	21.8	3.3	0.3	55.6	52.5	1.4	41	6.3
Bss3	115-144	7.3	30.9	6.4	6.9	48.5	61.8	0.78	0.24	8.3	7.9	17.7	28.9	16.4	1.6	0.7	47.6	47.0	1.7	35	3.4
Bc	144-155	21.5	41.5	9.2	14.6	13.2	37.0	0.36	0.52	5.4	8.0	23.3	18.0	16.9	2.9	0.2	38.0	37.5	1.1	45	7.7
Pedon 25 : SOKHDA : Rajkot : Arid dry : *Calcic Haplusterts*																					
Ap	0-11	31.6	21.8	5.5	9.4	26.0	40.9	0.63	1.45	1.0	8.2	21.9	21.1	9.8	1.0	0.7	32.6	27.6	2.2	35	3.6
Bw1	11+37	30.6	20.0	5.4	5.9	34.1	45.4	0.75	1.53	4.4	8.4	21.4	20.4	8.9	1.2	0.6	31.1	27.5	2.3	32	4.4
Bw2	37-63	29.4	21.0	4.5	5.4	39.7	49.6	0.80	1.40	3.8	8.7	21.5	18.0	13.1	2.6	0.5	34.2	28.5	1.4	46	9.1
Bss1	63-98	27.3	22.0	4.5	6.9	39.3	50.7	0.77	1.24	3.6	8.8	22.0	14.4	13.8	4.7	0.5	33.4	29.0	1.0	47	16.2
Bss2	98-145	23.9	21.3	8.0	4.3	42.5	54.8	0.77	1.12	3.5	8.6	21.6	12.7	15.6	8.5	0.5	37.3	30.3	0.8	51	28.0
BC	145-160	8.5	42.6	7.4	7.1	34.4	48.9	0.70	0.20	3.7	8.5	11.6	11.8	14.0	10.1	0.5	36.4	32.3	0.8	43	31.3

Staff, 2003). However, illuviation of clay particles usually results in the development of clay skins (Soil Survey Staff, 1975) that can be recognized in the field with a 10x lens. In Vertisols the presence of clay skins is not a reality because they get destroyed by the shrinking and swelling of smectitic clays (Dudal and Eswaran, 1988).

Depth distribution of WDC, Exch. Ca/Mg, ESP, EMP and soil $CaCO_3$

Like total and fine clay, WDC and soil $CaCO_3$ show a gradual increase with depth whereas Exch Ca/Mg and EMP show a decrease and an increase, respectively. This suggests that the dispersion and movement of smectite clay particles are related to the increase in the concentration of soluble Mg^{2+} ions due to the precipitation of soluble Ca^{2+} ions as $CaCO_3$ due to aridity (Balpande *et al.*, 1996; Vaidya and Pal, 2002). A significant positive correlation between EMP and WDC (r = 0.41 at the 5 percent level), a significant negative correlation between WDC and Exch. Ca/Mg (r = -0.42 at the 5 percent level), a significant positive correlation between EMP and soil CaCO3 (r = 0.42 at the 5 percent level) and a significant negative correlation between Exch. Ca/Mg and soil $CaCO_3$ (r = 0.45 at the 5 percent level) suggest that Mg^{2+} ions are less efficient than Ca^{2+} ions in flocculating soil colloids (Rengasamy *et al.*, 1986) although the United States Salinity Laboratory (Richards, 1954) grouped Ca^{2+} and Mg^{2+} together as both the ions improve soil structure. Although the ESP shows in general, a gradual increase with depth, no significant correlation was found between WDC, EMP, Exch. Ca/Mg and soil $CaCO_3$ because its effect has been undermined by the presence of Ca-zeolites in the soils (Pedons 6, 15, 22 and 25, Pal *et al.*, 2003a).

Discussion

The results of the study clearly indicate that the fine sized smectitic clay which has a high specific surface area, has all the conditions necessary for dispersion, translocation and accumulation in subsurface horizons in calcareous Vertisols under sub-humid to arid soil moisture regime. Clay illuviation was also identified earlier in clayey soils with slickensides in Canada (Dasog *et al.*, 1987) and in Uruguay (Wilding and Tessier, 1988). Thus, in Vertisols, clay illuviation can be phenomenal and its evidence is not always obliterated due to pedoturbation as indicated by many researchers (Mermut *et al.*, 1996). Often Vertisols are conceived to be an example of proisotropic pedoturbation caused by argilliturbation, which destroys horizons or soil genetic layers and make them regressed to a simpler state (Johnson *et al.*, 1987). However, the illuviation induced clay enriched Bss horizons in Vertisols of the present study strongly suggests that argilliturbation may not at all be a primary pedogenetic process for the formation of Vertisols as proposed by many researchers (Dan and Singer, 1973; Soil Survey Staff, 1975; Buol *et al.*, 1980).

