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Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic soils

D.K. Pal*, T. Bhattacharyya, S.K. Ray, P. Chandran, P. Srivastava, S.L. Durge, S.R. Bhuse

Division of Soil Resource Studies, National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur 440 010, India

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Abstract

Earlier hypothesis on the factors and processes of natural degradation in Vertisols and also their evaluation for crops on the basis of only hydraulic properties was developed on limited soils by the Division of Soil Resource Studies (DSRS) of the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Nagpur, India. In order to validate the above similar soils occurring in major states of the Peninsular India and also to document the extent of modification by gypsum and Ca-zeolites therein, the present study on twenty-six benchmark Vertisols representing a climosequence from sub-humid moist to arid dry climate was undertaken. The results of the present study validates the hypothesis that formation of pedogenic calcium carbonate (PC) at the expense of non-pedogenic calcium carbonate (NPC) is the prime chemical reaction for the natural chemical degradation realized in terms of impairment of hydraulic properties of soils mediated through the development of subsoil sodicity. Presence of gypsum and Ca-zeolites, on the other hand, prevented the rise of pH, decrease in Ca/Mg ratio of exchange sites and improved the hydraulic properties amidst an exchangeable sodium percentage (ESP) >15. The improvement in saturated hydraulic conductivity (sHC) ($>10\,\mathrm{mm\ h^{-1}}$) of zeolitic sodic soils does commensurate fairly well with the performance of rainy season crops. Thus characterization of sodic soils in terms of sHC $<10\,\mathrm{mm\ h^{-1}}$ (weighted mean in 0–100 cm depth of soil) instead of any ESP or sodium adsorption ratio (SAR) emerges as a robust criterion that stands for a universal acceptance for the better use and management of such naturally degraded soils, not only in the Indian semi-arid tropics, but also in similar climatic and geologic areas elsewhere.

Keywords: Natural degradation; Soil modifiers; Sodicity criteria; Soil classification; Soil management

1. Introduction

The global distribution (except in Antarctica) of Vertisols and Vertic intergrades indicates that an area of 257×10^6 ha are confined between the 45°N and 45°S latitudes of which India occupies ~30% area (Dudal, 1965). Vertisols of sub-humid, semi-arid and arid climatic regions of the Peninsular India are calcareous. Detailed micromorphological studies on twenty-three benchmark Vertisols (Srivastava et al., 2002) indicated that Vertisols contain PC and NPC irrespective of the ecosystems to which they belong. The NPCs are part of

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* Corresponding author. Fax: +91 712 2500534.
E-mail addresses: dkpal@nbsslup.ernet.in, paldilip2001@yahoo.com (D.K. Pal).

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the parent material of Vertisols. Dissolution of NPCs and recrystallization of dissolved Ca^{2+} ions are responsible for the formation of PCs. Vertisols of arid and semi-arid climates contain more PC in their soil control sections (SCSs) than those of sub-humid climates. Based on information of this study and related studies made earlier (Balpande et al., 1996; Pal et al., 2000, 2001; Vaidya and Pal, 2002) it was reported that formation of PC is the prime chemical reaction responsible for the increase in pH, the decrease in the Ca/Mg ratio of exchange site with depth and in the development of subsoil sodicity. These authors advocated an ESP much lower than 15 to define sodic Vertisols. Similar observations were made earlier for soils of Australia (Sumner, 1995).

Kadu et al. (2003) indicated than an optimum yield of cotton in these Vertisols can be obtained when the soils are non-sodic ($ESP < 5$). They also found a 50% reduction in yield of cotton when soils are sodic ($ESP > 5$, < 15). These observations were made on the basis of limited soils. Therefore, to accept an $ESP > 5$, but < 15 as a universal criterion for sodic soils, additional research endeavours are needed on Vertisols of major states of the Peninsular India. Moreover, the studies made so far did not include Vertisols with soil modifiers like Ca-zeolites and gypsum that are quite common in Vertisols (Pal, 2003) and soils of the Indo-Gangetic Plains (IGP) (Gupta and Abrol, 1990). The presence of zeolites as soil modifiers creates a unique pedo-chemical environment as these minerals have abilities to hydrate and dehydrate reversibly and to exchange some of their constituent cations (Bhattacharyya et al., 1993, 1999). The presence of gypsum as soil modifiers prevents the development of sodicity in Vertisols of aridic region of southern India (Kalbande et al., 1992) due to its relatively rapid solubility (30 times more than Ca-zeolite in distilled water). This suggests that a new initiative is required to document the extent of modifications in soil properties by these modifiers and also to pinpoint what characteristics a sodic soil should possess that would resolve satisfactorily to give a universally acceptable definition.

The present study was undertaken to establish pedogenetic relationships between sodicity related properties with hydraulic properties of twenty-six benchmark Vertisols representative of geographic and climatic regions of the Peninsular India (Table 1) with and without modifiers. It is hoped that this study will provide (a) an understanding that the development of sodicity is not only due to the anthropogenic reason (Lal et al., 1989) but can also be due to natural soil degradation process with and without soil modifiers and (b) a universally acceptable soil parameter to define sodic soils not only of India but also of similar soils occurring elsewhere for their efficient use and management.

2. Materials and methods

Twenty-six benchmark Vertisols were selected in the states of Madhya Pradesh, Maharashtra, Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat and Rajasthan. They were selected from sub-humid (moist), sub-humid (dry), semi-arid (moist), semi-arid (dry) 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). Undisturbed soil blocks (8 cm long, 6 cm wide and 5 cm thick) were collected from soil horizons, and thin sections were prepared by the methods of Jongerius and Heintzberger (1975). They were described according to the nomenclature of Bullock et al. (1985). The amounts of calcium carbonates were determined by the frequency distribution chart of Bullock et al. (1985).

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). The $CaCO_3$, pH, cation exchange capacity (CEC) and exchangeable Na and K were determined on the total fine earth (<2 mm) by standard methods (Richards, 1954). 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 Collin's calcimeter. The saturated hydraulic conductivity (sHC) was determined using a constant head permeameter (Richards, 1954). The coefficient 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. Available water content (AWC) was calculated using the water retained between 33 kPa and 1500 kPa of less than 2 mm size soil samples (Richards , 1954). The bulk density (BD) was determined by a field-moist method using core samples (diameter 50 mm) of known volume ($100 cm^3$) (Klute, 1986).

Table 1
General properties of the Vertisols in different rainfall and temperature regions of India

Pedon no.	Soil series (Soil Taxonomy)[a] (District, State)	Parent material(s)	MAR[b], MRw, MRd (mm)	MAT[c], MTw, MTd (°C)	Structure/lime nodules[d]	Soil reaction (pH 1:2) water	Cracks (width, depth), slickensides (depth)[e] (values in cm), effervescence[f] (with dilute HCl)
Sub-humid moist							
1	Kheri (Typic Haplusterts) (Jabalpur, Madhya Pradesh)	Basaltic alluvium	1448 1228 160	25.1 28.1 23.7	Moderate medium subangular blocky in the Ap horizon and strong, medium angular blocky in the Bss horizons/fine and medium lime nodules	7.5–8.0	3–4, 40 41 e-ev
2	Sakka (Chromic Haplusterts) (Dindori, Madhya Pradesh)	Basaltic alluvium	1420 1316 104	24.4 26.9 22.6	Moderate medium subangular blocky in the Ap horizon and strong, coarse angular blocky in the Bss horizons/many very fine and common fine lime nodules	5.2–7.9	2–10, 120 34 nil-es
3	Boripani (Leptic Haplusterts) (Nagpur, Maharashtra)	Basaltic alluvium	1279 1120 159	26.7 27.3 26.2	Moderate medium subangular blocky to weak, coarse prismatic structure in the A horizon and Moderate medium subangular blocky to angular blocky in the Bss horizon/common fine, medium and coarse lime nodules	7.3–7.7	1–2, 20 44 nil-ev
4	Nabibagh (Typic Haplusterts) (Bhopal, Madhya Pradesh)	Basaltic alluvium	1209 1105 104	25.3 27.4 24.2	Moderate medium subangular blocky in the Ap horizon and moderate coarse angular blocky in the Bss horizons/many, very fine, fine and few coarse lime nodules	7.8–8.0	>0.5, 20 42 nil-e
5	Pahur (Sodic 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	8.0–8.9	3–5, 150 40 e-es
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
7	Panjri (Typic Haplusterts) (Nagpur, Maharashtra)	Basaltic alluvium	1127 983 144	26.9 28.6 26.0	Moderate medium subangular blocky in the Ap horizon and strong, coarse angular blocky in the Bss horizons/common very fine, fine and medium lime nodules	7.8–8.1	2.5–3.0, 13 38 nil-e
Sub-humid dry							
8	Sarol (Typic Haplusterts) (Indore, Madhya Pradesh)	Basaltic alluvium	1084 951 133	24.4 26.6 23.3	Strong medium subangular blocky in the Ap horizon and strong, coarse angular blocky in the Bss horizons/common, very fine and fine and few medium lime nodules	7.8–7.9	0.5–1.0, 25 66 nil-e
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

