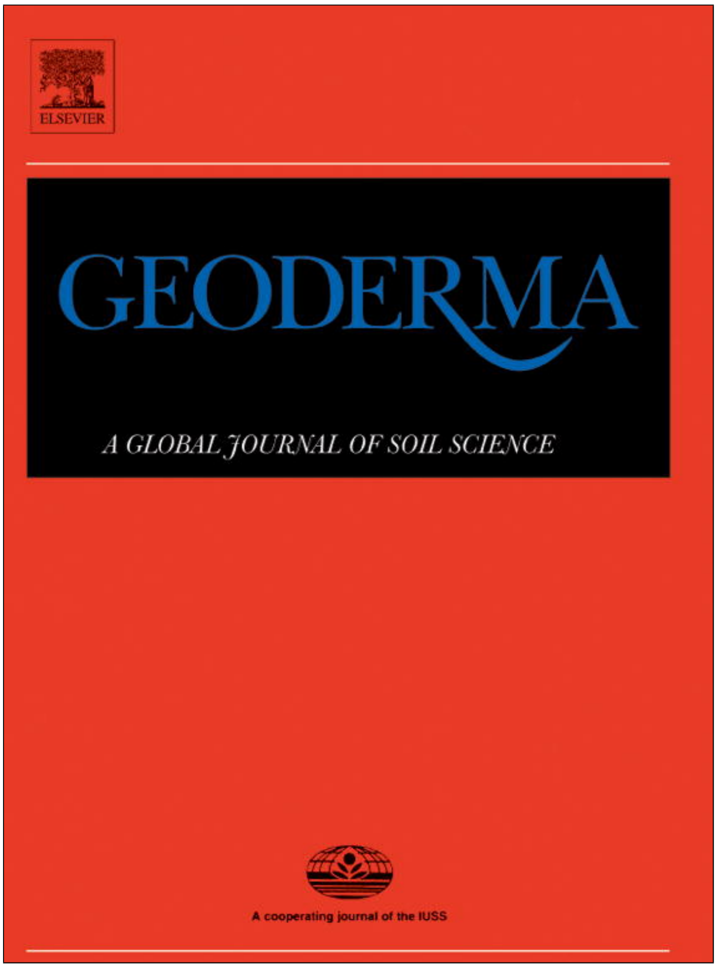
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Review

Vertisols of tropical Indian environments: Pedology and edaphology

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ABSTRACT

Vertisols in the tropics occur in a range of climates and are used in a range of production systems. This review is a synthesis of the recent developments in pedology of vertisols achieved via high-resolution micro-morphology, mineralogy, and age-control data along with their geomorphologic and climatic history. This knowledge has contributed to our understanding of how the climate change-related pedogenic processes during the Holocene altered soil properties in the presence or absence of soil modifiers (Ca-zeolites and gypsum), calcium carbonate and palygorskite minerals. These state-of-the-art methods have established an organic link between pedogenic processes and bulk soil properties; the review also considers the need to modify the classification of vertisols at the subgroup level. We hope this review will fulfil the need for a handbook on vertisols to facilitate their better management for optimising their productivity in the 21st century.

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1. Introduction

Vertisols have attracted global attention in research, yielding a large body of data on their properties and management (Coulombe et al., 1996; Mermut et al., 1996). Although substantial information is available on vertisols, it remains challenging to optimise their use and management (Coulombe et al., 1996; Myers and Pathak, 2001; Syers et al., 2001).

The global area under vertisols is estimated to be approximately 308 M ha, covering nearly 2.23% of the global ice-free land area (USDA-SCS, 1994); however, the reliability of this estimate remains uncertain because several countries have not yet been included in the inventory (Coulombe et al., 1996). In addition, the area under vertisols in a soil survey area may often be too small to resolve at the scale of map compilation (Table 1). Vertisols and vertic intergrades occur in 80 countries, but more than 75% of the global vertisol area is contained in only 6 countries: India (25%), Australia (22%), Sudan (16%), the USA (6%), Chad (5%), and China (4%; Dudal and Eswaran, 1988; Wilding and Coulombe, 1996).

Vertisols occur in wide climatic zones, from the humid tropics to arid areas (Ahmad, 1996), but they are most abundant in the tropics and subarid regions. In the tropics, they occupy 60% of the total area; in the subtropics, they cover 30%, while they cover only 10% in cooler regions (Dudal and Eswaran, 1988; Wilding and Coulombe, 1996). In humid and sub-humid regions, vertisols occupy 13% of the total land area; in sub-arid regions, 65%; in arid regions, 18%; and in the Mediterranean climate, 4% (Coulombe et al., 1996).

Vertisols are an important natural agricultural resource in many countries including Australia, India, China, the Caribbean Islands and the USA (Coulombe et al., 1996). Because of their shrink–swell properties and stickiness, vertisols are known by a number of local regional and vernacular names (Dudal and Eswaran, 1988). They are known in India by at least 13 different names (Murthy et al., 1982). These names are related to the characteristic dark colour and/or to aspects of their workability. These soils are often difficult to cultivate, particularly for small farmers using handheld or animal-drawn implements. The roots of annual crops do not penetrate deeply because of poor subsoil porosity and aeration; therefore, farmers (especially in India) allow these soils to remain fallow during the rainy season and cultivate them only in the post-rainy season.

Table 1
Distribution of vertisols in different states of India under a broad bioclimatic system. Adapted from Bhattacharyya et al. (2009).

States	Bio-climate[a]	Area (mha)(%)[b]
Uttar Pradesh	SAM, SHD	0.41 (0.12)
Punjab	SAM[c]	
Rajasthan	AD	0.98 (0.30)
Gujarat	AD, SAD, SAM	1.88 (0.57)
Madhya Pradesh	SAM, SHD, SHM[d]	10.75 (3.27)
Maharashtra	SAD, SAM, SHD, SHM[d]	5.60 (1.70)
Andhra Pradesh	SAD, SAM, SHD	2.24 (0.68)
Karnataka	AD, SHD, SHM, H	2.80 (0.85)
Tamil Nadu	SAD, SAM, SHD, SHM, H	0.91 (0.28)
Puducherry and Karaikal	SHM	0.011 (0.003)
Jharkhand	SHM, SHD	0.11 (0.034)
Orissa	SHM, SHD, H	0.90 (0.28)
West Bengal	SHD, SHM[c]	
Bihar	SHM[c]	
India		26.62 (8.10)

[a] AD: arid dry: 100–500 mm MAR(mean annual rainfall); SAD: semi arid dry: 500–700 mm MAR; SAM: semi arid moist: 700–1000 mm MAR; SHD : subhumid dry: 1000–1200 mm MAR; SHM: subhumid moist: 1200–1600 mm MAR; H: Humid: 1600–2500 mm MAR.

[b] Parentheses indicate percent of the total geographical area of the country.

[c] In the states of Punjab, Bihar, and West Bengal vertisols and vertic intergrades also occur in SHM, SHD, and SAM climates (Pal et al., 2010) but they are not mappable in 1:250,000.

[d] In addition vertisols occur in HT climate (>2500 mm MAR) in Madhya Pradesh and Maharashtra but they are not mappable in 1:250,000 scale (Bhattacharyya et al., 1993, 2005, 2009; Pal et al., 2011a).

Current agricultural land uses (edaphological) demonstrate that although vertisols are a relatively homogeneous soil group, they occur in a wide range of climatic environments globally and also show considerable variability in their uses and crop productivity (Pal et al., 2011a). Vertisol use is not confined to a single production system. In general, management of vertisols is site-specific and requires an understanding of degradation and regeneration processes to optimise management strategies (Coulombe et al., 1996; Syers et al., 2001). Basic pedological research is needed to understand some of the unresolved edaphological aspects of vertisols (Puentes et al., 1988) to develop optimal management practices. Thus, a critical review is in order to establish the connection between the pedology and edaphology of vertisols.

Most of the vertisols in India lie in the Torrid Zone between the Tropic of Cancer and the Tropic of Capricorn, where the soils are classed as "tropical". As in several parts of the world, vertisols also occur in wider climatic zones in India (Table 1), 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. In total, they occupy 8.1% of the total geographical area of the Indian sub-continent (Table 1). Additionally, outside the Deccan basalt region of the peninsula, in the states of Punjab, Bihar and West Bengal, vertisols and their vertic intergrades occur in SHM, SHD and SAM climates (Pal et al., 2010), but they are not mappable at the 1:250,000 scale. Over the past two decades; however, the focus of research has shifted from general pedology to mineralogical and micro-morphological research. By 2009, a total number of 306 BM (benchmark) vertisols and vertic intergrades had been identified by the National Bureau of Soil Survey & Land Use Planning (NBSS&LUP; ICAR), Nagpur, India, which included 112 BM vertisols (Pal et al., 2009c). They have been indicated (along with their global distribution) on a 1:1 million-scale map (NBSS&LUP, 2002; Pal et al., 2011a). Although this review is based on the Indian vertisols, data from other tropical parts of the world are included where relevant. This review uses state-of-the-art data on the recent developments in the pedology of vertisols, including variation in their morphological, physical, chemical, biological, mineralogical and micro-morphological properties. The aim of this review is to provide a better understanding of vertisols created by the climate change phenomena of the Holocene, with the goal of optimising their efficient use and management in tropical India and other tropical regions. The main objective of the paper is to join pedology and edaphology for better management of vertisols and to optimise their productivity in the tropical world during the 21st century.

2. Factors in the formation of vertisol

The soil-forming factors are the most relevant and appropriate factors explaining vertisol formation. They are interdependent and highly variable and therefore influence the properties of vertisols in multiple ways (Coulombe et al., 1996). In view of recent developments in studies of vertisol formation (Bhattacharyya et al., 2005; Pal et al., 2001a, 2006a, 2006b, 2009a, 2009b, 2009c; Srivastava et al., 2002), each of these five factors merits discussion.

2.1. Parent material

Several geologic formations provide the basic parent materials involved in vertisol development (Coulombe et al., 1996; Murthy et al., 1982). Parent materials from inheritance or weathering provide a large quantity of smectites; however, the distinction between inherited and newly formed clay minerals is difficult to discern (Coulombe et al., 1996). A study of the vertisols of the sub-humid, semi-arid and arid climates of Peninsular India clearly indicates that both plagioclase and micas are either fresh or weakly to moderately altered, suggesting that chemical weathering of these minerals has not been substantial (Fig. 1a,b). These data discount the formation of smectite during the development of vertisols (Srivastava et al., 2002) and validate the hypothesis that vertisol formation reflects a positive entropy change (Smeck et al., 1983). As smectite is solely responsible for the vertic properties of soils (Shirsath et al., 2000), smectite appears to be the exclusive parent material of vertisols.

2.2. Climate

The characteristics of vertisols are related to overall climate; however, other factors such as texture, clay mineralogy, cation saturation, and the amount of exchangeable sodium equally influence soil morphology (Dudal and Eswaran, 1988; Eswaran et al., 1988).

Large quantities of smectite are required to create shrink–swell properties in vertisols. Smectite is ephemeral in an HT climate (Bhattacharyya et al., 1993; Pal et al., 1989). In sub-humid to arid climates, the weathering of primary minerals contributes very little to smectite formation (Srivastava et al., 2002). Smectite cannot be formed or retained in HT vertisols or in sub-humid to arid climatic conditions.

The occurrence of vertisols in the alluvium of weathering Deccan basalt, as well as in HT, SHM, SHD, SAM, SAD, and AD environments in the Indian peninsula (Pal et al., 2009c), may suggest that the basaltic parent material influenced soil formation such that similar soils are formed under different climatic conditions (Mohr et al., 1972). The soils are vertisols (Soil Survey Staff, 2003), but their morphological and chemical properties differ. Cracks >0.5 cm wide extend down to the zones of sphenoids and wedge-shaped peds with smooth or slickensided surfaces in HT, SHM, SHD and SAM soils, but cracks cut through these zones in SAD and AD soils (Fig. 2). Soil reactions and the $CaCO_3$ content indicate that a reduction in mean annual rainfall (MAR) leads to the formation of calcareous and alkaline soils. Hence, the soils are Typic Haplusterts in HT, Typic/Udic Haplusterts in SHM, SHD and SAM climates, and Sodic Haplusterts and Sodic Calciusterts in SAD and AD climates. Such examples help to define the climatic signatures in soils that allow researchers to infer the occurrence of climate change in tropical and subtropical regions of India and elsewhere (Pal et al., 2009c).

2.3. Topography

Vertisols generally occur at low elevations, but they also occur at higher elevations in the Ethiopian plateau or on higher slopes, as in the West Indies (Coulombe et al., 1996). The majority of the vertisols in India occur in lower physiographic areas, i.e., in the lower piedmont plains and valleys (Pal and Deshpande, 1987a; Pal et al., 2009c) or in micro-depressions (Bhattacharyya et al., 1993; Pillai et al., 1996). Vertisols in micro-depressions are spatially associated with red ferruginous soils (alfisols) and are seen as distinct entities under similar topographical conditions on the Deccan basalt plateau in the HT (Bhattacharyya et

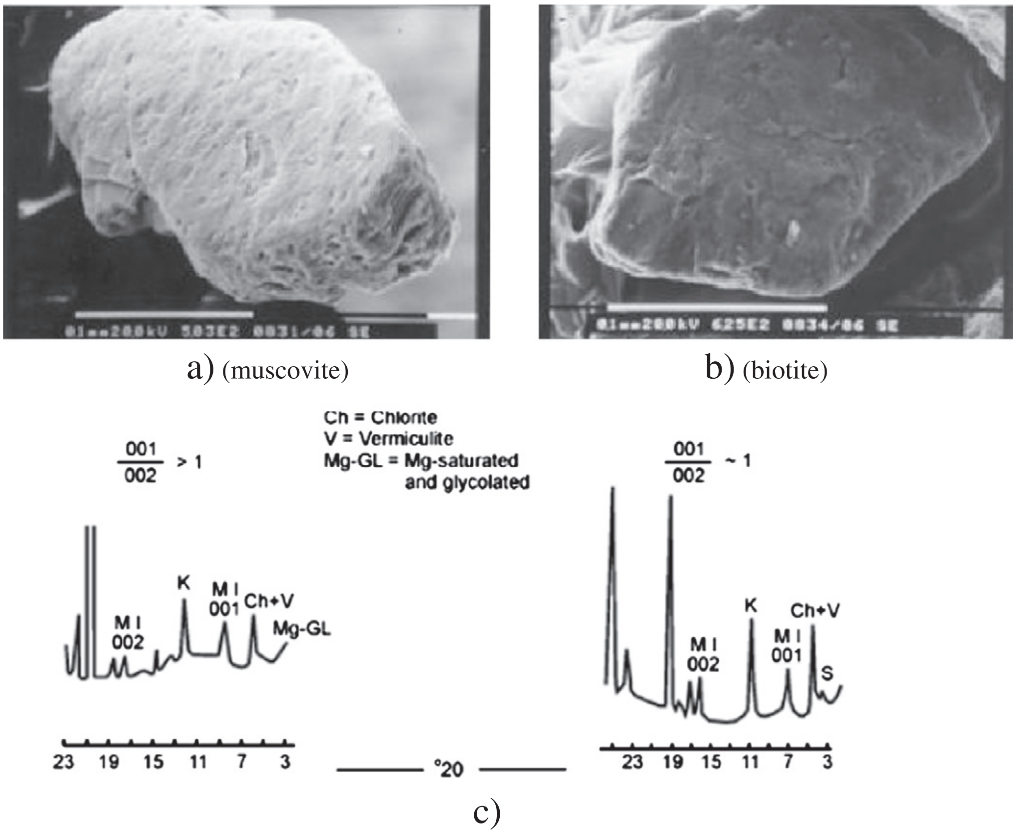
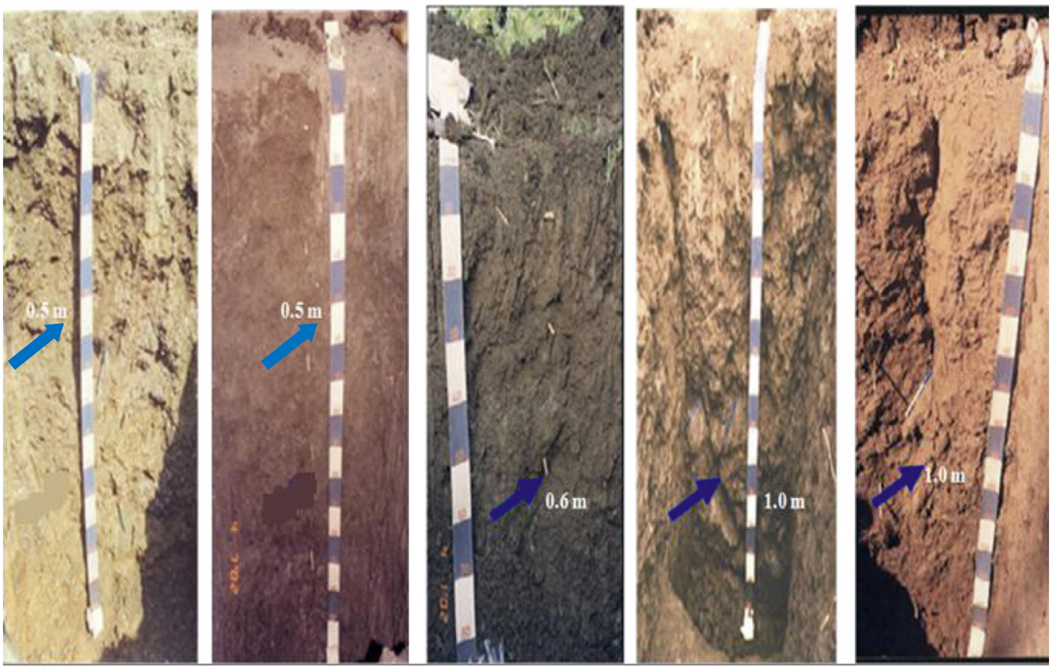


Fig. 1. Representative SEM photographs showing no or very little alteration of micas (a, b) and XRD diagrams of the silt and clay fractions (c) of vertisols of Peninsular India. Adapted from Pal et al. (2006c).