Allan and Hole (1968) and Arnold (1965), however, implied that for soils developing from 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. It was thought earlier that calcium ion enhances flocculation and immobilization of colloidal material (Bartelli and Odell, 1960). Marshall (1964) indicates that $CaCO_3$ maintains a concentration of Ca^{2+} ions in a solution of 0.25 - 5.00 meq/l, depending upon 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 Vertisols under study indicates a very low amount of Ca^{2+} ions ($\ll$ 5 meq/l) (Pal *et al.*, 2003a). It thus suggests that the presence of $CaCO_3$ has minimal role to cause flocculation of clay particles, suggesting that movement of deflocculated clay and its subsequent accumulation in the Bss horizons is possible in calcareous Vertisols. This is in contrast to the experimental study of Hallsworth (1963) that indicated no movement of clay in an artificial mixture of sand and clay >20%. However, the presence of pedogenic $CaCO_3$ in Vertisols as irregular shaped micrite-sparite crystals in the Bss horizons (Pal *et al.*, 2000; Srivastava *et al.*, 2002) indicated their origin in the sub-humid and semi-arid climate prevailing during the late Holocene period (Pal *et al.*, 2001). During the same time, and climate, illuviation of clay appears to remain a major pedogenic process. Thus the formation of $CaCO_3$ and illuviation of clay particles are occurring simultaneously as explained in the following.

Petrographic and SEM examination of plagioclase and micas in similar Vertisols indicated that both the minerals are only slightly altered and lack etch pits and/or dissolution pits. The plagioclase feldspars are, thus not the primary source of Ca^{2+} ions in soil solution, rather non-pedogenic $CaCO_3$ is the major source (Srivastava *et al.*, 2002). The depth distribution of Exch. Ca/Mg (Table 2) suggests that the maintenance of the higher Ca/Mg ratio

(~2, Pal *et al.*, 2000) in the soil solution becomes difficult because Ca^{2+} ions are precipitated as $CaCO_3$ during high evaporative demands for soil water. This results in an increase in soil $CaCO_3$ with depth with the concomitant increase in ESP and EMP (Table 2). This clearly suggests that the movement of clay during the formation of Vertisols was not prevented by the presence of $CaCO_3$. Rather, the precipitation of $CaCO_3$ created a chemical environment charged with Mg^{2+} and Na^+ ions that facilitated the deflocculation of clay particles and their subsequent movement down the soil profile. Therefore, illuviation of clay and the formation of pedogenic $CaCO_3$ are two concurrent pedogenic events in Vertisols of the Peninsular India during the drier climate of the late Holocene.

Conclusions

The results of the present study indicate that substantial illuviation of clay particles in calcareous Vertisols is possible when the illuviation of clay and the formation of $CaCO_3$ are two concurrent and active pedogenic process in dry climates. They are contemporary events and provide an example of pedogenic threshold (Pal *et al.*, 2003b) during the late Holocene. Clay illuviation in calcareous Vertisols appears to be a more important pedogenetic process than argilliturbation towards proisotropic pedoturbation.

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References

Ahmad, N. 1983. Vertisols. In (L.P. Wilding, N.E. Smeck and G.F. Hall, Eds), *Pedogenesis and Soil Taxonomy. II The Soil Orders*. Developments in Soil Science. 11B, Elsevier Pub. Co., Amsterdam, pp.91-123.

Allan, R.J. and Hole, F.D. 1968. Clay accumulation in some Hapludalfs as related to calcareous fill and incorporated loess on drumlins in Wisconsin. *Soil Sci. Soc. Am. Proc.*, **32**: 403-408.

Arnold, R.W. 1965. Multiple working hypothesis in soil genesis. *Soil Sci. Soc. Am. Proc.*, **29**: 717-724.

Balpande, S.S. 1993. Characteristics, Genesis and Degradation of Vertisols of the Purna Valley, Maharashtra. Ph.D. thesis. Dr. PDKV, Akola.

Balpande, S.S., Deshpande, S.B. and Pal, D.K. 1996. Factors and processes of soil degradation in Vertisols of the Purna valley, Maharashtra, India. *Land Degrad. & Dev.*, **7**: 313-324.

Barshad, I. 1964. Chemistry of soil development. In (F.E. Bear, Ed.), *Chemistry of the Soil*. Reinhold, New York, pp.1-70.

