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Vertisols (cracking clay soils) in a climosequence of Peninsular India: Evidence for Holocene climate changes

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A B S T R A C T

Smectitic parent material from the weathering Deccan basalt has been deposited in the lower piedmont plains, valleys and microdepressions during a previous wetter climate. The cracking clay soils (Vertisols) were developed in such alluvium during drier climate of the Holocene period. In India they occur in humid tropical (HT), sub-humid moist (SHM), sub-humid dry (SHD), semi-arid moist (SAM), semi-arid dry (SAD) and arid dry (AD) climatic environments and thus indicate an array of soils in a climosequence. The soils show a change in their morphological, physical, chemical and micromorphological properties in the climosequence. Soils of HT climate are dominated by Ca^{++} ions in their exchange complex throughout depth. However, in the sub-humid climates Mg^{++} ions tend to dominate in the lower horizons. The sub-humid moist to aridic climatic environments caused a progressive formation of pedogenic calcium carbonates (PC) with the concomitant increase in Na^{+} ions in soil solution. This facilitated the translocation of Na-clay in the soil profile. This is responsible for the increase in pH, decrease in Ca/Mg ratio of exchange sites with depth and finally in the development of subsoil sodicity. The reduction in mean annual rainfall (MAR) from sub-humid moist to arid climates accelerated the formation of PC and thus the soils of semi-arid and arid climates (SAM, SAD and AD) are more calcareous and sodic than soils of other climates (SHM and SHD).

Formation of PC, illuviation of clay and the development of subsoil sodicity are concurrent, contemporary and active pedogenetic processes operating during the climate change of the Holocene period. These processes impaired the hydraulic properties of soils in general, and in soils of drier climates in particular. As a result, cracking pattern, chemical composition and plasmic fabric were more modified in soils of the drier climates. Such modifications in soil properties have a place in the rationale of Vertisol order of the US Soil Taxonomy. The soils of wetter climates (HT, SHM and SHD) are grouped in Typic Haplusterts whereas the soils of drier climates (SAM, SAD and AD) are classified as Aridic Haplusterts, Sodic Haplusterts and Sodic Calciusterts. The present study demonstrates how the intrinsic soil properties of the cracking clay soils in a climosequence may help in inferring the change in climate in a geologic period.

1. Introduction

The cracking clay soils (Vertisols) occur in wider climatic zones of the world (Ahmad, 1996). Dudal and Eswaran (1988) stated that Vertisols show characteristics that are related to overall climate. They also pointed out that other factors such as texture, clay mineralogy, the nature of cation saturation, and the amount of exchangeable sodium have an equally important influence on soil morphology and therefore, a correlation with climate appears to be somewhat complicated. However, Eswaran et al. (1988) suggested that the abundance of Vertisols in the semi-arid parts of the world apparently suggests the role of climate in their genesis.

Large amounts of smectite are required for the manifestation of shrink–swell process in Vertisols. The smectite minerals may be derived from the original rock or develop after sedimentation through neo-genesis or transformation from primary minerals. The stability of smectite is ephemeral in the tropical humid climate as evident from its transformation to kaolin (Pal et al., 1989; Bhattacharyya et al., 1993). In sub-humid to arid climates, weathering of primary minerals contributes very little towards the formation of smectite (Srivastava et al., 2002). It is thus difficult to reconcile the retention of smectite in Vertisols of tropical humid climate and also its formation in sub-humid to arid climatic conditions. Although over the past few decades knowledge has

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grown greatly (Blokhuis, 1982; Murthy et al., 1982; Dudal and Eswaran, 1988; Murthy, 1988; Wilding and Tessier, 1988; Eswaran et al., 1988; Ahmad, 1996; Mermut et al., 1996), a comprehensive synthesis to capture the subtle changes of pedogenetic processes in Vertisols of varied climatic zones still remains elusive.

There are 243 benchmark (BM) cracking clay soils (CCS) (Vertisols and Vertic Intergrades) identified by the National Bureau of Soil Survey & Land Use Planning (NBSS&LUP), Nagpur, India (Bhattacharyya et al., 2007a). This data set has been broadened by the Division of Soil Resource Studies (DSRS) of the NBSS&LUP (Fig. 1) to 306 CCS soils which include 112 Vertisols (Fig. 1). During the last two and half a decade the DSRS examined about 100 Vertisols in the states of Madhya Pradesh, Maharashtra, Chhattisgarh, Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, Rajasthan and West Bengal in India. They belong to humid tropical (HT), sub-humid moist (SHM) and dry (SHD), semi-arid moist (SAM) and dry (SAD) and arid dry (AD) climatic environments.

The majority of the Vertisols in India occur in the lower physiographic position i.e., in the lower piedmont plains or valleys (Pal and Deshpande, 1987) or in microdepressions (Bhattacharyya et al., 1993). They are developed in the same parent material i.e., mainly in the alluvium of weathering Deccan basalt (Pal and Deshpande, 1987; Bhattacharyya et al., 1993) mostly during the Holocene period (Pal et al., 2001, 2006). These soils are impoverished in organic carbon both in surface and sub-surface layers (<1%, Tables 1–6), indicating no substantial role of biotic factors in the formation of Vertisols in general and sodic Vertisols in particular (Pal et al., 2003a). The average depth to the water table ranges between 10 and 15 m. Thus the Vertisols have limitations that restrict their full potential to grow both rainy and winter crops (Kadu et al., 2003). Thus they are generally less intensively cultivated (Bhattacharyya et al., 2007b), indicating that management interventions in these soils have no positive role in their formation and also in modifications.

In response to global climate during the Quaternary, the soils of many places of the world witnessed climatic fluctuations, especially in the last post-glacial period. Frequent climatic changes also occurred during the Quaternary (Ritter, 1996). Brunner (1970) reported evidence for tectonic movements during the Plio–Pleistocene transition which caused the formation of different relief types and relief generation. With the formation of the Western Ghats during the Plio–Pleistocene crustal movements, the humid climate of the Miocene–Pliocene was replaced by the semi-arid conditions which continue to prevail in central and southern Peninsular India. The Arabian Sea currently flanks the Western Ghats, which rise precipitously to an average height of 1200 m. The result is an orographic rainfall, being heavy all along the west coast. The lee-side towards the east receives less than 1000 mm rainfall and is typically rain-shadowed (Rajaguru and Korisetter, 1987). The current aridic environment prevailing in many parts of the world, including India (Eswaran and van den Berg, 1992), may create adverse physical and chemical environments of soils. Thus a new research initiative is warranted to follow the changes in properties of soils amidst climatic change.

The present study considered six Vertisols representing one each from HT, SHM, SHD, SAM, SAD and AD climates (Fig. 1; Tables 1–6). Minerals of an intermediate weathering stage can be regarded as potential indicators of climate changes in southern and central Peninsular India (Pal et al., 1989; Srivastava et al., 1998). The present study demonstrates how the morphological, physical, chemical, mineralogical and micromorphological data can provide insight into the subtilities of pedogenetic processes that have taken place in Vertisols of Peninsular India in response to change in climate from humid to arid during the Holocene period.

2. Methods

The characteristic of each pedon and its individual horizons were described following the procedure of the Soil Survey Manual (Soil Survey Division Staff, 1995). Undisturbed soil blocks (8 cm long, 6 cm wide and 5 cm thick) were collected from the Bss horizons, thin sections were prepared by the methods of Jongerious and Heintzberger (1975), and the features were described according to the nomenclature of Bullock et al. (1985). The amounts of calcium carbonates ($CaCO_3$) were determined by the frequency distribution chart of Bullock et al. (1985). The ^{14}C age of soil organic carbon in the last horizon (Bss2/Bss3/Bss4/Ck1/BC/BCk1/Bw3/2C/Bk2 horizons) was estimated at Birbal Sahni Institute of Paleobotany, Lucknow, India. 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 μm), total clay (<2 μm), and fine clay (<0.2 μm) fractions were separated according to the procedure of Jackson (1979). $CaCO_3$ was determined by rapid titration (Piper, 1966). After equilibrating the soil with distilled water in the ratio of 1:2 with occasional stirring for 30 min, the pH of the soil suspension was measured (Richards, 1954). The cation exchange capacity (CEC) was determined by saturating the soil with 1 N sodium acetate (pH 8.2) and exchanging the Na^+ ions in 1 N ammonium acetate (pH 7) (Richards, 1954). The Na^+ ions were measured in atomic absorption spectro-photometer to calculate the CEC. Exchangeable Ca and Mg were determined following the 1 N NaCl solution extraction method (Piper, 1966). Carbonate clay (Shields and Meyer, 1964) was determined on the basis of the gravimetric loss of carbon dioxide using Collins' calcimeter. The saturated hydraulic conductivity (sHC) was determined using a constant head permeameter (Richards, 1954). The co-efficient of linear extensibility (COLE) was determined following the method of Schafer and Singer (1976). 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 h, 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.

Mineralogy of the silt and clay fractions was carried out by X-ray diffraction (XRD) of oriented aggregates saturated with either Ca/Mg or K, using a Phillips diffractometer with Ni-filtered CuKα at a scanning speed of $2°2\theta$/min. The minerals were identified using the diagnostic methods of Jackson (1979) and Brown (1984). Semi-quantitative estimates of clay minerals in the clay fractions were carried out following the method of Gjems (1967).

3. Results

Vertisols of humid tropical environments will be discussed first followed by soils of other climatic environments.

3.1. Vertisols of HT environments

This area is characterized by humid tropical climate with MAR of 3287 mm, MAT (mean annual temperature) of 29 °C, MTw (mean temperature wet months when rainfall exceeds half PET) of 26 °C, and MTd (mean temperature dry months when rainfall is less than half PET) of 28 °C.