Panjri, Nagpur, Maharashtra.
Typic Haplusterts
SHM, MAR 1127mm

Nipani, Adilabad, Andhra Pradesh
Typic Haplusterts
SHD, MAR 1071 mm

Bhatumbra, Bidar, Karnataka
Udic Haplusterts
SAM, MAR 977 mm

Paral, Akola, Maharashtra
Sodic Haplusterts
SAD, MAR 794 mm

Sokhda, Rajkot, Gujarat
Sodic Calciusterts
AD, MAR 533 mm

Fig. 2. Cracks are extending beyond the zone of slickensides with increase in aridity (SHM to AD bioclimates). Adapted from Pal et al. (2003a).

al., 1993) and SAD (Pillai et al., 1996) climates. The red soils are mildly acidic entisols/inceptisols/alfisols in SAD climates, whereas they are moderately acidic alfisols in an HT climate. The red soil clays of an HT climate are composed primarily of smectite–kaolin (Sm–K), whereas those of the SAD climate contain only small amounts of Sm–K. Sm–K was formed at the expense of smectite in red HT soils, and in red SAD soils, it is considered to have originated under a previous, humid climate regime (Pal, 2003). The genesis of both red soils (alfisols) and vertisols in the contrasting climate has been explained through the landscape-reduction process (Bhattacharyya et al., 1993; Pal, 1988), as in similar soils elsewhere (Beckman et al., 1974). In the initial stage of soil formation, smectite-rich products of weathering from the hills were deposited in micro-depressions, as is evident from the lithic/paralithic contacts of such vertisols (Fig. 3). Over time, these sites gradually flattened, and internal drainage dominated over surface run-off. After peneplanation, the red soils (alfisols) of the present (Bhattacharyya et al., 1993) and the past (Pillai et al., 1996) HT climates on relatively stable surfaces continued to weather, forming Sm–K. In contrast, vertisols continued to exist in the micro-depressions (Fig. 4) even in HT climates because of the continuous supply of bases from Ca-rich zeolites that helps to stabilise the smectite (Bhattacharyya et al., 1993). Because the period of the HT climate ended during the Plio-Pleistocene transition (Pal et al., 1989), both smectite and Sm–K in SAD vertisols were preserved to the present. The SAD climate restricted further leaching in vertisols and caused calcareousness and the rise in pH (Pillai et al., 1996). Thus, vertisols are not common *in residuum* on the Deccan basalt of the plateau.

The formation of "gilgai" micro-topography in vertisol areas is not very well understood (Coulombe et al., 1996). At present, gilgai micro-topographies are very rare on the Indian sub-continent because most were obliterated by post-cultural human activities; however, the depth distribution of soil properties generally differs between the mounds and depressions of the gilgai topography (Wilding and Coulombe, 1996; Wilding et al., 1991), resulting in vertical and horizontal spatial variability in vertisols within distances as short as a few metres or less. Such spatial and horizontal variability in SAD vertisols in a central Indian watershed was observed by Vaidya and Pal (2002). Watershed vertisols occur in both micro-high (MH) and micro-low (ML) positions. The distance between these positions is approximately 6 km, and the elevation difference is 0.5–5 m. Vertisols in MH positions

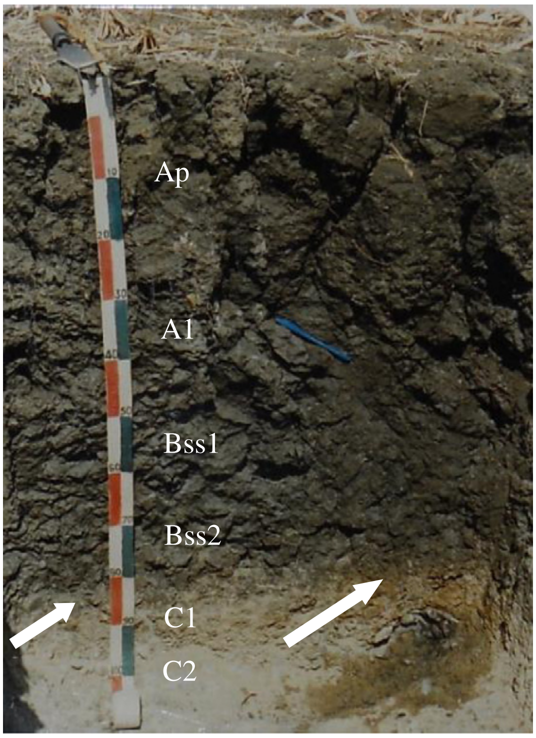


Fig. 3. A representative vertisol (Typic Haplustert) developed in micro-depression of a plateau, showing paralithic contact with the Deccan basalt of central India. Photograph, courtesy of DKP.

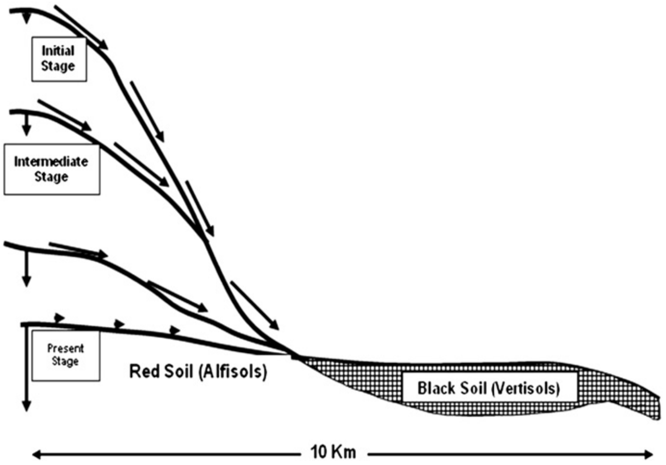


Fig. 4. Schematic diagram of the pedon site of red soils (alfisols) and black soils, (vertisols) showing the landscape reduction process explaining the formation of spatially associated red and black soils. Adapted from Pal (2008).

are strongly alkaline, and those in ML positions are mildly alkaline (Fig. 5). The formation of sodic soils in MH positions alongside non-sodic soils in ML positions is a unique phenomenon that occurs because of micro-topographic differences; these differences result in the non-uniform distribution of water across the landscape and facilitate greater penetration of rainwater in ML positions.

2.4. Vegetation

Reports on the influence of vegetation on pedogenesis and distribution of vertisols are very few (Coulombe et al., 1996). Vertisols that are not cultivated are associated with native vegetation, such as grasslands and savannahs (Probert et al., 1987). Vertisols can tilt large trees (Bhattacharyya et al., 1999b). Not surprisingly, few, if any, commercial forests are found on vertisols (Buol et al., 1978), but mixed pine and deciduous forests are reported in selected regions of east Texas. At present, most vertisols are under post-cultural activities that make it difficult to identify and infer the influence of native vegetation (Coulombe et al., 1996). Vertisols in India are generally less intensively cultivated (Bhattacharyya et al., 2007), indicating that management has little role in their formation and modification. These soils are low in organic carbon on both the surface and sub-surface layers (<1%), indicating that biotic factors have no substantive role in the genesis of vertisols(Pal et al., 2009c).

2.5. Time

Most vertisols are derived from geological rock systems that are millions of years old (Bardaoui and Bloom, 1990; Yerima, 1986). The age of the parent material provides only a maximum chronological point; in reality, millions of years are much older than the true age of the geomorphic surface or the time required for vertisol formation (Coulombe et al., 1996). Many researchers suggest that the formation of slickensides is very rapid and that vertisols are formed on geomorphic surfaces in as few as 550 years (Parsons et al., 1973). For example, a Vertic Haplustalf formed <100 yr BP (^{14}C age, Pal et al., 2006a) in the alluvium of the central Indian SHD Deccan basalt, which exhibits pressure faces but lacks slickensides. The occurrence of shrink–swell soils and slickensides (Singh et al., 1998) in the SHM lower Indo-Gangetic Plains 500–1500 yr BP (TL ages) indicates that a minimum of 500 yr is adequate to form vertisols. The vertisols of central and western peninsular India developed in the Deccan basalt alluvium of the Upper Cretaceous, mostly during the Holocene period, indicating a minimum ^{14}C age of 3390 yr. and a maximum of 10,187 yr. BP (Pal et al., 2006b 2009c). These data suggest that vertisols in India and elsewhere are of Holocene origin.

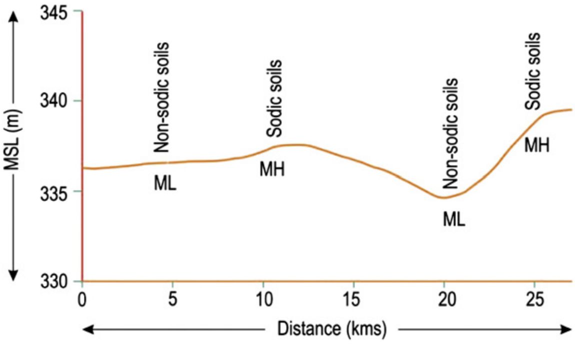


Fig. 5. Juxtaposition of the occurrence of sodic and non-sodic soils (vertisols) on MH and ML positions in black soil region. Adapted from Pal et al.(2009b).

3. Smectite clay minerals in vertisols

3.1. Characteristics of smectites

Smectite is considered the major mineral in vertisols, with kaolinite being of secondary importance (Hajek, 1985). In contrast, kaolinite has been reported to be abundant in some vertisols in El Salvador (Yerima et al., 1985, 1987) and Sudan (Yousif et al., 1988). In addition, several non-expanding clay minerals (kaolin, micas, chlorites, palygorskite and vermiculites) are associated with vertisols and their vertic intergrades (Coulombe et al., 1996; Heidari et al., 2008). The shrink–swell behaviour is primarily governed by the nature of the clay minerals, particularly their surface properties. Although the soils containing all other clays shrink and swell with changes in moisture content, changes are particularly extreme in smectites (Borchardt, 1989). Other minerals, such as kaolin, micas, chlorites, palygorskite and vermiculite do not expand on solvation. Bhattacharyya et al. (1997) concluded that the vertic properties of soils are a function of smectite content. A close examination of the X-ray diffraction (XRD) diagrams of the fine clays of El Salvador soils in which shrink–swell processes are related to the fine-clay kaolin content (Yerima et al., 1985; 1987) indicates the presence of a smectite peak in the Atiocoyo soils, in which Sm–K also dominates. Thus, the higher value of COLE (0.10–0.12) and the clay CEC value (62–79 cmol (+)/kg) are compatible with their vertic character. The presence of expansible minerals might have escaped the notice of researchers in the few shrink–swell soils of the USA (Hajek, 1985) because the CEC of their clays is >40 (Eswaran et al., 1988).

It was stipulated earlier that the montmorillonitic mineralogy of soils is associated with vertic properties when smectite exceeds 50% of the total mineral content in the <2 μm clay fraction (Soil Survey Staff, 1975, 1994). A qualitative smectite mineralogy class was proposed for the soils that contain more smectite by weight than any other single clay mineral (Soil Survey Staff, 1998, 1999). This class provided a means by which smectite can reflect a quantitative dimension of the vertic properties of soils. Quantitative determination of minerals in the clay fractions of soils by XRD analysis is difficult, as any attempts in this regard have yielded semi-quantitative estimates (Gjems, 1967). Moreover, such estimation is questionable when minerals are in the interstratified phase. The presence of Sm–K in shrink–swell soils is common in India and elsewhere (Bhattacharyya et al., 1993, 1997; Pal et al., 1989). Peak-shift analysis (Wilson, 1987) is a useful method to determine the smectite content in Sm–K. When the smectite component in Sm–K is highly chloritised, the swelling of smectites on glycolation is restricted, making the peak-shift analysis ineffective. To circumvent this problem, the chemical method of Alexiades and Jackson (1965) has proven effective as a way to quantitatively determine the smectite content in soil clays, thus establishing the link between bulk soil properties and clay mineral type (Pal and Durge, 1987). Shirsath et al.

(2000) revealed a strong relationship between marked shrink–swell properties and smectite content in the clay fraction (<2 μm). Vertic properties with a linear extensibility (LE) of 6 in shrink–swell soils correspond to a minimum threshold value of 20% smectite, thus suggesting that only smectitic soils should be considered shrink–swell soils in the US Taxonomy.

Smectite species such as montmorillonite, beidellite and nontronite are reported in vertisols. Of these three, montmorillonite and beidellite are the most commonly reported, while reports of nontronite are rare (Coulombe et al., 1996); however, its presence was reported in vertisols of Upper Volta (Trauth et al., 1967). Coulombe et al. (1996), however, are of the opinion that although the soil smectites do contain an appreciable amount of iron, they seldom qualify as nontronite. The occurrence of iron-rich smectite is related to the ferromagnesian richness of the parent materials derived from basic igneous rocks. In the Indian sub-continent, the majority of shrink–swell soils are developed in the alluvium of weathering Deccan Basalt, which encompasses an area of 500,000 km^2 (Duncan and Pyle, 1988). A review on the mineralogy of shrink–swell soils (vertisols and vertic intergrades) of India (Ghosh and Kapoor, 1982) indicates that these soils are dominated by beidellite–nontronite type minerals; the authors compute clay minerals based on smectite; however, such an approach is not infallible (Sawhney and Jackson, 1958). X-ray diffraction analysis of large numbers of smectite-dominated fine clays of shrink–swell soils in India (Pal, 2003; Pal et al., 2000a, 2003a) indicates the presence of small to moderate amounts of hydroxy-interlayer (HI) material in the smectite interlayers, alongside a small amount of vermiculite. Hydroxy-interlayers are not easily detected in the glycolation samples but are discernible during the gradual heating from 110° to 550 °C of the K-saturated samples that occurs as a result of the low-angle-side broadening of the 1.0-nm peak at 550 °C (Wildman et al., 1968; Fig. 6). The presence of vermiculite is also not discernible in the glycolation samples; it is detected only when the 1.0-nm peak of mica is reinforced on heating to 110 °C (Pal and Durge, 1987). Even a small quantity of such impurities (HI materials and vermiculite) affects the charge and sum relationships using smectite formulae.