Bartelli, L.J. and Odell, R.T. 1960. Laboratory studies and genesis of a clay-enriched horizon in the lowest part of the solum of some

Brunizem and Grag-Brown Podzolic soils in Illinois. *Soil Sci. Soc. Am. Proc.*, **24**: 390-395.

Blokhuis, W.A. 1982. Morphology and genesis of Vertisols. In *Vertisols and Rice Soils in the Tropics*. Transactions 12th International Congress of Soil Science, New Delhi, Vol. 3, pp.23-47.

Buol, S.W., Hole, F.D. and McCracken, R.J. 1980. *Soil Genesis and Classification*. Iowa State University Press, Ames.

Culver, J.R. and Gray, F. 1968. Morphology and genesis of some grayish clay pan soils of Oklahoma. 2 Mineralogy and genesis. *Soil Sci. Soc. Am. Proc.*, **32**: 851-857.

Dan, J. and Singer, A. 1973. Soil evolution on basalt and basic pyroclastic materials in the Golan Heights. *Geoderma*, **9**: 165-192.

Dankert, W.N. and Drew, J.V. 1970. Pedogenic distribution of zinc in Mollisols and associated Entisols in Nebraska. *Soil Sci. Soc. Am. Proc.*, **34**: 916-919.

Dasog, G.S., Acton, D.F. and Mermut, A.R. 1987. Genesis and classification of clay soils with vertic properties in Saskatchewan. *Soil Sci. Soc. Amer. J.*, **51**: 1243-1250.

Dudal, R. 1965. *Dark Clay Soils of Tropical and Sub-tropical Regions*. FAO Agriculture Development Paper 83, 161pp.

Dudal, R. and Eswaran, H. 1988. Distribution, properties and classification of Vertisols. In (L.P. Wilding, and R. Puentes, Eds), *Vertisols : Their distribution, Properties, Classification and Management"*, Tech. Mono. 18, Texas A&M Printing Centre, College Station, TX. pp.1-22.

Eswaran, H., Kimble, J. and Cook, T. 1988. Properties, genesis and classification of Vertisols. In (L.R. Hirekerur, D.K. Pal, J.L. Sehgal and Deshpande, S.B., Eds), *Transactions International Workshop - Classification, Management and Use Potential of Swell-Shrink Soils*. Oxford Univ. Press and IBH, New Delhi, pp.1-22.

Gabhane, V.V. 1996. Occurrence of Shallow to Deep Black Soils on the Basaltic Plateau of Malegaon - their Genesis and Landuse Potential. Ph.D. thesis, Dr. PDKV, Akola.

Hallsworth, E.G. 1963. An examination of some factors affecting the movement of clay in an artificial soil. *J. Soil Sci.*, **14**: 360-371.

Jackson, M.L. 1979. *Soil Chemical Analysis*. Advanced Course, 2nd edn., Published by the author, University of Wisconsin, Madison.

Jenny, H. 1941. *Factors of Soil Formation*. McGraw-Hill, New York, NY 281pp.

Johnson, D.L., Watson-Stegner, D., Johnson, D.N. and Schaetzl, R.J. 1987. Proisotropic and proanisotropic processes of pedoturbation. *Soil Sci.*, **143**: 278-292.

Kadu, P.R. 1997. Soils of Adasa Watershed : Their Geomorphology, Formation, Characteristics and Land Evaluation for Rational Land Use. Ph.D. thesis, Dr. PDKV, Akola.

Mandal, C., Mandal, D.K., Srinivas, C.V., Sehgal, J.L. and Velayutham, M. 1999. *Soil Climatic Database for Crop Planning in India*. NBSS Publication No. 53, NBSS&LUP, Nagpur, 1014 pp.

Marshall, C.E. 1964. *Physical Chemistry and Mineralogy of Soils*, Vol 1, Wiley, New York.

Mermut, A.R., Padmanabham, E., Eswaran, H. and Dasog, G.S. 1996. Pedogenesis. In (N. Ahmad and A. Mermut, Eds.), *Vertisols and Technologies for Their Management*, Developments in Soil Science, Elsevier, Amsterdam, pp.43-61.

Murthy, R.S., Bhattacharjee, J.C., Landey, R.J. and Pofali, R.M. 1982. Distribution, characteristics and classification of Vertisols. In *Vertisols and Rice Soils of the Tropics.* Symposia Paper II, 12th International Congress of Soil Science, Vol. 3, Indian Society of Soil Science, New Delhi, pp.3-22.

Pacharne, T.K. 1992. Characteristics and Genesis of associated Red and Black Soils of a Part of the Saptadhara Watershed. M.Sc. thesis, Dr. PDKV, Akola.

