Chapter 2
Cracking Clay Soils (Vertisols): Pedology, Mineralogy and Taxonomy

Abstract 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 geomorphic and climatic history, 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. The climate change has caused modifications in the soil properties in the presence or absence of Ca-zeolites, gypsum, $CaCO_3$ and palygorskite minerals. The formation and persistence of Vertisols in the Deccan basalt areas under humid tropical (HT) climatic conditions, provides a unique example of tropical soil formation. Such soil formation remained incomprehensible unless the role of zeolites was highlighted by the Indian soil scientists during the last two decades. Persistence of these soils in HT climate for millions of years has provided a deductive check on the inductive reasoning of the conceptual models on the formation of Vertisols in HT climate. The novel insights will serve as guiding principles to improve and maintain their health and quality 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 ≥5, <15), Typic Haplusterts (with palygorskite) and the improvement of drainage in Sodic Haplusterts/Sodic Calciusterts with soil modifiers. The semi-arid tropics (SAT) Vertisols at present are less intensively cultivated because of their inherent limitations. It is hoped that new knowledge on pedology, mineralogy and taxonomy of dry and wet climates will fulfil the need for a handbook on Vertisols to facilitate their better management for optimizing their productivity in the 21st century.

Keywords Tropical soils · Vertisols · Pedology · Soil classification · Climate change

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2.1 Introduction

Vertisols are the most interesting and widely occurring soils of the world in general and the Indian subcontinent in particular. Because of their unique morphology these soils have attracted attention of both pedologists and edaphologists. This treatise is primarily based on the Indian Vertisols. However, relevant data from other tropical parts of the world are included. It 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, and aims to provide a better understanding of Vertisols created by the climate change phenomena of the Holocene. The updated information will facilitate in optimizing the efficient use and management of Vertisols in tropical India and other tropical regions.

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). Despite the availability of substantial information on Vertisols; it still remains challenging to optimize their use and management (Coulombe et al. 1996; Myers and Pathak 2001; Syers et al. 2001; Pal et al. 2012a). The global area under Vertisols is estimated to be approximately 308 M ha, covering nearly 2.23% of the global ice-free land area (USDASCS 1994). But the reliability of this estimate still remains uncertain because several countries have not yet been included in the inventory (Coulombe et al. 1996). Moreover, the area under Vertisols in a soil survey may often be too small to resolve at the scale of map compilation. Such an example from the Indian sub-continent is shown in Table 2.1. 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 sub arid regions. In the tropics, they occupy 60% of the total area; in the subtropics, they cover 30%, and 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 4% in the Mediterranean climate, (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). Due to 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), which 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 since the roots of annual crops do not penetrate deeply due to poor subsoil porosity and aeration. This unfavourable physical condition of these soils compels farmers (especially in India) to allow these

Table 2.1 Distribution of Vertisols in different states of India under a broad bioclimatic systems

States	Bio-climate[a]	Area (m ha) (%)[b]
Uttar Pradesh	SAM, SHD	0.41 (0.12)
Punjab	SAM[d]	
Rajasthan	AD	0.98 (0.30)
Gujarat	AD, SAD, SAM	1.88 (0.57)
Madhya Pradesh	SAM,SHD, SHM[c]	10.75 (3.27)
Maharashtra	SAD, SAM, SHD, SHM[c]	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[d]	
Bihar	SHM[d]	
India		26.62 (8.10)

Adapted from Bhattacharyya et al. (2009)
[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 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. 2012b)
[d]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

soils to remain fallow during the rainy season and cultivate them only in the post-rainy season. Current agricultural land uses reflect a fact 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. 2012b). As a matter of fact, 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 optimize management strategies (Coulombe et al. 1996; Syers et al. 2001). It is often realized by the researchers (Puentes et al. 1988) that basic pedological research is needed to understand some of the unresolved edaphological aspects of Vertisols to develop optimal management practices.

Vertisols occur in wider bio-climatic zones in India (Table 2.1), 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 2.1). Additionally, outside the Deccan basalt region of the Peninsula, in the states of Punjab, Bihar and West Bengal, Vertisols and their vertic inter grades occur in SHM, SHD and SAM climates (Pal et al. 2010), but they are not mappable at the 1:250,000 scale. By 2009, a total number of 306 BM (benchmark) Vertisols and vertic intergrades were identified by the ICAR-NBSS&LUP, Nagpur, India, which included 112 BM Vertisols (Pal et al. 2009a). This data set has been broadened to 425 BM soils by the National Agricultural Innovative Project (NAIP) (Component 4), sponsored research on 'Georeferenced soil information system for land use planning and monitoring soil and land quality for agriculture (GEOSIS) (www.geosis-naip-nbsslup.org).' through the Indian Council of Agricultural Research, New Delhi (Bhattacharyya et al. 2014; Mandal et al. 2014). Research scientists of Division of Soil Resource Studies of the ICAR-NBSS&LUP and GEOSIS team members during the last two and half a decade examined more than 200 Vertisols in the states of Madhya Pradesh, Maharashtra, Chhattisgarh, Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, Rajasthan and West Bengal in India. They have been indicated (along with their global distribution) on a 1:1 million-scale map (NBSS&LUP 2002; Pal et al. 2012a). Further, based on a larger data set (Mandal et al. 2014) a fresh initiative by the GEOSIS developed a revised map (on a 1:1 million-scale) of the black soil region (BSR) of the Indian sub-continent, which shows the presence of Vertisols.

2.2 Factors of Vertisol Formation: A Revisit

The soil-forming factors are the most relevant and appropriate features that explain Vertisol formation. They are interdependent and highly variable and therefore influence the properties of Vertisols in multiple ways as described and explained in several text books on soil science. However, in view of the recent developments in studies of Vertisol formation in the Indian sub-continent Pal et al. (2001, 2006a, b, 2009a, b, c, 2012a, b, c; Bhattacharyya et al. 2005; Ray et al. 2006a; Srivastava et al. 2002, 2010, 2015), each of these five factors merits revisit and discussion.

2.2.1 Parent Material

The basic parent materials, essentially required for the formation of Vertisols, are made available through several geologic formations (Murthy et al. 1982). The parent materials from inheritance or weathering provide a large quantity of smectites but the distinction between inherited and newly-formed clay minerals is difficult to discern. However, in Vertisols of the sub-humid, semi-arid and arid climates of Peninsular India, chemical weathering of primary minerals is not substantial as evidenced from the presence of either fresh or weakly to moderately altered plagioclase and micas (Fig. 2.1a, b). Such stages of mineral weathering discount the formation of smectite during the development of Vertisols (Srivastava et al. 2002) and thus validate the hypothesis that Vertisol formation reflects a

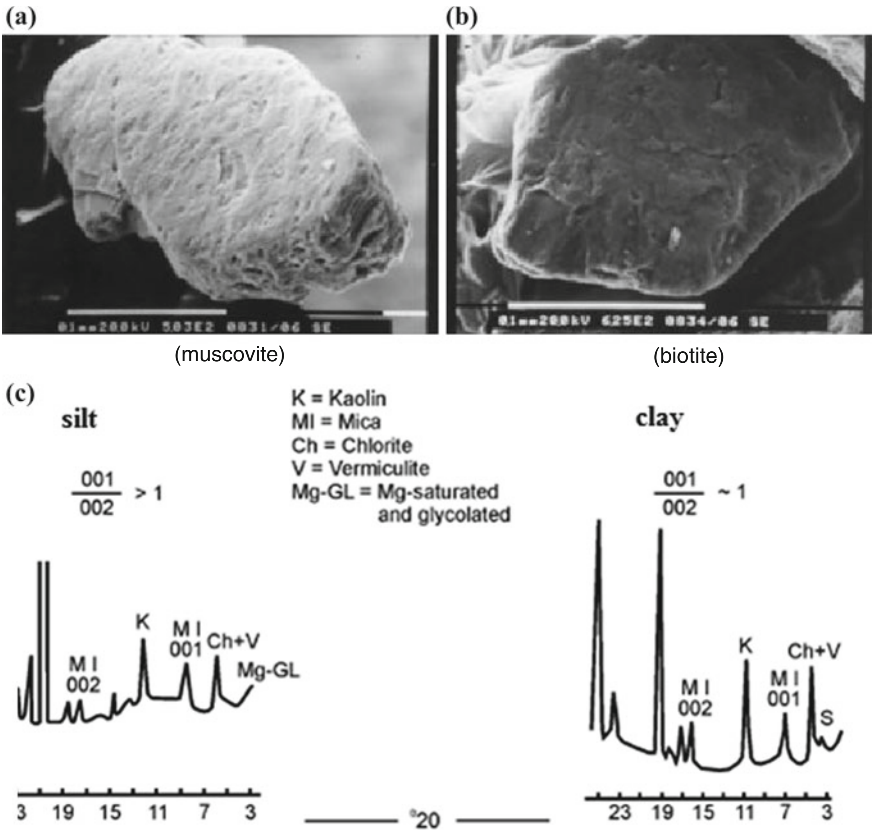


Fig. 2.1 Representative SEM photographs showing no or very little alteration of micas (**a**, **b**), and XRD diagrams of the silt and clay fractions (**c**) of Vertisols of Peninsular India (Adapted from Pal et al. 2006c)

positive entropy change (Smeck et al. 1983). Smectite clay is solely responsible for the shrinking and swelling phenomena to create vertic properties of soils (Shirsath et al. 2000). Therefore, smectite is the exclusive parent material for the formation of Vertisols.