Table 1 (*continued*)

Pedon no.	Soil series (Soil Taxonomy)[a] (District, State)	Parent material(s)	MAR[b], MRw, MRd (mm)	MAT[c], MTw, MTd (°C)	Structure/lime nodules[d]	Soil reaction (pH 1:2) water	Cracks (width, depth), slickensides (depth)[e] (values in cm), effervescence[f] (with dilute HCl)
Sub-humid dry							
10	Linga (Typic Haplusterts) (Nagpur, Maharashtra)	Basaltic alluvium	1011 861 150	26.0 26.5 25.7	Moderate medium subangular blocky in the Ap horizon and strong, medium angular blocky in the Bss horizons/ common, very fine and fine and few medium lime nodules	7.8–7.9	0.5–1.0, 35 69 e-es
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
12	Asra (Sodic Haplusterts) (Amravati, Maharashtra)	Basaltic alluvium	975 831 144	27.2 27.8 26.9	Moderate medium subangular blocky in the Ap horizons and strong coarse angular blocky in the Bss horizons/many very fine and fine and few medium lime nodules	7.8–8.3	2–4, 40 59 e-es
13	Vasmat 1 (Sodic Haplusterts) (Vasmat, Mahaashtra)	Basaltic alluvium	924 786 138	26.3 27.3 25.8	Weak medium subangular blocky in the Ap horizon and moderate medium angular blocky in the Bss horizons/few very fine fine and few medium lime nodules		1–2, 70 42 es
14	Vasmat 2 (Typic Haplusterts) (Vasmat, Maharashtra)	Basaltic alluvium	924 786 138	26.3 27.3 25.8	Weak medium subangular blocky in the Ap horizon and moderate medium angular blocky in the Bss horizons/few very fine fine and few medium lime nodules		1–1.5, 63 45 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
16	Paral (Sodic Haplusterts) (Akola, Maharashtra)	Basaltic alluvium	794 674 120	26.5 27.2 26.1	Moderate medium subangular blocky in the Ap horizon and strong coarse angular blocky in the Bss horizons/common very fine and fine lime nodules	8.0–8.5	4–6, 70 35 es

(continued on next page)

Table 1 (*continued*)

Pedon no.	Soil series (Soil Taxonomy) [a] (District, State)	Parent material(s)	MAR [b], MRw, MRd (mm)	MAT [c], MTw, MTd (°C)	Structure/lime nodules [d]	Soil reaction (pH 1:2) water	Cracks (width, depth), slickensides (depth) [e] (values in cm), effervescence [f] (with dilute HCl)
Semi-arid dry							
17	Jajapur (Sodic Haplusterts) (Mehboobnagar, Andhra Pradesh)	Alluvia of basalt and granite-gneiss	792 694 98	27.9 27.8 28.0	Moderate medium subangular blocky in the Ap horizon and moderate medium subangular blocky in the subsurface horizons/few very fine, fine and medium lime nodules	7.7–9.2	2–3, 35 48 e-ev
18	Kasireddipalli (Sodic Haplusterts) (Medak, Andhra Pradesh	Alluvia of basalt and 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
19	Konheri (Leptic Haplusterts) (Solapur, Maharashtra)	Basaltic alluvium	742 652 90	26.5 27.1 26.0	Moderate medium subangular blocky in the Ap horizon and moderate medium angular blocky in the Bss horizons/ common very fine and fine lime nodules	8.0–8.2	0.5–1.0, 20 34 ev
20	Kalwan (Sodic Haplusterts) (Nashik, Maharashtra)	Basaltic alluvium	692 574 118	26.0 27.5 25.3	Weak very coarse prismatic structure in the Ap horizon and strong coarse angular blocky in the Bss horizons/ many fine and few medium lime nodules	7.7–8.2	5–7, 48 48 e-ev
21	Kovilpatti (Gypsic Haplusterts) (Thoothokudi, Tamil Nadu)	Alluvium of metamorphic rocks	660 392 268	29.4 29.1 29.4	Weak fine granular in the Ap horizon and strong medium angular blocky in the Bss horizons/ common very fine and fine and few medium lime nodules	7.4–8.0	2–3, 20 74 e-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
23	Teligi (Sodic Haplusterts) (Bellary, Karnataka)	Alluvia of basalt and granite-gneiss	632 444 188	26.6 26.4 26.6	Moderate medium subangular blocky in the Ap horizon and strong medium angular blocky in the Bss horizons/many very fine and few fine lime nodules	7.9–8.6	3–4, 40 44 es-ev
24	Sollapuram (Sodic Haplusterts) (Anantapur, Andhra Pradesh)	Alluvia of basalt and granite-gneiss	583 334 249	27.6 27.6 27.7	Moderate medium subangular blocky in the Ap horizon and moderate medium angular blocky in the Bss horizons/few very fine and fine and medium lime nodules	8.0–8.6	5–6, 40 63 ev

Table 1 (*continued*)

Pedon no.	Soil series (Soil Taxonomy)[a] (District, State)	Parent material(s)	MAR[b], MRw, MRd (mm)	MAT[c], MTw, MTd (°C)	Structure/lime nodules[d]	Soil reaction (pH 1:2) water	Cracks (width, depth), slickensides (depth)[e] (values in cm), effervescence[f] (with dilute HCl)
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
26	Nimone (Aridic Haplusterts) (Ahmadnagar, Maharashtra)	Basaltic alluvium	520 336 184	25.6 26.3 25.4	Weak medium subangular blocky in the Ap horizon and strong medium subangular to angular blocky in the Bss horizons/common very fine and few fine lime nodules	8.4–8.5	2–3, 30 55 es-ev

[a] Soil classification according to Soil Survey Staff (1999).

[b] 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.

[c] 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.

[d] Described according to Soil Survey Staff (1951).

[e] Indicates the depth of the first occurrence of slickensides.

[f] e = slight; es = strong; ev = violent effervescence.

The silt and clay fractions were analysed mineralogically by XRD of oriented aggregates saturated with either Ca or K, using a Philips diffractometer with Ni-filtered CuKα at a scanning speed of 2° 2θ/min. The minerals were identified using the method of Jackson (1979). Quantitative values of clay smectites were determined from linear extensibility (LE) using the regression equation of Shirsath et al. (2000).

3. Results

3.1. Morphological, physical and chemical 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.

The soils are clayey, fine clay ($<0.2\,\mu m$) constitutes $>50\%$ of the total clay. The soils have COLE value ranging from 0.10 to 0.28 indicating their very high shrink–swell potential. The bulk density value ranges from 1.1 to 1.8 (Tables 2–4).

The electrical conductivity values of the saturation extracts (ECe) are much less than 4 dS m^{-1} and thus the majority of soils are not saline (Tables 2–4). However, ESP values varied widely among the soils. In soils of MAR > 1100 and 1084–1011 mm, ESP is <5 but it increased with depth in pedons 5 and 6 and ranged from 2 to 16 in pedon 5. The development of sodicity (ESP > 5, < 15) in pedon 5 is however due to the use of river water for the last 20 years, indicating poor quality of river water for irrigation. In soils of semi-arid (moist and dry) and arid regions, ESP increased downwards to reach values >15 in the Bss horizons of pedons 5, 13, 16, 17, 18, 23, 24 and 25. However, some soils despite their occurrence in semi-arid and arid climates have ESP < 5 (pedons 15, 19, 21) as well as ESP > 5 and < 15 (pedons 20, 22, 26). Base saturation percent in excess of 100% in these six soils suggests the presence of Ca-bearing soil modifiers (Fig. 1). The substantial release of Ca^{2+} ions from soil modifiers might have prevented the rise in ESP in these soils. This is, however, reflected in a lesser value of correlation coefficient between ESP and SAR in zeolitic sodic soils than non-zeolitic sodic soils (Table 5). During profile examination gypsum in soils of pedon 21 and zeolites in pedons 19, 22 and 26 were detected. Zeolites in alluvium of weathered Deccan basalt in general belong to silica-poor heulandite type (Bhattacharyya et al., 1993, 1999).