The Greene-Kelly test (Greene-Kelley, 1953; Hoffman–Klemen effect) confirmed the presence of both montmorillonite and beidellite in the fine-clay fractions of Indian shrink–swell soils in basaltic alluvium, and the former dominates over the latter (Bhattacharyya et al., 1993; Kapse et al., 2010; Murthy, 1988; Pal and Deshpande, 1987a); however, on glycerol vapour treatment (Harward et al., 1969), the clay smectites expand to approximately 1.9 nm, indicating only the presence of montmorillonite (Fig. 6). In other words, fine-clay smectite is nearer to montmorillonite in the montmorillonite–beidellite series. Because nontronite would behave like beidellite in these tests and because clay smectite is unstable under HCl treatment, consequently releasing considerable iron in solution, it was concluded that the smectite in vertisols is nearer to the montmorillonite of the montmorillonite–nontronite series (Pal and Deshpande, 1987a). Smectite expands beyond 1.4 nm after glycolation of the K-saturated and heating samples (300 °C; Fig. 6), indicating its low-layer charge density (as also evidenced by its no K-selectivity; Pal and Durge, 1987).

It is important to determine the layer charge of smectite minerals. Theoretically, this parameter should range between 0.3 and 0.6 electrons per half unit cell in smectites. Tessier and Pedro (1987), however, reported that high-charge smectite (between 0.45 and 0.60 electrons per half unit cell), is common in soils. Several researchers (Bardaoui and Bloom, 1990; Chen et al., 1989) also reported the presence of smectite in vertisols with a layer charge in the range of vermiculite (0.6–0.9 electrons per half unit cell). Clay smectite in selected Indian vertisols also showed a high layer charge (0.28 to 0.78 mol electrons/$(SiAl)_4.O_{10}(OH)_2$), and low-charge smectite constitutes >70% in them (Ray et al., 2003); however, a charge >0.6 was attributed to the presence of a small quantity of vermiculite (5–9%, Pal and Durge, 1987) and to the presence of hydroxy-interlayering in smectite interlayers (Ray et al., 2003). The layer charge of clay smectites in Indian vertisols by the alkyl ammonium method (Lagaly, 1994) showed the presence of monolayer to bilayer and bilayer to pseudotrilayer transitions, indicating heterogeneity in the layer-charge density (Ray et al., 2003).

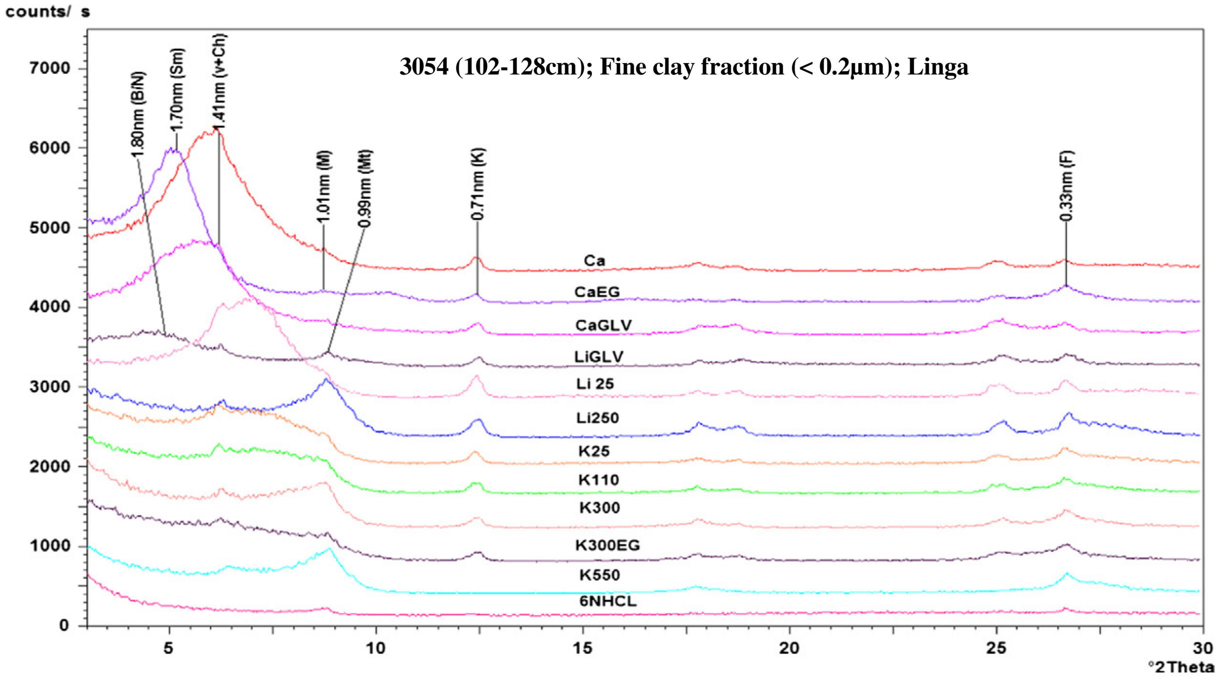


Fig. 6. Representative X-ray diffractograms of fine clay fractions (<0.2 μm) of the Bss horizons of vertisols of central India; Ca = Ca saturated; Ca–EG = Ca saturated plus ethylene glycol vapour treated; CaGLV = Ca-saturated plus glycerol vapour treated; Li = Li-saturated and heated to 25 °C, 250 °C (16 h), LiGLV 30-D = Li-saturated and heated at 250 °C plus glycerol vapour treated and scanned after 30 days;K25/110/300/550 C = K-saturated and heated to 25, 110, 300, 550 °C; K300EG = K-saturated and heated to 300 °C plus ethylene glycol vapour treated; 6NHCl = 6 N HCl treated fine clays; Sm = smectite, B/N = beidellite/nontronite; V + Ch = vermiculite plus chlorite; M = mica; Mt = montmorillonite; K = kaolinite; F = feldspars. Adapted from Pal et al. (2003a) and Bhople (2010).

3.2. Hydroxy-interlayering in smectites and determination of layer charge

The presence of low to moderate hydroxy-interlayering in smectites is more common than its absence in vertisol smectites in peninsular India (Pal, 2003; Pal and Deshpande, 1987a). Ray et al. (2002) observed that the higher the tetrahedral charge, the greater the probability that hydroxy-interlayers will form in fine clay smectites. Hydroxy-Al interlayer clays give 2:1 layer phyllosilicate great weathering resistance, and the interlayered clays are an important component of both moderately weathered and intensively weathered soils. The hydroxy-interlayers prevent the determination of the layer charge by the alkylammonium method (Lagaly, 1994) by obstructing the normal intrusion of alkylammonium ions into interlayers (Ray et al., 2006a). Such interlayers result in the formation of relatively more paraffin-type layers with bi-pseudotrilayer transition, which causes the overestimation of the layer charge of core lattice mineral. Ray et al. (2006a) used several extractants to remove the HI materials from the fine-clay smectites of Indian vertisols to determine the layer charge of the cleaned clays. The results were not satisfactory when extractants other than EDTA were used. The removal of HI materials by 0.25 N EDTA solution (pH 7.0) was almost complete. Ray et al. (2006a) obtained the weighted-average layer charge of the pre-treated clays from 0.40 to 0.46 mol $(-)/(\mathrm{Si, Al})_4\mathrm{O}_{10}(\mathrm{OH})_2$, and after EDTA treatment, the charge ranged from 0.27 to 0.33 mol $(-)/(\mathrm{Si, Al})_4\mathrm{O}_{10}(\mathrm{OH})_2$. These authors also observed that the Ca-saturated and glycolated fine clays showed greater intensity than their corresponding Ca-treated curves. The K-treated curves also showed marked differences when compared with the original fine clays. The removal of HI materials by EDTA is effective in determining the actual layer charge in soil-clay smectites.

3.3. Genesis of smectites in vertisols

Smectite, either as a discrete mineral or as a mineral interstratified with any other layer silicates, remains the most abundant and essential phyllosilicate in vertisols worldwide. The initiation of vertic properties at a linear extensibility (LE) of 6 in shrink–swell soils requires a minimum of 20% smectite in their clay fractions ($<2\ \mu$m; Shirsath et al., 2000). Smectite-clay minerals are ephemeral in the HT climate, where they are rapidly transformed to kaolin. Therefore, it is difficult to understand the formation of vertisols in HT climates without the presence of soil modifiers such as Ca-zeolites (Bhattacharyya et al., 1993; Pal et al., 2006b) that release Ca^{2+} ions to prevent the transformation of smectite to kaolin. The formation and persistence of slightly acidic to acidic Typic Haplusterts with predominant Sm–K in clay fractions in India (Bhattacharyya et al., 1999a, 2005; Pal et al., 2009c) and elsewhere (Ahmad, 1983) is possible in the presence of soil modifiers that maintain the base saturation well above 50% (Pal et al., 2003a, 2006b).

Despite the abundance of vertisols in semi-arid regions (Eswaran et al., 1988), large quantities of dioctahedral smectite cannot form in these soils, as the primary minerals contribute little towards the formation of smectites in the prevailing dry climates (Pal et al., 2009c; Srivastava et al., 2002). XRD analysis of fine clays in Indian SHM, SHD, SAM, SAD and AD vertisols indicates that dioctahedral smectites are fairly well crystallised, as they yield sharp basal reflections on glycolation and show regular higher (though short and broad) reflections. Smectites show no sign of transformation except for the HI in the smectite interlayers (Pal et al., 2009c). Such interlayering was also observed in the vermiculite in the silt and coarse-clay fractions (HIV) that resulted in the formation of pseudo- or pedogenic chlorite (PCh; Vaidya and Pal, 2003; Fig. 7). The presence of hydroxy-interlayered dioctahedral smectite (HIS) in the fine-clay fractions, as well as HIV and PCh in the silt and coarse-clay fractions, indicates that the hydroxy-interlayering in the vermiculite and smectite occurred when positively charged hydroxy-interlayer materials (Barnhisel and Bertsch, 1989) entered into the inter-layer spaces. Moderately acidic conditions are optimal for hydroxyl-Al interlayering of vermiculite and smectite; the optimum pH values for interlayering in smectite and vermiculite are 5.0–6.0 and 4.5–5.0, respectively (Rich, 1968), as small hydroxyl ions are most likely to be produced at low pH (Rich, 1960). The pH of the majority of vertisols in subhumid to arid climates all over the world is either near to neutral or well above 8.0 throughout, suggesting that the 2:1 layer silicates suffer congruent dissolution under mildly to moderately alkaline conditions (Pal, 1985). This finding discounts the hydroxy-interlayering of smectites after deposition of the basaltic alluvium (Pal et al., 2011b). The hydroxy-interlayering in vermiculite and smectite and the subsequent transformation of vermiculite to PCh do not, therefore, represent contemporary pedogenesis of vertisols in dry climates. Indian vertisols contain both NPC (relict Fe–Mn coated carbonate nodules) and PC (pedogenic $\mathrm{CaCO_3}$; Pal et al., 2000b, 2009c). Based on ^{14}C dates of carbonate nodules, Mermut and Dasog (1986) concluded that vertisols with Fe–Mn coated $\mathrm{CaCO_3}$ are older than those with PCs that are formed in soils of dry climate soils (Pal et al., 2000b). Thus, NPCs were formed in a climate that was much wetter than the present climate, ensuring adequate water for reduction and oxidation of iron and manganese to form Fe–Mn coatings. Although the vertisols contain muscovite and biotite mica in the silt and clay fractions (Pal, 2003), dioctahedral smectite (DOS) cannot be formed at the expense of muscovite (dioctahedral mica) because the weathering of muscovite is very sensitive to potassium levels in soil. Biotite converts to trioctahedral vermiculite (TOV; Pal, 2003); thus, the simultaneous formation of DOS and TOV from mica is very unlikely (Pal et al., 1989; Ray et al., 2006b). Moreover, in the sub-humid and semi-arid climates that facilitate the formation of $\mathrm{CaCO_3}$ from plagioclase (Pal et al., 2011b), mica may not yield as much DOS as do vertisols. Thus, the large quantity of DOS formed under a previous, humid climate regime in the source area as an alteration product of plagioclase (Pal et al., 1989; Srivastava et al., 1998). On the other hand, the formation of smectite from biotite is quite unlikely in a humid climate (Tardy et al., 1973), but vermiculite could have transformed to HIV, which in turn transforms to PCh under acidic conditions. The formation of HIS did not continue in the HT climate, as evidenced from the presence of very small quantities of clay kaolin (Sm–K). In the event of prolonged weathering of HIS, kaolin should become dominant (Bhattacharyya et al., 1993). Thus, the HIS in the vertisols were formed under a previous, more humid climate regime and its crystallinity, and also the HIV and PCh were preserved in the non-leaching environment of the latter sub-humid to dry climates (Pal et al., 2009c, 2011b).

4. Pedogenic processes in vertisols — recent advances

Over the past three decades, excellent reviews have been published on the formation and pedogenesis of vertisols of the world (Ahmad, 1983, 1996; Blokhuis, 1982; Coulombe et al., 1996; Dudal and Eswaran, 1988; Eswaran et al., 1988; Mermut et al., 1996; Murthy, 1988; Murthy et al., 1982; Smeck et al., 1983; Wilding and Tessier, 1988; Yaalon, 1983; Yaalon and Kalmar, 1978); however, during the last decade and a half, the focus of vertisol research has changed qualitatively because mineralogical, micro-morphological and age-control tools can be used to measure the relatively subtle processes related to pedology, palaeopedology and edaphology (El-Swaify et al., 1985; Kadu et al., 2003; Myers and Pathak, 2001; Pal et al., 2009a, 2009b, 2009c, 2011a; Srivastava et al., 2002; Swindale, 1989; Syers et al., 2001). Hence, a critical review is in order to place recent research results in the context of past research; this review is needed to better understand the following basic issues related to vertisol pedogenesis, with implications for efficient use and management of vertisols for agricultural development.

4.1. Clay illuviation: proanisotropism in vertisols

A review of previous work (Ahmad, 1983; Murthy et al., 1982) indicates that the distribution of clay is uniform throughout vertisols

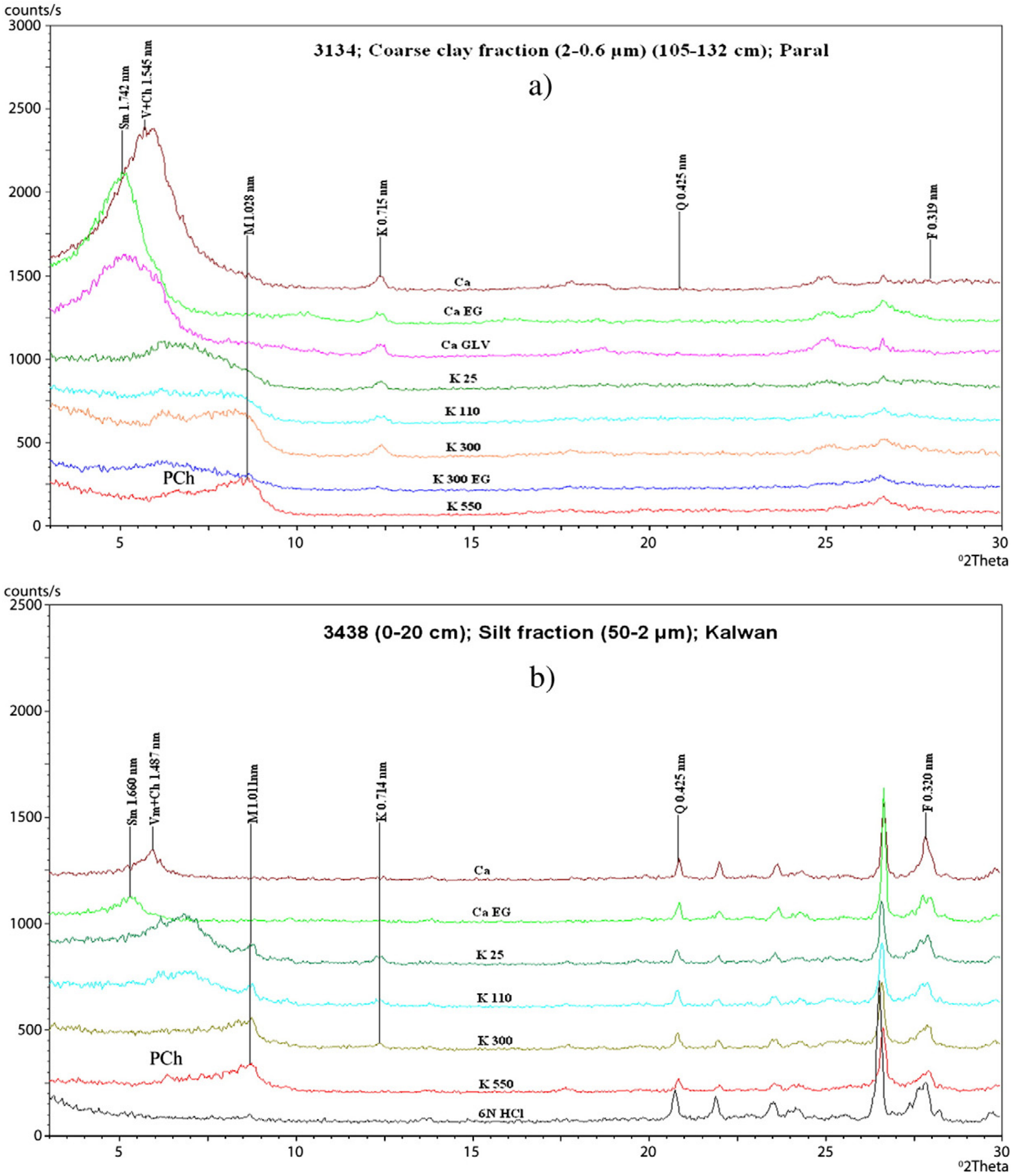


Fig. 7. Representative X-ray diffractograms of coarse clay (a), and silt (b) fractions of vertisols of Peninsular India; Ca = Ca saturated; Ca–EG = Ca saturated plus ethylene glycol vapour treated; K25/110/300/550 C = K-saturated and heated to 25, 110, 300, 550 °C; 6NHCl = 6 N HCl treated silt fraction; Sm = smectite, V + Ch = vermiculite plus chlorite; PCh = pseudo chlorite; K = Kaolin; F = feldspars; Q = quartz. Adapted from Pal et al. (2003a) and Bhople (2010).

because haploidisation within the pedon caused considerable pedoturbation (Mermut et al., 1996); however, earlier studies reported that in selected cases, there is a gradual increase in clay content with depth (Dudal, 1965). It was thought that the increase in clay content with depth is due not to clay migration but to inheritance from parent material (Ahmad, 1983).