2.2.2 Climate

Vertisols occur from the humid tropics to arid areas (Ahmad 1996). Although their characteristics are often related to overall climate, 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; Pal et al. 2012a). But the formation of Vertisols in humid and arid bio-climatic environments is difficult to follow because large quantities of smectite are required to create their shrink–swell properties. Smectite is ephemeral in an HT climate (Bhattacharyya et al. 1993; Pal et al. 1989) while in sub-humid to arid climates, the weathering of primary minerals contributes very little to smectite formation (Srivastava et al. 2002). Thus smectite clay minerals cannot be retained in HT Vertisols while they are in huge quantity in Vertisols of sub-humid to arid climatic conditions. The occurrence of Vertisols in the alluvium of weathering Deccan basalt in HT, SHM, SHD, SAM, SAD, and AD environments of the Indian peninsula (Pal et al. 2009a), may suggest that the basaltic parent material influenced soil formation such that Vertisols are formed under different climatic conditions (Mohr et al. 1972). It is interesting to note that the morphological and chemical properties of these Vertisols differ. In general, the colour of soils of the HT climate is dark brown (7.5YR 3/3) to dark reddish (5YR 3/3) and yellowish brown (10YR 3/4) and it is dark (10YR 3/1) to very dark grayish brown (10YR 3/2) in soils of other climates. The subsoils of the HT climate have weak and small wedge-shaped aggregates with pressure faces that break to weak angular blocky structure whereas those of SHM, SHD, SAM, SAD and AD climates have strong medium sub-angular blocky to strong coarse angular blocky structure with pressure faces and slickensides that break into small angular peds. More interestingly, 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. 2.2). 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 (Pal et al. 2009a). In view of these observations, the hypothesis of Mohr et al. (1972) for the formation of similar soils in basaltic alluvium under different climates is inadequate to explain the formation of Vertisols of tropical India. The abundance of Vertisols in dry climates may suggest a role of climate in their genesis (Eswaran et al. 1988) but it will be more appropriate to follow their genesis as influenced by a specific bio-climatic environment. Occurrence of Vertisols in a climosequence provides evidence for the Holocene climate changes in tropical and subtropical regions of India and elsewhere (Pal et al. 2009a).

2.2.3 Topography

Despite the fact Vertisols occur abundantly in low elevations they do occur at higher elevations in the Ethiopian plateau or on higher slopes, as in the West Indies (Coulombe et al. 1996) and in micro-depressions on the Deccan basalt plateau in the Indian sub-continent (Bhattacharyya et al. 1993; Pillai et al. 1996). The majority of the Indian Vertisols occur in lower physiographic areas, i.e., in the lower piedmont plains and valleys (Pal and Deshpande 1987; Pal et al. 2009a). Vertisols in micro-depressions on the Deccan basalt plateau are spatially associated with red

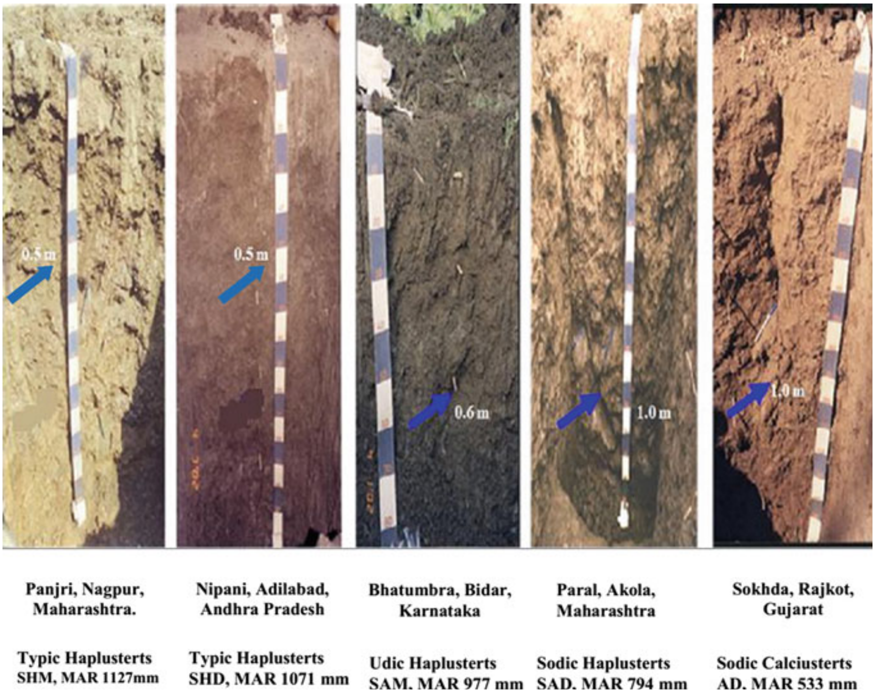


Fig. 2.2 Cracks are extending beyond the zone of slickensides with increase in aridity (SHM to AD bioclimates) (Adapted from Pal et al. 2003a)

ferruginous soils (Alfisols) and exist as distinct entities under almost similar topographical conditions in the HT (Bhattacharyya et al. 1993) and SAD (Pillai et al. 1996) climates. The red soils are mildly acidic Entisols/Inceptisols/Alfisols in SAD climates, but they are moderately acidic Alfisols in HT climate. The red soil clays of an HT climate contain predominant amount of smectite–kaolinite (Sm–K), whereas those of the SAD climate contain only small amounts of Sm–K. The clay 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). Formation 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). It is believed that in the initial stage of soil formation, weathering products rich in smectite from the hills were deposited in micro-depressions, as is evident from the lithic/paralithic contacts of such Vertisols (Fig. 2.3a). Over time, the hill 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 to form the Sm–K. The spatially-associated Vertisols, however, continued to exist in the micro-depressions (Fig. 2.4) even in HT climates because the smectite was

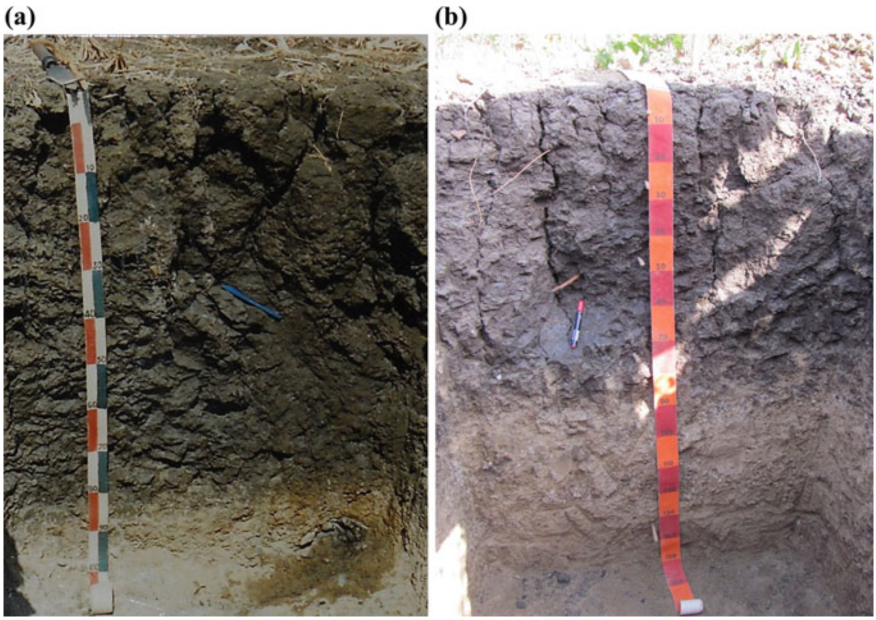


Fig. 2.3 A representative Vertisol (Typic Haplusterts) developed in micro-depression of a plateau, showing paralithic contact with the Deccan basalt of central India (**a**) and in the Purna Valley developed in the alluvium of the Deccan basalt (**b**). *Photograph* courtesy—DKP

stabilized due to the continuous supply of bases from Ca-rich zeolites (Bhattacharyya et al. 1993). During the Plio-Pleistocene transition, the period of the HT climate ended (Pal et al. 1989), and both smectite and Sm–K in SAD Vertisols were preserved to the present. The reduced rainfall in 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 plateau of the Deccan basalt, and also in the valley of the Deccan basalt areas (Fig. 2.3b).