Sodification of Vertisols of the Peninsular India is only observed in soils of semi-arid and arid climates. Judging by their pH, ECe and ESP, soils of pedons 13, 17, 23, 24 and 25 qualify as Sodic Haplusterts (Soil

Table 2
Physical and chemical properties of Nabibagh soils (pedon 4: Typic Haplusterts) as representative of sub-humid moist and dry climates

(a) Physical properties

Lab. no.	Horizon	Depth (cm)	Size class and particle diameter (mm)			Fine clay (%)	Fine clay/ total clay (%)	BD (Mg/m^3)	COLE	HC[a] (cm/h)	WDC (%)	AWC (%)
			Total									
			Sand (2–0.05)	Silt (0.05–0.002)	Clay (<0.002)							
			(% of <2mm)									
3090	Ap	0–23	2.1	49.0	48.9	31.3	64.0	–	0.17	1.5	8.3	15.5
3091	Bw1	23–42	1.7	46.8	51.4	34.4	67.0	1.3	0.19	2.9	9.5	15.1
3092	Bss1	42–81	1.8	42.5	55.7	38.2	68.6	1.5	0.20	2.1	12.1	13.2
3093	Bss2	81–122	1.8	45.2	53.0	35.5	67.0	1.5	0.20	1.7	11.6	15.8
3094	Bss3	122–150	1.6	42.5	55.9	38.2	68.3	1.4	0.22	1.1	11.4	15.8

(b) Chemical properties

Depth (cm)	pH water (1:2)	$CaCO_3$ (%)	Extractable bases					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	B.S. (%)
			Ca	Mg	Na	K	Sum			
			(cmol(p+) kg^{-1})							
0–23	7.8	3.8	39.2	7.8	0.3	0.5	47.8	46.7	95	102
23–42	7.9	4.5	38.4	5.6	0.3	0.5	44.8	51.8	111	86
42–81	8.0	4.2	37.9	7.8	0.4	0.6	46.7	45.7	107	102
81–122	8.0	4.1	37.7	7.1	0.4	0.6	45.8	44.3	98	103
122–150	8.0	5.3	36.6	8.2	0.4	0.7	45.9	45.7	107	100

(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) (%)
0–23	4.9	84	17	0.6	1.6	0.8
23–42	6.7	74	11	0.6	2.0	1.0
42–81	4.9	83	17	0.9	2.7	1.5
81–122	5.3	85	16	0.9	2.4	1.3
122–150	4.4	80	18	0.9	2.7	1.5

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)					Soluble anions (meq/l)				SAR
	ECe (dS m^{-1})	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	
0–23	0.4	1.44	0.5	0.76	0.18	–	2.0	0.9	–	0.8
23–42	0.2	0.81	0.4	1.57	0.08	–	2.2	0.5	0.2	2.0
42–81	0.2	1.25	0.4	2.40	0.02	–	3.2	0.5	0.4	2.6
81–122	0.2	0.75	0.3	1.70	0.04	–	2.7	0.1	–	2.3
122–150	0.4	2.00	0.8	2.90	0.04	–	4.2	1.5	–	2.4

[a] 20 mm h^{-1} is the HC (WM) in 0–100 cm depth of soil.

Survey Staff, 1999). As per the Soil Taxonomy for a sodic subgroup in the Vertisols, the minimum limit of ESP is 15. Indian researchers considered that even a low level of sodicity (ESP 5–15) is enough to impair HC (<10 mm h^{-1} as weighted mean in 0–100 cm depth of soil, Kadu et al., 2003) that reflects in very poor performance of rainy and winter season crops (Kadu et al., 2003). Thus they proposed soils having ESP 5–15 with sHC <10 mm h^{-1} to be considered as Sodic Haplusterts as shown for pedons 5, 12, 16, 18, 20 (Table 1). On the other hand zeolitic Semla (pedon 22) and Nimone (pedon 26) soils of dry climate having an ESP 5–15 but with an sHC > 10 mm h^{-1} are Aridic Haplusterts. This indicates that under ustic soil moisture and hyperthermic temperature regimes, soils under study have distinctly different chemical environments, even when they are, in general, not affected by a seasonal water table.

The sHC values in their SCS of soils with ESP < 5 ranged from 6 to 34 mm h^{-1} and in most soils it rapidly decreased with depth (Tables 2–4). The soils of ESP > 5 or more (Pedons 16, 18, 24) have sHC values <5 mm h^{-1},

Table 3
Physical and chemical properties of Paral soils (pedon 16: Sodic Haplusterts) as representative of semi-arid moist and dry climates

(a) Physical properties

Lab. no.	Horizon	Depth (cm)	Size class and particle diameter (mm) Total Sand (2–0.05)	Silt (0.05–0.002)	Clay (<0.002)	Fine clay (%)	Fine clay/ total clay (%)	BD (Mg/m^3)	COLE	HC[a] (cm/h)	WDC (%)	AWC (%)
			(% of <2 mm)									
3130	Ap	0–9	2.5	42.2	55.3	22.6	40.9	–	0.22	1.7	4.1	15.8
3131	Bw1	9–35	0.8	40.2	58.9	30.7	52.1	1.6	0.18	0.5	4.0	17.0
3132	Bss1	35–69	2.6	40.5	56.9	29.5	51.8	1.5	0.17	0.2	6.0	19.5
3133	Bss2	69–105	1.6	35.7	62.6	35.6	56.9	–	0.19	0.3	7.2	21.7
3134	Bss3	105–132	1.0	37.3	61.8	37.6	60.8	1.5	0.23	0.1	8.6	23.1
3135	Bss4	132–150	0.5	43.1	56.3	37.6	66.8	1.5	0.22	0.1	6.2	25.9

(b) Chemical properties

Depth (cm)	pH water (1:2)	CaCO$_3$ (%)	Extractable bases Ca	Mg	Na	K	Sum	CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	B.S. (%)	
			(cmol(p+) kg^{-1})								
0–9	8.0	9.7	34.3	10.6	0.7	1.2	46.8	54.4	85	84	
9–35	8.2	9.9	32.2	11.2	2.3	0.8	46.5	56.5	79	79	
35–69	8.4	10.2	27.5	12.9	3.9	0.9	45.2	47.8	79	92	
69–105	8.4	10.4	27.2	15.8	7.4	0.9	51.3	51.8	82	97	
105–132	8.5	10.2	23.7	14.5	8.8	0.8	47.8	52.5	77	91	
132–150	8.5	11.8	0.5	18.9	14.4	9.1	0.8	43.2	43.3	77	100

(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) (%)
0–9	3.2	66.8	14.0	1.4	1.9	1.0
9–35	2.8	57.0	16.3	4.1	2.3	1.3
35–69	2.1	59.6	22.8	8.1	2.9	1.6
69–105	2.0	54.4	26.6	14.2	2.8	1.7
105–132	1.6	45.1	27.6	16.7	3.8	2.3
132–150	1.3	43.6	33.2	21.0	2.8	1.6

(d) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l) ECe (dS m^{-1})	Ca	Mg	Na	K	Soluble anions (meq/l) CO$_3$	HCO$_3$	Cl	SO$_4$	SAR
0–9	0.4	1.08	0.6	0.87	0.12	–	1.75	0.5	0.44	1.0
9–35	0.4	0.48	0.7	1.74	0.02	–	2.12	0.4	0.46	2.2
35–69	2.9	0.65	0.9	7.30	0.18	–	7.40	0.4	0.30	8.4
69–105	4.0	0.57	0.5	8.60	0.35	–	8.00	0.5	0.78	12.0
105–132	–	–	–	–	–	–		–	–	–
132–150	–	–	–	–	–	–	–	–	–	–

[a] 4 mm h^{-1} is the HC (WM) in 0–100 cm depth of soil.

indicating poor internal drainage conditions. However, in soils with ESP > 5 and soil modifiers (as identified in general by base saturation value in excess of 100%) (pedons 4, 5, 13, 14, 20, 22, 23, 25, 26) have much higher HC values (> 5 mm h^{-1}). Soil modifiers improved the hydraulic properties and prevented the rise in ESP and pH values beyond 5 and 8.5 respectively, even in soils of semi-arid (dry) climates (pedons 15, 19, 21, 22).