Studies on vertisols by NBSS&LUP (ICAR) in Nagpur, India, over the past decade and a half indicated that the clay content of the Bss horizons ranges from zero to substantially enriched with clay (~20% increase from the eluvial horizon; Pal et al., 2003a, 2009c). Morphological examination of the vertisols indicated no sign of stratification in the parent material and showed no clay skins. However, micro-morphological investigation of the thin sections indicates the presence of >2% impure clay pedofeatures (Fig. 8a); these features confirm that the clay is enriched in the Bss horizons of vertisols by clay illuviation. Therefore, such vertisols can also have argillic horizons (Pal et al., 2009c). Clay illuviation was also identified in clay soils with vertic properties in Canada (Dasog et al., 1987), Uruguay (Wilding and Tessier, 1988) and Argentina (Blokhuis, 1982). In the past, it was thought that pedoturbation would obliterate all evidence of illuviation, except in the lower horizons (Eswaran et al., 1988; Mermut et al., 1996). Thus, Johnson et al. (1987) considered this process to be an example of proisotropic pedoturbation caused by argilli-turbation, which was thought to destroy horizons or soil genetic layers and to make vertisols revert to a

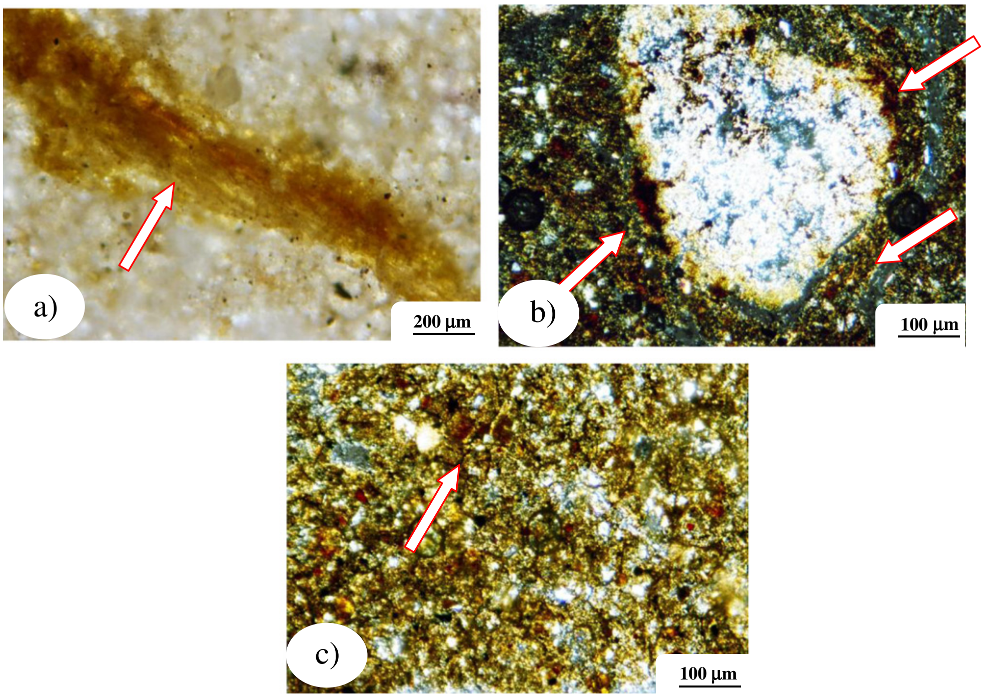


Fig. 8. Representative photograph in cross polarised light. (a) Impure clay pedofeatures, (b) weakly oriented clay pedofeatures and (c) undifferentiated clay pedofeatures. Adapted from Pal et al. (2009a).

simpler state. The clay-enrichment of Bss horizons via illuviation suggests that the argilli-turbation is not a primary pedogenetic process in vertisols (Pal et al., 2009c) and represents a proanisotropism in the soil profile. This finding is further confirmed by a steady decrease in soil organic carbon and by increases in $CaCO_3$, exchangeable magnesium percentage (EMP), exchangeable sodium percentage (ESP), water-dispersible clay (WDC) and carbonate clay (fine earth based) with depth (Table 2; Pal et al., 2009c). Therefore, pedoturbation in vertisols is a partially functional process that is not able to overshadow the more important long-term clay illuviation process. Although argillic horizons are common in vertisols, the B_t horizon does not get better than their dominant property (slickensides) because vertisol soil order keys out before the alfisols according to the US Soil Taxonomy. Thus, at present, these soils would still be classed as vertisols (Pal et al., 2009c).

4.2. Factors of clay illuviation in vertisols

The majority of calcareous vertisols contain a considerable amount of WDC, which increases with depth (Table 2). This finding suggests that the dispersion of clay smectite is possible under slightly acidic to moderately alkaline pH conditions at a very low electrolyte concentration ($ECe \leq 1$ me L^{-1}; Table 2) that ensure a pH higher than the zero point of charge required for a full dispersion of clay (Eswaran and Sys, 1979). Many researchers have postulated carbonate removal as a pre-requisite for illuviation of clay, as Ca^{2+} ions enhance the flocculation and immobilisation of colloidal material (Bartelli and Odell, 1960); however, low quantities of soluble Ca^{2+} ions ($\ll 5$ me L^{-1}, Table 2) are not generally sufficient to cause flocculation of clay particles in vertisols. Therefore, movement of deflocculated fine clay smectite (and its subsequent accumulation in the Bss horizons) is possible in non-calcareous as well as calcareous vertisols (Pal et al., 2003b).

The primary source of Ca^{2+} ions in the soil solution is the dissolution of NPCs (Srivastava et al., 2002). The depth distribution of EMP, ESP, carbonate clay, and soluble Na^+ ions in the majority of vertisols in India (Table 2) suggests that the precipitation of $CaCO_3$ as PC enhances the pH and the relative abundance of Na^+ ions in soil exchange and in solution. The Na^+ ions in turn cause dispersion of clay smectites, and the dispersed smectites translocate even in the presence of $CaCO_3$. The formation of PC creates a chemical environment that facilitates the deflocculation of clay particles and their subsequent movement downward. This finding suggests that PC formation and clay illuviation are two concurrent and contemporary pedogenic events that provide examples of pedogenic thresholds in dry climates (Pal et al., 2003b, 2009c).

4.3. Relative rapidity of clay illuviation, pedoturbation and slickenside formation

The formation of slickensides has hitherto been considered to be a very rapid pedogenic process (Parsons et al., 1973; White, 1967; Yaalon, 1971), as the vertisols are formed on geomorphic surfaces that are <200 to 550 yr old (Blokhuis, 1982; Parsons et al., 1973). A Vertic Haplustalf <100 yr age (^{14}C age, Pal et al., 2006a) developed in the alluvium of the central Indian Deccan basalt during the SHD climate regime, exhibits pressure faces but lacks in slickensides and clay skins; however, it exhibits weakly oriented clay pedofeatures (Fig. 8b), undifferentiated clay pedofeatures (Fig. 8c) and poorly separated plasma (Fig. 9a). Such Vertic Haplustalfs have >8% more clay in the B horizons than in the Ap horizons, and the fine clay/total clay ratio in the B horizon is >1.2 times greater than that of the Ap horizon. The thin sections of the soils did not show any of the disrupted clay pedofeatures that could be expected in soils with high COLE (>0.10, Pal et al., 2009a; Eswaran et al., 1988; Mermut et al., 1996). Thus, the illuviation of clay in the absence of slickensides suggests that illuviation is a faster pedogenetic process than the formation of slickensides, which does not take place within a 100-year span. The occurrence of shrink-swell soils over 500–1500 yr (TL ages) with the illuviated clay features and slickensides of the eastern lower Indo-Gangetic Plains (IGP) under an SHM climate regime (Singh et al., 1998) suggests that a minimum time of 500 years is required to form slickensides in vertisols. Other evidence also supports a longer time span for vertisol formation (Aslan and Autin, 1998). Intensive pedoturbation is therefore not required or important in the

Table 2
Physical and chemical properties of Sodic Haplusterts[a] as representative of vertisols of Peninsular India.

(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[b] cm/h	WDC (%)
			Total								
			Sand (2–0.05)	Silt (0.05–0.002)	Clay (<0.002)						
			(% of <2 mm)								
3114	Ap	0–14	0.9	36.7	62.4	26.7	42.8	_	0.28	1.1	6.6
3115	Bw1	14–40	0.9	34.2	64.9	26.7	41.1	1.5	0.26	2.1	13.9
3116	Bw2	40–59	0.8	33.3	65.9	28.9	43.8	1.6	0.26	1.0	14.8
3117	Bss1	59–91	1.3	35.3	63.4	29.0	45.7	1.5	0.29	0.5	6.4
3118	Bss2	91–125	2.4	37.3	60.3	28.7	47.6	1.5	0.25	0.4	7.6
3119	Bss3	125–150	1.9	38.1	60.0	25.7	42.8	1.6	0.25	0.3	10.0

(b) Moisture at various tensions

Horizon	Depth (cm)	Moisture retention %							AWC
		33 kPa	100 kPa	300 kPa	500 kPa	800 kPa	1000 kPa	1500 kPa	
Ap	0–14	40.1	35.1	30.9	28.3	25.1	22.5	20.3	19.7
Bw1	14–40	41.7	37.3	30.6	28.2	26.2	25.1	19.1	22.7
Bw2	40–59	42.4	40.3	32.2	30.0	26.9	26.8	22.2	20.2
Bss1	59–91	43.9	43.1	33.2	32.6	28.5	27.9	19.8	24.1
Bss2	91–125	43.5	42.7	32.8	32.6	27.8	25.7	19.5	24.1
Bss3	125–150	48.5	42.7	37.5	33.0	29.4	28.3	26.2	22.3

(c) Chemical properties

Depth (cm)	pH water (1:2)	$CaCO_3$ (%)	OC (%)	Extractable bases					CEC (cmol(p+)kg^{-1})	Clay CEC (cmol(p+)kg^{-1})	B.S. (%)
				Ca	Mg	Na	K	Sum			
				(cmol(p+)/kg^{-1})							
0–14	7.8	9.3	0.81	46.2	14.4	0.6	1.0	62.2	65.2	99	95
14–40	7.9	9.4	0.66	43.4	15.6	2.1	0.7	61.0	61.8	94	98
40–59	8.0	10.7	0.59	42.0	17.8	2.7	0.7	63.0	63.5	95	99
59–91	8.4	11.0	0.61	38.2	20.2	4.2	0.7	63.3	63.5	100	99
91–125	8.5	13.7	0.48	28.9	22.0	5.8	0.6	57.3	62.2	95	92
125–150	8.5	15.6	0.42	25.8	22.4	8.6	1.1	57.9	66.7	96	87

(d) 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	3.2	71	22	1.0	0.4	0.2
14–40	2.8	70	25	2.1	0.4	0.2
40–59	2.3	66	28	4.4	1.2	0.8
59–91	1.9	60	32	6.6	3.2	2.0
91–125	1.3	46	35	9.3	1.8	1.1
125–150	1.1	38	33	12.9	1.9	1.1

(e) Saturation extract analysis

Depth (cm)	Soluble cations (meq/l)							Soluble anions (meq/l)					RSC	SAR
	Sat %	ECe	Ca	Mg	Na	K	Sum	CO_3	HCO_3	Cl	SO_4	Sum		
0–14	72.8	0.3	1.43	0.8	3.2	0.1	5.53	–	3.2	0.8	1.53	5.50	0.97	3.0
14–40	70.4	0.3	0.67	0.4	0.8	0.04	1.91	–	1.3	0.6	–	1.90	0.23	1.1
40–59	73.0	–	0.46	0.3	1.1	0.05	1.90	1.0	0.5	0.7	–	2.20	0.74	1.8
59–91	77.1	0.4	0.39	0.3	1.7	0.03	2.46	1.0	1.0	0.9	–	2.90	1.31	3.0
91–125	63.3	4.7	0.72	0.5	6.0	1.43	8.65	1.0	3.0	0.2	4.45	8.65	2.78	8.0
125–150	85.9	–	0.49	0.3	6.3	0.05	7.14	2.0	4.0	0.1	1.04	7.14	5.21	10.0

Adapted from Pal et al. (2003a).

[a] As defined by Pal et al. (2006b).

[b] 9 mm h^{-1} is the HC (WM) in 0–100 cm depth of soil.

creation of typical morphogenetic characteristics in a vertisol (Yaalon and Kalmar, 1978).