Another form of micro-topography “gilgai” in Vertisol areas is not very well understood and at present, gilgai micro-topographies are very rare on the Indian sub-continent because most were obliterated by post-cultural human activities. Wilding and Coulombe (1996) reported that the depth distribution of soil properties generally differs between the mounds and depressions of the gilgai topography, which results 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 is common in a central Indian watershed (Vaidya and Pal 2002). Vertisols in the watershed 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 (Fig. 2.5). MH Vertisols are more clayey and strongly calcareous, alkaline and have poor drainage (saturated hydraulic conductivity, sHC < 10 mm/h), and those in ML positions are less clayey and calcareous, mildly alkaline and have better drainage (sHC > 10 mm/h) (Table 2.2). MH

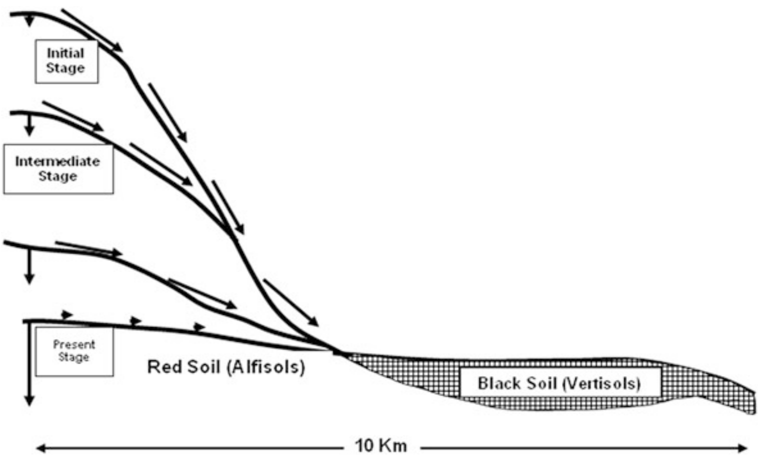
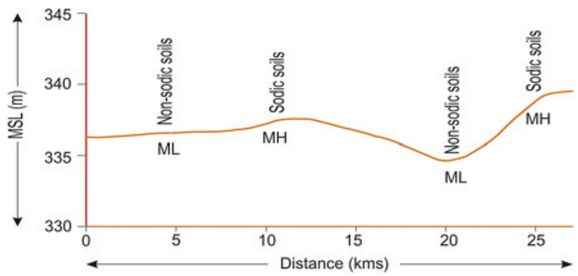


Fig. 2.4 Schematic diagram of the pedon site of red soils (Alfisols) and black soils, (Vertisols) showing the landscape reduction process explaining the formation of spatially associated red and black soils (Adapted from Pal 2008)

Fig. 2.5 Juxtaposition of the occurrence of sodic and non-sodic soils (Vertisols) on MH and ML positions in black soils region (Adapted from Vaidya and Pal 2002)



Vertisols have larger amounts of $CaCO_3$ because of their relatively more aridic environment than in ML Vertisols. During the winter season, moisture of sodic soils of the Bss horizons of the MH positions is held at 300 kPa while it is between 33 and 100 kPa in non-sodic soils of the ML positions (Kadu 1997; Deshmukh et al. 2014), confirming that the soils of the MH positions remain relatively more arid. During the very hot summer months, this results in much less water in the subsoils of the MH positions where deep cracks cut through the Bss horizons. The lack of adequate soil water during the shrink–swell cycles restricts the swelling of smectite and results in weaker plasma separation in soils of the MH positions. The ML Vertisols showed strong plasma separation with parallel/porostriated b-fabric (Fig. 2.6a) whereas the MH Vertisols showed weak plasma separation with stipple-speckled to mosaic-speckled plasmic fabric (Fig. 2.6b). The plasma separation is more pronounced and the preferred orientation in zones adjacent to grains and voids is stronger in soils of ML than those of the MH positions. Thus, although surface-oriented plasma separation of soils indicates a high degree of clay activity

Table 2.2 Physical and chemical properties of Vertisols on MH and ML positions in Pedhi Watershed of Maharashtra

Horizon	Depth (cm)	pH (1:2) H_2O	ECe (dS m^{-1})	Organic carbon (%)	$CaCO_3$ < 2 mm (%)	Clay %	sHC (mm/h)[a]	ESP[b]
Representative sodic Vertisols of MH position: Pedon 6: Khartalegaon: Sodic Haplusterts								
Ap	0–15	8.1	0.4	0.9	13.3	54	7.7	2.0
Bw1	15–37	8.3	0.5	0.7	11.9	58	6.5	3.5
Bw2	37–55	8.5	0.9	0.7	11.8	66	1.0	8.8
Bss1	55–86	8.6	0.7	0.5	11.2	64	0.9	10.2
Bss2	86–136	8.8	1.0	0.4	11.4	64	0.8	16.8
Bss3	136–150	8.8	2.4	0.4	15.2	64	0.5	20.2
Representative non-sodic Vertisols of ML position: Pedon 2: Wadura: Aridic Haplusterts								
Ap	0–13	8.1	0.8	0.9	5.8	82	7.2	4.1
Bw1	13–36	8.1	0.8	0.6	6.4	76	12.4	4.3
Bw2	36–58	8.1	0.7	0.8	6.6	79	16.4	4.1
Bss1	58–87	8.0	0.5	0.8	6.7	81	29.8	2.6
Bss2	87–125	8.0	0.5	0.8	6.4	86	21.2	1.8

Adapted from Vaidya and Pal (2002), [a]Saturated hydraulic conductivity, [b]Exchangeable sodium percentage

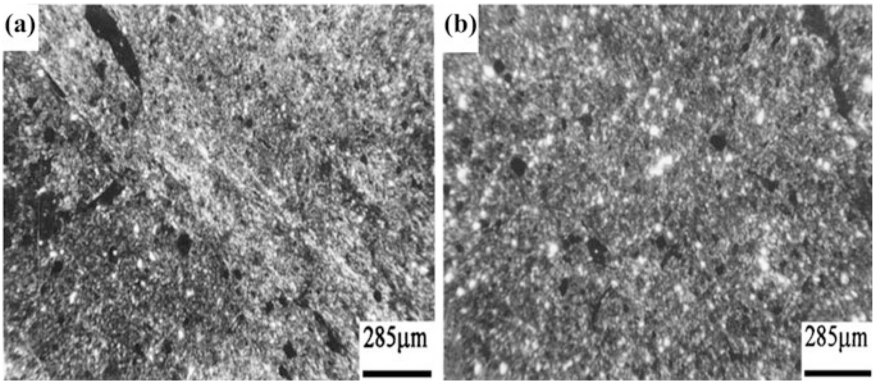


Fig. 2.6 Representative photograph of plasmic fabric in cross polarized light. **a** Strong plasma separation with parallel-striated b fabric, **b** weak plasma separation with mosaic–speckled plasma separation (Adapted from Vaidya and Pal 2002)

and shrink–swell, the plasmic fabric is not uniform among the soils of the ML and MH positions. The formation of sodic soils in MH positions alongside nonsodic soils in ML positions is a unique phenomenon and is described in further details under soil degradation in Chap. 6.

2.2.4 Vegetation

Influence of vegetation on pedogenesis and distribution of Vertisols in the world are rarely observed (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. 1999). 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. Most Vertisols at present are under post-cultural activities and that make it difficult to identify and infer the influence of native vegetation (Coulombe et al. 1996).