In Vertisols with ESP < 5, the AWC values (> 15 but < 30%, Tables 2–4) remain almost the same throughout their depth. However, in soils with ESP > 5, the AWC increases with depth. In shrink–swell soils the AWC is primarily dependent upon the content of smectite clay mineral and this fact is realized from the significant positive correlation between AWC and smectic clay (Table 5). The AWC is also affected by the exchangeable

Table 4
Physical and chemical properties of Sokhda soils (pedon 25: Calcic Haplusterts) as representative of arid climate

(a) Physical properties

Lab. no.	Horizon	Depth (cm)	Size class and particle diameter (mm)			Fine clay (%)	Fine clay/ total clay (%)	BD (Mg/m^3)	COLE	HC^a (cm/h)	WDC (%)	AWC (%)
			Total									
			Sand (2–0.05)	Silt (0.05–0.002)	Clay (<0.002)							
			(% of <2mm)									
3279	Ap	0–11	29.1	39.4	31.5	12.6	39.7	–	0.16	3.2	1.0	6.8
3280	Bw1	11–37	29.4	40.1	30.5	13.4	43.9	1.4	0.15	3.0	4.4	12.5
3281	Bw2	37–63	26.4	33.4	40.1	17.9	44.6	1.5	0.16	1.5	3.8	12.7
3282	Bss1	63–98	26.6	32.5	40.8	19.2	47.0	1.7	0.13	0.4	3.6	14.0
3283	Bss2	98–145	22.8	34.5	42.7	20.4	47.7	1.6	0.11	0.2	3.5	13.9
3284	BC	145–160	7.8	42.0	50.2	33.0	65.8	1.6	0.17	2.1	3.7	14.0

(b) Chemical properties

Depth (cm)	pH water (1:2)	$CaCO_3$ (%)	Extractable bases					CEC (cmol(p+) kg^{-1})	Clay CEC (cmol(p+) kg^{-1})	B.S. (%)
			Ca	Mg	Na	K	Sum			
			(cmol(p+) kg^{-1})							
0–11	8.2	21.9	21.1	9.8	1.0	0.7	32.6	27.6	88	118
11–37	8.4	21.4	20.4	8.9	1.2	0.6	31.1	27.5	90	113
37–63	8.7	21.5	18.0	13.1	2.6	0.5	34.2	28.5	71	120
63–98	8.8	22.0	14.4	13.8	4.7	0.5	33.4	29.0	71	115
98–145	8.6	21.6	12.7	15.6	8.5	0.5	37.3	30.3	71	123
145–160	8.5	11.6	11.8	14.0	10.1	0.5	36.4	32.3	64	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)				SAR
	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	0.8
11–37	0.4	1.5	1.1	1.7	0.07	1.5	1.7	1.0	0.1	1.5
37–63	0.5	0.5	0.5	4.4	0.01	1.8	2.1	1.5	–	6.1
63–98	0.7	0.6	0.6	8.7	0.02	1.1	3.9	3.6	1.3	11.2
98–145	4.2	3.2	0.5	34.8	0.16	1.7	1.0	32.1	–	25.5
145–160	0.4	1.6	0.9	32.7	0.04	1.1	2.1	30.8	1.3	29.2

[a] 17 mm h^{-1} is the HC (WM) in 0–100 cm depth of soil.

cations especially the Na^+ ions. This is reflected from a significant positive correlation between AWC and ESP and a significant negative correlation between AWC and exchangeable Ca/Mg ratio (Table 5). It is a paradoxical situation that even with a high amount of AWC, these Vertisols have limitations that restrict their full potential to grow both rainy season and winter crops due to their poor subsoil porosity and aeration (NBSSLUP- ICRISAT, 1991). Farmers faced with these difficulties keep non-zeolitic sodic soils (pedons 12, 16, 17, 18, 24) fallow for one or more rainy seasons and cultivate them only in the post-rainy season. In contrast, in zeolitic sodic soils (pedons 20, 22, 23, 25, 26) regular cultivation of deep rooted rainfed crops including cotton is a reality. This

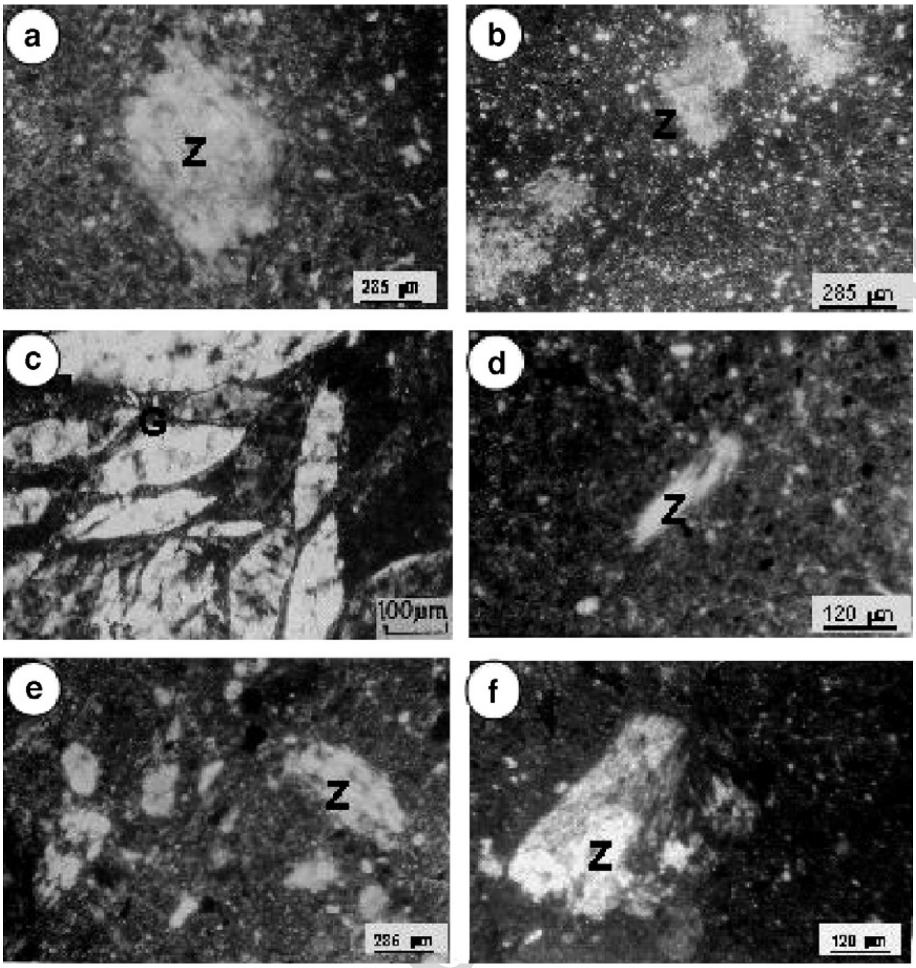

Fig. 1. Representative features of soil modifiers: zeolite in pedon 1 (a), pedon 4 (b), gypsum in pedon 21 (c), zeolite in pedon 19 (d), pedon 20 (e) and pedon 22 (f).

suggests that the zeolites release enough Ca^{2+} ions that facilitates the infiltration of rainwater as well as helps in storing moisture at depths.

3.2. Mineralogical properties

The XRD analysis indicated the dominant presence of fairly well crystalline smectite in both coarse (>50%) and fine clay (>90%) along with some non-expanding minerals like mica, chlorite, palygorskite, vermiculite and kaolin. In silt fraction smectite content was less (10–20%) along with other non-expanding minerals and zeolites. In general the fine clay smectites are little hydroxy-interlayered and the extent of hydroxy-interlayering increased in soils of semi-arid and arid climates.

3.3. Micromorphological properties

3.3.1. Plasmic fabric

Shrinking and swelling result in a very dense groundmass exhibiting porostriated, granostriated, parallel-striated and reticulate striated plasmic fabric (Wilding, 1985). Soils of sub-humid moist climate showed strong plasma separation with parallel/cross/reticulate striated plasmic fabrics (Fig. 2a) whereas soils of sub-humid dry climate showed moderate to strong plasma separation with parallel striated plasmic fabric (Fig. 2b). Soils of semi-arid moist showed moderate to strong parallel striated and also stripple-speckled plasmic fabric whereas soils of semi-arid dry climate showed crystallitic, weak cross-striated, and weak reticulated, and granostriated plasmic fabric (Fig. 2c–f). Soils of arid dry climate showed crystallitic and granostriated plasmic fabric (Fig. 2h). It was also noticed that some soils of semi-arid dry climate (pedons 19, 21) showed moderately strong parallel striated plasmic fabric (Fig. 2g), presumably because of their favourable hydraulic properties containing soil modifiers. Despite a high degree of clay activity and shrink–swell process, the plasmic fabric is not uniform among the soils of different climates. Similar observations were also made by other researchers (Kalbande et al., 1992; Balpande et al., 1997b; Pal et al., 2001; Vaidya and Pal, 2002).