4.4. Development of microstructures and vertical cracks in vertisols as controlled by smectite swelling

Huge quantities of smectitic clay induce both horizontal and vertical stresses in vertisols. Lateral stresses in the upper horizons are not severe because of low overburden pressure. In addition, cracks also prevent the development of stress; however, in the sub-surface regions where sphenoids and/or slickensides are formed, the difference between horizontal stress and vertical stress is quite large (Knight, 1980) when soils swell. As a result, failure occurs when the vertical stress is confined and the lateral stress exceeds the shear strength of the soils. Failure occurs along a grooved shear plane (theoretically 45° to the horizontal; Wilding and Tessier, 1988). In reality, such shear failure may range from 10 to 60° (Knight, 1980). The shear failure is manifested as the appearance of poro/parallel/reticulate/grano-striated plasmic fabric, indicating a prominent surface-oriented plasma separation (Fig. 9b) or stipple-speckled/mosaic-speckled/crystallitic plasmic fabric related to

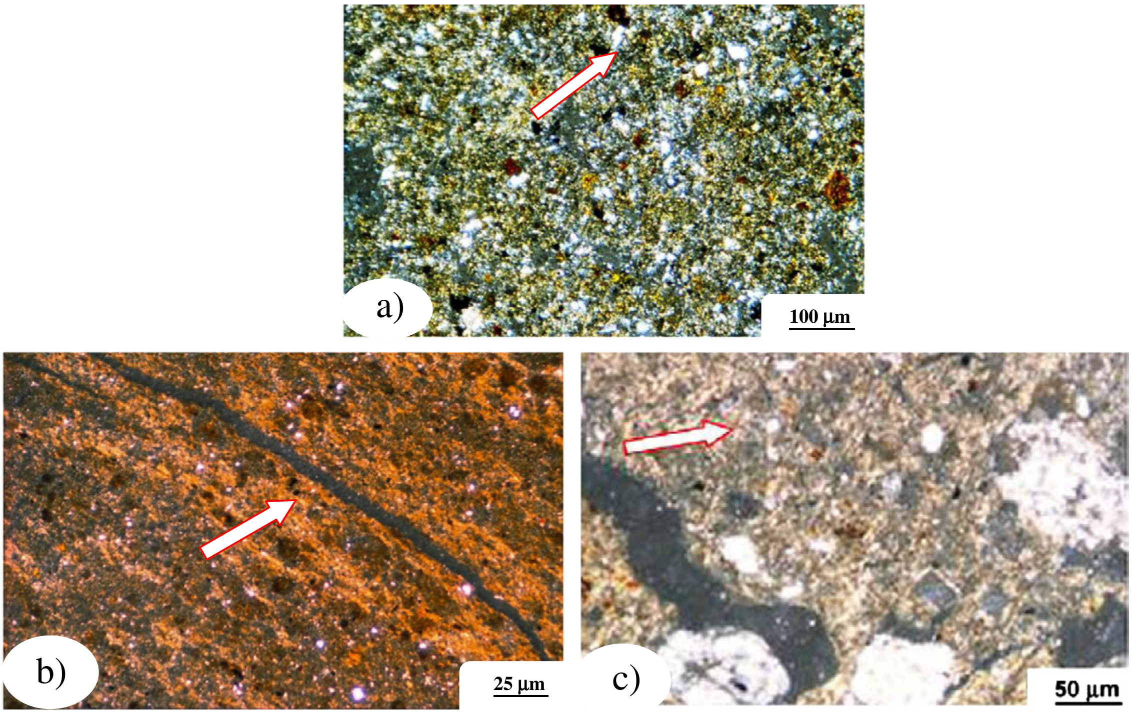


Fig. 9. Representative photograph of cross polarised light: poorly separated plasma in Vertic Haplustalfs (a), strong parallel plasmic fabric in Typic Haplusterts (b), and mosaic/stippled-speckled plasmic fabric in Aridic/Sodic Haplusterts of Peninsular India. After Pal et al. (2009a, 2009c).

poor plasma separation in the Bss horizons (Fig. 9c; Kalbande et al., 1992; Pal et al., 2009c). The presence of sphenoids and/or slickensides and the dominance of poro/parallel/grano/reticulate-striated plasmic fabric in Indian vertisols in HT and SHM climates indicate that the shrink–swell activity of smectites has been extensive. In contrast, the dominance of stippled/mosaic-speckled plasma in SHD soils, mosaic/crystallitic plasma in SAM soils, mosaic/stippled-speckled plasma in SAD soils and crystallitic plasma in AD soils clearly suggests that shrink–swell is much less significant in the soils of drier climates compared to HT and SHM climates, and it manifests in poor plasma separation. Therefore, weak swelling of smectite is sufficient for the development of sphenoids and/or slickensides, but it is not adequate to cause strong plasma separation (Pal et al., 2001a, 2009c), despite the fact that the soils have almost identical COLE values and comparable amounts of expansible clays (Pal et al., 2006b, 2009c). In these soils, swelling of smectites, however, has been restricted neither by the presence of $CaCO_3$ and calcite crystals, nor by the decrease in smectite interlayer surface area by partial hydroxy-interlayering (Pal et al., 2009c).

The saturated hydraulic conductivity (sHC) of all vertisols is not identical but decreases rapidly with depth. The decrease is sharper in SAD and AD soils because of their subsoil sodicity ($ESP>5$, Pal et al., 2009c). The reduced sHC restricts the vertical and lateral movement of water in the subsoils. As a result, during the very hot summer months (April to June), there would be less water in SAD and AD subsoils. This deficit becomes evident from the deep cracks cutting through their Bss horizons, in contrast to higher MAR soils in which the cracks do not extend beyond the slickensided horizon at 40–50 cm (Fig. 2). The lack of adequate soil water during the shrink–swell cycles restricts the swelling of smectite and results in weaker plasma separation in SAD and AD soils (Pal et al., 2009c). Thus, the SAM, SAD and AD subsoils remain, in general, under less amount of water compared to those of HT, SHM, and SHD climates during the Holocene period and are modified in terms of subsoil sodicity, poor plasma separation, and cracks cutting through the Bss horizons due to the accelerated formation of PC. Therefore, Pal et al. (2001a, 2009c) designated such vertisols as polygenic soils.

4.5. Evolutionary sequences in vertisol formation

Successive stages of pedogenic evolution in vertisols were conceptualised by Blokhuis (1982), who thought that vertisols would lose their vertic characters and subsequently convert to non-vertic soils. Eswaran et al. (1988), however, suggested that a vertisol ($pH<6.5$) in surface horizons would form an argillic horizon as leaching advanced, and with the accumulation of translocated clay, the soils may qualify as Vertic Haplustalfs. Both researchers assumed that the original vertisols had no argillic horizon.

Recent studies on the evolution of soils in HT parts of the Western Ghats (Bhattacharyya et al., 1993, 1999a) and north-eastern (Bhattacharyya et al., 2000), and southern India (Chandran et al., 2005) suggest that with time, vertisols in the presence of Ca-zeolites (Typic Haplusterts) of HT remain as vertisols as long as the zeolites continue to provide bases by which to prevent the total formation of kaolin at the expense of smectites (Fig. 10a). In the absence of zeolites, the soils would gradually become acidic and kaolinitic and phase towards ultisols through an intermediate stage of non-vertic alfisols (Fig. 10a). As silica is insoluble in an acidic environment, the complete transformation of smectite to kaolinite is improbable; thus, ultisols would remain unchanged, with Sm–K as the dominant minerals (Chandran et al., 2005).

An extensive pedogenetic study of vertisols in an Indian climosequence expands the basic understanding of vertisol evolution from Typic Haplusterts to Udic/Aridic/Sodic Haplusterts and Sodic Calciusterts (Pal et al., 2009c, Fig. 10b). These vertisols may remain in equilibrium with their climatic environments until the climate changes further, after which another pedogenic threshold is reached. These soils are of Holocene origin but are the products of polygenic evolution. Due to subsoil sodicity caused by illuviation of Na-clay smectites in vertisols of the SAM, SAD and AD climates, the initial impairment of the percolative moisture regime would yield a soil system in which gains exceed losses. This self-terminating process (Yaalon, 1971) would lead to the development of sodic soils in which ESP decreases with depth if aridity continues (Fig. 11). The soils that exhibit regressive pedogenesis

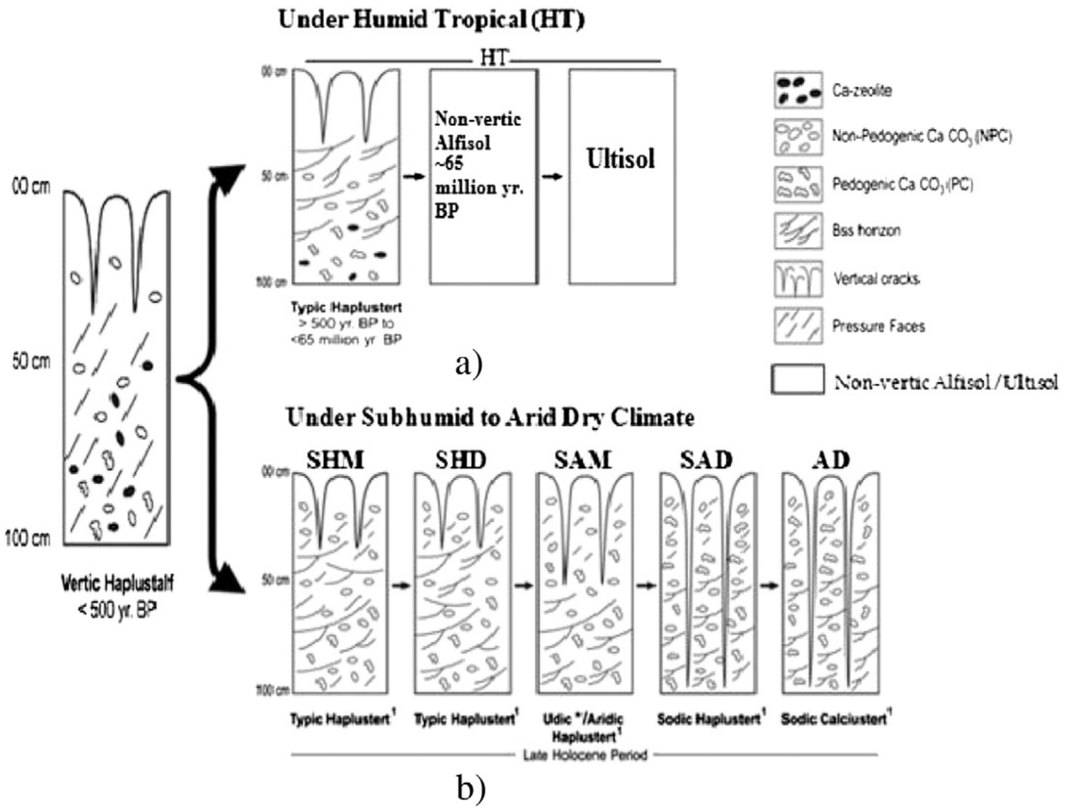


Fig. 10. Successive stages of pedogenic evolution in vertisols. Adapted from Pal et al. (2009a). [1]Clay illuviation, a requisite for argillic horizon (indicating legacy of Alfisols), although common does not get better than the slickensides (Vertisol's dominant property). Since Vertisol soil order keys out before Alfisol in Soil Taxonomy these soils would continue to be grouped as Vertisols.

(Johnson and Watson-Stegner, 1987) suggest that soil degradation is a climatically induced, basic and natural process (Pal et al., 2000b).

5. Importance of pedology in the edaphology of vertisols

5.1. Impact of the close association of non-sodic and sodic shrink–swell soils (vertisols) on crop performance

Natural soil degradation (in terms of PC formation and development of subsoil sodicity in the vertisols of the Purna Valley of Maharashtra, central India; total area ~0.6 M ha) is triggered by the semi-arid climate, with an MAR of 875 mm, a tropustic moisture regime and a hyperthermic temperature regime (Balpande et al., 1996: Pal et al., 2000b). Such soils have severe drainage problems, but in the Pedhi Watershed, in the adjacent east upland of the Purna valley (area ~45,000 ha), vertisols also have drainage problems. The area, however, has a higher MAR (975 mm) than the Purna valley and has similar moisture and temperature regimes to the Purna Valley. Vertisols are the dominant soil type in the watershed, but as a result of micro-topographic variation (0.5–5 m; Fig. 5), Sodic Haplusterts occur on micro-high (MH) positions and at a distance of approximately 6 km, while Aridic Haplusterts occur on micro-low (ML) positions (Vaidya and Pal, 2002). Cotton performs better in Aridic Haplusterts (ESP<5; 0.6–1.6 t/ha of seed + lint, yield obtained by the farmers following typical managements as detailed elsewhere, Kadu et al., 2003) than in Aridic Haplusterts (ESP>5, <15; 0.6–1.0 t/ha) and Sodic Haplusterts (ESP≥15; 0.2–0.8 t/ha yield; Table 3; Kadu et al., 2003). In view of the comparatively poor crop productivity of the Aridic Haplusterts with the Sodic Haplusterts with an ESP>5 but <15 (having no soil modifiers; Pal et al., 2006b), Aridic Haplusterts were classified as Sodic Haplusterts (Balpande et al., 1996; Pal et al., 2000b) because their resilience could be improved by appropriate management interventions to enhance crop productivity. Such a close association of Aridic and Sodic Haplusterts under similar topographical conditions in a relatively small watershed may be unique from the pedological viewpoint, but this finding poses a challenge for land resource managers in comprehending the differences in the chemical environment between the Aridic Haplusterts with ESP<5 and the Aridic Haplusterts with ESP>5 but <15. Thus, for optimised use and management of the latter type of Aridic Haplusterts, the proposed modifications in their subgroup-level classification (as per US Soil Taxonomy) are mandatory (Pal et al., 2006b).

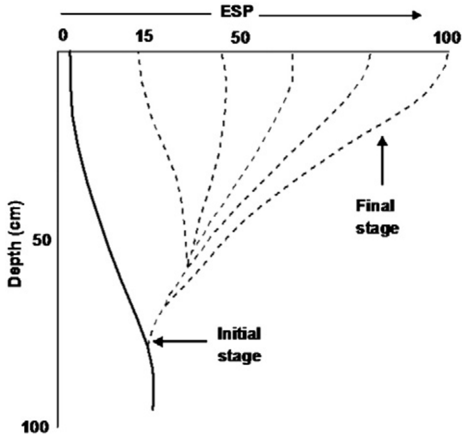


Fig. 11. Progressive development of sodicity in vertisols while aridity continues with time. Adapted from Pal et al. (2011a). ESP = exchangeable sodium percentage.

5.2. Linear distance of cyclic horizons in vertisols and its relevance to agronomic practices

Vertisols develop deep, wide shrinkage cracks in the summer. These cracks close as the soil rewets because of up-thrusting that forces one

Table 3
Range in values of PC, ESP, sHC and yield of cotton in vertisols of Vidarbha, Central India.

District, Vidarbha Region, Maharashtra, Central India	Soil classification	PC (%)	ESP	sHC (mm h^{-1}) weighted mean in the profile (1 m)	Cotton yield (t ha^{-1}) (seed + lint)
Nagpur (MAR – 1011 mm)	Typic Haplusterts/Typic Calciusterts	3–6	0.5–11	4–18	0.9–1.8
Amravati (MAR – 975 mm)	(a) Aridic Haplusterts	3–7	0.8–4	2–19	0.6–1.6
	(b) Sodic Haplusterts	3–13	16–24	0.6–9.0	0.2–0.8
Akola (MAR – 877 mm)	(a) Aridic Haplusterts	3–4	7–14	3–4	0.6–1.0
	(b) Sodic Haplusterts	3–4	19–20	1–2	0.6

PC = pedogenic $CaCO_3$, ESP = exchangeable sodium percentage (sodicity), sHC = saturated hydraulic conductivity. Adapted from Kadu et al. (2003).

swelling clay mass to slip over another, resulting in the formation of slickensides. The cyclic horizons repeat in the subsoil, the size of which depends on the length of cycle. One-half of the linear distance (LD) of the cycle is a measurement of the lateral dimension of a cyclic horizon (Johnson, 1963). To evaluate subsoil variability and determine LD, it is necessary to have trenches at least 10 m long with depths of 2 m or more (Bhattacharjee et al., 1977; William et al., 1996). This fieldwork is time consuming, laborious and expensive.

A large area of vertisols is used for pastures, and cracks developed therein may be wide enough to cause dangerous footing for animals (Buol et al., 1978). Agronomic uses of vertisols vary widely, depending on the climate. Field moisture conditions, drainage conditions and patterns of vegetation indicate that the maximum oscillation between wet and dry conditions manifests in micro-depressions that retain moisture for longer periods and in microknolls, which dry out faster. Vertisols are capable of tilting large trees, and surprisingly, few if any commercial orests are cultivated on vertisols (Buol et al., 1978). In addition, highways, buildings, fences, pipelines, and utility lines are moved and distorted by the shrinking and swelling of these soils. Prior knowledge about the highs and lows of the cyclic pedons may help the stakeholders plan their programmes and avoid mishaps. In view of the need for a method to determine LD, a mathematical equation has been proposed to measure the LD of the cyclic horizons, taking into account the depth of occurrence of slickensides (Bhattacharyya et al., 1999b). A standard parabolic equation represented by ($y^2 = 4ax$) was considered, where a is the focus of the parabola. The concept of cyclic horizons of vertisols in terms of this parabolic pattern (Fig. 12) centres around two basic assumptions. The first assumption is that the depth of the first occurrence of slickensides (b) coincides with the focus of the parabola. The second assumption is that b holds constant within a cyclic horizon.

To calculate LD using the equation ($LD = MN = 2KN = 4[a(a+b)]^{1/2}$ (Fig. 12), the values of a and b are needed. The value of b (the depth of the first occurrence of slickensides) is obtained in the field; however, the value of a can be obtained only by examining the profile exactly in the centre of the cyclic horizon. This value is difficult to acquire because cyclic horizons in the subsurface cannot be identified from the surface, especially where microknolls and microdepressions are obliterated. When the profile is examined away from the centre of the cyclic horizon, the value of a cannot be obtained, and calculation of LD becomes difficult. Thus, Bhattacharyya et al. (1999b) proposed the following equation.