In India, Vertisols are often difficult to cultivate because of their poor subsoil porosity and aeration. As a result roots of annual crops do not penetrate deeply and farmers allow these soils to lie fallow for one or more rainy seasons or cultivate them only in the post-rainy season. Thus, Vertisols have limitations that restrict their full potential to grow during both rainy season and winter crops and generally are less intensively cultivated (Pal et al. 2012a). Thus the present management interventions have a minimal role in their formation and modification. Vertisols have low organic carbon status on both the surface and sub-surface layers (<1%) and a moderate to high content of $CaCO_3$, indicating that biotic factors have no substantive role in the genesis of Vertisols (Pal et al. 2009a, b).

2.2.5 Time

Almost all Vertisols are derived from geological rock systems that are millions of years old but their real age is not so old (Pal et al. 2012a). The age of the parent material provides only a maximum chronological point. In reality, the true age of the geomorphic surface or the time required for Vertisol formation is much less than millions of years (Pal et al. 2012a). Many pedologists suggest that the formation of slickensides (the most essential physical characteristic to qualify for vertic properties) 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 year. BP (^{14}C age, Pal et al. 2006a) in the Deccan basalt alluvium of the central Indian SHD bio-climate, exhibits pressure faces but lacks slickensides. The occurrence of shrink–swell soils and slickensides in the SHM lower Indo Gangetic Plains of 500–1500 year. BP (TL ages) indicates that a minimum of 500 year. is adequate to form Vertisols (Singh et al. 1998). The Vertisols of central and western peninsular India developed in the Deccan basalt alluvium of the Upper Cretaceous, mostly during the Holocene period are, however, older than this age; they have a minimum ^{14}C age of 3390 year, and a maximum of 10,187 year. BP (Pal et al. 2006a, 2009a). These data suggest that Vertisols in India and elsewhere are developed during the Holocene period.

2.3 Smectite Clay Minerals in Vertisols: Recent Initiatives for Their Proper Characterization

To establish a link between smectitic mineralogy and important bulk properties of Vertisols especially their shrink-swell characteristic, often becomes difficult because on many occasions the description of smectitic minerals is inadequate or incomplete. As soil smectites differ from "type" minerals, it becomes essential to identify and characterize them properly as they occur in soil systems. Although the Vertisol clays are in general a mixture of several other clay minerals, adequate description of clay smectite is possible with sustained efforts and such exercises made in recent years, are illustrated in the following.

2.3.1 Characteristics of Smectite

The shrinking and swelling of soils is primarily governed by the nature of the clay minerals, particularly their surface properties. The soils containing all other clays shrink and swell with variations in moisture content but changes are particularly extreme in smectites (Borchardt 1989). While relating the shrink-swell properties and clay mineral types Bhattacharyya et al. (1997) concluded that the vertic properties of soils are a function of smectite content. Despite this basic understanding, several non-expanding clay minerals (kaolin, micas, chlorites, palygorskite and vermiculites) are often mentioned to be associated with shrink-swell properties of Vertisols and their vertic intergrades (Hajek 1985; Coulombe et al. 1996; Heidari et al. 2008). In addition, kaolinite is reported to be abundant in some Vertisols in El Salvador (Yerima et al. 1985, 1987) and Sudan (Yousif et al. 1988) and given secondary importance in Vertisols of the USA (Hajek 1985). Many such soils of the USA do have clay CEC > 40 and those of El Salvador show higher clay CEC (62–79 cmol (+)/kg) and COLE (0.10–0.12). Such high clay CEC values do indicate that the presence of expansible minerals might have escaped the notice of researchers in the few shrink–swell soils of the USA (Hajek 1985) and El Salvador (Yerima et al. 1985, 1987). However, 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. Moreover, soils also have dominating amount of Sm–K, which is capable of inducing the vertic character in soils (Bhattacharyya et al. 1993).

Soil Survey Staff (1994) stipulated 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. Later on, a qualitative smectite mineralogy class was proposed by the Soil Survey Staff (1998, 1999) for the soils that contain more smectite by weight than any other single clay mineral. This requirement provided a means by which smectite can reflect a quantitative dimension of the vertic properties of soils. Quantitative determination of minerals in the soil clay fractions by XRD analysis is difficult, as any attempts in this regard have yielded semi-quantitative estimates. Moreover, such estimation is not infallible when minerals are in the interstratified phase. The presence of Sm–K in shrink–swell soils is common in India and elsewhere (Pal et al. 2012a). Although the peak-shift analysis (Wilson 1987) is a useful method to determine the smectite content in Sm–K, it becomes ineffective when the smectite component in Sm–K is highly chloritised and the swelling of smectites on glycolation is restricted. To circumvent this problem, the chemical method of Alexiades and Jackson (1965) is an effective way to quantitatively determine the smectite content in soil clays and thus, Shirsath et al. (2000) observed 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% clay smectite, therefore suggesting that only smectitic soils should be considered shrink–swell soils in the US Taxonomy. Of the three smectite species (montmorillonite, beidellite and nontronite), montmorillonite and beidellite are the most commonly reported in Vertisols, while reports of nontronite are rare (Coulombe et al. 1996). In the Indian sub-continent, the majority of shrink–swell soils are developed in the alluvium of weathering Deccan Basalt, covering an area of 500,000 km^2 (Duncan and Pyle 1988). A review on the mineralogy of Indian shrink–swell soils (Vertisols and vertic intergrades) (Ghosh and Kapoor 1982) indicates that the soil clays are dominated by beidellite–nontronite type minerals. These authors reported the results of computed clay minerals based on smectite formulae, although such an approach is not infallible (Sawhney and Jackson 1958). X-ray diffraction analysis of large numbers of smectite dominated fine clays of Indian shrink–swell soils (Pal 2003) indicates the presence of small to moderate amounts of hydroxy-interlayer (HI) material in the smectite interlayers, alongside a small amount of vermiculite. Both hydroxy-interlayers and vermiculite are not easily detected in the glycolation samples but are discernible during gradual heating from 110 to 550 °C of the K-saturated samples. Hydroxy-interlayered smectite is detected from low-angle-side broadening of the 1.0-nm peak at 550 °C (Wildman et al. 1968; Fig. 2.7) while vermiculite is detected 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 presence of both montmorillonite and beidellite in the fine-clay fractions of Indian shrink–swell soils in basaltic alluvium was confirmed by the Greene-Kelly test (Greene-Kelly 1953), and the former dominates over the latter (Pal et al. 2012a). It is interesting to note that on glycerol vapour treatment (Harward et al. 1969), the clay smectites expand to approximately 1.9 nm, indicating only the presence of montmorillonite (Fig. 2.7). In other words, fine-clay smectite is nearer to montmorillonite in the montmorillonite–beidellite series. Since the nontronite would behave like beidellite in these tests and 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

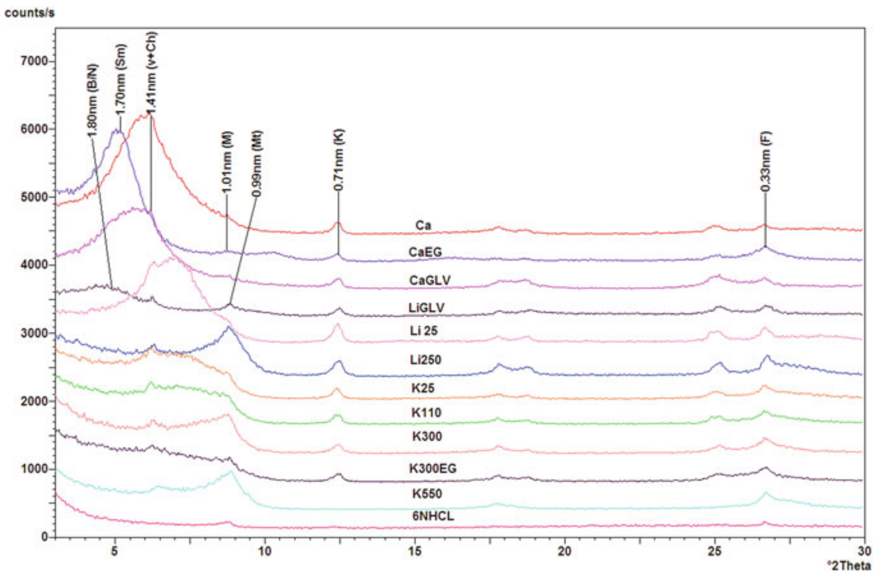


Fig. 2.7 Representative X-ray diffractograms of fine clay fractions (<0.2 µm) of the Bss horizons of Vertisols of central India; Ca = Ca saturated; Ca-EG = Ca saturated plus ethylene glycol vapour treated; CaGLV = Ca-saturated plus glycerol vapour treated; Li = Li-saturated and heated to 25, 250 °C (16 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 = 6N 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. 2003b; Bhople 2010)

montmorillonite–nontronite series (Pal and Deshpande 1987). Smectite expands beyond 1.4 nm after glycolation of the K-saturated and heated samples (300 °C; Fig. 2.7). This expansion behaviour indicates its low-layer charge density as of specimen dioctahedral smectite, which is also evidenced by its no K-selectivity (Pal and Durge 1987).