Vertisols occur as one of the components of catenary association with Mollisols and Alfisols on the Deccan basalt area of central and western India (Bhattacharyya et al., 2005, 2006). These soils occur in gently sloping to undulating lands and are developed in the alluvium of the Deccan basalt. These soils are dark brown in colour and ≥150 cm thick (Table 1). They show slightly hard to very hard

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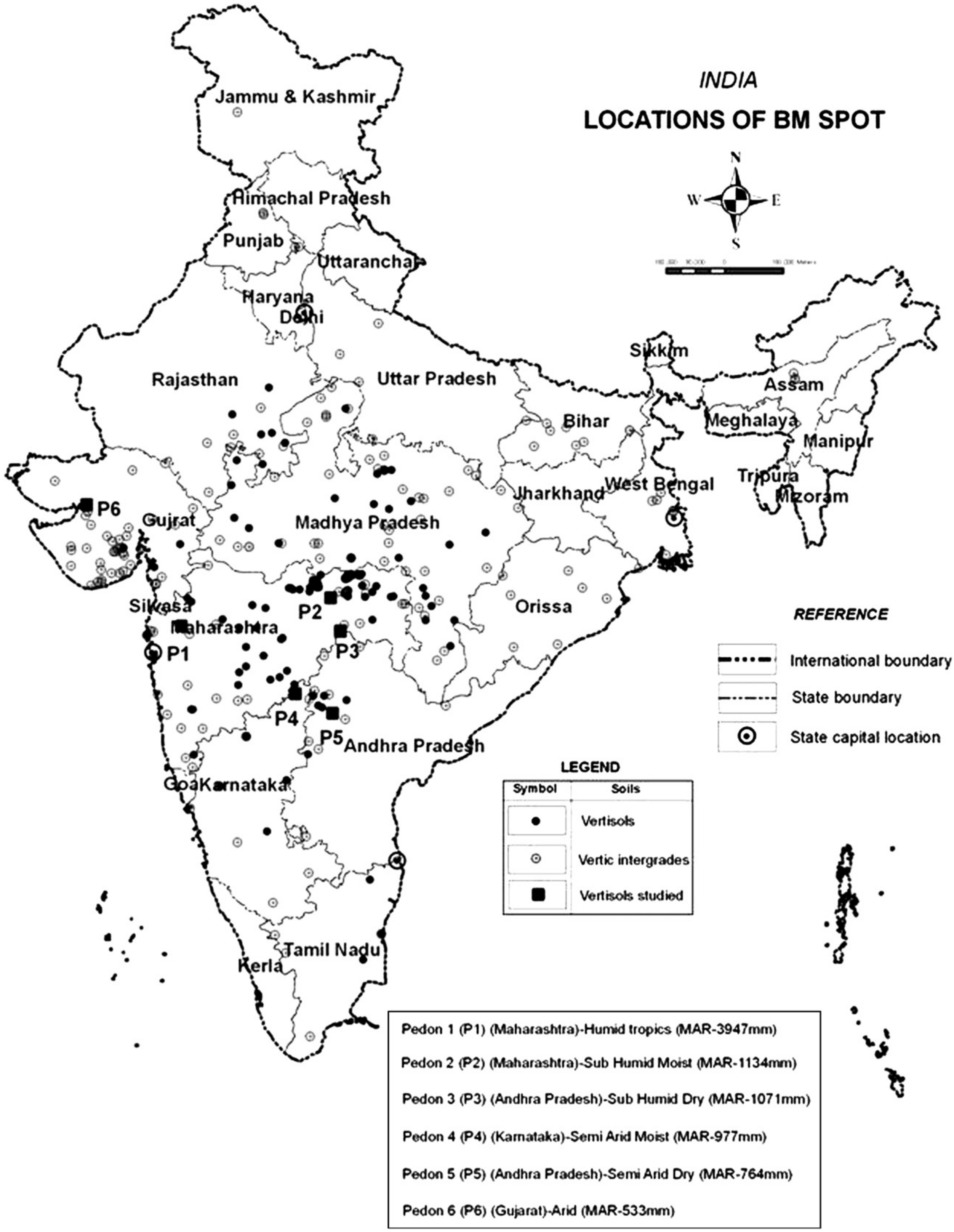

Fig. 1. Locations of Vertisols and Vertic Intergrades including Vertisols studied.

(dry) and friable (moist) consistency. Weak and wedge-shaped aggregates breaking to weak angular blocks with pressure faces were common. The soils also showed cracks of width 2–3 cm and extend up to 25–30 cm depth.

These soils contain very small amount of sand (<5%) but a large amount of clay (57–66%) (Table 1). The total clay content shows more than 8% clay in the Bss horizons than in the Ap horizons. The ratio of fine clay to total clay (FC/TC) in the Bss horizons is greater

Table 1
Physical, chemical and mineralogical properties of Pedon 1 (Typic Haplusterts) as representative of the HT climate.

(a) Physical properties

Horizon	Depth (cm)	Size class and particle diameter (mm)				Fine clay (%)	Fine clay/total clay	COLE	sHC (cm h^{-1})	WDC (%)
		Total								
		Sand (2–0.05)	Silt (0.05–0.002)	Fine silt (0.006–0.002)	Clay (<0.002)					
		(% of <2 mm)								
Ap	0–15	4	39	12	57	33	0.58	0.09	3.0	9.0
Bw	15–35	3	37	13	60	42	0.70	0.09	2.8	9.5
Bss1	35–82	4	35	12	61	44	0.72	0.20	3.0	15.0
Bss2	82–125	4	30	14	66	46	0.70	0.21	2.2	16.0
Bss3	125–150	4	35	15	61	51	0.83	0.09	1.6	10.2

(b) Chemical and mineralogical properties

Depth (cm)	pH water (1:2)	OC (%)	$CaCO_3$ (%)	Extractable bases (cmol(p+) kg^{-1})					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	Smectite in clay <2 μm (%)	BS (%)
				Ca	Mg	Na	K	Sum				
0–15	6.6	0.9	Trace	17.0	6	0.5	0.4	23.9	31	51	48	77
15–35	6.4	0.7	Trace	17.0	6	0.5	0.4	23.9	29	48	50	82
35–82	6.8	0.6	Trace	18.0	11	0.7	0.5	30.2	29	47	50	104
82–125	6.7	0.5	Trace	18.0	12	0.8	0.4	31.2	30	46	58	104
125–150	6.5	0.5	Trace	19.0	11	0.8	0.4	31.2	39	64	62	80

(c) Exch. Ca/Mg, ECP, EMP and ESP

Depth (cm)	Exch. Ca/Mg	ECP	EMP	ESP
0–15	2.8	56	20	2
15–35	2.8	60	22	2
35–82	1.6	61	38	2
82–125	1.5	61	39	3
125–150	1.7	48	28	2

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)			
	ECe (dS m^{-1})	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
0–15	0.2	0.5	0.5	0.4	0.02	–	0.8	0.6	–
15–35	0.2	0.5	0.4	0.2	0.02	–	0.8	0.2	0.1
35–82	0.1	0.6	0.5	0.3	0.01	–	1.0	0.4	–
82–125	0.1	0.7	0.5	0.5	0.01	–	1.4	0.2	0.1
125–150	0.1	1.0	0.5	0.5	0.01	–	1.5	0.4	0.1

COLE = co-efficient of linear extensibility; sHC = saturated hydraulic conductivity; WDC = water dispersible clay; effective smectite [discrete smectite + smectite after peak shift analysis of Sm/K, Wilson (1987)]; ECP = exchangeable calcium percentage; EMP = exchangeable magnesium percentage; ESP = exchangeable sodium percentage; ECe = electrical conductivity of the saturation extract.

than 1.2 times than the ratio in the Ap horizon. Depth distribution of total and fine clays suggests the clay illuviation process which enriched the Bss horizons (Soil Survey Staff, 2003).

The soils are slightly acidic to neutral and non-calcareous. Their CEC ranges from 29 to 39 cmol(p+) kg^{-1} and these values are, in general, low as compared to Vertisols of lesser mean annual rainfall (MAR) regions (Tables 2–6). The XRD analysis of fine clays indicates the dominance of both smectite and smectite–kaolin (Sm/K) minerals. The presence of Sm/K minerals indicates the advanced stage of weathering in HT climate. Smectite content in their clay fractions is much higher (Table 1) than the required minimum threshold value of 20% for the manifestation of vertic characters (Shirsath et al., 2000). Base saturation in these soils is high, and in some horizons it is ≃100% (Table 1). Calcium and magnesium ions together dominate the exchange complex due to the presence of Ca-zeolites (Bhattacharyya et al., 2005).

3.2. Vertisols of SHM and SHD environments

The area under SHM is characterized by MAR of 1134 mm, MAT of 26.9 °C, MTw of 27.3 °C and MTd of 26.7 °C. The area under SHD is characterized by MAR of 1071 mm, MAT of 27 °C, MTw of 26.6 °C and MTd of 23.3 °C.

The soils of SHM occurring in very sloping lands are developed in the alluvium of the Deccan basalt whereas those of SHD climate in the alluvium of the Deccan basalt, granite-gneiss and limestone. Soils of SHM climate are very dark gray to very dark grayish brown, fine textured and >150 cm thick. The surface horizons had moderate medium subangular blocky structures and were hard (dry) with friable consistency (moist). Strong, medium, subangular blocky structures with pressure faces and weak wedge-shaped aggregates in the surface horizons and strong coarse angular blocky structure with wedge-shaped aggregates and slickensides that break into small angular peds were prominent in the subsoils.

The soils of SHD climate are very dark grayish brown, fine textured and >150 cm deep. The surface horizons had a medium subangular blocky structure with pressure faces and were friable. Strong, medium, subangular blocky to weak subangular blocky structures with pressure faces and weakly developed slickensides to strong medium angular blocky (weak) structure with weakly developed wedge-shaped aggregates and slickensides that break into weak angular peds were predominant in the subsoils.

The soils of SHM and SHD climates have cracks of width 1–2 cm, extending up to 25–35 cm, and have sand <10%. Clay content is higher (64–76%) in soils of SHM than those (43–52%) of SHD climate (Tables 2 and 3). Both soil groups show >8% clay in the Bss horizons than their Ap horizon. The ratio of FC/TC in the Bss horizons is greater than 1.2 times than the ratio in the Ap horizon (Tables 2 and 3). The trends suggest an increase of clay in the Bss horizons is due to the illuviation of clay (Soil Survey Staff, 2003).

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Table 2
Physical, chemical and mineralogical properties of Pedon 2 (Typic Haplusterts) as representative of the SHM climate.