$LD\ (cm) = 200/Y\ (2500 + b\ Y)^{1/2}$, where $Y = y_1 + y_2 - 2(y_1\ y_2)^{1/2}$ and y_1 and y_2 are the vertical distances (cm) from the first occurrence of slickensides to the intersecting points of the cyclic pedon such that $y_1 > y_2$ and b is the depth of the first occurrence of slickensides. It is always possible to find the values of y_1 and y_2 if the profile is examined on either side of the centre of the cyclic horizon (Fig. 12). This equation can eliminate some of the need for fieldwork to determine the LD with the help of three variables, namely y_1 (the length of the slickensided zone on the right-hand side of the profile wall from the depth of the occurrence of slickensides), y_2 (the length of the surface and the slickensided zone on the left-hand side of the profile wall) and b (the depth of the occurrence of slickensides). These values can easily be obtained by soil survey and mapping. The accuracy of the equation proposed by Bhattacharyya et al. (1999b) is between 81 and 86% in vertisols in arid to semi-arid climates. The equation provides a new method of locating micro-depressions and micro-knolls in an effort to better manage vertisols for agricultural and non-agricultural purposes.

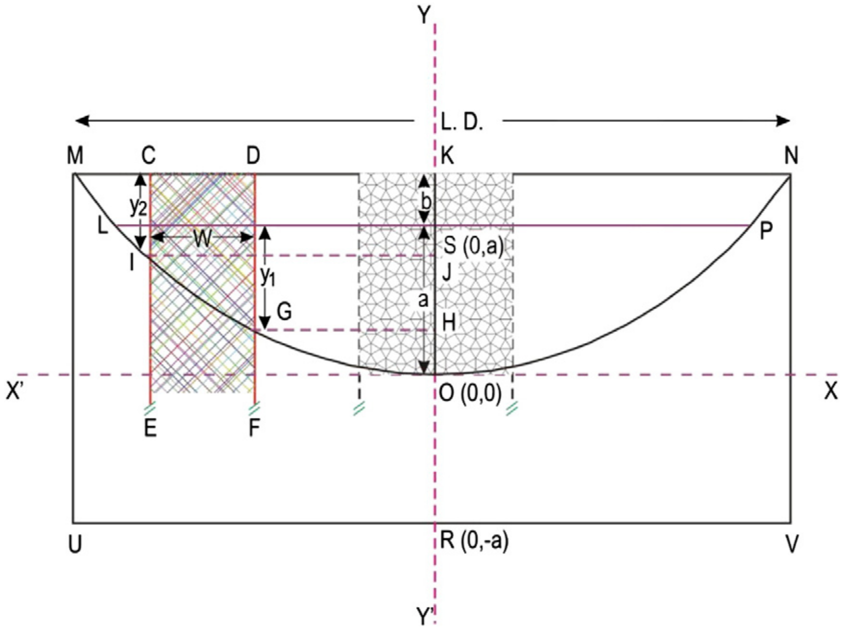


Fig. 12. The parabolic path of cyclic pedon where PL, S, UV, O, and KR are latus rectum, focus, directrix, vertex and axis of the parabola (KN = KM, OS = OR, KN = NV, KM = MU, $OJ - OH = y_1 - y_2 = HJ$, $OJ + OH = y_1 + y_2$, $OJ.OH = y_1.y_2$). Adapted from Bhattacharyya et al. (1999b).

5.3. Importance of smectite clay minerals in growing vegetation on weathered basalt and in very shallow cracking clay soils

In general, gabbros and basalts, which are dominated by dark ferromagnesian minerals, are more easily weathered than granites and other light-coloured rocks. The alluvium of the weathering Deccan basalt is principally responsible for the formation of deep black soils in the Peninsular India, as the first weathering product of the Deccan basalt is low-charge dioctahedral smectite (Pal and Deshpande, 1987a; Pal et al., 2009c). In the Deccan basalt litho logs, boulders of different sizes adjoin each other and exhibit spheroidal weathering (Fig. 13a). These boulders have concentric rings similar to onions (Fig. 13b) that easily come away under gentle pressure from fingers. The boulders also contain DOS (Fig. 13c) similar to that of vertisols (Pal and Deshpande, 1987a). Smectites are known for their excellent capacity to hold moisture and nutrients; thus, they help several tree species to anchor on weathered basalt, even on steep slopes (> 40%). The long-term preservation of tree species under national forest management in Maharashtra and Madhya Pradesh of western and central Peninsular India has become possible under favourable MAR conditions in HT, SHM, SHD, and SAM climates. In SAD and AD climates, care is needed at the initial stage of establishment of tree species. The largest Deccan basalt area with the greatest forest cover lies in the state of Madhya Pradesh, in central India; it is followed by Maharashtra, in western India. Smectite mineral has been enormously useful to preserve and sustain the spectacular natural forest vegetation (Bhattacharyya et al., 2005). The mineral also helps to maintain and preserve the forests in lower-MAR areas; however, initial care is needed during the establishment of tree species. Thus, the natural abundance of smectite in the Deccan basalt areas of lower MAR can also prove useful in establishing agri-horticultural crops even on shallow soils (entisols; depth <50 cm) strewn with small and weathered basalt rocks.

5.4. Role of smectite, soil modifiers and palygorskite minerals in influencing the drainage of vertisols

The vertisols of dry climates of peninsular India have poor drainage, but they show no salt-efflorescence on the soil surface as evidence of the threat of soil sodicity. These soils also do not qualify as salt-affected soils per the United States Salinity Laboratory criteria; however, the sHC of their subsoils is adversely affected by clay dispersion caused by exchangeable magnesium (Vaidya and Pal, 2002). This point suggests that the saturation of vertisols, not only with Na^+ ions but also with Mg^{2+} ions, blocks small pores in the soil. In other words, Mg^{2+} ions are less efficient than Ca^{2+} ions at flocculating soil colloids, although the United States Salinity Laboratory (Richards, 1954) grouped Ca^{2+} and Mg^{2+} together because both improve soil structure. This action is further impaired by a low level of ESP (>5, <15), which reduces the sHC to <5 mm/h, causing a >50% reduction in cotton yield (Table 3; Kadu et al., 2003). This result is due to large amounts of smectite minerals in vertisols (Typic/Aridic Haplusterts). In general, vertisols developed in the alluvium of weathering Deccan basalt contain >95%, 35–40% and 8–10% smectite in the fine-clay (<0.2 μm), coarse-clay (2–0.2 μm) and silt (50–2 μm) fractions, respectively (Pal et al., 2000a), suggesting that 100 g of vertisols from western and central Peninsular India may contain 40–50 g of smectite. Therefore, the current lower limit of a 15 ESP by the United States Salinity Laboratory for all soils is arbitrary and necessitates the evaluation of a lower ESP limit. To validate this suggestion, Pal et al. (2006b) undertook an extensive study on vertisols with and without soil modifiers (Ca-zeolites and gypsum),

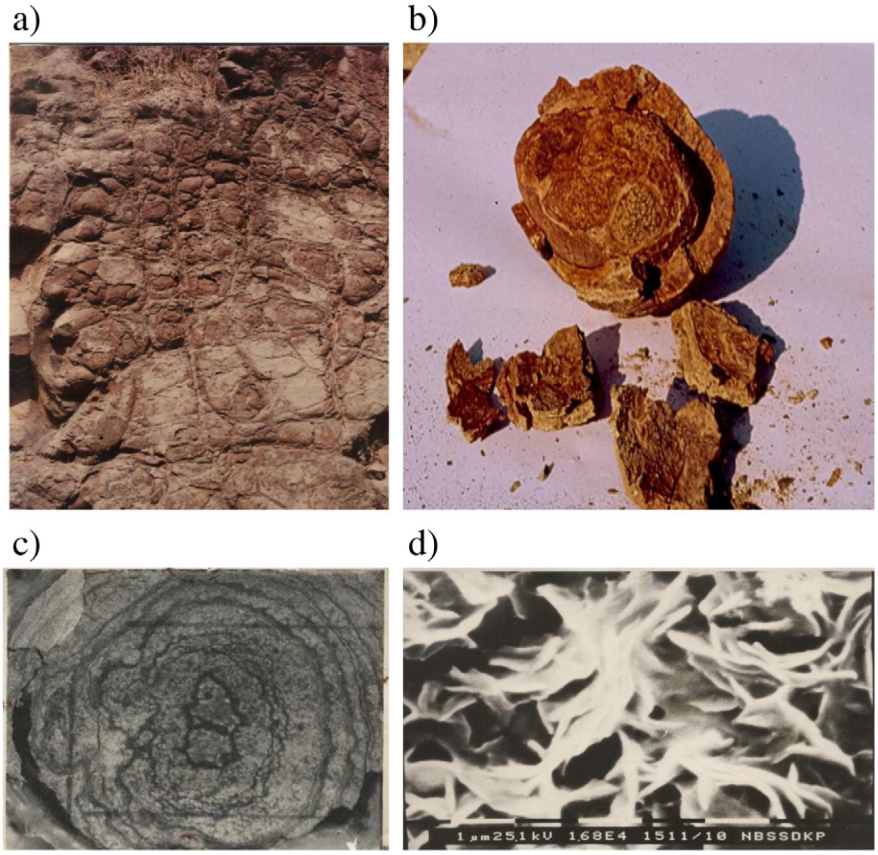


Fig. 13. Deccan basalt litholog showing spheroidal weathering (a), onion like peeling in basalt boulders (b), thin section of basalt boulder showing concentric weathering rinds (c), and SEM photograph of clay sized dioctahedral smectite as its first weathering product (d). Adapted from Pal et al. (2000a) and photographs (a–d), courtesy of DKP. Adapted from Pal and Deshpande (1987a) and photographs (a–b), courtesy of DKP.

representing a climo-sequence from an SHM to an AD climate that occurs in major states in peninsular India. The results of this study indicate that a precise cause–effect relationship between PC and NPC and exchangeable Mg, Na and Ca percentages exists in Sodic/Calcic Haplusterts with and without modifiers. However, the release of Ca^{2+} ions from soil modifiers prevented the rise in pH and ESP and modified sHC (>10 mm/h) in high ESP, which supports the performance of rain-fed crops. Therefore, a lower limit of sodicity at an ESP$>$40 for IGP soils (Abrol and Fireman, 1977), at an ESP$>$5 but $<$15 for Indian vertisols (Kadu et al., 2003), at an ESP 6 for Australian soils, or at an ESP$>$15 for all soil types (Soil Survey Staff, 1999) is incompatible with the performance of crops in highly sodic vertisols that contain soil modifiers, especially Ca-zeolites (Pal et al., 2006b). sHC impairment in soils, mediated by dispersibility, is the most important factor in soil degradation (Sumner, 1995). Thus, the characterisation of sodic soils based on sHC appears to be most appropriate when a 50% reduction in crop yields has been recorded. Therefore, Pal et al. (2006b) advocated a value of sHC$<$10 mm h^{-1} (weighted mean in soil 1 m deep) instead of ESP or SAR. Hence, the deciding feature of soil classification must be the native vegetation because it indicates the nature of the land much more explicitly and authoritatively than any other arbitrary definition or nomenclature (Hilgard, 1906).

The dispersibility of clay colloids impairing the sHC of vertisols is generally an effect of ESP or EMP in the presence or absence of soil modifiers; however, the sHC of zeolitic vertisols of the Marathwada region, Maharashtra state, in semi-arid western India is reduced to $<$10 mm/h, although the soils are non-sodic (Typic Haplusterts; Zade, 2007). Such vertisols have neutral to mildly alkaline pH, ESP$<$5, but EMP increases with depth. In some pedons, EMP is greater than ECP (exchangeable calcium percentage) at depths below 50 cm. Mineralogical studies indicate that palygorskite is found mainly in the silt and coarse-clay fractions (Zade, 2007). Palygorskite minerals are present in Typic Haplusterts and also in Sodic Haplusterts/Sodic Calciusterts in association with Typic Haplusterts in India (Zade, 2007) and elsewhere (Heidari et al., 2008). This mineral is the most magnesium-rich of the common clay minerals (Singer, 2002). Neaman et al. (1999) examined the influence of clay mineralogy on disaggregation in some palygorskite-, smectite-, and kaolinite-containing soils (ESP$<$5) of the Jordan and Betshe'an valley in Israel. Palygorskite was the most disaggregated of the clay minerals, and its fibre did not associate into aggregates in soils and suspensions even when the soils were saturated with Ca^{2+} ions. Palygorskite particles thus move downward in the profile preferentially over smectite and eventually clog the soil pores (Neaman and Singer, 2004). Therefore, vertisols with palygorskite content have high EMP values, causing dispersion of the clay colloids that form a 3D mesh in the soil matrix. This interaction causes drainage problems when such soils are irrigated, presenting a predicament for crop production. In view of their poor drainage conditions and loss of productivity, non-sodic vertisols (Typic Haplusterts) with palygorskite minerals must be considered naturally degraded soils. Similar soils may be found elsewhere in the world; thus, a new initiative to classify them is warranted.

5.5. Climate change, polygenesis, impairment of soil properties and evaluation of vertisols

Frequent climatic changes occurred during the Quaternary Period (Ritter, 1996). As a result, soils worldwide were subjected to climatic fluctuations, especially in the last post-glacial period. Brunner (1970) reported evidence for tectonic movements during the Plio-Pleistocene transition, which caused the formation of various relief types. 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 that still prevail in central and southern peninsular India. The Arabian Sea flanks the Western Ghats, which rise precipitously to an average height of 1200 m, the result of a heavy orographic rainfall all along the west coast. The lee-side towards the coast receives less than 1000 mm of 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 soil environments. This is evident from the occurrence of more alkaline, calcareous and sodic shrink-swell soils (Sodic Haplusterts/Calciusterts) of Peninsular India due to a progressive increase in the PC content from HT to AD climates (Pal et al., 2009c; Fig. 10b), as aridity of the climate is the main factor in the formation of calcareous sodic soils (Pal et al., 2000b). The subsoils (SAM Aridic Haplusterts, SAD Sodic Haplusterts and AD Sodic Calciusterts) remain under less water than those of Typic Haplusterts in HT, SHM and SAM climates. As a result, the vertisols in drier regions of India have relatively more PC and ESP, reduced sHC, (Table 2) and poor micro-structure (Fig. 9c), as well as deep cracks cutting through the slickensided zones (Fig. 2). Thus, these modified vertisols qualify as polygenic soils (Pal et al., 2009c). Deep-rooted crops on Aridic Haplusterts (ESP$>$5, $<$15) and Sodic Haplusterts show poor productivity (Table 3). Recently, Kadu et al. (2003) attempted to identify bio-physical factors that limit the yield of deep-rooted crops (cotton) in 29 basaltic-alluvium vertisols of the Nagpur, Amravati and Akola districts in the Vidarbha region in central India. Under rain-fed conditions, the yield of deep-rooted crops on vertisols depends primarily on the amount of rain stored at depth in the soil profile and the extent to which this soil water is released during crop growth. Both the retention and release of soil water are governed by the nature and content of clay minerals, as well as by the nature of the exchangeable cations. The AWC (available water content), calculated based on moisture content, varied between 33 and 1500 kPa (Table 4), indicating that not only the Typic/Aridic Haplusterts but also the Sodic Calciusterts can hold sufficient water; however, a non-significant negative correlation between cotton yield and AWC (Table 4) indicates that this water is not released during the growth of crops. The prevalence of Na^{+} ions on exchange sites of Aridic Haplusterts and Sodic Haplusterts/Calciusterts with ESP$>$5 thus amounts to overestimation (Gardner et al., 1984). In fact, moisture remains at 100 kPa for Typic Haplusterts and Aridic Haplusterts (ESP$<$5) after the cessation of rains during June to September, while it is held at 300 kPa for Sodic Haplusterts (Kadu, 1997) as the movement of water is governed by sHC, which decreases rapidly with depth, and the decrease is sharper in Aridic/Sodic Haplusterts (ESP$>$5, Pal et al., 2009c). This conclusion is supported by a significant positive relationship between ESP and AWC, and a significant negative correlation between yield and ESP (Table 4). A significant positive correlation between yield and exchangeable Ca/Mg (Table 4) indicates that a

Table 4
Co-efficient of correlation among various soil attributes and yield of cotton[a].