2.3.2 *Seat of Charge in and Layer Charge of Fine Clay Smectites*

Although some knowledge on low charge density of clay smectites is gained as discussed above, determination of their layer charge always remains a fundamental requirement to all physical and chemical properties of soils such as soil structure, drainage, aeration, water retention (Laird et al. 1988), cation exchange reactions, specific surface area and degree of hydration (Wilding and Tessier 1988). Ideally, the charge in the layer silicate minerals should be either in the tetrahedral sheet or octahedral sheet, but it is usually observed that the charge is distributed over both the sheets (Malla and Douglas 1987). It is essential to locate seat of charge and also to study changes in the proportion of tetrahedral and octahedral charge during the pedogenetic processes of soil formation. Information about the position of charge in smectites of Indian Vertisols was made available by some researchers (Kapse et al. 2010; Bhople et al. 2011) who made attempts to locate the seat of charge of some selected bench mark Vertisols' fine clay smectites of central India by using cation exchange capacity (CEC) method of fine clays with the aid of mechanism of charge reduction advocated by Hofmann and Klemen (1950). Their results indicate that CECs are distributed in both tetrahedral and octahedral layers of which the contribution of the former is higher (>50%) than the latter (Table 2.3). These researchers suggested that the determination of reduced CECs from Greene-Kelley test (Greene-Kelly 1953) is an effective means of measuring the octahedral and tetrahedral CECs and also for calculating the charge of soil clays.

The layer charge also determines the properties of soil clay minerals and indicates a mineral's capacity to retain cations and adsorb water and other polar organic molecules (Malla and Douglas 1987).It is also known that different swelling properties of clays with identical interlayer cations are mainly due to differences in layer charge densities (Weiss et al. 1955). Thus, 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

Table 2.3 CECs (total, tetrahedral and octahedral) and the contribution of tetrahedral and octahedral CECs to total CEC of fine clay smectites of some representative benchmark Vertisols of central India

Horizon	Depth (cm)	CEC total cmol (p+)kg^{-1}	$CEC_{Tetrahedral}$ cmol (p+) kg^{-1}	$CEC_{Octahedral}$ cmol (p +) kg^{-1}	Contribution of $CEC_{Tetrahedral}$ to CEC_{Total} (%)	Contribution of $CEC_{Octahedral}$ to CEC_{Total} (%)
Linga Series: Nagpur: Maharashtra: Typic Haplusterts						
Ap	0–16	83	68	15	82	18
Bw1	16–44	75	59	16	78	22
Bw2	44–69	80	52	28	65	35
Bss1	69–102	84	54	30	64	36
Bss2	102–128	93	48	45	52	48
Bss3	128–150	84	49	35	58	42
Nimone Series: Ahmadnager: Maharashtra: Sodic Haplusterts						
Ap	0–13	59	58	1	98	2
Bw1	13–38	66	46	20	69	31
Bw2	38–55	72	47	25	65	35
Bss1	55–94	66	41	25	62	38
Bss2	94–128	54	38	26	70	30
Bw/Bc	128–150	59	39	20	66	34

Adapted from Kapse et al. (2010), Bhople et al. (2011)

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). The smectite charge in selected bench-mark Indian Vertisols is distributed in both tetrahedral and octahedral layers and also showed a high layer charge (0.28–0.78 mol electrons/$(SiAl)_4O_{10}(OH)_2$), 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 (i.e. hydroxy-interlayered smectites, HIS) (Ray et al. 2003). Conversely, in some Vertisols of central India developed in Deccan basalt alluvium where hydroxy-interlayering in the smectite interlayers is negligible, especially in Sodic Haplusterts, the layer charge of fine clay smectites showed a lowest value of 0.307–0.353 and 0.328–0.360 mol(−)/$\{(Si, Al)_4O_{10}(OH)_2\}$ for Paral (Sodic Haplusterts) and Boripani (Typic Haplusterts) soils in the state of Maharashtra of central India, respectively. These values are nearer to the layer charge of bentonite (Wyoming) having 0.26 mol(−)/$\{(Si, Al)_4O_{10}(OH)_2\}$ (Thakare et al. 2013).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 (Fig. 2.8) (Ray et al. 2003; Bhople 2010; Thakare et al. 2013).

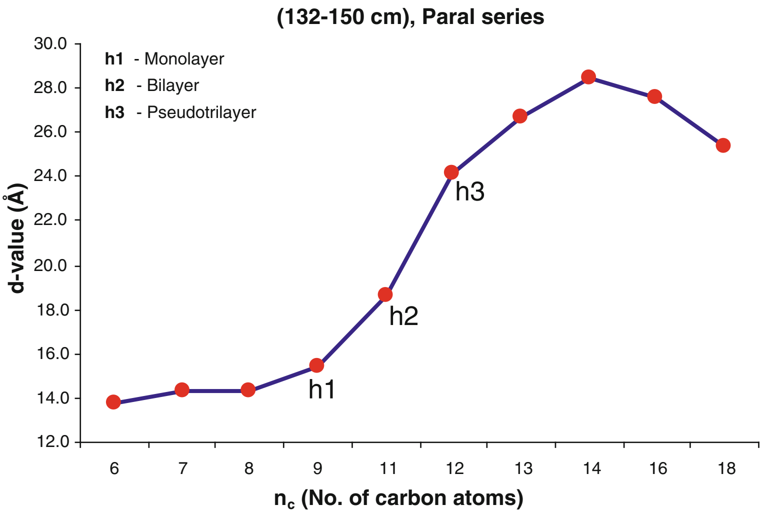


Fig. 2.8 Representative S-type curve relationship between d-spacings (001) of fine clay smectites intercalated with alkylammonium chlorides and number of carbon atoms, indicating the heterogeneity in layer charge of fine clay smectites of Indian Vertisols (Adapted from Bhople 2010)

2.3.3 *Hydroxy-Interlayered Smectites (HIS) and Determination of Layer Charge*

Although the occurrence of HIS is very common in Vertisols of peninsular India, the extent of hydroxy-interlayering however varies. In some soils it is in negligible amounts (Thakare et al. 2013) but the presence of low to moderate hydroxy-interlayering is more common (Pal 2003; Pal and Deshpande 1987). Ray et al. (2002) observed that higher the tetrahedral charge; greater is the probability of hydroxy-interlayering in fine clay smectites. But the Vertisols' fine clay smectites do have higher tetrahedral charge than in octahedral layer (Kapse et al. 2010; Bhople et al. 2011). Therefore, the precise reason for such variation in amount of hydroxy-interlayering is yet to be resolved. 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. 2006b). Such interlayers result in the formation of relatively more paraffin type layers with bi-pseudotrilayer transition (Fig. 2.8), which causes the overestimation of the layer charge of core lattice mineral. In order to determine the layer charge of the core lattice minerals, Ray et al. (2006b) used 0.25 N EDTA solutions (pH 7.0) to remove the HI materials from the fine-clay smectites of Indian Vertisols to determine the layer charge of the cleaned clays and observed the removal of HI materials by the EDTA solutions was almost complete. Ray et al. (2006b) obtained the weighted-average layer charge of the pre-treated clays from 0.40 to 0.46 mol(−)/(Si, $Al)_4O_{10}(OH)_2$, and after EDTA treatment, the charge ranged from 0.27 to 0.33 mol(−)/(Si, $Al)_4O_{10}(OH)_2$, a value range close to the layer charge of Wyoming bentonite (montmorillonite species of the smectite group of layer silicate minerals) (Thakare et al. 2013). These authors also observed that after EDTA treatment, the Ca-saturated and glycolated fine clays showed greater X-ray intensity than their corresponding Ca-treated curves. The K-treated curves also showed marked differences when compared with the original untreated fine clays. The improvement in the intensities of glycolated and K-saturated samples showed the effectiveness of EDTA solutions in the removal of HI materials and also in determining the actual layer charge in soil-clay smectites.