Pal, D.K., Balpande, S.S. and Srivastava, P. 2001. Polygenetic Vertisols of the Purna Valley of Central India. *Catena,* **43**: 231-249.

Pal, D.K., Bhattacharyya, T., Ray, S.K. and Bhuse, S.R. 2003a. Developing a model on the formation and resilience of naturally degraded black soils of the Peninsular India as a decision support system for better land use planning. NRDMS, DST Project Report, NBSSLUP (ICAR), Nagpur, 144 p.

Pal, D.K., Srivastava, P. and Bhattacharyya, T. 2003b. Clay illuviation in calcareous soils of the semi-arid part of the Indo-Gangetic Plains, India. *Geoderma,* **115**: 177-192.

Pal, D.K., Dasog, G.S., Vadivelu, S., Ahuja, R.L. and Bhattacharyya, T. 2000. Secondary calcium carbonate in soils of arid and semi-arid regions of India. In (R. Lal, J.M. Kimble, H. Eswaran & B.A. Stewart, Eds), *Global Climate Change and Pedogenic Carbonates,* Lewis Publishers, Boca Raton, Fl, pp.149-185.

Paranjape, M.V. 1995. Study of Waterlogged Soils of the World Bank Watershed Project (WRWBD-5) Near Tamasvada, Wardha district. M.Sc. thesis, Dr. PDKV, Akola.

Pillai, M. 1993. Spatially Associated Red and Black Soils of Malegaon Plateau - their Characteristics, Genesis and Evaluation. M.Sc. thesis, Dr. PDKV, Akola.

Piper, C.S. 1966. *Soil and Plant Analysis.* Han Publishers, Bombay, India.

Rengasamy, P., Greene, R.S.B. and Ford, G.W. 1986. Influence of magnesium on aggregate stability in sodic red-brown earths. *Aust. J. Soil Res.*, **24**: 229-237.

Richards, E.A. (Ed.) 1954. *Diagnosis and Improvement of Saline and Alkali Soils.* USDA Agriculture Handbook, Vol. 60, US Government Printing Office, Washington, DC.

Rimmer, D.L. and Greenland, D.J. 1976. Effect of CaCO3 on swelling behaviour of a soil clay. *J. Soil Sci.,* **27**: 129-139.

Schaetzl, R. 1996. Spodosol-Alfisol intergrades : bisequal soils in NE Michigan, USA. *Geoderma,* **74**: 23-47.

Smith, G.D., Alloway, W.H. and Riecken, F.F. 1950. Prairie soils of the upper Mississippi Valley. *Adv. Agron.,* **2**: 157-205.

Soil Survey Staff 1975. *Soil Taxonomy.* Agriculture Handbook No. 436, SCS-USDA, U.S. Govt. Printing Office, Washington, DC.

Soil Survey Staff 2003. *Keys to Soil Taxonomy,* 9th Edition, USDA, NRCS, Washington, DC.

Soil Survey Staff, 1951. *Soil Survey Manual.* USDA Agriculture Handbook No. 18, Department of Agriculture, Washington, DC.

Soil Survey Staff, 1999. *Soil Taxonomy : A Basic System of Soil Classification for Making and Interpreting Soil Surveys.* Agri. Handbook, USDA, 436, 869 pp.

Srivastava, P., Bhattacharyya, T. and Pal, D.K. 2002. Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (Vertisols) of India. *Clays & Clay Miner.*, **50**: 111-126.

Timpson, M.E., Lee, S.Y., Annous, J.T. and Foss, J.E. 1996. Mineral investigation of soils formed in calcareous gravelly alluvium, eastern Crete, Greece. *Soil Sci. Soc. Am. J.*, **60**: 299-308.

Vaidya, P.H. 2001. Evaluation of Shrink-Swell Soils and Groundwater of the Pedhi watershed in Amravati district for Land Use Planning. Ph.D. thesis, Dr. PDKV, Akola.

Vaidya, P.H. and Pal, D.K. 2002. Microtopography as a factor in the degradation of Vertisols in central India. *Land Degrad. & Dev.*, **13**: 429-445.

Wilding, L.P. and Tessier, D. 1988. Genesis of Vertisols : Shrink-swell phenomenon. In (L.P. Wilding and R. Puentes, Eds.), *Vertisols : their Distribution, Properties, Classification and Management.* SMSS-Texas A&M University, pp.55-79.

Yaalon, D.H. and Kalmar, D. 1978. Dynamics of cracking and swelling clay soils : displacement of skeletal grains, optimum depth of slickensides and rate of intra-pedogenic turbation. *Earth Surf. Processes,* **3**: 31-42.