No.	Parameter Y	Parameter X	r
Based on 165 soil horizons samples of 29 vertisols			
1	sHC (mm h^{-1})	Exch. Ca/Mg	0.51[*]
2	sHC (mm h^{-1})	ESP [b]	−0.56[*]
3	ESP	AWC (%)	0.40[*]
4	ESP	Exch. Ca/Mg	−0.40[*]
Based on 29 vertisols			
5	Yield of cotton (q ha^{-1})	AWC (%) WM [c]	−0.10
6	Yield of cotton (q ha^{-1})	ESP max [a]	−0.74[*]
7	Yield of cotton (q ha^{-1})	sHC WM [b]	0.76[*]
8	Yield of cotton (q ha^{-1})	carbonate clay[d]	−0.64[*]
10	Yield of cotton (q ha^{-1})	Exch. Ca/Mg WM[c]	0.50[*]
11	ESP max [a]	AWC (%) WM[c]	0.30[*]
12	ESP max [a]	Exch. Ca/Mg WM[c]	−0.55[*]
13	ESP max[a]	carbonate clay[d]	0.83[*]

AWC, available water content; ESP, exchangeable sodium percentage; sHC, saturated hydraulic conductivity.

[a] Adapted from Kadu et al., 2003.

[b] Maximum in pedon.

[c] Weighted mean.

[d] Fine earth basis.

[*] Significant at 1% level.

dominance of Ca^{2+} ions in the exchange sites of vertisols is required to improve the hydraulic properties for a favourable growth and final yield of crops. The development of subsoil sodicity (ESP$\geq$5) replaces Ca^{2+} ions in the exchange complex, causing a reduction in the yield of cotton in Aridic/Sodic Haplusterts (ESP$\geq$5). A significant negative correlation between ESP and exchangeable Ca/Mg (Table 4) indicates an impoverishment of soils with Ca^{2+} ions during sodification by the illuviation of Na-rich clays. This pedogenic process depletes Ca^{2+} ions from the soil solution in the form of CaCO$_3$, with the concomitant increase of ESP with pedon depth. Thus, these soils contain PC (Pal et al., 2000b), and carbonate clay, which, on a fine earth basis, increases with depth (Table 2). This chemical process is evident from the positive correlation between ESP and carbonate clay (Table 4). A significant positive correlation between the yield of cotton and carbonate clay (Table 4) indicates that, like ESP, PC formation also reduces yield and is a more important soil parameter than total soil CaCO$_3$ (NBSS&LUP, 1994; Sys et al., 1993). An accelerated rate of PC formation in dry climates impairs the hydraulic properties of vertisols, and a significant negative correlation exists between ESP and sHC (Table 4). The processes operating in the soils of dry climates also influence the sHC of the vertisols. A significant positive correlation exists between the yield of cotton and sHC. In view of the pedogenic relationship among SAT environments, PC formation, exchangeable Ca/Mg, ESP and sHC, all of which ultimately impair the drainage of vertisols, the evaluation of vertisols for deep-rooted crops based on sHC alone may help in planning and management of soils, not only of vertisols in the Indian SAT areas, but also of vertisols under similar climatic conditions elsewhere (Kadu et al., 2003).

5.6. Nature and layer charge of smectite and other minerals in adsorption and desorption of major nutrients

5.6.1. Nitrogen

One of the forms of mineral nitrogen (N) is fixed NH$_4$-N, and several reports indicate that many tropical soils are endowed with large amounts of fixed ammonium (Dalal, 1977); however, information on this important form of N is scarce, especially in the SAT soils (Burford and Sahrawat, 1989). Thus, realising its overall importance in the N economy of soils, Sahrawat (1995) determined the fixed NH$_4$-N distribution in two of the BM vertisols of Indian SAT, namely from Kasireddipalli at ICRISAT Center and Patancheru and Barsi in Maharashtra state, western India. The amount of fixed NH$_4$-N was reported to have a share of 22 to 59% in the former and 16 to 31% in the latter in the total soil N, and its percentage was higher in the subsoils. Vermiculites are known to fix NH$_4$-N; however, illites and smectites are often considered able to fix NH$_4$-N (Nommik and Vahtras, 1982). Smectites have no selectivity for non-hydrated monovalent cations such as K$+$ because of their low-level charge (Brindley, 1966). NH$_4^+$, also a non-hydrated monovalent cation with almost the same ionic radius as K, is not expected to be fixed in the interlayers of smectites. It is equally difficult to understand the NH$_4$ ion-fixing capacity of illites because illites do not expand on being saturated with divalent cations (Sarma, 1976). Vertisols developed in the basaltic alluvium of the Deccan basalt of Peninsular India, are not devoid of vermiculite as reported (Dhillon and Dhillon, 1991; Mengel and Busch, 1982). Vertisols contain vermiculite in their silt (50–2 μm), coarse-clay (2–0.2 μm) and fine-clay (<0.2 μm) fractions (Pal and Durge, 1987), including the Kasireddipalli soils (Pal and Deshpande, 1987b). Vermiculite, determined quantitatively (Alexiades and Jackson, 1965), constitutes 2.0 to 3.5% of the silt, 3.5 to 10% of the coarse-clay and 5.0 to 9.5% of the fine-clay fractions (Pal and Durge, 1987). Moreover, the XRD analysis of the total clay fraction (<2 μm) of the Kasireddipalli soils indicates that smectite (a low-charge dioctahedral in nature) is the dominant clay mineral (>50%, <70%) and is associated with vermiculite (10–15%; Pal and Deshpande, 1987a). Vermiculite is trioctahedral in nature and is an alteration product of biotite in the presence of its dioctahedral variety (muscovite; Pal and Durge, 1987; Pal et al., 2001b). Both the micas are not part of the Deccan Basalt, and their presence in vertisols is attributed to erosional and depositional episodes in the Deccan Basalt areas (Pal and Deshpande, 1987a). The identification of vermiculite by XRD analysis in different soil size fractions is fraught with some difficulty in the ubiquitous presence of chlorite. Its presence is resolved by following the progressive reinforcement of the 1.0 nm peak of mica while heating the K-saturated samples at 25, 110, 300 and 550 °C (Pal and Deshpande, 1987a; Pal and Durge, 1987), and its quantity is estimated semi-quantitatively following the method of Gjems (1967). Thus, it would be prudent to attribute the observed NH$_4$-N fixation in vertisols by Sahrawat (1995) to the presence of vermiculite only. Both Kasireddipalli and Barsi vertisols have an almost uniform distribution of sand, indicating any lack of lithological discontinuity in the profile, and amidst this, the clay increases >8% in the subsoils than in the surface layer (Sahrawat, 1995). Thus the clay-enriched subsoils have been the result of clay illuviation (Pal et al., 2009c). During this pedogenetic process, the fine clay fractions containing not only the Na-saturated smectite but also vermiculite could translocate downward in the profile. The translocation of clay-vermiculite might have enriched the subsoils with vermiculite that may possibly explain the observed increasing fixation of NH$_4$-N with soil depth (Sahrawat, 1995). Such a basic understanding is essential to include fixed NH$_4$-N in assessing the potentiality of N available in tropical soils in general and the vertisols in particular.

5.6.2. Phosphorus

Among the soil properties that influence phosphorus (P) adsorption by soil minerals are the nature and amount of soil components such as clay, organic matter, and hydrous oxides of iron and aluminium (Sanyal and DeDatta, 1991). These authors critically analysed the findings of several researchers, which indicated a significant correlation of P sorption parameters with clay content, and they proposed that this is a mere reflection of the effect of specific surface area on P adsorption. In soils, hydrous oxides of iron and aluminium occur as fine coatings on the surfaces of clay minerals (Haynes, 1983), and these coatings have large specific surface areas that can adsorb large amounts of added P. This characteristic suggests that crystalline aluminosilicate minerals merely play a secondary role in P adsorption (Ryden and Pratt, 1980). Fine clay smectites of vertisols of HT, SHM, SHD, SAM, SAD, and AD of Peninsular India are partially hydroxy interlayered (Pal et al., 2009c). The hydroxy interlayering in smectite interlayers is the not a contemporary pedogenic process because in the prevailing mild to moderately alkaline pH conditions, the hydroxides of iron and aluminium cannot remain as positively charged cations to enter the negative environment of the interlayers of smectites (Pal et al., 2011b). The presence of HIS in the fine clay fractions indicates that the hydroxy-interlayering in the smectite interlayers did occur when positively charged hydroxy interlayer materials entered into the interlayer spaces at a pH far below 8.3 (Jackson, 1964). Moderately acidic conditions are optimal for the hydroxy-Al interlayering of smectite, and the optimum pH for interlayering in smectite is 5.0–6.0 (Rich, 1968). The pH of the vertisols is mildly to moderately alkaline. Under such a chemical environment, 2:1 layer silicates suffer congruent dissolution (Pal, 1985). This scenario discounts the hydroxy-interlayering of smectites during the formation of vertisols in the Holocene period (Pal et al., 2011b) and the creation of any positively charged hydroxides that can fix added P, as in highly weathered acidic soils. Therefore, the highest surface area of smectite and/or hydroxides of iron and aluminium with no positive sites plays a small role in the adsorption of added negatively charged phosphate ions in vertisols. This supports the ICRISAT's classical experimental observations on P adsorption and desorption on vertisols (Kasireddipalli soils), which clearly indicate that P adsorption is not a major problem in the vertisols and that all the adsorbed P is easily exchangeable by P^{32} and a small amount of P is adsorbed in the non-exchangeable form (Sahrawat and Warren, 1989; Shailaja and Sahrawat, 1994; Warren and Sahrawat, 1993). ICRISAT (1988) envisaged that $CaCO_3$ could adsorb P because the effective sorption by $CaCO_3$ is not well understood, and P adsorption is not always related to $CaCO_3$ content (Goswami and Sahrawat, 1982); perhaps the critical factor here is the quality of the $CaCO_3$. The vertisols of Peninsular India under a SAT environment contain $CaCO_3$ of both non-pedogenic (NPC) and pedogenic (PC) origin, and both of them effervesce with HCl and cannot be distinguished without examining the soil thin sections under a microscope (Pal et al., 2000b). During the formation of vertisols in the SAT environment, NPCs (pedorelict) dissolve, and the soluble Ca^{2+} ions released from NPCs become precipitated as PC at a pH of approximately 8.2 and may also react with phosphate ions to form Ca-P. Both PC and Ca-P may have the least solubility in the prevailing mild to moderately alkaline pH conditions of vertisols. This may be the reason why Ca-P in the vertisols of SAT has a dominant share among the other soil P compounds, such as Fe–P and Al–P, causing a very low level of soluble extractable P (<5 mg kg^{-1}soil) by Olsen's method (ICRISAT, 1988). It is interesting to note that grain sorghum grown on vertisols responds little to applied P unless the level of Olsen's P was <2.5 mg kg^{-1} soil (ICRISAT, 1988). Additionally, some leguminous crops such as chickpea and pigeonpea are less responsive to fertiliser P than sorghum and pearl millet (ICRISAT, 1981). The root systems of chickpea exude organic acids (malic or citric) (ICRISAT, 1988) and those of pigeon pea produce piscidic acid (Ae et al., 1990), which can dissolve Ca–P and Fe–P, making more P available to the plants. The root exudates containing such organic acids and the rootlets in the soil through which rainwater passes, or other sources of CO_2, can cause an increase in the solubility of PC and Ca–P. The improved management (including pigeonpea) in the long-term heritage watershed experiment at the ICRISAT Center, Patancheru, under rain-fed conditions (Wani et al., 2003, 2007) indicates that during the last 24 years, the rate of dissolution of $CaCO_3$ was 21 mg yr^{-1} in the first 100 cm of the Kasireddipalli soils, which caused a slight increase in exchangeable Ca/Mg and a decrease in pH (Pal et al., 2011a). The rate of dissolution of Ca–P under the present improved management system is sufficient, as it does not warrant the application of a high dose of added P fertiliser to produce an incremental grain yield of 82 kg ha^{-1} yr^{-1}. However, predicting a time scale when soils will be devoid of Ca–P is difficult unless a new research initiative in this direction is taken up.

5.6.3. Potassium

Vertisols are stated to be adequately supplied with potassium (K), and therefore, responses to applied K are generally not obtained (Finck and Venkateswarlu, 1982). Extensive research on K behaviour in Indian vertisols for the last two-and-a-half decades may be a good example for understanding the basic issues of K adsorption and desorption (Pal, 2003). As the Deccan basalt does not contain micas (Pal and Deshpande, 1987a), the vertisols derived from its alluvium are not expected to be micaceous. The small amounts of micas in vertisols are concentrated mainly in their silt and coarse clay fractions (Pal and Durge, 1987; Pal et al., 2001b), and their parental legacy is ascribed to erosional and depositional episodes experienced by the Deccan basalt areas during the post-Plio-Pleistocene transition period (Pal and Deshpande, 1987a). Petrographic and scanning electron microscope (SEM) examinations of the muscovites and biotites of the vertisols of Peninsular India indicate little or no alteration (Fig. 1a,b) (Pal et al., 2001b; Srivastava et al., 2002). Therefore, highly available K status of vertisols appears to be related to the retention of elementary layers of the micas, which favours the release of K^+ even though its content is low. The precise nature of soil mica in the silt and clay fractions was determined on the basis of the X-ray intensity ratio of peak heights of 001 and 002 basal reflections of mica (Pal et al., 2001b). The ratio is generally greater than unity in the silt but is close to unity in the clay fraction (Fig. 1c). The ratio >1 suggests the presence of muscovite and biotite minerals. If muscovite minerals were present alone, the ratio would have been close to unity (Tan, 1982). In the event of a mixture of these two micas, both will contribute to the intensity of the 1.0 nm reflections, whereas the contribution of biotite to the 0.5 nm reflection would be nil or negligible, thus giving a higher value to the intensity ratio of these reflections (Kapoor, 1972). Thus, the silt fractions of the soils contain both muscovite and biotite, whereas the clay fractions are more muscovitic in character (Fig. 1c). The enrichment of soils with muscovite is not favourable so far as the K release is concerned. This is evidenced by the reduced rate of K release in the vertisols compared with the much higher rate of K release from the biotite-enriched soils of the IGP (Pal et al., 2001b) when they were subjected to repeated batch-type Ba–K exchange under identical experimental conditions (Pal and Durge, 1989). Muscovite and biotite micas co-exist in soil environments. The weathering of muscovite in the presence of biotite is improbable. Therefore, the quantity of muscovite cannot be used as an index of K reserve in soils (Pal et al., 2001b). For this reason, Pal et al. (2001b) felt it was necessary to provide a selective quantification of biotite mica in the common situation in which soils contain mixtures of biotite and muscovite. The contents of biotite in vertisols and their size fractions were estimated through a rigorous and exhaustive Ba-K exchange reaction. The cumulative amount of K released at the end of final extraction by the soil's size fractions when the release of K nearly ceased was considered as mainly coming from biotite (Pal et al., 2006c) (Fig. 14). The amount of clay biotite, silt biotite and sand biotite in the representative vertisols of central India ranged from 1.0 to 1.6, 0.2 to 0.3 and 0.2 to 0.4%, respectively, constituting 7–19, 2–3 and 2–5% of the total mica in the respective size fractions. In the <2 mm fine earth fraction, the biotite quantity does not exceed 1%, which constitutes approximately 6–8% of the total mica. For any size fraction, the cumulative amount of K released on a biotite weight basis follows the order $>$ cumulative amount of K released on the entire mica weight basis $>$ cumulative amount of K released on the weight basis of the size fraction (Table 5). The significant positive correlation between the cumulative K release of soils and their size fractions is mainly from biotite and is established from the statistical analysis of bivariate data sets of several parameters that directly or indirectly influence K release. The significant positive correlations between cumulative K release from sand, silt and clay and their corresponding total K contents, respectively (Table 6), indicate that the K release is a function of total K content in micas and feldspars. However, the positive correlations between total K contents in sand, silt, clay and soil and their mica contents (Table 6) indicate the predominant influence of mica to supply K to the plants grown in vertisols. Furthermore, significant positive correlations between the cumulative K release of sand, silt, clay and soil and their respective mica contents (Table 6) indicate that the K release from either the soils or different size fractions are controlled mainly by

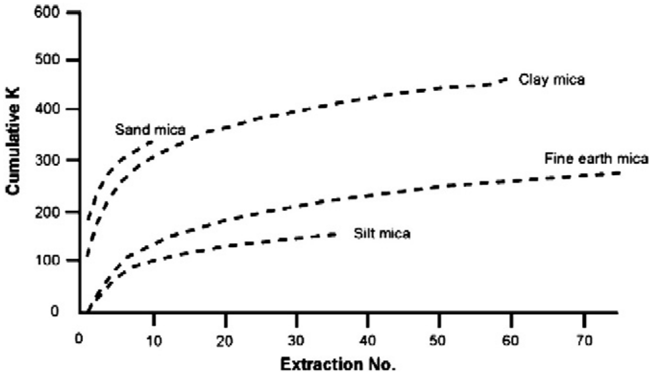


Fig. 14. Relationship between numbers of extractions and cumulative K release (mg/100 g^{-1} mica) of micas in various size fractions of a vertisol. Adapted from Pal et al. (2006c).