2.4 Genesis of Smectites in Vertisols: A Revised Status

It is observed that smectite is the most abundant and essential phyllosilicate in Vertisols worldwide, and it remains either as a discrete mineral or as a mineral interstratified with any other layer silicates. A minimum of 20% smectite in their clay fractions (<2 μm; Shirsath et al. 2000) is required for the manifestation of vertic properties at a linear extensibility (LE) of 6 in shrink–swell soils.

Smectite-clay minerals are ephemeral in the HT climate, where they are rapidly transformed to kaolin (a 0.7 nm mineral consisted of hydroxy-interlayered smectite and kaolinite, Sm-K). Therefore, it is difficult to understand the formation of Vertisols in HT climates. Recent research has explained their formation with the presence of soil modifiers such as Ca-zeolites (Bhattacharyya et al. 1993; Pal et al. 2006a) that release Ca^{2+} ions to prevent the complete transformation of smectite to kaolin, and the high base status helps in stabilizing and retention of smectite. Therefore, the formation and persistence of slightly acidic to acidic Typic Haplusterts with predominant Sm–K in clay fractions in India (Bhattacharyya et al. 1999, 2005; Pal et al. 2009a) and elsewhere (Ahmad 1983) is possible only in presence of soil modifiers that maintain the base saturation well above 50% (Pal et al. 2006b, 2013a).

Despite the fact that Vertisols are abundant in semi-arid regions (Eswaran et al. 1988), the large quantities of dioctahedral smectite required for the formation of Vertisols cannot form in semi-arid soils, as the primary minerals contribute little towards the formation of smectites in the prevailing dry climates (Srivastava et al. 2002; Pal et al. 2009a). XRD analysis of fine clays in Indian SHM, SHD, SAM, SAD and AD Vertisols indicates that dioctahedral smectites are fairly well crystallized, as they yield sharp basal reflections on glycolation and show regular higher (though short and broad) reflections, and show no sign of transformation except for the low to moderate amounts of hydroxy interlayering in the smectite interlayers (Pal et al. 2009a). Hydroxy-interlayering is also observed in the silt and coarse clay sized vermiculite (HIV) that resulted in the formation of pseudo- or pedogenic chlorite (PCh; Pal et al. 2012b; Fig. 2.9). The presence of fine clay size hydroxy-interlayered dioctahedral smectite (HIS), as well as the silt and coarse clay sized HIV and PCh indicates that the hydroxy-interlayering in the vermiculite and smectite did not occur in the present slight to moderate alkaline soil reaction induced by dry climates. It can only occur when positively charged hydroxy interlayer materials (Barnhisel and Bertsch 1989) entered into the inter-layer spaces in acidic soil pH (<6.0) (Rich 1968). The majority of Vertisols in sub humid to arid climates all over the world have pH values either near to neutral or well above 8.0 throughout. Under such alkaline soil reaction, the 2:1 layer silicates suffer congruent dissolution (Pal 1985), and thus discounts the hydroxy interlayering of smectites after deposition of the basaltic alluvium (Pal et al. 2012b). 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 calcium carbonate nodules) and PC (pedogenic $CaCO_3$; Pal et al. 2000, 2009a). Vertisols with Fe–Mn coated $CaCO_3$ are older than those with PCs (Mermut and Dasog 1986) that are formed in soils of dry climate soils (Pal et al. 2000). NPCs were formed in a much wetter climate than the present climate, ensuring adequate water for reduction and oxidation of iron and manganese to form Fe–Mn coatings. Although the Vertisols contain both silt and clay sized muscovite and biotite mica (Pal 2003), dioctahedral smectite (DOS) cannot be formed at the expense of muscovite (dioctahedral mica) because the weathering of muscovite is very

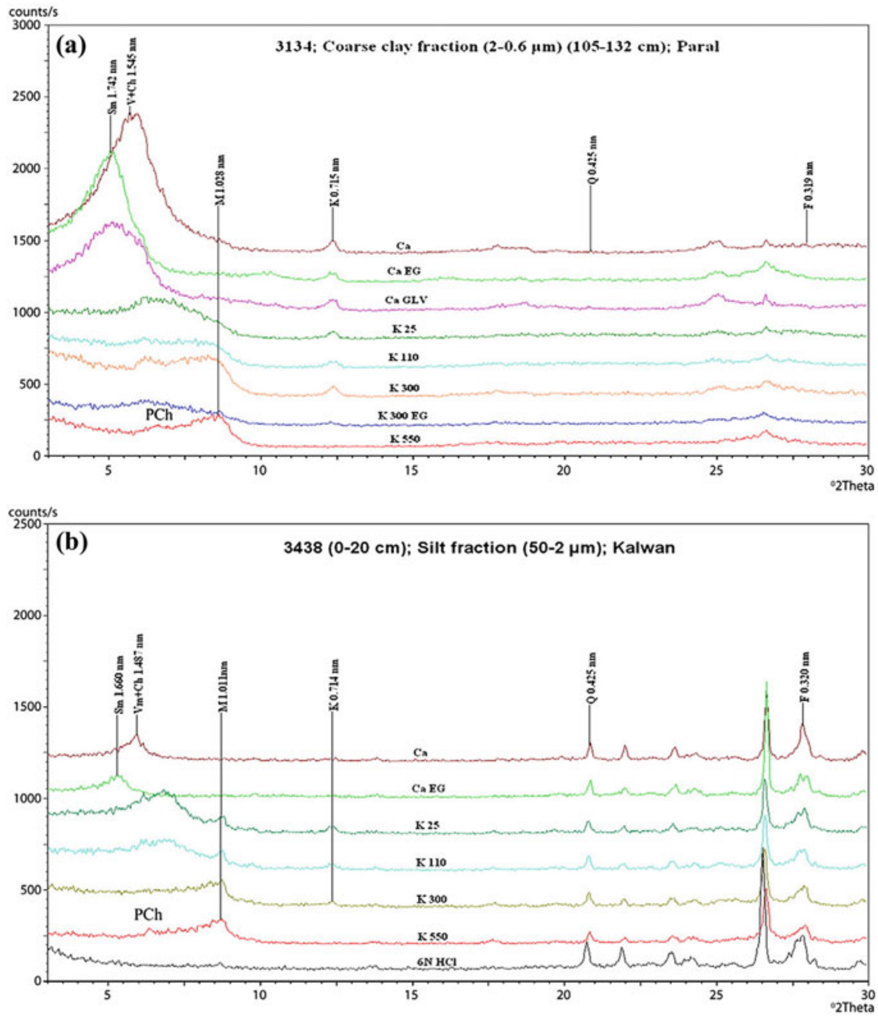


Fig. 2.9 Representative X-ray diffractograms of coarse clay (**a**), and silt (**b**) fractions of Vertisols of Peninsular India; Ca = Ca saturated; Ca-EG = Ca saturated plus ethylene glycol vapour treated; K25/110/300/550 °C = K-saturated and heated to 25, 110, 300, 550 °C; 6NHCl = 6N HCl treated silt fraction; Sm = Smectite, V + Ch = vermiculite plus chlorite; PCh = Pseudo chlorite; K = Kaolin; F = Feldspars; Q = Quartz (Adapted from Pal et al. 2003b; Bhople 2010)

sensitive to potassium levels in soils. 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. 2006a). Moreover, in the sub-humid and semi-arid climates that facilitate the formation of $CaCO_3$ from plagioclase (Pal et al. 2012b), mica may not yield as much DOS as required for Vertisols. The large quantity of DOS is, therefore, 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). The formation of smectite from biotite is quite unlikely in a humid climate (Pal et al. 1989), but vermiculite could have transformed to HIV, which further transforms to PCh under acidic conditions. Hence, the formation of HIS did not continue for long 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 would have become dominant mineral (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. 2009a, 2012b).