(a) Physical properties

Horizon	Depth (cm)	Size class and particle diameter (mm) Total (% of <2 mm)				Fine clay (%)	Fine clay/total clay	COLE	sHC (cm h^{-1})	WDC (%)
		Sand (2–0.05)	Silt (0.05–0.002)	Fine silt (0.006–0.002)	Clay (<0.002)					
Ap	0–14	6	30	13	64	32	0.50	0.10	2.7	7.5
Bw1	14–36	4	27	12	69	32	0.46	0.14	3.9	7.5
Bw2	36–65	3	27	13	70	43	0.61	0.17	3.9	15.2
Bss1	65–99	5	19	10	76	47	0.61	0.25	3.1	10.3
Bss2	99–144	4	27	13	69	45	0.65	0.26	3.3	14.4
Bss3	144–160	4	25	13	71	40	0.56	0.10	1.8	19.4

(b) Chemical and mineralogical properties

Depth (cm)	pH water (1:2)	OC (%)	$CaCO_3$ (%)	Extractable bases (cmol(p+) kg^{-1})					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	Smectite in clay <2 μm (%)	BS (%)
				Ca	Mg	Na	K	Sum				
0–14	6.3	1.1	6.0	43.3	18.0	0.5	1.2	63.0	60.9	96	90	103
14–36	6.3	0.6	4.0	36.9	25.6	0.8	0.6	63.9	61.1	88	88	104
36–65	6.4	0.6	6.5	27.8	35.3	2.3	0.6	66.0	63.0	90	86	105
65–99	6.4	0.6	3.0	37.8	27.3	1.3	0.7	67.1	63.0	82	80	106
99–144	6.5	0.5	4.0	23.8	42.9	3.0	0.5	70.2	66.6	97	95	105
144–160	6.6	0.1	4.0	25.6	42.0	1.3	0.7	69.6	72.0	102	96	97

(c) Exch. Ca/Mg, ECP, EMP, ESP and carbonate clay in soil and on fine earth basis (feb)

Depth (cm)	Exch. Ca/Mg	ECP	EMP	ESP	CO_3 clay (%)	CO_3 clay (feb) (%)
0–14	2.4	71	29	0.8	3.0	1.9
14–36	1.4	60	42	1.3	3.2	2.2
36–65	0.8	44	56	3.6	3.4	2.4
65–99	1.4	60	43	2.1	3.5	2.7
99–144	0.6	36	64	4.5	3.6	2.5
144–160	0.6	35	58	1.8	4.5	3.2

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)			
	ECe (dS m^{-1})	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
0–14	0.94	5.15	5.04	1.52	0.02	2.12	3.18	0.34	6.09
14–36	0.31	1.60	1.70	1.96	0.01	2.12	1.06	0.66	1.43
36–65	0.41	1.06	2.00	4.10	0.03	2.12	1.59	0.80	2.68
65–99	0.38	2.02	1.71	5.22	0.02	2.12	0.53	0.60	5.72
99–144	0.63	1.40	3.26	6.09	0.03	1.06	2.12	1.00	6.60
144–160	0.54	1.20	2.43	4.78	0.01	1.06	2.12	1.10	4.14

COLE = co-efficient of linear extensibility; sHC = saturated hydraulic conductivity; WDC = water dispersible clay; ECP = exchangeable calcium percentage; EMP = exchangeable magnesium percentage; ESP = exchangeable sodium percentage; feb = fine earth basis; ECe = electrical conductivity of the saturation extract.

Vertisols of SHM climate are slightly acidic to neutral and calcareous whereas those of SHD are mildly to moderately alkaline and highly calcareous due to $CaCO_3$ parent material. The clay CECs of both the soils are higher than those of HT climate (Tables 1–3). The fine clays are almost dominated by smectite (Tables 2 and 3). The soils have high base saturation and it is almost 100% in soils of SHM climate because of the presence of zeolites (Pal et al., 2006). Calcium and magnesium ions dominate the exchange complex. However, exchangeable magnesium and sodium percentage (EMP and ESP) show their increase with depth (Tables 2 and 3) and this increase is related to the precipitation of soluble Ca^{+2} ions as $CaCO_3$ in dry climate. The EMP and ESP caused impairment of the hydraulic properties of soils (Balpande et al., 1996; Pal et al., 2000, 2006). However, the impairment is not of higher magnitude as reflected in their sHC values >1 cm h^{-1} (Tables 2 and 3).

3.3. Vertisols of SAM and SAD environments

The area under SAM is characterized by MAR of 977 mm, MAT of 25.9 °C, MTw of 25.6 °C and MTd of 26.1 °C. The area under SAD is characterized by MAR of 764 mm, MAT of 25.9 °C, MTw of 26.3 °C and MTd of 25.5 °C.

These soils occur in very gently sloping and level lands. The soils of SAM are developed in the alluvium of the Deccan basalt and the soils of SAD climate in the alluvium of the Deccan basalt and granite-gneiss. The soils of SAM climate were dark grayish brown to very dark grayish brown in colour, fine textured and >150 cm thick. The surface horizons had medium, moderate to strong subangular blocky structures and were friable when moist. Strong, medium to coarse, angular blocky structure with well-developed wedge-shaped aggregates and slickensides that break easily into small angular peds, were predominant in the subsoils. Subsoils are occasionally slightly firm when moist.

The soils of SAD climate were very dark gray to very dark grayish brown, fine textured and >150 cm thick. The surface horizons had a moderate to strong, medium to coarse sub-angular blocky structures and were friable when moist. Strong, medium to coarse, angular blocky structures with slickensides and wedge-shaped aggregates that break into small angular peds and which have firm to very firm consistency when moist, were prominent in the subsoils. The soils have cracks of about

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Table 3
Physical, chemical and mineralogical properties of Pedon 3 (Typic Haplusterts) as representative of the SHD climate.

(a) Physical properties

Horizon	Depth (cm)	Size class and particle diameter (mm)				Fine clay (%)	Fine clay/total clay	COLE	sHC (cm h^{-1})	WDC (%)
		Total								
		Sand (2–0.05)	Silt (0.05–0.002)	Fine silt (0.006–0.002)	Clay (<0.002)					
		(% of <2 mm)								
Ap	0–13	9	48	19	43	22	0.51	0.19	1.3	12.6
Bw1	13–35	7	41	21	52	37	0.71	0.16	1.8	14.5
Bw2	35–62	7	44	21	49	30	0.61	0.20	1.7	8.8
Bss1	62–88	5	43	21	52	37	0.72	0.14	1.6	10.1
Bss2	88–127	5	45	20	50	32	0.64	0.16	1.8	10.1
Bss3	127–155+	6	41	21	52	35	0.67	0.22	1.0	13.1

(b) Chemical and mineralogical properties

Depth (cm)	pH water (1:2)	OC (%)	$CaCO_3$ (%)	Extractable bases (cmol(p+) kg^{-1})					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	Smectite in clay <2 μm (%)	BS (%)
				Ca	Mg	Na	K	Sum				
0–13	7.9	1.1	24.0	23.2	9.6	0.9	1.0	34.6	42.2	97	95	82
13–35	8.0	0.6	26.3	19.1	17.9	0.9	0.3	38.2	40.4	78	90	94
35–62	8.1	0.5	24.7	14.3	22.2	0.8	0.3	37.6	39.5	80	90	95
62–88	8.3	0.4	25.0	9.8	27.8	0.9	0.2	38.7	43.2	84	91	89
88–127	8.4	0.3	24.7	8.3	30.1	1.3	0.2	39.9	42.2	85	92	94
127–155+	8.4	0.3	25.2	8.3	28.3	1.5	0.2	38.3	42.2	80	93	91

(c) Exch. Ca/Mg, ECP, EMP, ESP and carbonate clay in soil and on fine earth basis (feb)

Depth (cm)	Exch. Ca/Mg	ECP	EMP	ESP	CO_3 clay (%)	CO_3 clay (feb) (%)
0–13	2.4	55	23	2.0	4.0	1.7
13–35	1.6	47	44	2.1	4.4	2.3
35–62	0.6	36	56	2.0	3.4	1.7
62–88	0.3	23	64	2.0	3.1	1.6
88–127	0.3	20	71	3.1	3.3	1.6
127–155+	0.3	20	67	3.5	3.3	1.7

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)			
	ECe (dS m^{-1})	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
0–13	1.12	6.9	3.9	0.8	0.4	–	1.5	8.0	2.5
13–35	0.32	1.4	1.4	0.8	0.1	–	2.0	1.0	1.6
35–62	0.36	1.4	1.7	1.1	0.0	0.5	1.5	1.5	0.7
62–88	0.40	1.1	2.2	1.7	0.0	–	1.0	1.5	2.6
88–127	0.43	0.6	1.7	3.2	2.4	–	2.5	2.5	2.8
127–155+	0.37	0.7	1.0	2.2	0.0	–	2.0	1.5	0.4

COLE = co-efficient of linear extensibility; sHC = saturated hydraulic conductivity; WDC = water dispersible clay; ECP = exchangeable calcium percentage; EMP = exchangeable magnesium percentage; ESP = exchangeable sodium percentage; feb = fine earth basis; ECe = electrical conductivity of the saturation extract.

0.5–4.0 cm wide and it extends up to 30 cm in SAM and 125 cm in SAD climate.

Soils of SAM have ~5% and SAD have up to 22% sand (Tables 4 and 5). The clay content is higher (~70%) in the soils of SAM than those of SAD climate (<60%, Tables 4 and 5). In both the cases soils show >8% clay in the Bss horizons than in their Ap horizon. The FC/TC in the Bss horizons is >1.2 times than the ratio in the Ap horizon (Tables 4 and 5). Depth function of clays indicates that the enrichment of clay in the Bss horizon is likely due to the illuviation of clay (Soil Survey Staff, 2003).