Table 5
Correlation coefficient between soil attributes

Parameter *Y*	Parameter *X*	*r*
Based on 157 soil horizon samples of 26 Vertisols		
AWC (%)	Clay (<2 μm) (%)	0.41*
AWC (%)	Fine clay (<0.2 μm) (%)	0.33*
AWC (%)	ESP	0.44*
AWC (%)	Exch. Ca/Mg	−0.21*
Based on 50 soil horizon samples of 9 non-sodic Vertisols (pedons 1, 2, 3, 4, 7, 8, 9, 10, 11)		
sHC (mm h^{-1})	ESP	−0.46*
sHC (mm h^{-1})	WDC (%)	−0.47*
ESP	WDC (%)	0.42*
ESP	EMP	0.46*
ESP	Exch. Ca/Mg	−0.42*
Based on 32 soil horizon samples of 5 zeolitic sodic Vertisols (pedons 20, 22, 23, 25, 26)		
ESP	Carbonate clay (feb)	0.53*
ESP	EMP	0.35*
ESP	Exch. Ca/Mg	−0.49*
ESP	SAR	0.89*
Based on 31 soil horizon samples of 5 non-zeolitic sodic Vertisols (pedons 12, 16, 17, 18, 24)		
ESP	Carbonate clay (feb)	0.73*
ESP	EMP	0.57*
ESP	Exch. Ca/Mg	−0.72*
sHC (mm h^{-1})	Carbonate clay (feb)	−0.40*
AWC (%)	ESP	0.69*
ESP	SAR	0.92*

AWC: available water content; ESP: exchangeable sodium percentage; sHC: saturated hydraulic conductivity; EMP: exchangeable magnesium percentage; WDC: water dispersible clay; feb: fine earth basis.
* Significant at 1% level.

3.3.2. PC and NPC

It is difficult to consider that the $CaCO_3$ in these soils is entirely of pedogenic origin because many of these soils may have non-pedogenic $CaCO_3$ due to their polygenesis (Pal et al., 2000, 2001). The Vertisols under study exhibit the presence of both PC and NPC. Some $CaCO_3$ glaebules are sub-rounded to rounded nodules coated with Fe–Mn oxides and sharp boundaries with soil matrix and these are considered to be NPC (Pal et al., 2000; Srivastava et al., 2002). The other glaebules that are fine textured with irregular shapes and diffuse boundaries and without Fe–Mn coatings are considered to be PC (Pal et al., 2000; Srivastava et al., 2002). The PCs and NPCs were observed in Vertisols in five climatic regions. The distribution of the NPCs indicates that they are present throughout the soil irrespective of climatic region. The PCs are present at a depth of ≥70 cm in soils of sub-humid climate, at ≥50 cm in sub-humid dry climate, ≥30 cm in semi-arid moist climate and throughout the soil depth in semi-arid dry and arid dry climate.

As determined by the frequency distribution chart of Bullock et al. (1985), the PC constitutes 1–4% of the total volume in soils of sub-humid moist climate (Fig. 3a). The NPCs were observed throughout the depth and marked by dissolution features (Fig. 3b) and consists of sparite and microsparite crystals. In soils of sub-humid dry climate, 1–6% PCs were observed below 50 cm depth. They occur as dull white-coloured diffuse nodules and dense micrite crystals in the groundmass. About 2–5% NPCs occur throughout the depth of soils. These carbonates consists mainly of sparite and microsparite crystals and are marked by extensive dissolution features (Fig. 3c).

Vertisols of semi-arid moist climate contains PC below 30 cm depth whereas soils of semi-arid dry climate contain PC in all parts. The PCs were dull white diffuse nodules of micrite crystals and found in close association with NPC. In general they showed an increase with depth. The NPCs occur throughout the soils as sub-rounded nodules coated with Fe–Mn oxides showing sharp boundaries with the matrix (Fig. 3d–j) and range from 1% to 15%. They are maximum (15%) in Semla soils (pedon 22) that have crystallitic plasmic fabric. These NPCs also showed features of dissolution although the extent was much less than for those of the sub-humid climatic regions. The PCs occur as diffuse dull white nodules of micrite and NPCs are made up of dense sparite and microsparite. In soils of arid dry climate, PCs occur as diffuse dull white nodules of micrite throughout soils (Fig. 3k) and were very close to NPC (Fig. 3l) in their SCSs. The PC content was 2–3% at the surface and increased to 4–5% with depth. The NPCs were sub-rounded nodules of microsparite crystals and range between 10% and 15%. These are coated with Fe and Mn and show very few dissolution features. The observed depth distribution of PC in soils of sub-humid to arid climates suggests the water loss through evapotranspiration and/or lowering $p\mathrm{CO}_2$ as the primary mechanism in the precipitation of PC (Pal et al., 2000).

3.3.3. Rate of formation of PC

Calcareous Vertisols under study are developed in microdepressions after being filled with smectite in an earlier more humid climate and have attained stability in the present dry climate. Dry climate during the late Holocene restricted further leaching and as a result formation of PC was favoured (Pal et al., 2001). The amount of $CaCO_3$ (<2 mm) in soils of representative climatic region in the first 1 m of the profile (Table 6) includes both NPC and PC. To apportionate the content