Table 5
Cumulative K release from a representative Vertisol and its size fractions.

Horizon depth (cm)		Fine earth (<2 mm) cumulative K release in 75 extractions			Sand (2–0.05 mm) cumulative K release in 10 extractions			Silt (0.05–0.002 mm) cumulative K release in 35 extractions			Clay (<0.002 mm) cumulative K release in 60 extractions		
		SF[a]	MB	BB	SF	MB	BB	SF	MB	BB	SF	MB	BB
		mg K $100g^{-1}$											
Ap	0–15	69	429	6059	20	272	7000	16	191	7004	114	561	6990
Bw1	15–41	41	277	4230	12	162	7006	15	195	7009	92	509	6998
Bw2	41–70	39	267	4097	23	297	6997	13	184	7011	88	502	6999
Bss1	70–95	45	261	4638	15	191	6986	14	161	6990	91	433	7000
Bss2	95–135	49	286	4793	24	334	6991	15	162	6991	92	462	6999
Bss3	135–155	37	235	3849	13	147	6907	16	184	7008	94	471	6984

Adapted from Pal et al. (2006c).

[a] SF = on the basis of size fraction; MB = on the basis of mica content; BB = on the basis of biotite content.

mica. However, better correlations than those between the cumulative K release of sand, silt, clay and soil and their biotite contents (Table 6) provide incontrovertible evidence that the K release in soils is primarily controlled by biotite mica. This further supports the earlier observations on the inertness of muscovite mica in the release of K in the presence of biotite (Pal et al., 2001b). The released amount of K from sand-, silt- and clay-sized biotite (Table 6) is in contrast to the relationships observed between cumulative K release and particles of specimen biotite by earlier researchers (Pal, 1985; Pal et al., 2001b; Reichenbach, 1972). This indicates that large-sized biotite particles have a lower K selectivity than finer particles. Comparable cumulative amounts of K released from sand and silt biotite (Table 6) indicate that not only the sand-sized but also some portion of silt-sized biotite of the vertisols have a greater number of elementary layers along with little weathered biotite. It is observed that during the formation of vertisols since the Holocene (Pal et al., 2006b), there has been no substantial weathering of biotite under the SAT environments. This validates the earlier hypothesis (Srivastava et al., 2002) that the formation of vertisols reflects a positive entropy change due to a lack of any substantial weathering of primary minerals. The relevance of the almost-unaltered biotites (Fig. 1b) is that both sand and silt biotites have highly favourable K release potential, which is reflected in the medium to highly available K status of the vertisols of India and elsewhere (Finck and Venkateswarlu, 1982). Agronomic experiments on the vertisols of central India have indicated crop response to K fertilisers after two years of cropping with hybrid cotton (Pal and Durge, 1987). Therefore, the present available K status may not be sustainable over a longer term because the contents of sand and silt biotites are low. This information helps dispel the myth that the vertisols are rich in available K and that they may not warrant the application of K fertilisers.

Table 6
Co-efficient of correlation among various soil characteristics.

Parameter		r
Cumulative K of sand	Total K in sand	0.635**
Cumulative K of silt	Total K in silt	0.771**
Cumulative K of clay	Total K in clay	0.822**
Total K in sand	Sand mica	0.933**
Total K in silt	Silt mica	0.766**
Total K in clay	Clay mica	0.981**
Total K in soil	Soil mica	0.979**
Cumulative K of sand	Sand mica	0.524*
Cumulative K of silt	Silt mica	0.694**
Cumulative K of clay	Clay mica	0.851**
Cumulative K of soil	Soil mica	0.429*
Cumulative K of sand mica	Sand biotite	0.894**
Cumulative K of silt mica	Silt biotite	0.917**
Cumulative K of clay mica	Clay biotite	0.978**
Cumulative K of soil mica	Soil biotite	0.435*

Adapted from Pal et al. (2006c).

* Significant at 0.05 level.

** Significant at 0.01 level.

Potassium adsorption/fixation in vertisols does not appear to be sufficiently severe to conclude that K becomes completely unavailable to plants (Finck and Venkateswarlu, 1982). Bajwa (1980) reported that soil clay beidellites can fix more K than vermiculite, being nearly 80% against added K, whereas clay montmorillonites can fix only approximately 18%, much less than by the vermiculite clays. The study by Pal and Durge (1987) on K adsorption by the vertisols of Peninsular India indicates that fine clay smectites adsorbed 50–60% of added K, amounting 25–30 mg K/100 g clay. This apparently suggests that the fine clay smectites of Indian vertisols are close to beidellite (Bajwa, 1980). Through a series of diagnostic methods to characterise the fine clay smectites, Pal and Deshpande (1987a) confirmed that they are nearer to the montmorillonite of the montmorillonite–nontronite series. Because smectites can have no K selectivity (Brindley, 1966), further characterisation of fine clay smectites (Pal and Durge, 1987a) indicated the presence of vermiculites, which are generally not detected on the glycolation of Ca-saturated samples but can be detected by a progressive reinforcement of the 1.0 nm peak of mica while heating the K-saturated samples from 25 to 550 °C (Fig. 6). Similar results were reported by Ruhlicke (1985) while reporting a K adsorption of 60 mg K/100 g in bentonite (montmorillonite) deposits. The content of vermiculite was quantified following the method of Alexiades and Jackson (1965) by Pal and Durge (1987), and the vermiculite content ranged from 5 to 9% in the fine clay of vertisols. Pal and Durge (1987) concluded that the observed K adsorption by the silt and clay fractions is due to the presence of vermiculite and not to smectite. The smectites of vertisol clays belong to the low-charge dioctahedral type, and thus, they expand beyond 1.0 to 1.4 nm with the glycolation of K- saturation and heating the samples at 300 °C (Fig. 6). These smectites, when treated according to the alkylammonium method (Lagaly, 1994), showed the presence of both monolayer to bilayer and bilayer to pseudotrilayer transitions. The layer charge of the half-unit cell of smectite ranges from 0.28 to 0.78 mol $(-)/(\mathrm{SiAl})_4\mathrm{O}_{10}(\mathrm{OH})_2$, and the low-charge smectite constitutes $>70\%$ in them (Ray et al., 2003). The position of the higher charge with 0.78 units or lower appears to be due to the presence of small amounts of vermiculite as determined quantitatively by Pal and Durge (1987). The limited leaching in vertisols and small amount of vermiculite would lessen the rate of added K-fertilisers when required. If K-fertilisers are added as a basal dose, the K^+ ions would be fixed in the interlayer of vermiculite, which would make the NH_4 ions from N-fertilisers more labile for ready assimilation by growing plants if not added as a basal dose. In addition, ammonium retention by low charge smectites is expected to be low, and thus, the addition of K may not cause a reduction in crop yield, as experienced elsewhere with high-charge smectite (Chen et al., 1989).

5.7. Role of soil modifiers (zeolites, gypsum and CaCO3) in making vertisols productive in adverse climatic environments

5.7.1. Ca-zeolites

During the last 3 decades, zeolite minerals have been recognised with increasing regularity as common constituents of Cenozoic volcanogenic sedimentary rocks and altered pyroclastic rocks (Ming and Mumpton, 1989). Zeolites have also been reported as secondary minerals in the Deccan flood basalt of the Western Ghats in the state of Maharashtra, India (Jeffery et al., 1988; Sabale and Vishwakarma, 1996). Among the commonly occurring species of zeolites, heulandites have a wide occurrence both in time and space (Sabale and Vishwakarma, 1996). Zeolites have the ability to hydrate and dehydrate reversibly and to exchange some of their constituent cations. Consequently, they can influence the pedochemical environment during the formation of soils. The significance of zeolites has recently been realised in the formation and persistence of slightly acidic to acidic vertisols (Typic Haplusterts) in HT climatic environments, not only in central and western India (Bhattacharyya et al., 2005), but elsewhere (Ahmad, 1983). Zeolites can indeed provide sufficient bases to prevent the transformation of smectite to kaolinite, thus making the formation and persistence of vertisols possible even in a humid tropical climate (Bhattacharyya et al., 2005), as zeolites can maintain the base saturation of soils well above 50% (Bhattacharyya et al., 1993; Pal et al., 2006b). The formation and persistence of vertisols in the Western Ghats over millions of years (Bhattacharyya et al., 1993; Pal et al., 2009c) has provided a unique example that in an open system such as soil, the existence of a steady state appears to be a more meaningful concept than equilibrium, in a rigorous thermodynamic sense (Smeck et al., 1983). The knowledge gained on the role of zeolites in the persistence of vertisols not only provides a deductive check on inductive reasoning regarding the formation of soil in the humid tropical climate (Chesworth, 1973, 1980), but it also throws light on the role of these minerals in preventing the loss of soil productivity even in an intense leaching environment. This indeed may be the reason why crops do not show a response to liming in the acid soils of the tropical Western Ghats (Kadrekar, 1979).

Many productive vertisols under rain-fed conditions have been rendered unproductive for agriculture under irrigated conditions in the longer-term. However, some zeolitic vertisols of the SAD parts of western India have been irrigated through canals for the last twenty years to produce sugarcane. These soils lack salt-efflorescence on the surface and are not waterlogged at present, suggesting that these soils are not degraded due to their better drainage. However, these soils are now Sodic Haplusterts in view of their pH, ECe and ESP values, but they have sHC$>$10 mm hr^{-1} (weighted mean in the 0–100 cm, Pal et al., 2011). A constant supply of Ca^{2+} ions from Ca-zeolites in these soils most likely helps maintain a better drainage system. Because of such natural endowment with a soil modifier, no ill effects of high ESP ($>$15) in crop production in the vertisols of Gezira in Sudan (El Abedine et al., 1969; Robinson, 1971) and in Tanzania (Ahmad, 1996) were observed. In addition, some vertisols of the AD climate of western India produce deeply rooted crops such as cotton under rain fed conditions comparable to those of the Typic Haplusterts of the SAM climate of central India. The sHC (weighted mean, 0–100 cm) of these soils is $>$15 mm hr^{-1}, despite being Sodic Calciusterts (Pal et al., 2009c). However, the sustainability of crop productivity in the dry climate depends on the solubility and supply of Ca^{2+} ions from zeolites such that it is sufficient to overcome the ill effects of the pedogenic threshold of dry climates (Pal et al., 2003b, 2009c). Such situations are unique in nature and pose a great challenge to soil mappers to classify them as per the US Soil Taxonomy when they have good productive potential despite being sodic in nature.

5.7.2. Gypsum

Arid and semi-arid environments trigger natural soil degradation processes in terms of the precipitation of $CaCO_3$ and the concomitant development of sodicity (Pal et al., 2000b). Despite this possibility, selected vertisols of the SAD climate in southern India are non-sodic and support the growth of crops such as cotton, pigeonpea and sorghum. The development of sodicity has been prevented by the presence of gypsum in these soils, but the soils are calcareous in nature. The soils have an sHC$>$30 mm hr^{-1} despite the rapid formation of PC, unlike in the zeolitic vertisols of the SAD climate (Pal et al., 2009c). This can be attributed to the greater solubility of gypsum (30 me/L) than that of Ca-zeolites ($<$0.1 me/L) in distilled water (Pal et al., 2006b). The gypsum in such soils is antagonistic to the formation of more soluble salts in soils, as it prevents clay dispersion. Although the sustainability of crop productivity in these soils depends on the gypsum stock, the present poor productivity of cotton (approximately 2 t ha^{-1}) may be enhanced by irrigation because the gypsum present would prevent water logging because of better drainage (Pal et al., 2009b).

5.7.3. $CaCO_3$

The subsoil sodicity impairs the hydraulic properties of the vertisols of SAT environments, and this leads to the formation of sodic soils with ESP decreasing with depth. These soils are impoverished in organic carbon but have become enriched with $CaCO_3$ with poor sHC (Pal et al., 2009c). However, such soils show enough resilience under the improved management (IM) (catchment management followed by adopting legume-based crop rotation, improved nutrient management and without any chemical amendments) system of ICRISAT, implemented in Patancheru, India. Through the implementation of such practices, a substantial increase in soil organic carbon (SOC) stock was observed (Wani et al., 2003). The resilience of such soils has been maintained by implementing IM practices in vertisols. The increase in SOC is, however, related to chemical changes after the specified management interventions. In vertisols (Sodic Haplusterts, Pal et al., 2011a) after 30 years of IM, the weighted mean (WM) of sHC in the first 100 cm of the profile increased by almost 2.5 times due to the reduction of ESP through the dissolution of $CaCO_3$, making the soils more permeable to air and water. In the last 24 years (since 1977), the rate of dissolution of $CaCO_3$ has been 21 mg yr^{-1} in the first 100 cm of the profile. Dissolved Ca^{2+} ions improve the Ca/Mg ratio on the exchange complex of soils under IM compared with those under traditional management (Pal et al., 2011a).

The changes in soil properties, as stated above, suggest that $CaCO_3$ is dissolved through the cations of acidic root exudates and carbonic acid that formed due to evolved CO_2 from the root respiration in an aqueous solution, resulting in the formation of $Ca\ (HCO_3)_2$. The soluble $Ca\ (HCO_3)_2$, therefore, helps restore both the soluble and exchangeable Ca ions in the soils. The ESP decreases and the soil structure improves; as a result, the hydraulic properties of soils are improved. This improvement in soil properties highlights the role of $CaCO_3$, which remains chemically inert (Pal et al., 2000b) during its sequestration (Sahrawat, 2003) but acts as a soil modifier during the amelioration of degraded soils. The improvements in soil properties are also reflected in the classification of vertisols. The original Kasireddipalli soils (Sodic Haplusterts) now qualify as Typic Haplusterts (Pal et al., 2011a).

6. Concluding remarks

Vertisols are used for the production of various agricultural crops under both irrigation and rain-fed conditions. Agronomic practices for growing crops under irrigation do not cause soil degradation in HT, and crops grow well in SAD and AD climates due to the presence of soil modifiers. Without soil modifiers, however, the soils degrade under irrigation in SAT environments and lose their productivity. Non-sodic vertisols (Typic Haplusterts) with minerals such as palygorskite have severe drainage problems, like the non-zeolitic Aridic Haplusterts, even with an ESP$\geq$5 but$<$15. Zeolitic Sodic Haplusterts have no drainage problem and are productive like Typic Haplusterts at present. These agricultural land uses clearly highlight that even though vertisols make up a relatively homogeneous major soil group, they show a considerable variability in their land use and crop productivity. It is therefore important to understand the factors that cause the variability in their properties. A synthesis of recent developments in the pedology of vertisols achieved through the use of high resolution micro-morphology, mineralogy, and age control data along with their geomorphologic and climatic history, has helped us better understand the effects of pedogenetic processes due to changes in climate during the Holocene in modifying the soil properties in the presence or absence of soil modifiers (Ca-zeolites and gypsum), $CaCO_3$ and palygorskite minerals. The state-of-the-art information developed through this review has helped establish an organic link between pedogenetic processes and bulk soil properties and has provided a better understanding of many pedological and edaphological issues related to vertisols. It is hoped that this review will serve as a handbook to assess the health and quality of vertisols while developing suitable management practices to enhance and sustain their productivity. However, much of the success of the management interventions still depends on the proper classification of vertisols at the subgroup level, identifying the impairment of drainage in Aridic Haplusterts ($ESP \geq 5, <15$), Typic Haplusterts (with palygorskite) and the improvement of drainage in Sodic Haplusterts/Sodic Calciusterts with soil modifiers. At present, the vertisols of the SAT environments are less intensively cultivated because of their inherent limitations, despite that they represent a productive resource under improved management. Therefore, areas dominated by vertisols require immediate national attention so that they can be used judiciously to produce more food required for the populous Indian subcontinent and other countries in the developing world.

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