2.5 Recent Advances in Pedogenic Processes in Vertisols

Although an extensive research on Vertisols of the Indian sub-continent was made in the past (Murthy et al. 1982; Murthy 1988), during the last decade and a half, the focus of Vertisol research has changed qualitatively (Pal et al. 2012a). Mineralogical, micro-morphological and age-control tools were used to measure the relatively subtle pedogenetic processes in Vertisols that have implications to their polygenesis (Pal et al. 2009a, b, c, 2012a, b, c), paleopedology (Pal et al. 2009a, b, c, 2012a, b, c) and edaphology (El-Swaify et al. 1985; Srivastava et al. 2002; Kadu et al. 2003; Bhattacharyya et al. 2009). Hence, to place recent research in the context of past research, critical appraisal of some important basic issues in Vertisol pedogenesis with regard to (a) importance of clay illuviation over pedoturbation, (b) relative rapidity of clay illuviation, pedoturbation and slickenside formation and developments of cracks, and (c) evolution sequences in the genesis of Vertisols is warranted.

2.5.1 Clay Illuviation in Vertisols: An Example of Proanisotropism

Earlier reviews of the past research work (Ahmad 1983; Murthy et al. 1982) explained that the distribution of clay is uniform throughout Vertisols because haploidisation within the pedon caused considerable pedoturbation (Mermut et al. 1996). But some studies reported that in selected cases, there is a gradual increase in clay content with depth (Dudal 1965); although, it was thought that the increase in clay content with depth is due to inheritance from parent material (Ahmad 1983).

Recent studies on Vertisols (that have no stratification in the parent material and no clay skins) indicated that the Bss horizons are substantially clay enriched with clay even up to ∼20%; an increase from the eluvial horizon (Pal et al. 2009a, 2012a). Micro-morphological investigation of the thin sections indicates the presence of >2% impure clay pedofeatures (Fig. 2.10a), which confirm that the clay is

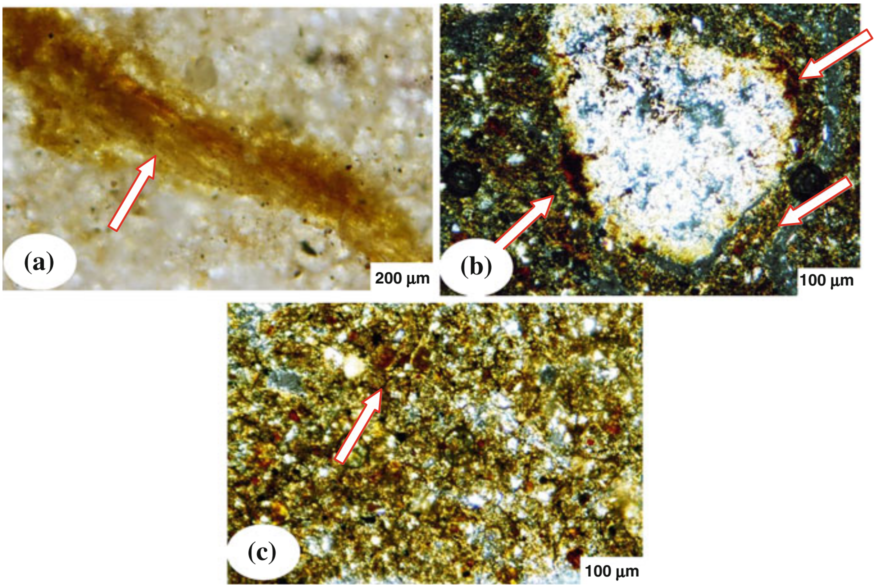


Fig. 2.10 Representative photograph in cross polarised light. **a** Impure clay pedofeatures, **b** weakly oriented clay pedofeatures and **c** undifferentiated clay pedofeatures (Adapted from Pal et al. 2009a)

enriched in the Bss horizons of Vertisols by clay illuviation. Therefore, such Vertisols can also have argillic horizons (Pal et al. 2009a, 2012a), which justify the subsoil horizon designation as 'B' (Soil Survey Staff 2014) instead of 'A' in earlier concept on Vertisols with no horizonation (Soil Survey Staff 1975). The clay illuviation process in Indian Vertisols is no exception as it is observed in operation in clay soils with vertic properties in Canada (Dasog et al. 1987), Uruguay (Wilding and Tessier 1988) and Argentina (Blokhuis 1982). Pedoturbation was too much favoured as an important pedogenic process in Vertisols by the past researchers till early nineties (Soil Survey Staff 1992) that would obliterate all evidence of illuviation, except in the lower horizons (Eswaran et al. 1988; Mermut et al. 1996). The emphasis on pedoturbation possibly led Johnson et al. (1987) to consider 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 simpler state. The recent evidence of clay-enriched Bss horizons caused by illuviation suggests that the argilli-turbation is not a primary pedogenetic process in 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. 2009a) and represents a proanisotropism in the soil profile. This finding is reinforced 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 2.4). Therefore, pedoturbation in Vertisols is a partially functional process that is not able to overshadow the more significant long-term clay illuviation process. Although argillic horizons are common in Vertisols, the Bt 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, the classification of these soils as Vertisols would still be continued (Pal et al. 2009a, b, 2012a).

2.5.2 Factors of Clay Illuviation in Vertisols

The fine-sized smectite clay with a high surface area has all conditions required for dispersions, translocation and accumulation in subsurface horizons in Vertisols. This fact is evident from the considerable amount of WDC in majority of calcareous Vertisols, which increases with depth (Table 2.4). The presence of WDC in Vertisols indicate 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 2.4) that ensure a pH higher than the zero point of charge required for a full dispersion of clay (Eswaran and Sys 1979). Thus, for the illuviation of clay removal of carbonate is not pre-requisite as postulated by many researchers (Pal et al. 2003a), who thought Ca^{2+} ions enhance the flocculation and immobilization of colloidal material. Indian calcareous Vertisols have low quantities of soluble Ca^{2+} ions ($\ll$5me L^{-1}, Table 2.4) that are not sufficient to cause flocculation of clay particles. 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. 2012a). The primary source of Ca^{2+} ions in Vertisols' 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 2.4) 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. Therefore, the PC formation and clay illuviation are two concurrent and contemporary pedogenic events that provide examples of pedogenic thresholds in dry climates (Pal et al. 2003a, 2009a, 2012a).

2.5.3 Relative Rapidity of Clay Illuviation, Pedoturbation and Slickenside Formation

Many researchers (Parsons et al. 1973; White 1967; Yaalon 1971) considered that the formation of slickensides is a very rapid pedogenic process as the Vertisols are

Table 2.4 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/hr	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

(continued)

Table 2.4 (continued)

(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. (2006a); [b]9 mm h^{-1} is the HC (WM) in 0–100 cm depth of soil

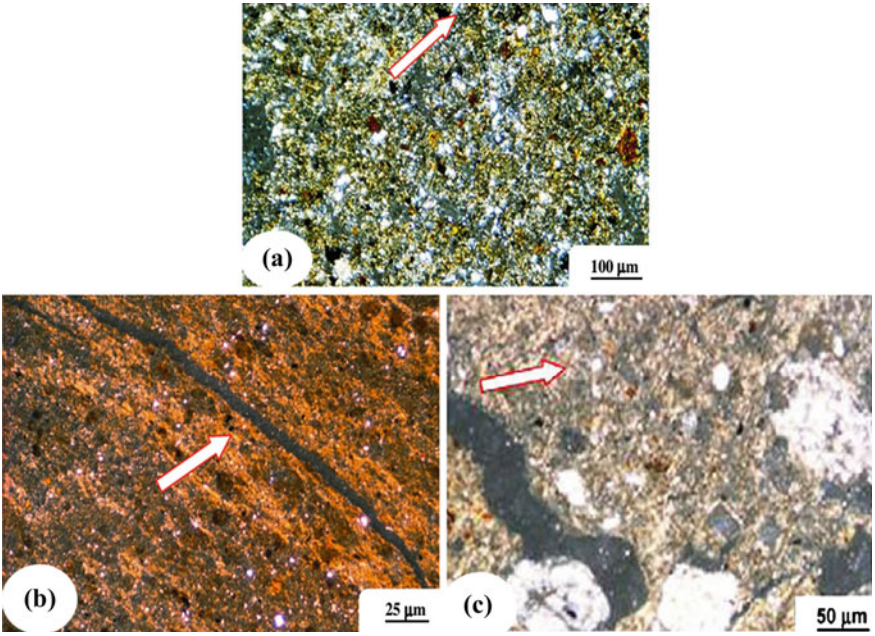


Fig. 2.11 Representative photograph of cross polarized light: poorly separated plasma in Vertic Haplustalfs (**a**), strong parallel plasmic fabric in Typic Haplusterts (**b**), and mosaic/stippled-speckled plasmic fabric in Aridic/Sodic Haplusterts (**c**) of Peninsular India (Adapted from Pal et al. 2009a, c)

formed on geomorphic surfaces that are <200–550 year old (Blokhuis 1982; Parsons et al. 1973). After their formation slickensides approach equilibrium with their environment in a period ranging from 100 to 1000 years (Yaalon 1971). A Vertic Haplustalf <100 year 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. 2.10b), undifferentiated clay pedofeatures (Fig. 2.10c) and poorly separated plasma (Fig. 2.11a). 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. Despite having vertic character, 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). The illuviation of clay in the absence of slickensides therefore indicates that illuviation is a faster pedogenetic process than the formation of slickensides, which possibly takes place within a 100-year span. The occurrence of shrink-swell soils over 500–1500 year (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. Therefore, intensive pedoturbation is not essential or important in the creation of typical morphogenetic characteristics in a Vertisol (Yaalon and Kalmar 1978).