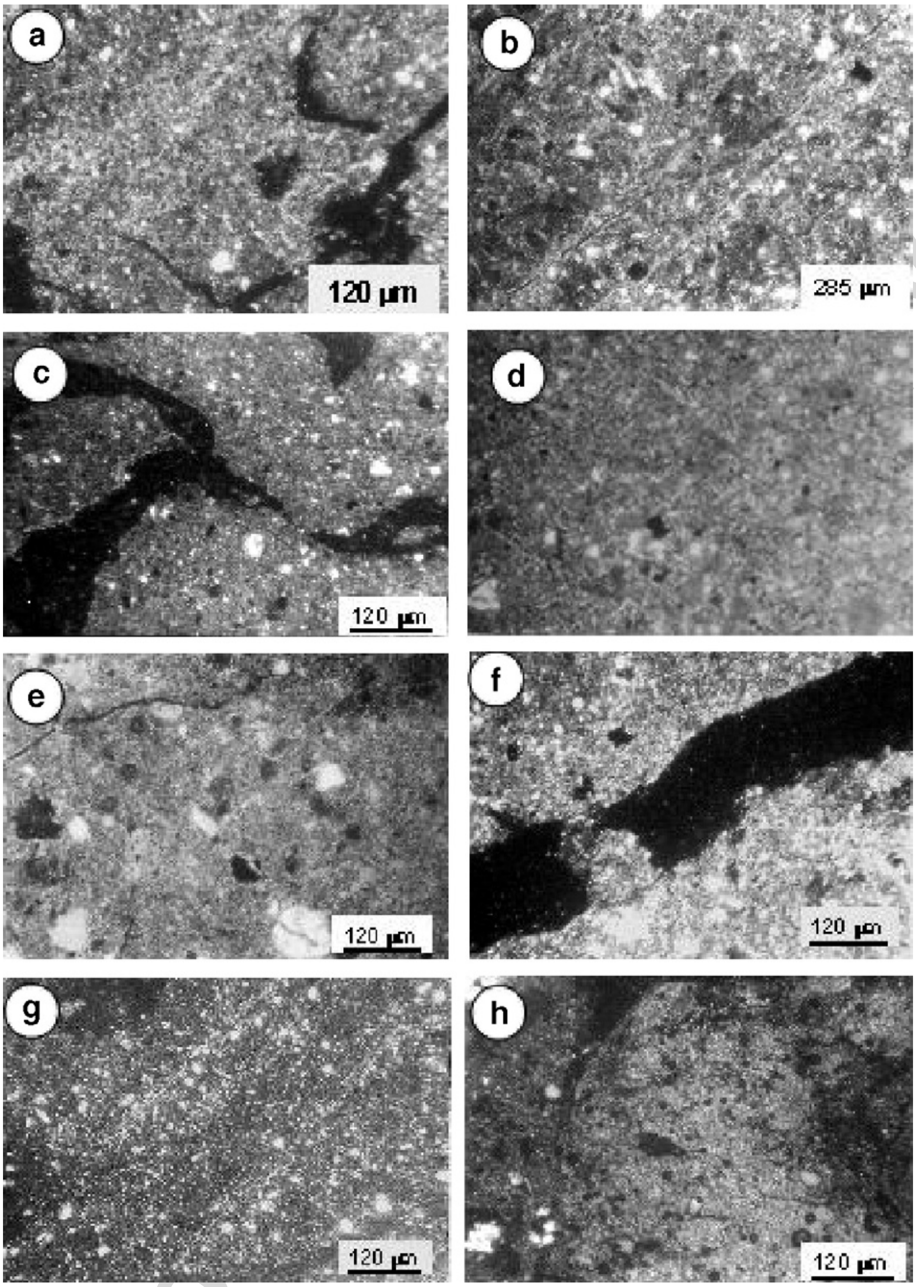

Fig. 2. Representative photograph of plasmic fabric in cross polarized light. (a) Strong cross and reticulate plasmic fabric, Nabibagh soils (pedon 4), 126–134 cm. (b) Moderately developed parallel-striated plasmic fabric, Sarol soils (pedon 8), 86–94 cm. (c) Crystallitic plasmic fabric, Semla soils (pedon 22), 40–48 cm. (d) Weak cross-striated plasmic fabric, Paral soils (pedon 16), 76–84 cm. (e) Weakly developed reticulate striated plasmic fabric, Sollapuram soils (pedon 24), 134–142 cm. (f) Granostriated plasmic fabric, Teligi soils (pedon 23), 61–69 cm. (g) Weakly developed parallel-striated plasmic fabric, Kalwan soils (pedon 20), 61–69 cm. (h) Granostriated plasmic fabric, Sokhda soils (pedon 25), 51–59 cm.

of PC the frequency distribution chart of Bullock et al. (1985) was followed and the percentage of PC in total $CaCO_3$ was calculated and then the rate of formation of PC was determined on the basis of age of the soils. The data indicate a general progressive increase in the rate of formation of PC from sub-humid to arid climate (from 0.39 mg/100 g^{-1} soil $year^{-1}$ in sub-humid moist to 2.12 mg 100 g^{-1} soil $year^{-1}$ in arid dry in the first 1 m of the profile) (Table 6).

4. Discussion

4.1. Nature and extent of soil degradation

The high values of COLE and WDC suggest that swelling of fine clay smectite, together with dispersion of clay, have adversely affected the hydraulic properties of these soils. Earlier studies on chemical degradation of Vertisols (Balpande et al., 1996; Vaidya and Pal, 2002)

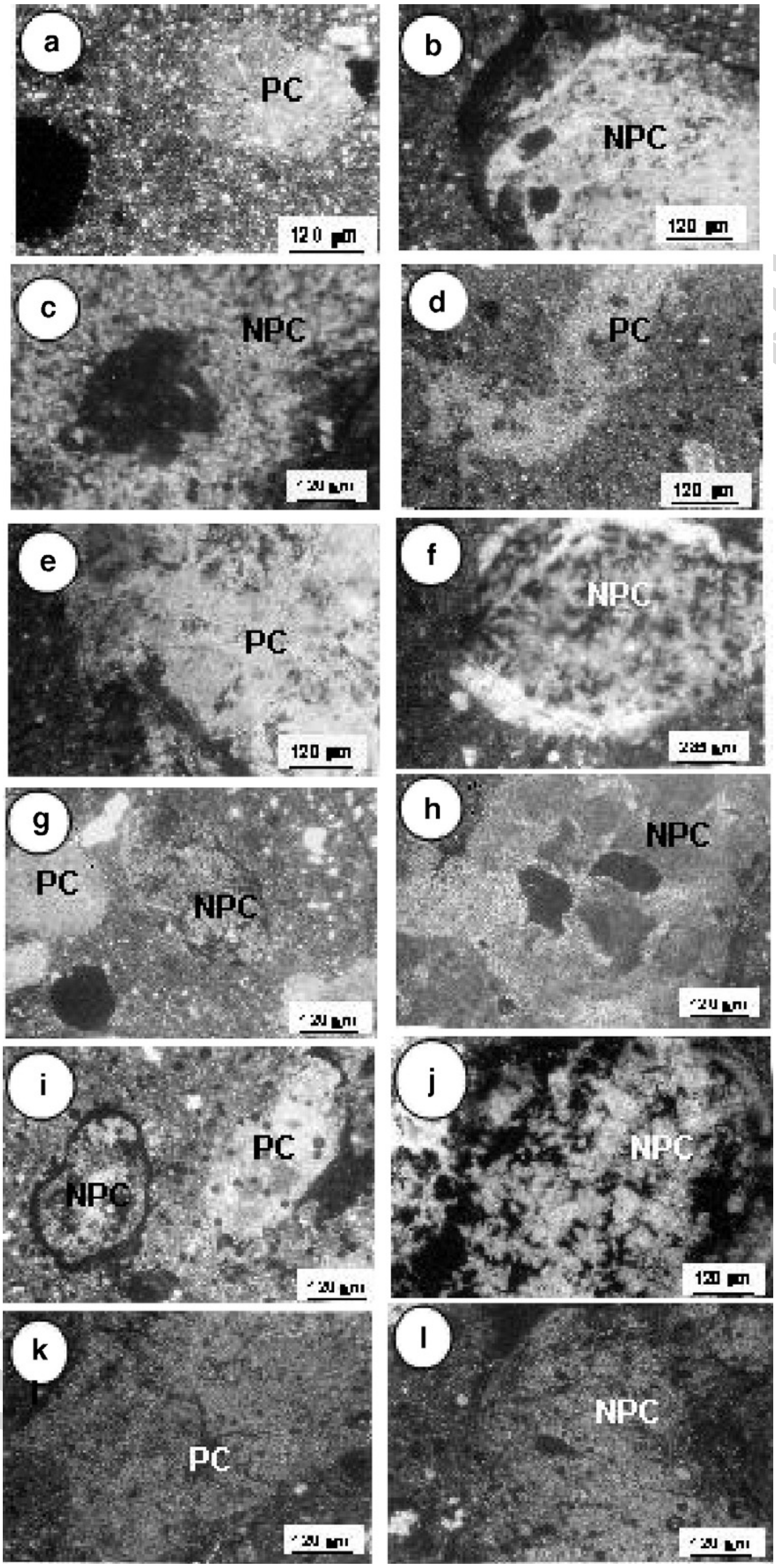

Fig. 3. Representative photograph of calcium carbonate in cross polarized light. (a) PC and (b) NPC in Nabibagh soils (pedon 4), 62–70 cm. (c) NPC showing dissolution in Linga soils (pedon 10), 106–114 cm. (d) PC in Semla soils (pedon 22), 40–48 cm. (e) PC and (f) NPC with dissolution in Paral soils (pedon 16), 76–84 cm. (g) PC and (h) NPC with dissolution in Kovilpatti soils (pedon 21), 25–33 cm. (i) PC and NPC in Sollapuram soils (pedon 24), 134–142 cm. (j) NPC in Kasireddipalli soils (pedon 18), 47–55 cm. (k) PC and (l) NPC in Sokhda soils (pedon 25), 51–59 cm.