Vertisols of SAM are mildly to moderately and SAD climates are mildly to strongly alkaline, and both are calcareous. CEC values of soils of SAM are higher than those of SAD climates (Tables 4 and 5). Their high clay CEC values indicate that the soils of both SAM and SAD climates are dominated by smectites (Tables 4 and 5). Base saturations of both soils are high. Calcium plus magnesium dominate the exchange complex. The EMP increases with depth in both SAM and SAD climates. The ESP in soils of SAM climate is <5 but it is >5 and increases with depth in soils of SAD climate. Depth distribution of both EMP and ESP indicates that the subsoils of SAM and SAD climates are chemically degraded (Pal et al., 2000, 2006), however, its extent is higher in soils of SAD than those of SAM climates as it is manifested in their lower values of sHC (<1 cm h^{-1}) (Tables 4 and 5).

3.4. Vertisols of AD environments

The area under AD is characterized by MAR of 533 mm, MAT of 26.7 °C, MTw of 28.2 °C and MTd of 26.2 °C. These soils occur in very gently sloping lands and are developed in the alluvium of the Deccan basalt. The soils are very dark grayish brown to dark brown in colour, fine textured and >150 cm thick. The surface horizons had moderate to strong, medium to coarse subangular blocky structure and are friable when moist. Strong, medium to coarse, angular blocky structures with wedge-shaped aggregates and slickensides are prominent in the subsoils. The soils have cracks of width 0.5–3.0 cm and extending to 125 cm depth.

Soils have <30% sand and the least amount of clay (31.0–50.0%) among all the soils under study (Table 6). The soils have >8% clay in the Bss horizons than in the Ap horizon. The FC/TC in the Bss horizons is >1.2 times than the ratio in the Ap horizon. Both the

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Table 4
Physical, chemical and mineralogical properties of Pedon 4 (Udic Haplusterts) as representative of the SAM climate.

(a) Physical properties

Horizon	Depth (cm)	Size class and particle diameter (mm)				Fine clay (%)	Fine clay/total clay	COLE	sHC (cm h^{-1})	WDC (%)
		Total								
		Sand (2–0.05)	Silt (0.05–0.002)	Fine silt (0.006–0.002)	Clay (<0.002)					
		(% of <2 mm)								
Ap	0–12	4	36	19	60	25	0.42	0.28	1.3	13.3
Bw	12–37	5	36	13	59	27	0.46	0.24	0.7	14.0
Bss1	37–79	5	34	12	61	35	0.57	0.20	0.5	12.3
Bss2	79–110	4	26	11	70	45	0.64	0.29	0.6	16.6

(b) Chemical and mineralogical properties

Depth (cm)	pH water (1:2)	OC (%)	$CaCO_3$ (%)	Extractable bases (cmol(p+) kg^{-1})					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	Smectite in clay <2 μm (%)	BS (%)
				Ca	Mg	Na	K	Sum				
0–12	8.2	1.0	9.0	29.1	24.8	2.6	0.8	57.3	58.6	97	92	98
12–37	8.1	0.8	10.2	33.7	21.4	2.3	0.3	57.7	58.6	99	95	98
37–79	7.7	0.8	10.0	20.6	24.4	2.0	0.3	47.3	49.8	82	87	95
79–110	8.0	0.6	11.0	20.1	38.8	2.0	0.4	61.3	63.0	90	89	97

(c) Exch. Ca/Mg, ECP, EMP, ESP and carbonate clay in soil and on fine earth basis (feb)

Depth (cm)	Exch. Ca/Mg	ECP	EMP	ESP	CO_3 clay (%)	CO_3 clay (feb) (%)
0–12	1.2	49.6	42.3	4.4	3.3	1.9
12–37	1.6	57.5	36.5	4.0	3.3	1.9
37–79	0.8	41.4	49.0	4.0	3.3	2.2
79–110	1.9	31.9	61.6	3.2	3.8	2.6

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)			
	ECe (dS m^{-1})	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
0–12	0.4	2.2	1.5	8.9	0.08	–	1.5	5.0	6.2
12–37	0.7	1.1	0.6	3.6	0.09	–	1.5	2.5	1.4
37–79	0.4	1.1	0.8	4.0	0.07	0.5	1.5	2.5	1.5
79–110	0.3	0.7	0.9	1.0	0.03	–	1.8	0.8	–

COLE = co-efficient of linear extensibility; sHC = saturated hydraulic conductivity; WDC = water dispersible clay; ECP = exchangeable calcium percentage; EMP = exchangeable magnesium percentage; ESP = exchangeable sodium percentage; feb = fine earth basis; ECe = electrical conductivity of the saturation extract.

data suggest the enrichment of clay in the Bss horizons as a result of clay illuviation (Soil Survey Staff, 2003).

The soils of AD climate are moderately alkaline and calcareous. CEC of soils is not as high as those of other climates (SHM, SHD, SAM and SAD) (Table 6). The clay CEC values, however, indicate the dominance of smectite clay mineral. Base saturation of the soils is about 100% because of the presence of zeolites in these soils (Pal et al., 2006). Calcium and magnesium together dominate the exchange complex. High EMP (>40) and ESP (>15) apparently suggest that these soils are highly degraded by chemical processes. Because of the presence of zeolites, soils have favourable sHC (>1 cm h^{-1}) (Table 6).

3.5. Micromorphological properties

The micromorphology of soils was recorded as this method can effectively distinguish between pedogenic calcium (PC) and non-pedogenic calcium (NPC) carbonates. PCs occur as coating, filling and nodules. They are micritic, microsparitic or sparitic. They have fabric similar to adjacent soil fabric and occur together with illuvial clay pedofeatures. NPCs have sharp boundary with soil matrix and are relatively pure having no inclusion of primary minerals. They are coarse textured and free from other features like illuviated clay (Pal et al., 2000). This method is also the best for identifying illuvial clay and plasmic fabrics (Bullock and Thompson, 1985).

3.5.1. Plasmic fabric

Shrinking and swelling of smectite in Vertisols result in a very dense groundmass exhibiting poro/grano/parallel/reticulate-striated plasmic fabric (Wilding, 1985). Soils of HT climate indicated strong plasma separation with poro/parallel/grano-striated plasmic fabric (Fig. 2a and b). Soils of SHM climate also indicated strong plasmic separation with parallel/reticulate plasmic fabric with some occasional presence of stipple-speckled fabrics (Fig. 2c). Soils of SHD climate showed dominant presence of crystallitic and stipple-speckled plasma with some grano-striated fabric (Fig. 2d). The crystallitic fabric is due to calcareous parent material. However, soils developed mostly in basaltic alluvium of SHD climate had parallel/grano-striated fabrics with some stipple-speckled and plasmic fabric (Pal et al., 2001).

Soils of SAM climate indicated mostly mosaic/stipple-speckled and crystallitic with some parallel/grano-striated plasmic fabric (Fig. 2e), whereas soils of SAD exhibited the dominance of both mosaic/stipple-speckled and parallel/grano-striated plasmic fabric (Fig. 2f). Soils of AD climate showed primarily crystallitic with some grano-striated plasmic fabric (Fig. 2g). Plasma separation was more pronounced around grains and on the walls of the voids in all soils except however in the soils of AD climate. Despite high degree of shrink–swell process, the plasmic fabric is not uniform even among the soils with fairly high COLE values (Tables 1–6) against the minimum threshold value of 0.06 for the manifestation of vertic properties of soils (Soil Survey Staff, 2003). Similar observations were also made by other researchers (Kalbande et al., 1992; Balpande et al., 1997; Pal et al., 2001; Vaidya and Pal, 2002).

3.5.2. Pedogenic (PC) and non-pedogenic (NPC) $CaCO_3$

The soils exhibited both PC and NPC (Fig. 3a–f). Some $CaCO_3$ glaebules are sub-rounded to rounded nodules coated with Fe–Mn oxides and have sharp boundaries with soil matrix and these are

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Table 5
Physical, chemical and mineralogical properties of Pedon 5 (Sodic Haplusterts) as representative of the SAD climate.

(a) Physical properties

Horizon	Depth (cm)	Size class and particle diameter (mm)				Fine clay (%)	Fine clay/total clay	COLE	sHC (cm h^{-1})	WDC (%)
		Total								
		Sand (2–0.05)	Silt (0.05–0.002)	Fine silt (0.006–0.002)	Clay (<0.002)					
		(% of <2 mm)								
Ap	0–12	22	30	17	48	26	0.54	0.26	0.7	6.3
Bw1	12–30	19	30	18	51	30	0.59	0.24	0.6	10.0
Bss1	30–59	18	30	16	52	32	0.61	0.20	0.6	11.6
Bss2	59–101	17	28	17	55	36	0.65	0.24	0.2	12.0
Bss3	101–130	8	33	20	59	31	0.52	0.25	0.2	15.0
BCK	130–160	13	29	19	58	39	0.67	0.23	0.1	11.3

(b) Chemical and mineralogical properties

Depth (cm)	pH water (1:2)	OC (%)	$CaCO_3$ (%)	Extractable bases (cmol(p+) kg^{-1})					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	Smectite in clay <2 μm (%)	BS (%)
				Ca	Mg	Na	K	Sum				
0–12	7.8	0.6	5.9	34.2	10.7	0.9	0.4	46.2	48.7	99	95	95
12–30	7.8	0.4	6.2	34.9	12.7	1.9	0.3	49.8	52.1	101	96	95
30–59	8.1	0.4	6.0	29.3	14.0	3.7	0.3	47.3	52.2	99	96	90
59–101	8.5	0.4	6.4	26.2	14.4	6.8	0.3	47.7	53.5	96	95	89
101–130	8.5	0.4	6.5	35.8	11.5	8.6	0.5	56.4	57.8	97	92	90
130–160	8.2	0.1	9.1	25.1	16.2	11.1	0.5	48.9	49.5	85	85	98

(c) Exch. Ca/Mg, ECP, EMP, ESP and carbonate clay in soil and on fine earth basis (feb)

Depth (cm)	Exch. Ca/Mg	ECP	EMP	ESP	CO_3 clay (%)	CO_3 clay (feb) (%)
0–12	3.2	70	22	2.0	3.4	1.6
12–30	2.8	67	24	4.0	3.1	1.6
30–59	2.1	56	27	7.1	2.9	1.5
59–101	1.8	49	27	13.0	3.3	1.8
101–130	3.1	62	20	14.8	3.2	1.9
130–160	1.5	51	33	22.4	3.4	1.9

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)			
	ECe (dS m^{-1})	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
0–12	0.3	1.23	0.9	1.8	0.03	–	1.3	2.0	–
12–30	0.3	0.87	0.7	2.7	0.07	–	2.2	2.2	–
30–59	0.4	0.21	0.3	4.8	0.05	–	2.4	2.8	–
59–101	0.4	0.54	0.2	8.1	0.04	0.4	6.7	1.3	–
101–130	0.8	0.24	0.3	13.4	0.11	2.7	8.0	4.0	–
130–160	2.7	0.99	0.7	20.2	0.11	1.1	4.2	1.5	15.2

COLE = co-efficient of linear extensibility; sHC = saturated hydraulic conductivity; WDC = water dispersible clay; ECP = exchangeable calcium percentage; EMP = exchangeable magnesium percentage; ESP = exchangeable sodium percentage; feb = fine earth basis; ECe = electrical conductivity of the saturation extract.

considered to be NPC (Pal et al., 2000, 2001, 2006; Srivastava et al., 2002), as they are relict carbonate nodules or pedorelict (Brewer, 1976). The other glaebules that are fine textured with irregular shapes and diffuse boundaries and without any Fe–Mn coatings are considered to be PC (Pal et al., 2000, 2001, 2006; Srivastava et al., 2002). The NPCs are marked by dissolution features (Fig. 3g–i).