2.5.4 Development of Microstructures and Vertical Cracks in Vertisols as Controlled by Smectite Swelling

Horizontal and vertical stresses in Vertisols are induced by abundance of smectite. In the upper horizons, low overburden pressure and cracks prevent the development of high lateral stresses. In the subsoils, where sphenoids and/or slickensides are formed, the difference between horizontal stress and vertical stress is quite large. These two sets of stresses act on soil during its swelling. 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. 2.11b) or stipple-speckled/mosaic-speckled/crystallitic plasmic fabric related to poor plasma separation in the Bss horizons (Fig. 2.11c; Kalbande et al. 1992; Pal et al. 2009a, b). 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. It is, therefore, understood that weak swelling of smectite is sufficient for the development of sphenoids and/or slickensides, but it is not definitely adequate to cause strong plasma separation (Pal et al. 2001, 2009a, b), even when the soils have almost identical COLE values and comparable amounts of expansible clays (Pal et al. 2006a, 2009a). The swelling of smectites in these soils, 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. 2009a).

It is interesting to note that the saturated hydraulic conductivity (sHC) of all Vertisols is not identical but decreases rapidly with depth. However, the decrease is sharper in SAD and AD soils because of their subsoil sodicity (ESP > 5, Pal et al. 2009a). The reduced sHC restricts the vertical and lateral movement of water in the subsoils. As a consequence, during the very hot summer months (April–June), subsoils of SAD and AD Vertisols would have less water. This deficit is manifested in the form of 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. 2.2). Thus, 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. 2009a, b). 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. Such dryness causes the modifications in subsoils of Vertisols in terms of subsoil sodicity, poor plasma separation, and cracks cutting through the Bss horizons due to the accelerated formation of PC. Therefore, such Vertisols qualify to be polygenetic soils (Pal et al. 2001, 2009a, 2012a).

2.6 Evolutionary Pathways of Vertisol Formation

The U.S. Soil Taxonomy recognizes ‘intergrade’ between Vertisols and soils of other orders with vertic character. Thus, successive stages of pedogenic evolution in Vertisols were conceptualized by Blokhuis (1982), who thought that Vertisols would lose their vertic characters and subsequently convert to non-vertic soils.

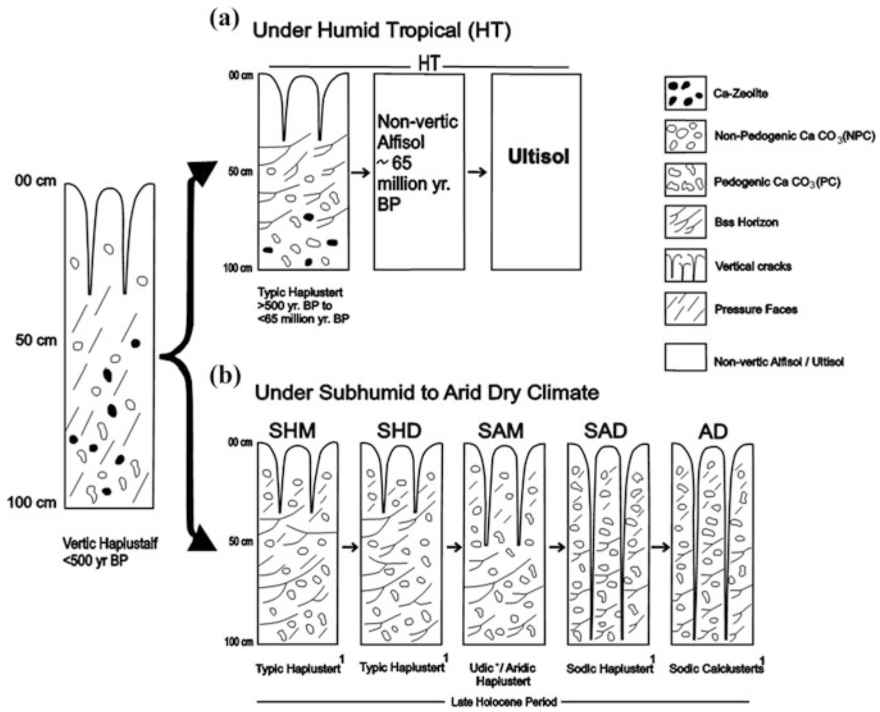


Fig. 2.12 Successive pathways of pedogenic evolution in Vertisols (Adapted from Pal et al. 2009b)

Eswaran et al. (1988), on the other hand, 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. In these conceptualizations the presence of argillic horizon in original Vertisols was not envisaged.

Studies on the evolution of soils in HT parts of the Western Ghats (Bhattacharyya et al. 1993, 1999) 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, which prevents the total transformation of smectites to kaolin (Fig. 2.12a). However, when the stocks of zeolites are depleted completely, the soils would gradually become acidic and kaolinitic and phase towards Ultisols through an intermediate stage of non-vertic Alfisols (Fig. 2.12a). Silica is insoluble in an acidic environment; therefore, the complete transformation of smectite to kaolinite is improbable. The end result will be that Ultisols would remain unchanged, with Sm–K as the dominant minerals (Chandran et al. 2005; Pal et al. 2014).

A recent extensive pedogenetic study of Indian Vertisols in a climosequence expands the basic understanding of Vertisol evolution from Typic Haplusterts to Udic/Aridic/Sodic Haplusterts and Sodic Calciusterts (Pal et al. 2009a; Fig. 2.12b). 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 period but exit as the products of polygenic evolution. Due to subsoil sodicity caused by illuviation of Na-clay smectites in Vertisols of the

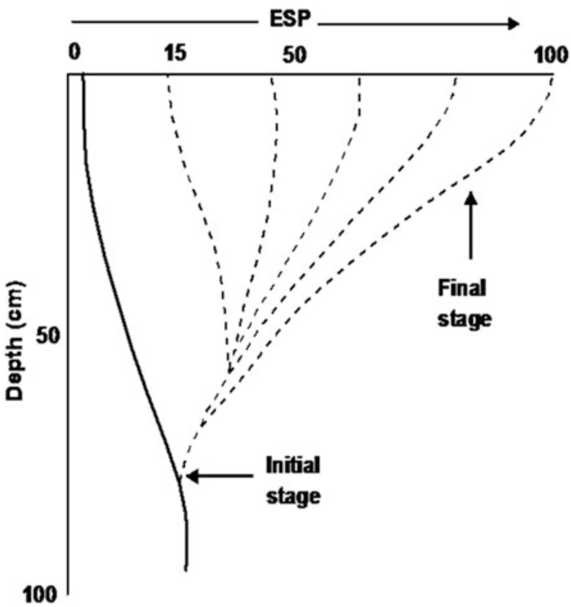


Fig. 2.13 Progressive development of sodicity due to illuviation of Na-clay in Vertisols while aridity continues with time (Adapted from Pal et al. 2012b). *ESP* exchangeable sodium percentage

SAM, SAD and AD climates, the initial impairment of the percolative moisture regime would create 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 finally decreases with depth if aridity continues (Fig. 2.13), and the formation of such sodic soils exhibit regressive pedogenesis (Johnson and Watson-Stegner 1987; Pal et al. 2013b).

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