Table 6
Rate of formation of PC in soils of representative climatic region

Pedon no.	Soil series	$CaCO_3$ (%) weighted mean in the first 1 m of the profile	^{14}C age of soils[a]	Rate of formation of PC in the first 1 m of the profile	
				mg 100 g^{-1} soil year^{-1}	kg ha^{-1} year^{-1}
Sub-humid moist					
4	Nabibagh	3.7	3967 years BP	0.39	51
5	Pahur	3.2	4500 years BP	0.40	52
Sub-humid dry					
8	Sarol	6.4	8990 years BP	0.53	69
10	Linga	7.8	4500 years BP	0.76	99
Semi-arid moist					
12	Asra	10.5	4500 years BP	0.53	69
11	Bhatumbra	10.1	6910 years BP	0.90	118
Semi-arid dry					
15	Jhalipura	5.5	3390 years BP	0.57	74
23	Teligi	9.6	8410 years BP	0.94	122
21	Kovilpatti	7.9	5910 years BP	1.02	132
24	Sollapuram	17.5	10187 years BP	1.32	172
16	Paral	10.4	4500 years BP	1.48	192
Arid dry					
26	Nimone	14.7	4565 years BP	1.61	209
25	Sokhda	21.7	4000 years BP	2.12	275

[a] Estimated at Birbal Sahni Institute of Paleobotany, Lucknow, India.

indicate that in soils with ESP < 5, the HC was affected by exchangeable magnesium, suggesting that saturation of Vertisols not only with Na^+ ions but also with Mg^{2+} ions leads to greater dispersion of clay. This is the opposite effect from that of saturation with Ca^{2+} ions, which leads to blocking of small pores in the soil. In other words, 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. However, in non-sodic Vertisols (Table 5) no significant positive correlation was obtained between sHC and EMP, and EMP and WDC (Table 5). This suggests that the release of Ca^{2+} ions from zeolites in Kheri (pedon 1), Sakka (pedon 2), Nabibagh (pedon 4), Sarol (pedon 8) and from gypsum in Boripani (pedon 3) soils undermines the influence of Mg^{2+} ions. A significant positive correlation between sHC and ESP, and sHC and WDC and a positive correlation between ESP and WDC (Table 5) indicate that in these soils even a low value of ESP < 5 can affect the hydraulic properties by dispersing the clay particles. A significant positive correlation between ESP and EMP and a negative correlation between ESP and exchangeable Ca/Mg (Table 5) justify this fact.

In non-zeolitic sodic soils (pedons 12, 16, 17, 18, 24) impairment of hydraulic properties has been observed at ESP > 5 and < 15 as indicated by low sHC value of ≤ 5 mm h^{-1}. Serious structural degradation of some Australian soils has also been observed, even at an ESP as low as 6 (Northcote and Skene, 1972). This value is low compared with the minimum value of 15 ESP adopted by USDA as their criterion for a soil to be sodic (Richards, 1954; Soil Survey Staff, 1999). Work by Kadu et al. (1993) and Balpande et al. (1996) showed that an sHC of 1.0 mm h^{-1} represents the lower limit for a satisfactory physical condition in highly smectitic Vertisols where Mg^{2+} ions behave negatively. Later study by Vaidya and Pal (2002) indicated an sHC of 1 mm h^{-1} at an ESP > 5 and < 15. Thus researchers of India (Kadu et al., 1993; Balpande et al., 1996; Vaidya and Pal, 2002) and Australia (McIntyre, 1979; Naidu et al., 1995) advocated an ESP much lower than 15 should be used to denote the value above which the physical properties of soils are seriously affected and such a critical ESP limit needs to be considered as the lower value, rather than the current universal minimum value of 15 ESP for a soil to be referred to as sodic.

The present study, however, indicates that some Vertisols with ESP > 5 and < 15 belonging to sub-humid moist (pedon 5), semi-arid moist (pedons 13, 14), semi-arid dry (pedons 20, 22, 23, 25) and arid dry (pedon 26) climates have much better hydraulic properties (sHC > 5 mm h^{-1}). The favourable release of Ca^{2+} ions from zeolites has enhanced the sHC in spite of high ESP (> 15) in some soils (pedons 5, 13, 23, 25) and this natural soil improvement is also experienced with the excellent performance of rainy season crops over the past several years. It is obvious that ESP value advocated by the US Salinity Laboratory (USSL) (Richards, 1954), Australian (Northcote and Skene, 1972; McIntyre, 1979), Italian (Crescimanno et al., 1995) and Indian (Kadu et al., 1993; Balpande et al., 1996; Vaidya and Pal, 2002) researchers cannot be held as a universal criterion for sodicity. It is now known that the original level of ESP > 15 by the USSL as the threshold above which soil structure was adversely affected was based on hydraulic conductivity measurements using tap water having a much higher total cation concentration (3–10 μmolc l^{-1}) than used in Australia (0.7 μmolc l^{-1}) (Shainberg et al., 1989). Thus the soil degradation in California was observed at a much higher ESP. Even when the hydraulic conductivity was measured in distilled water by DSRS of the NBSS and LUP, a lower ESP value than 15 could not be related to the impairment of physical properties of sodic soils with modifiers. It thus suggests that any universal criterion that can account for the dispersibility of soils may be of value and relevance to define a sodic soil (Sumner, 1995).

4.2. Factors and processes of soil degradation

In upper horizons of smectitic Vertisols, low over burden pressure and cracks prevent the development of high lateral stresses. However, in subsoils, the difference between lateral and vertical stresses is very large, and sphenoids and/or slickensides are developed (Yaalon and Kalmar, 1978; Knight, 1980). Under such circumstances, the Bss horizons are expected to have identical plasmic fabrics. However, plasmic fabrics are different in soils of different climatic regions of the study area. With the decrease in MAR the fabric changes from parallel/cross/striated in sub-humid to stipple-speckled/mosaic speckled in semi-arid and crystallitic in arid dry climates. According to earlier observations (Kalbande et al., 1992; Pal et al., 2001; Vaidya and Pal, 2002) the shrink–swell magnitude was the greatest in soils of sub-humid moist, followed by sub-humid dry, semi-arid moist, semi-arid dry and arid regions. However, this cannot be so as the soils of different climatic regions have high values of COLE (>0.10), clay (>35%), and fine clay (>20%) (Tables 2–4) required for the manifestation of vertic properties (Shirsath et al., 2000).

Rimmer and Greenland (1976) suggested that swelling of clays can be restricted by the presence of carbonate and Blokhuis et al. (1990) stated that in the presence of calcite, any plasma separation is weakly developed and the plasma is disorganized (Bellinfante et al., 1974). Carbonate maintains a concentration of Ca^{2+} ions in solution of 0.5–10.0 mmol dm^{-3}, depending upon the partial pressure of CO_2 in contact with it (Marshall, 1964). Rimmer and Greenland (1976) also pointed out that for a Ca^{2+} concentration of 10 mmol dm^{-3}, the swelling of smectite is only 15% less than in distilled water. As the Ca^{2+} concentrations in the saturation extracts of soils of the MAR < 842 mm are < 5 mmol dm^{-3} (Tables 2–4), the presence of carbonate is not enough to inhibit the swelling of smectite by restricting the expansion of diffuse double layer. Weak plasma separation could also result from a decrease in the internal surface area of fine clay smectite caused by hydroxy-interlayering (Kalbande et al., 1992). However, the highly comparable clay CEC values of non-zeolitic sodic and non-sodic soils (Tables 2–4) suggest that hydroxy-interlayering in the fine clay smectites do not have any substantial influence in modifying the microstructure of these soils. The decreased HC restricts vertical and lateral movement of water in the subsoils. During very hot summer months, this would result in much less water in the subsoils of the semi-arid and arid climates. This is evident from the deep cracks cutting through the Bss horizons especially in sodic soils without modifiers. The lack of adequate soil water during the shrink–swell cycles restricts the swelling of smectite and results in weaker plasma separation in soils of dry climates.

Despite the ustic soil moisture regime of all Vertisols under study and the depth of the water table, only the soils of semi-arid and arid climates are sodic. The presence of more amounts of bicarbonate than carbonate ions in the saturation extract (Tables 2–4) suggests that during periods of high evaporative demand maintenance of a higher Ca/Mg ratio (~2, Pal et al., 2000) in the soil solution becomes difficult because Ca^{2+} ions are precipitated as carbonate, resulting in increase in SAR and ESP. This is indicated by overall increase of clay carbonate (on a fine earth basis) with depth (Tables 2–4). Thus a significant positive correlation between ESP and clay carbonate in both zeolitic and non-zeolitic sodic soils exists (Table 5).

The proximity between PCs and NPCs and the greater dissolution of NPCs in soils of sub-humid climate as compared to those in drier climate suggest that PCs might have resulted from dissolution of NPCs (Fig. 3). This suggests that the NPCs may be a major source of Ca^{2+} ions in soil solution. Petrographic and SEM examinations of plagioclase of similar Vertisols indicated that the mineral is only slightly altered and lack etch pits and/or dissolution pits and thus the plagioclase feldspars are not the primary source of Ca^{2+} ions in soil solution (Srivastava et al., 2002).