Following the frequency distribution chart of Bullock et al. (1985), the contents of PC and NPC were determined. The PCs are present at a depth of >75 cm in the soils of HT climate, 70 cm in soils of SAM, ≥50 cm in soils of SHD, ≥30 cm in soils of SAM, and throughout the soil depth of SAD and AD climates (Fig. 4). The PCs were dull white diffuse nodules of micritic crystals and found in close association with NPC (Fig. 3j). In general, PCs showed an increase with depth in soils, and a decrease with mean annual rainfall (MAR). The observed depth of PC accumulation in soils of HT to AD climates (Fig. 4) suggests that water loss through evapotranspiration and/or lowering of pCO_2 as the primary mechanism in the precipitation of $CaCO_3$ (Pal et al., 2000).

3.5.3. Clay pedofeatures

The soils studied showed the presence of impure clay pedofeatures (Bullock et al., 1985) (Fig. 5). The internal boundaries of these features are generally distinct. These features under cross-polarized light are dark yellowish brown to reddish brown, mostly without distinct lamination and are poorly oriented and have low birefringence (Fig. 5).

Soils of HT climate showed impure clay pedofeature which is occasionally microlaminated along the voids (Fig. 5a). Calcitic pedofeatures (Fig. 5b) were observed along with disrupted clay pedofeatures (Fig. 5c). Soils of SHM showed pedofeatures (Fig. 5d) and the soils of SHD climate showed impure clay pedofeatures (Fig. 5e), disrupted clay pedofeatures (Fig. 5f) and compound calcitic pedofeatures along channel voids. The soils of SAM climate showed Fe–Mn coated impure clay pedofeatures (Fig. 5g) and disrupted clay pedofeatures. Soils of SAD climate showed pedofeatures (Fig. 5h) and disrupted clay pedofeatures all over the matrix (Fig. 5i). In the soils of AD climate compound calcitic pedofeatures along the channel voids (Fig. 5j) were observed.

Impure clay pedofeatures have been considered to be the result of rapid translocation of the material. Poor orientation has been attributed to the presence of fine silt mica in cutans (Howitt and Pawluk, 1985). However, Vertisols under study are enriched with fine clay smectite with very little amount of mica in general (Pal and Deshpande, 1987).

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Table 6
Physical, chemical and mineralogical properties of Pedon 6 (Sodic Calciusterts) as representative of the AD climate.

(a) Physical properties

Horizon	Depth (cm)	Size class and particle diameter (mm)				Fine clay (%)	Fine clay/total clay	COLE	sHC ($cm\,h^{-1}$)	WDC (%)
		Total								
		Sand (2–0.05)	Silt (0.05–0.002)	Fine silt (0.006–0.002)	Clay (<0.002)					
		(% of <2 mm)								
Ap	0–11	29	39	7	32	12	0.37	0.16	3.2	1.0
Bw1	11 + 37	29	40	7	31	13	0.42	0.15	3.0	4.4
Bw2	37–63	26	33	7	40	18	0.45	0.16	1.5	3.8
Bss1	63–98	27	32	8	41	19	0.46	0.13	0.4	3.6
Bss2	98–145	23	34	7	43	20	0.46	0.11	0.2	3.5
BC	145–160	8	42	17	50	33	0.66	0.17	2.1	3.7

(b) Chemical and mineralogical properties

Depth (cm)	pH water (1:2)	OC (%)	$CaCO_3$ (%)	Extractable bases ($cmol(p+)\,kg^{-1}$)					CEC ($cmol(p+)\,kg^{-1}$)	Clay CEC ($cmol(p+)\,kg^{-1}$)	Smectite in clay <2 μm (%)	BS (%)
				Ca	Mg	Na	K	Sum				
0–11	8.2	0.5	21.9	21.1	9.8	1.0	0.7	32.6	27.6	88	90	118
11 + 37	8.4	0.5	21.4	20.4	8.9	1.2	0.6	31.1	27.5	90	92	113
37–63	8.7	0.4	21.5	18.0	13.1	2.6	0.5	34.2	28.5	71	85	120
63–98	8.8	0.4	22.0	14.4	13.8	4.7	0.5	33.4	29.0	71	85	115
98–145	8.6	0.3	21.6	12.7	15.6	8.5	0.5	37.3	30.3	71	84	123
145–160	8.5	0.2	11.6	11.8	14.0	10.1	0.5	36.4	32.3	64	75	112

(c) Exch. Ca/Mg, ECP, EMP, ESP and carbonate clay in soil and on fine earth basis (feb)

Depth (cm)	Exch. Ca/Mg	ECP	EMP	ESP	CO_3 clay (%)	CO_3 clay (feb) (%)
0–11	2.2	76	35	3.6	5.8	1.8
11 + 37	2.3	74	32	4.4	8.2	2.5
37–63	1.4	63	46	9.1	6.2	2.5
63–98	1.0	49	47	16.2	5.8	2.4
98–145	0.8	42	51	28.0	8.7	3.7
145–160	0.8	36	43	31.3	4.5	2.2

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)			
	ECe ($dS\,m^{-1}$)	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
0–11	0.4	2.4	1.4	1.1	0.01	1.1	2.3	1.3	0.3
11–37	0.4	1.5	1.1	1.7	0.07	1.5	1.7	1.0	0.1
37–63	0.5	0.5	0.5	4.4	0.01	1.8	2.1	1.5	–
63–98	0.7	0.6	0.6	8.7	0.02	1.1	3.9	3.6	1.3
98–145	4.2	3.2	0.5	34.8	0.16	1.7	1.0	32.1	–
145–160	0.4	1.6	0.9	32.7	0.04	1.1	2.1	30.8	1.3

COLE = co-efficient of linear extensibility; sHC = saturated hydraulic conductivity; WDC = water dispersible clay; ECP = exchangeable calcium percentage; EMP = exchangeable magnesium percentage; ESP = exchangeable sodium percentage; feb = fine earth basis; ECe = electrical conductivity of the saturation extract.

The depth distribution of fine silt (6–2 μm) in these soils (Tables 1–6) does not indicate its substantial movement. Thus, downward movement of silt in these soils appears to be highly improbable. The impure clay pedofeatures appear to be related to the lack of parallel orientation of clay particles due to deflocculation in the presence of HCO_3^- and CO_3^{--} ions of the soil solution (Tables 1–6). Deflocculation of clay particles will disengage face-to-face association of clay particles (Van Olphen, 1966). This will lead finally to impairment of parallel orientation of the clay platelets. Thus, the textural pedofeatures of the “impure” type can also be considered typical in slightly acidic to neutral Vertisols of HT and slightly to moderately alkaline soils of SHM, SHD, SAM, SAD and AD climates as in soils of the Indo-Gangetic alluvial plains (IGP), India (Pal et al., 1994).

4. Discussion

4.1. Genesis of Vertisols in different climates

The occurrence of Vertisols in HT, SHM, SHD, SAM, SAD and AD climatic environments may apparently suggests that the basaltic parent material has influenced soil formation in such a way that similar soils are formed under different climatic conditions (Mohr et al., 1972). Despite the fact that the soils belong to Vertisol order of US Soil Taxonomy (Soil Survey Staff, 2003), their morphological and chemical properties are not identical. In general, the colour of soils of the HT climate is dark brown (7.5YR 3/3) to dark reddish (5YR 3/3) and yellowish brown (10YR 3/4) and it is dark (10YR 3/1) to very dark grayish brown (10YR 3/2) in soils of other climates. The subsoils of the HT climate have weak and small wedge-shaped aggregates with pressure faces that break to weak angular blocky structure whereas those of SHM, SHD, SAM, SAD and AD climates have strong medium subangular blocky to strong coarse angular blocky structure with pressure faces and slickensides that break into small angular peds. Cracks >0.5 cm wide extend down to the zones of sphenoids and wedge-shaped peds with smooth or slickensided surfaces in the soils of HT, SHM, SHD and SAM climate but cracks cut through these zones in soils of SAD and AD climates.

Soil reaction and the contents of $CaCO_3$ (<2 mm) and PC of the soils indicate that with the lowering of MAR the soils are becoming more alkaline, calcareous and sodic (Tables 1–6; Fig. 4). The progressive increase in PC content from HT to AD climates supports the water loss through evapotranspiration and/or lowering of pCO_2 as primary mechanism in the precipitation of $CaCO_3$ and rising

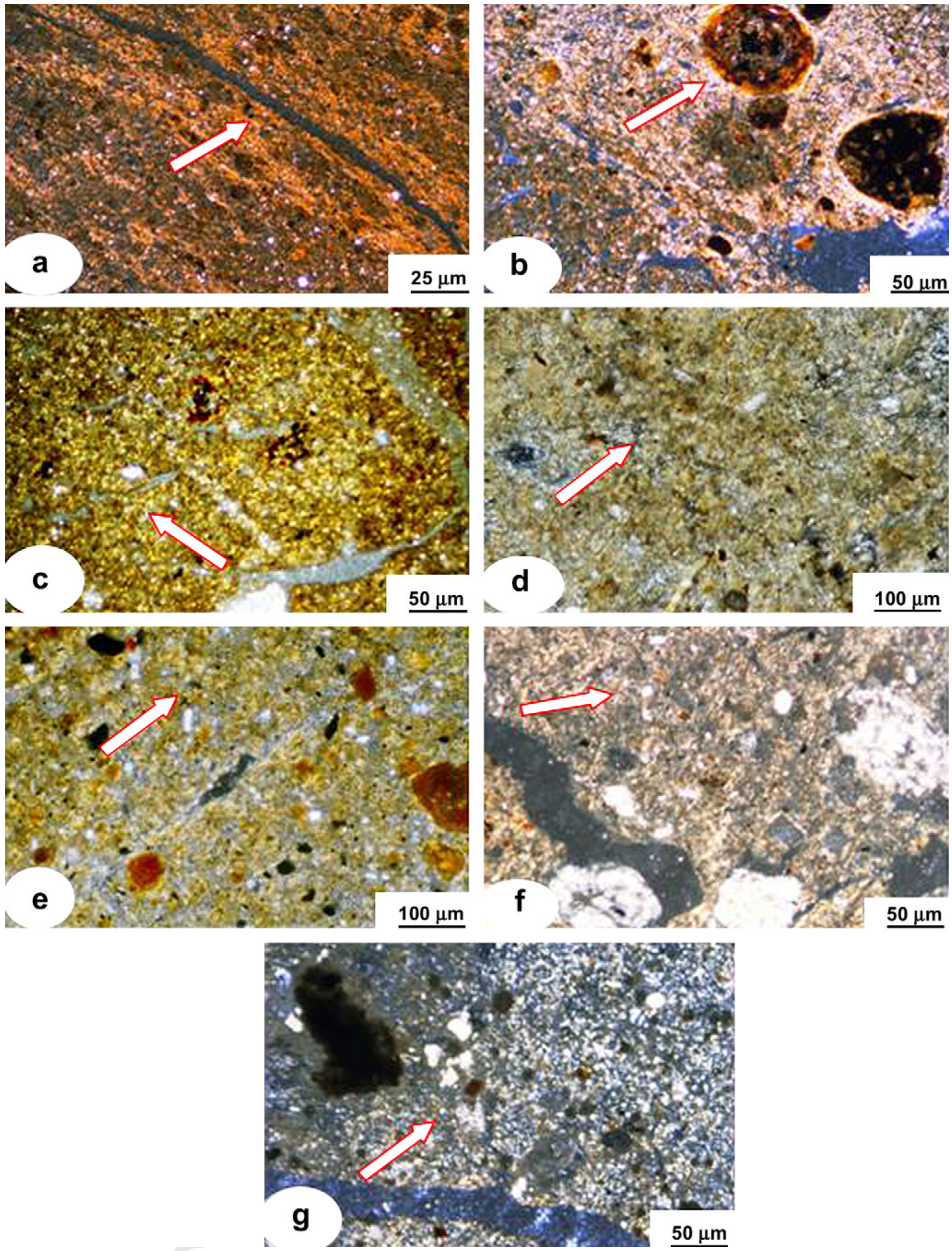

Fig. 2. Representative photographs of plasmic fabric in cross-polarized light. (a) Strong parallel and (b) grano-striated plasmic fabric, HT soils (Pedon 1, 125–133 cm). (c) Reticulate plasmic fabric, SHM soils (Pedon 2, 45–53 cm). (d) Stippled-speckled plasmic fabric, SHD soils (Pedon 3, 97–105 cm). (e) Stipple-speckled plasmic fabric, SAM soils (Pedon 4, 49–57 cm). (f) Mosaic/stippled-speckled plasmic fabric, SAD soils (Pedon 5, 47–55 cm). (g) Crystallitic plasmic fabric, AD soils (Pedon 6, 51–59 cm).

temperature as an additional factor plays an important role in controlling the water flow in the soil profile (Rabenhorst et al., 1984). This suggests that the aridity in the climate is the prime factor in the formation of calcareous sodic soils (Pal et al., 2000), considering an ESP 5–15 with, sHC < 10 mm h^{-1} as the lower limit of sodicity (Pal et al., 2006). Accordingly, the soils under study are Typic Haplusterts in HT, Typic/Udic Haplusterts in SHM, SHD and SAM and Sodic Haplusterts and Sodic Calciusterts in SAD and AD climates. Thus, the hypothesis of Mohr et al. (1972) for the formation of similar soils in basaltic alluvium under different climates is inadequate to explain the formation of Vertisols of tropical India.

Smectite clay minerals are ephemeral in the HT climate and they transform to kaolin (Pal et al., 1989; Bhattacharyya et al., 1993). The Vertisols of HT climate of western India is a member of Mollisol–Alfisol–Vertisol association (Bhattacharyya et al., 2005). The associated ferruginous Alfisols were formed in HT climate and are persisting since the early Tertiary (Bhattacharyya et al., 1999, 2005). The transformation of smectite to Sm/K during HT weathering began at the end of the Cretaceous and continued not only during the Tertiary (Kumar, 1986; Tardy et al., 1991) but also during the Holocene period (Bhattacharyya et al., 1993, 1999). The slow dissolution of Ca-zeolites (<1 me Ca L^{-1} in distilled water, Pal et al., 2006) provided sufficient bases to prevent the complete transformation of smectite to kaolin. The presence of smectites and zeolites made the formation of Vertisols possible in lower physiographic situation even under HT climate.

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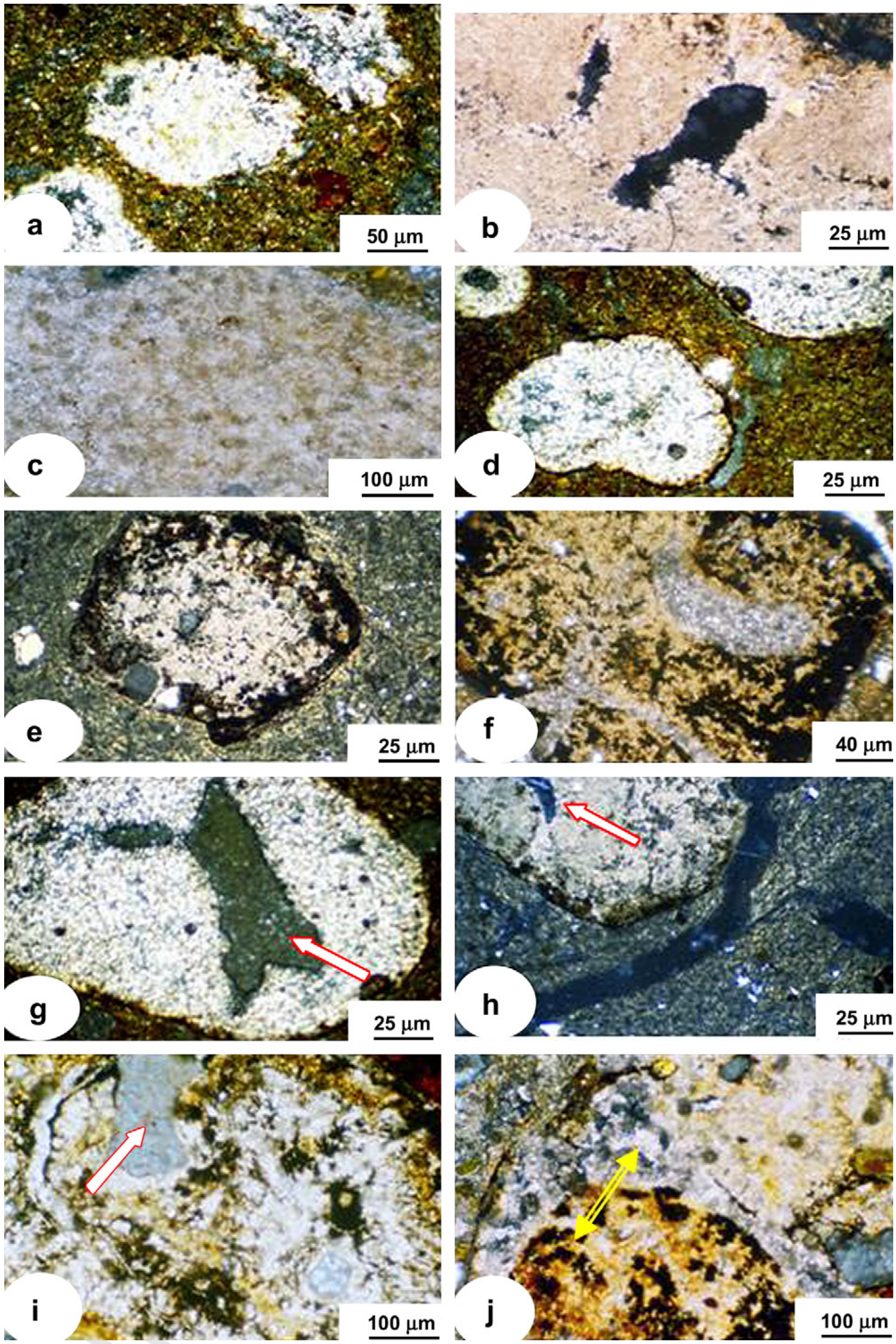

Fig. 3. Representative photographs of calcium carbonates in cross-polarized light. (a) PC of SHM soils (Pedon 2, 45–53 cm). (b) PC of SAD soils (Pedon 5, 47–55 cm). (c) PC of AD soils (Pedon 6, 51–59 cm). (d) NPC of SAM soils (Pedon 2, 45–53 cm). (e) NPC of SAD soils (Pedon 5, 47–55 cm). (f) NPC of AD soils (Pedon 6, 51–59 cm). (g) NPC with dissolution in SHM soils (Pedon 2, 45–53 cm). (h) NPC with dissolution of SAD soils (Pedon 5, 47–55 cm). (i) NPC with dissolution in AD soils (Pedon 6, 51–59 cm). (j) PC and NPC in close association, AD soils (Pedon 6, 20–28 cm).