Vertisols of sub-humid climate are dominated by Ca^{2+} ions on their exchange complex throughout the depth. However, in subsoils of Vertisols of semi-arid and arid climates with or without soil modifiers, the Mg^{2+} ion tends to dominate in the exchange complex. These are more calcareous in terms of PC content than the former soils and are sodic ($ESP \geq 5$), in the subsoils (Tables 2–4). The precipitation of $CaCO_3$ during evaporative demands for soil water results in an increase in EMP, ESP and carbonate clay and concomitant decrease in ECP down the profile (Tables 2–4). Thus a significant positive correlation between ESP and EMP, a negative correlation between ESP and exchangeable Ca/Mg and a positive correlation between ESP and carbonate clay exists in soils with and without soil modifiers (Table 5). In view of less formation of PC in the Bss horizons of soils of sub-humid climate no significant correlation thus exists between ESP and carbonate clay although a significant positive correlation and a negative correlation between ESP and EMP, and ESP and exchangeable Ca/Mg, respectively, exists (Table 5).

More rainfall of the sub-humid climate 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 (Table 2). Due to better hydraulic properties ($HC \geq 10$ mm h^{-1}), the Vertisols of sub-humid climate do not generally contain PC. In soils of semi-arid and arid climates, due to accelerated rate of formation and accumulation of PC, the subsoils become sodic and their hydraulic properties are impaired (Tables 3 and 4). Thus a significant negative correlation between HC and carbonate clay exists for sodic soils without soil modifiers (Table 5). Despite the formation of PC in soils of semi-arid climate, higher solubility of gypsum prevented the formation of sodicity and also enhanced the hydraulic properties of Kovilpatti soils (pedon 21). In soils of the same climatic region the presence of zeolite could not prevent the formation of sodic soils but could induce higher hydraulic properties (>6 mm h^{-1}) (pedons 20, 22, 23, 25, 26). The formation of PC can, therefore, be considered as a basic and natural process of soil degradation for the development of calcareous sodic soils (Pal et al., 2000). The Vertisols of the semi-arid and arid climates have been modified by the formation of PC, subsoil sodicity, poor plasma separation and cracks cutting through the Bss horizons. These are contemporary events during the semi-arid and arid climates and provide an example of pedogenic threshold (Chadwick and Chorover, 2001; Pal et al., 2003) in Vertisols during the early to late Holocene period (Pal et al., 2000, 2001).

4.3. Redefining the sodic soils

Some pioneer researchers (Quirk and Schofield, 1955; Shainberg et al., 1981) envisaged that the threshold of $ESP > 15$ may need reconsideration because soil degradation can take place even at low ESP in dilute solutions. Northcote and Skene (1972) reported serious structural degradation of some Australian soils at an ESP as low as 6. Subsequently many researchers of Australia (Sumner, 1995; Naidu et al., 1995), Italy (Crescimanno et al., 1995) and India (Pal, 2003) advocated that an ESP much lower than 15 should be used to denote the value above which a noticeable reduction in crop yields is observed as a result of deterioration of physical properties of soils. However, sodicity tolerance ratings of crops in loamy textured soils of the IGP indicate that 50% reduction in relative rice yields was observed when ESP was above 50 and for wheat it was around 40 (Abrol and Fireman, 1977). Since the reason for these apparently contrasting findings lay in the different values of solution concentration of the soils, Sumner (1995) opined that the establishment of a critical ESP threshold may be very arbitrary because properties exhibited by the so-called classic sodic soils are simply the upper end of a continuum of behaviour that extends across the full range of sodium saturations. The sodium saturations are increasingly dependent on reduced solution concentration. Sumner (1995) finally made a strong case to develop criteria based on dispersibility to characterize and predict the behaviour of soils with respect to infiltration, hydraulic conductivity and hard setting which will indicate the mechanisms of swelling and dispersion (Quirk and Schofield, 1955; Shainberg et al., 1981).

Dispersibility of soils is a result of the interactive effects of soil properties, such as clay content, nature of clay, cation suite, nature of soil solution compositions and organic matter (Naidu et al., 1995). However, Gupta and Abrol (1990) highlighted the importance and contribution of swelling and dispersion to hydraulic properties of soils in terms of clay mineralogy at the species level, the ESP of the soil, the electrolyte concentration and nature of electrolytes in the soil solution. Although soils containing all other clays swell with changes in moisture content, changes are particularly extreme in smectite (Borchardt, 1989). The importance of smectite in impairing the hydraulic properties of soils through swelling and dispersion was also highlighted when Vertisols ($ESP < 15$, 491 g kg^{-1} smectite in SCS) and soils of the IGP (ESP 50, 46 g kg^{-1} smectite in SCS) were compared in terms of their productivity (Balpande et al., 1997a).

The results of the present study clearly suggests that aridity is the prime factor responsible for the pedogenetic processes which result in the depletion of Ca^{2+} ions from the soil solution in the form of $CaCO_3$, and also in the simultaneous increase of ESP and SAR with depth. Even a low level of sodicity (ESP ≥ 5 and < 15) is enough to impair the hydraulic properties of the highly smectitic Vertisols. Attempts to increase the productivity of Vertisols of both high and low MAR of sub-humid climate (pedons 1 and 5) by introducing irrigation either through well or river water have further impaired hydraulic properties due to the precipitation of PC. However, naturally-occurring zeolites and gypsum in some soils of sub-humid, semi-arid and arid climates showing high ESP (> 15) have prevented the rise in pH but favoured an increase in exchangeable Ca/Mg, and hydraulic properties. Therefore, fixing a lower limit either of ESP 5–15 (Pal, 2003) or at ESP > 15 (Soil Survey Staff, 1999) for sodic shrink–swell soils may have no practical relevance to their use and management. Under rainfed conditions, the yield of deep-rooted crops in Vertisols depends primarily on the amount of rain stored at depth in the soil profile, and the extent to which this soil water is released during crop growth. Moreover, both retention and release of soil water are governed by the nature and content of clay minerals, and exchangeable cations. A significant positive correlation between AWC and ESP (Table 5) in sodic Vertisols without modifier indicates that although the soils can hold sufficient water, they do not support rainfed crops. In contrast, a non-significant correlation between AWC and ESP in sodic Vertisols with zeolites as modifiers indicates that despite having high ESP, these soils support rainfed crops. Creation of weak parallel-striated structure (Fig. 3g) due to the moisture held by zeolites help rainfed crops to sustain. Therefore, fixing a lower limit for sodic subgroup of Vertisols either at ESP 5–15 or at ESP > 15 may not reflect the impairment of drainage of soils. Characterizing such soils as sodic only on the basis of ESP may also mislead the end users of these soils.

In view of the pedogenetic processes that ultimately impair the drainage of soils, evaluation of Vertisols for deep-rooted crops on the basis of sHC alone (Kadu et al., 2003) brought out a fact that an optimum yield of cotton in Vertisols of semi-arid part of Central India can be obtained when the soils are non-sodic (ESP < 5) and have sHC ≥ 20 mm h^{-1}. These authors also reported 50% reduction in yield in the sodic (ESP > 5) soils and with HC < 10 mm h^{-1}. This shows that sHC as a single parameter can indicate dispersibility, the most influencing factor of soil sodicity (Sumner, 1995). Therefore, characterization of soil sodicity on the basis of sHC alone appears to be an incontrovertible parameter as compared to ESP or SAR. The study also permits to advocate a value of sHC < 10 mm h^{-1} in distilled water (weighted mean in 0–100 cm depth of soil) to define a sodic soil.

5. Conclusions

The results of the present study indicate that the precise cause–effect relationship between $CaCO_3$ of pedogenic and non-pedogenic origin and exchangeable Mg, Na and Ca percentages does exist also in sodic Vertisols endowed with modifiers. The release of Ca^{2+} ions from soil modifiers prevented the rise in pH and ESP and modified the hydraulic properties amidst high ESP which supports fairly well the performance of rainfed crops. Therefore, fixing a lower limit of sodicity at ESP > 40 for soils of the IGP (Abrol and Fireman, 1977), at ESP > 5 but < 15 for Indian Vertisols (Kadu et al., 2003), at ESP 6 for Australian soils or at ESP > 15 for all soil types (Soil Survey Staff, 1999) appears to be irrelevant to the performance of crops in highly sodic Vertisols with soil modifiers especially of Ca-zeolites. In view of the pedogenetic processes that ultimately impair the hydraulic properties of soils mediated through dispersibility, the most important factor for soil degradation (Sumner, 1995), characterization of sodic soils on the basis of sHC, appears to be most appropriate. To define a sodic soil we advocate a value of sHC < 10 mm h^{-1} (as weighted mean in 0–100 cm depth of soil) instead of ESP or SAR. This study reaffirms a fact that the decisive feature of soil classification must be evidently the crop performance because it indicates the nature of soil much more explicitly than any other arbitrary definition and nomenclature possibly can claim to do (Hilgard, 1906).

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