It is equally difficult to understand the formation of Vertisols in the present day climates (SHM, SHD, SAM, SAD and AD), since it requires a huge amount of smectite clay. In these climatic environments the weathering of primary minerals contributes very little towards the formation of smectites and the formation of PC is the prime chemical reaction responsible for the increase in pH, EMP and ESP. Thus the formation of such Vertisols reflects a positive entropy change (Srivastava et al., 2002). XRD analysis of fine clays indicates that smectites are fairly well crystallized and do not show any sign of transformation except for low hydroxy-interlayering in the smectite interlayers (Srivastava et al., 2002).

The soils under study have both NPC (relict carbonate nodules) and PC. The NPCs have sharp boundary with the soil matrix (Fig. 3). Brewer (1976) pointed out such forms are pedorelic features. Based

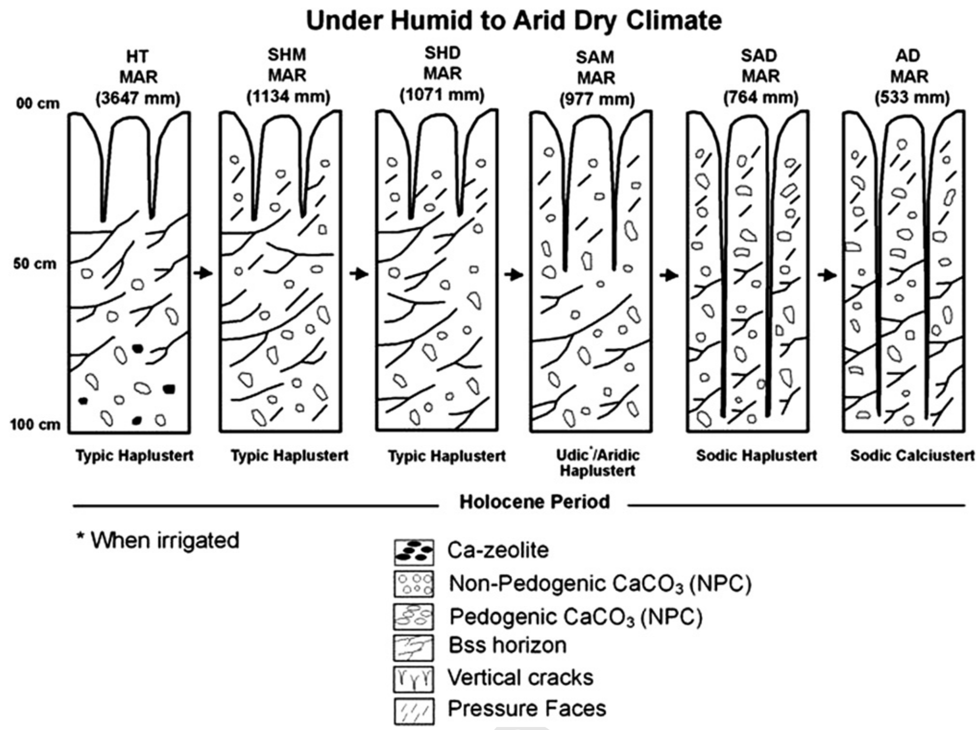

Fig. 4. Successive stages of pedogenic evolution in Vertisols.

on ^{14}C dates of carbonate nodules, Mermut and Dasog (1986) concluded that Vertisols with Fe–Mn coated glaebules are older soils than those with white glaebules. White glaebules (PCs) are formed in soils of dry climates (Pal et al., 2000). This suggests that NPCs were formed in a climate much wetter than the present, which ensured adequate soil water for reduction and oxidation of iron and manganese to form Fe–Mn coatings. The sub-rounded to rounded NPCs amidst PCs in <100 year old shrink–swell soils of central India are related to the alluvial history of the basaltic parent material (Pal et al., 2000).

The first weathering product of plagioclase-rich Deccan basalt is a dioctahedral smectite in aridic to humid climates (Pal and Deshpande, 1987). The majority of Vertisols in India occur in the lower piedmont plains or valleys or in depressions (Pal and Deshpande, 1987; Srivastava et al., 2002; Pal et al., 2006). Thus the smectite in these Vertisols must have formed in an earlier and more humid climate and its crystallinity was preserved in the non-leaching environment of the latter sub-humid to dry climates.

The ^{14}C age of soil organic carbon of the deeper horizon of the Vertisols of SHM, SHD, SAM, SAD and AD climates was estimated to be between 3390 and 10,187 years BP. This suggests that the drier climate occurred in Peninsular India during the Holocene (Pal et al., 2001, 2006; Deotare, 2006). Vertisols of the HT climate are dominated by Ca^{+2} ions on their exchange complex almost throughout the depth. However, in subsoils of Vertisols (both zeolitic and non-zeolitic) of sub-humid to arid climates, the Mg^{+2} ions tend to dominate in the exchange complex (Tables 1–6).

The soils of SAM, SAD and AD climates become more calcareous than those of SHM and SHD climates and are sodic (ESP 5–15 with sHC < 10 mm h^{-1}, Pal et al., 2006) in their subsoils (Tables 2–6). This indicates that due to the precipitation of $CaCO_3$, the maintenance of higher Ca/Mg ratio (~2, Pal et al., 2000) in the soil solution and on the exchange sites becomes difficult during high evaporative demands for the soil water. This results in an increase in EMP and ESP, and a concomitant decrease in exchangeable calcium percentage (ECP) down the profile (Tables 1–6).

Soils of SHM and SHD have better drainage (sHC > 10 mm h^{-1} as weighted mean in 0–100 cm depth) that causes downward movement of soluble bicarbonates which get precipitated as carbonates in the subsurface horizons. This observation is supported by the overall increase of clay carbonate (on a fine earth basis) with depth (Tables 1–6). Higher MAR of SHM and SHD climates must have resulted greater dissolution of NPC, causing an increase in Ca^{+2} ion concentration in soil solution and on exchange sites, thus improving the hydraulic properties of soils (Tables 2 and 3).

Vertisols of SHM and SHD do not generally contain PC in the first 50 cm of the profile effecting better drainage (sHC > 10 mm hr^{-1}). The subsoils of SAM, SAD and AD climates, due to the accelerated rate of formation and accumulation of PC, become sodic impairing their hydraulic properties even in presence of zeolites in these soils (Tables 4–6). The initial impairment of the percolative moisture regime in the subsoils (caused either by EMP or ESP or by both) results eventually in a soil system where gains exceed losses. This self-terminating process (Yaalon, 1983) subsequently leads to the development from Aridic to Sodic Haplusterts or Sodic Calciusterts, where ESP may show a decrease with depth as observed in Natrustalfs of the IGP soils (Pal et al., 2003a). These observations confirm the polygenesis of Vertisols (Pal et al., 2001) with the change in climate from humid to arid during the Holocene.

In the polygenesis of Vertisols, the formation of PC at the expense of NPCs is the prime chemical reaction responsible for the increase in pH, Ca/Mg ratio of exchange site with depth and in the development of subsoil sodicity. The abundance of Vertisols in dry climates may suggest a role of climate in their genesis (Eswaran et al., 1988) but it will be more appropriate to realize this fact only in their polygenesis as discussed here.

4.2. Pedogenic threshold in dry climates

The soils show considerable amount of WDC which increases with depth (Tables 1–6). This suggests that an adequate dispersion of clay smectites have been possible in slightly acidic to moderately

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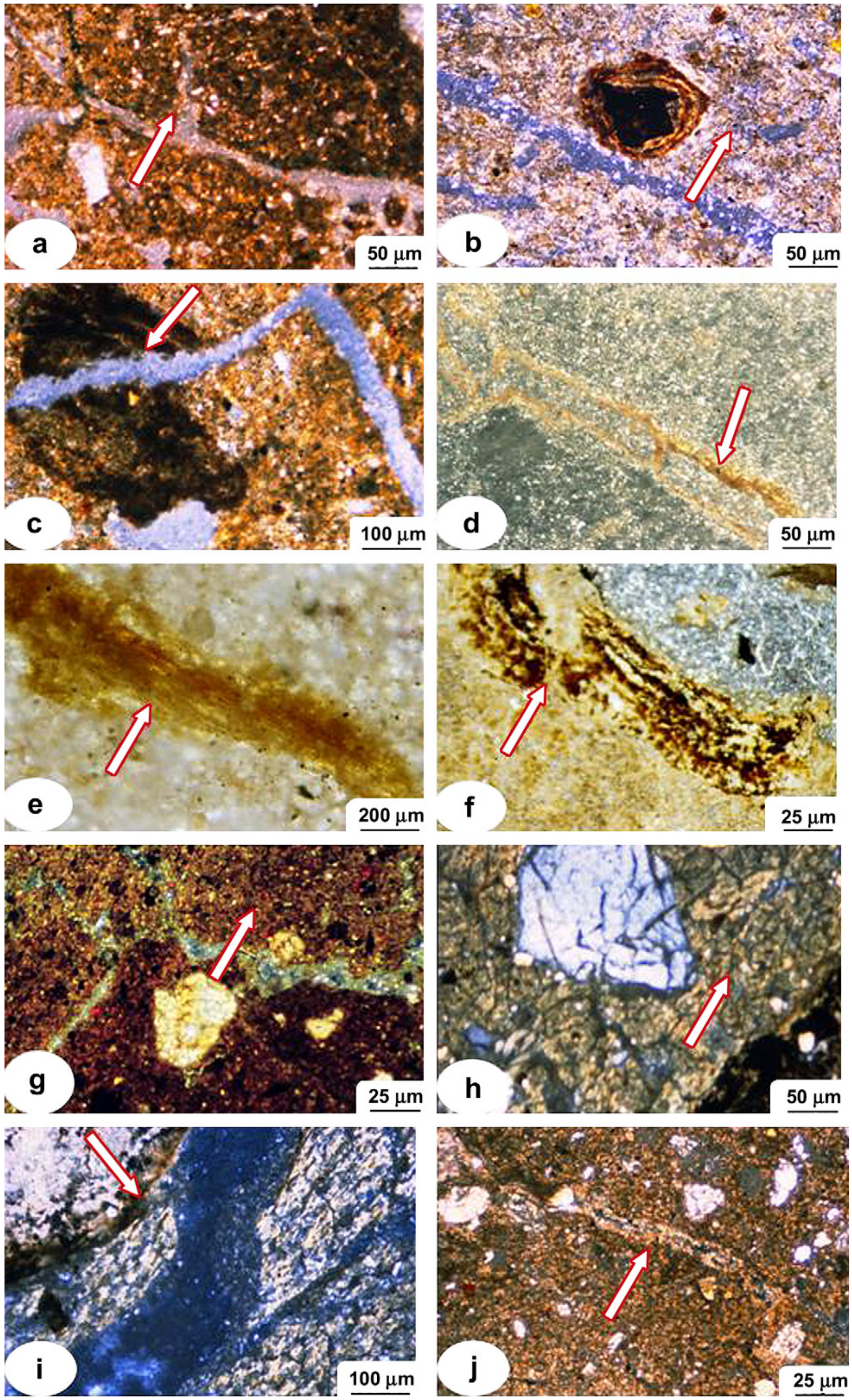

Fig. 5. Representative photographs of clay pedofeatures in cross-polarized light. (a) Impure clay pedofeatures, HT soils (Pedon 1, 82–125 cm). (b) Calcitic pedofeatures, HT soils (Pedon 1, 150+ cm). (c) Disrupted clay pedofeatures, HT soils (Pedon 1, 82–125 cm). (d) Impure clay pedofeatures, SHM soils (Pedon 2, 116–124 cm). (e) Impure clay pedofeatures, SHD soils (Pedon 3, 30–38 cm). (f) Disrupted clay pedofeatures, SHD soils (Pedon 3, 30–38 cm). (g) Fe–Mn coated clay pedofeatures, SAM soils (Pedon 4, 19–27 cm). (h) Impure clay pedofeatures, SAD soils (Pedon 5, 96–104 cm). (i) Disrupted clay pedofeatures, SAD soils (Pedon 5, 96–104 cm). (j) Compound calcitic pedofeatures, AD soils (Pedon 6, 51–59 cm).

alkaline pH condition with a very low electrolyte concentration (ECe $\leq$ 1 meL^{-1}, Tables 1–6) with HCO_3^- and CO_3^{2-} ions (Tables 1–6). This ensures a pH higher than the zero point of net charge required for full dispersion of clays (Eswaran and Sys, 1979). Petrographic and scanning electron microscope (SEM) examination of plagioclase and micas in such Vertisols indicated that both the minerals are only slightly altered and lack etch pits and/or dissolution pits (Zade et al., 2001; Srivastava et al., 2002; Nimkar, 2004). Further,

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the CaO and Na_2O contents of the sand and silt fractions of some benchmark Vertisols indicated their nearly uniform depth distribution (Zade et al., 2001; Srivastava et al., 2002). This suggested that the plagioclase feldspars are not the primary source of Ca^{+2} ions in the soil solution, rather the dissolution of NPCs is the major source (Srivastava et al., 2002). The depth distribution of Ca/Mg, EMP, ESP and soluble Na^+ ions (Tables 1–6) suggests that the precipitation of $CaCO_3$ as PC enhances the pH and also the relative abundance of Na^+ ions both in soil exchange sites and solution and the Na^+ ions in turn cause dispersion of smectites. The dispersed smectites translocate. The gradual increase in fine clay and WDC with depth (Tables 1–6) supports this fact. This process results in increase in EMP, ESP and carbonate clay with depth (Tables 1–6).

This observation again suggests that the movement of clay in Vertisols is not prevented by the presence of $CaCO_3$, rather the formation of PC creates a conducive chemical environment that facilitates the deflocculation of clay particles and their subsequent movement downward. Therefore, the formations of PC and clay illuviation are two concurrent and contemporary pedogenetic events. These pedogenetic events continue to represent a pedogenic threshold (Pal et al., 2003b) during the dry climates of the Holocene of the Peninsular India until a further change in climate sets in.

4.3. Modification in properties

The abundance of smectite results in high COLE (Tables 1–6), which induces horizontal and vertical stresses in the soils. In the upper horizons, low overburden pressure and cracks prevent the development of high lateral stresses. But in the subsoils, where sphenoids and/or slickensides are formed, the difference between horizontal stress and the vertical stress is quite large (Yaalon and Kalmar, 1978; Knight, 1980). On swelling, a soil is acted upon by these two sets of stresses. When the vertical stresses are confined and the lateral stresses exceed the shear strength of the soils, failure occurs along a grooved shear plane theoretically a 45° to the horizontal (Wilding and Tessier, 1988). In reality, however, such shear failure may range from 10 to 60° (Knight, 1980). Thus the shear failure is associated with poro/parallel/reticulate/grano-striated plasmic fabric, pointing out a prominent surface oriented plasma separation or stipple-speckled/mosaic-speckled/crystallitic plasmic fabric related to poor plasma separation in the Bss horizons (Kalbande et al., 1992; Balpande et al., 1997; Pal et al., 2001). The plasma separation and slickenside formation appear to be inherently related to each other during the genesis of Vertisols (Dasog et al., 1987; Wilding and Tessier, 1988; Kalbande et al., 1992; Pal et al., 2001). Presence of sphenoids and/or slickensides and the dominant presence of poro/parallel/grano/reticulate-striated plasmic fabric in soils of HT and SHM climates indicate the shrink–swell activity of smectites has been to a large magnitude. But, the dominant presence of stippled/mosaic-speckled plasma in soils of SHD, mosaic/crystallic plasma in soils of SAM, mosaic/stippled-speckled plasma in soils of SAD and crystallitic plasma in soils of AD climates clearly suggests that shrink–swell magnitude is much less in soils of drier climates as compared to HT and SHM climates and it is manifested in poor plasma separation. Weak swelling of smectite is sufficient for the development of sphenoids and/or slickensides but not adequate to cause a strong plasma separation.

Restriction of swelling of clays and consequent poor plasma separation may be due to the (a) presence of $CaCO_3$ (Rimmer and Greenland, 1976), (b) presence of calcite crystals that cause a state of disorganization in plasma (Bellinfante et al., 1974), and (c) decrease in the internal surface area of fine smectite caused by hydroxy-interlayering in smectite interlayers (Kalbande et al., 1992). Carbonate maintains a concentration of Ca^{+2} ions in solution of 0.5–10 mmol dm^{-3}, depending on the partial pressure of CO_2 in contact with it (Marshall, 1964). Low amount of soluble Ca^{+2} ions in Vertisols (<5 mmol dm^{-3}) in general (Kalbande et al., 1992; Pal et al., 2001; Srivastava et al., 2002) (Tables 1–6) is not enough to inhibit the swelling of smectite by contracting the diffuse double layer. The explanation is that at a concentration of Ca^{+2} ions of 10 mmol dm^{-3}, the swelling of smectite is only 15% less than in distilled water (Rimmer and Greenland, 1976). Examination of XRD diagram of fine clay smectites indicates a very little to little amount of hydroxy-interlayering in smectite interlayers (Pal et al., 2001; Srivastava et al., 2002), not enough to restrict swelling of smectite and plasma separation.

The sHC decreased rapidly with depth in all soils but the decrease was sharper in both zeolitic and non-zeolitic soils of SAD and AD climates (Tables 1–6) because of their subsoil sodicity ($ESP > 5$, Tables 5 and 6). The decreased sHC restricts vertical and lateral movement of water in the subsoils. During the very hot summer months, this would result in much less water in the subsoils of SAD and AD climates and this is evident from the deep cracks cutting through their Bss horizons. The lack of adequate soil water during the shrink–swell cycles restricts the swelling of smectite and results in weaker plasma separation in these soils.

The subsoils of SAM, SAD and AD remained under less amount of water as compared to those of HT, SHM and SHD climates during the Holocene. Soils of drier parts of Peninsular India were modified as a result of formation of PC, subsoil sodicity, poor plasma separation and cracks cutting through the slickensided zones. Thus they qualify as polygenetic soils (Pal et al., 1989, 2001).

4.4. Evolutionary sequences in the formation of Vertisols

Blokhuis (1982) and Eswaran et al. (1988) conceptualized successive stages of pedogenic evolution in Vertisols within the framework of US Soil Taxonomy that recognizes "intergrade" between Vertisols and soils of other orders. Blokhuis (1982) reported some examples where a Vertisol loses its vertic characteristics and changes into a non-vertic soil. Eswaran et al. (1988) envisaged that with advancement of leaching the surface horizons of Vertisols become acidic with a pH lower than 6.5 and accumulation of translocated clay to form an argillic horizon and this way forward, the soils evolve into Vertic Haplustalfs. Based on earlier studies on the evolution of soils in humid tropical parts of the Western Ghats (Bhattacharyya et al., 1993, 1999), it is envisaged that with time the Vertisols in presence of zeolites of HT climate would continue to remain as Vertisols depending on the reserves of base-rich zeolites (Fig. 4).

In view of modifications of properties of the Vertisols of the climosequence from humid to arid during the Holocene, this study expands the basic understanding on the evolution of Vertisols from Typic Haplusterts to Udic/Aridic/Sodic Haplusterts and Sodic Calciusterts, respectively (Fig. 4). These soils may remain in equilibrium with their climatic environments until a further change in climate after which another pedogenic threshold sets in. Therefore, these soils stand for recognition as contemporary soils of the Holocene, but of polygenetic evolution.

5. Conclusion

In Indian sub-continent, Vertisols in humid tropical, sub-humid moist, sub-humid dry, semi-arid moist, semi-arid dry and arid dry climatic environments indicate their occurrence in a climosequence. The soils show a change in their morphological, physical, chemical and micromorphological properties due to change of climate from humid to arid during the Holocene period. Modifications in soil properties in the climosequence from humid to arid, resulted in the formation of different types of Vertisols (Typic/Aridic/Sodic Haplusterts and Sodic Calciusterts). Such examples should help in finding out the climatic signatures in soils to infer climate change in tropical and subtropical parts of India and elsewhere.

Uncited references

Dudal, 1965; Soil Survey Staff, 1975.

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