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Pedogenetic processes in a shrink-swell soil of central India

D.K. PAL, T. BHATTACHARYYA, P. CHANDRAN, S.K. RAY, P.L.A. SATYAVATHI, P. RAJA, U.K. MAURYA and M.V. PARANJAPE

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

Abstract : In view of lack of precise information on the factors and processes in clay illuviation, pedoturbation and slickenside formation in shrink-swell soils, a study on a <100 years old shrink-swell soil (Vertic Haplustalf) of Central India was undertaken. The soil has typical physical, chemical and mineralogical properties of Vertisols but lack in slickensides. Detailed physical, chemical and micromorphological data indicate the presence of argillic horizon characterized by impure clay pedofeatures in voids and poorly separated plasma. The study proves a fact that clay illuviation is more important pedogenetic process than pedoturbation. A time of a century is not adequate for the formation of slickensides that are hitherto considered to be a rapid pedogenetic process for structure formation in Vertisols. The study suggests a highly probable pathway for the formation of Vertisols with time from Vertic Alfisols in sub-humid and semi-arid climatic conditions of central India.

Additional keywords : *Clay illuviation, impure clay pedofeatures, pedoturbation, slickenside formation*

Introduction

Shrink-swell phenomena in soils involve complex and dynamic processes for the genesis and behaviour of Vertisols and their vertic intergrades and thus remain to be fully understood (Wilding and Tessier 1988). Manifestations of this phenomena are observed in linear and normal gilgai, cyclic horizonation, surface cracking upon desiccation and slickenside formation. However, the appearance of slickensides or wedge-shaped aggregates is the unifying morphogenetic marker found in all Vertisols and their vertic intergrades (Wilding and Tessier 1988, Soil Survey Staff 2003).

A large body of research on the genesis and unusual properties emphasise pedoturbation or churning as a fundamental process in the formation of soils with vertic character (Mermut *et al.* 1996). However, Wilding and Tessier (1988) suggest that the pedoturbation is not sufficint to cause extensive mixing and is a slow process as distinct from the much more rapid process of structure formation. Blokhuis (1982) opines that the genesis of these soils has hitherto been considered to be rather simple. Thus he argues that the soils formed under multiple genetic pathways, are likely to be more complex than generally recognized. Mermut *et al.* (1996) reported that Vertisols developed on various parent materials, are basically young in age. Many researchers (White 1967, Yaalon 1971, Parsons *et al.* 1973) suggested that slickensides form very rapidly and that Vertisols were found on geomorphic surfaces as young as 550 years (Parsons *et al.* 1973). Blokhuis (1982) reported that the formation of slickensides took place < 200 years in Romania, and according to Yaalon (1971) after their formation, slickensides approach equilibrium with their environment in a period ranging from 100 to 1,000 years.

Pedoturbation would normally prevent the accumulation of clay as illuviation cutans or destroy developed cutans beyond recognition (Blokhuis 1982). However, there are a few references to clay illuviation based on micromorphological observations (Blokhuis 1982), indicating it to be more important pedogenetic process than pedoturbation. Pedoturbation is also reported to be incapable in removing the stratification of the parent material that contained distinct slickensides formed in 550 years (Parsons *et al.* 1973). Thus, Yaalon and Kalmar (1978) concluded that intensive pedoturbation is not the major, or even a required process for producing the typical characteristics of a Vertisol. Thus, the evidence of clay illuviation in terms of required depth distribution of clays for an argillic horizon (Soil Survey Staff 2003) may be a reality in Vertisols as clay illuviation process appears to be a more rapid process like the formation of slickensides as compared to pedoturbation process.

During our study on the genesis of shrink-swell soils for the last 25 years, we also came across deep shrink-swell soils associated with Vertisols and their intergrades in the alluvium of weathering Deccan basalt that have very high amount of smectitic clay and exhibit pressure faces but lack in slickensides and clay skins. It was presumed that such soils in the Jamni / Tamasvada Watershed (3990 ha area) of Wardha district of Maharashtra (Paranjape 1995) are much younger (Paranjape *et al.* 1997) than soils developed elsewhere (Pal *et al.* 2003a). Although an extensive research on shrink-swell soils of the Indian sub-continent has been made in the past (Murthy *et al.* 1982; Landey *et al.* 1982) and also in recent years (Kalbande *et al.* 1992; Balpande *et al.* 1996; Pacharne *et al.* 1996; Pillai *et al.* 1996; Paranjape *et al.* 1997; Pal *et al.* 2001; Srivastava *et al.* 2002; Vaidya and Pal 2002; Kadu *et al.* 2003; Pal *et al.* 2003a), precise information about the relative rapidity of processes of clay illuviation, pedoturbation and slickenside formation has been lacking. Such soils provide an excellent opportunity to study the factors and processes in clay illuviation, pedoturbation and development of structure. Also understanding these may help to develop a comprehensive knowledge about the major pedogenic processes that are likely to be operative in the genesis of Vertisols.

Materials and Methods

Geologically, the study area belongs to Deccan flood basalt. The area is a narrow entrenched valley surrounded by low linear rises which are the spurs of the elongated ridges of the flood basalt. The hillside drainage has extended and entrenched itself between the spurs exhibiting headward extension of the valley floors. The Tamasvada village and surrounding areas located on the infilled valley floors of the Tamasvada Nala exhibit colluvial-alluvial fills. The weathered products are fines removed from the upper reaches of the head slopes and deposited on the valley floors.

After thorough traversing of the area, seven sites were selected for examination. The pedons were dug at the selected sites and detailed morphological examination was carried out as per procedure of USDA Soil Survey Manual (Soil Survey Staff 1951). For the present study analytical data are reported only for one pedon taken as representative of deep shrink-swell soils without slickensides.

The soil samples collected from different horizons were analysed for pH, organic carbon, cation exchange capacity (CEC) and calcium carbonate ($CaCO_3$) by standard procedures (Richards 1954; Piper 1966; Jackson 1973). Exchangeable sodium percentage (ESP) and exchangeable magnesium percentage (EMP) were computed from the values of CEC and exchangeable cations. Sand (2000-50 mm), silt (50-2 mm), total clay (< 2 mm) and fine clay (< 0.2 mm) fractions were separated from the samples after dispersion according to the size segregation procedure of Jackson (1979). The co-efficient of linear extensibility (COLE) was determined as per the method of Schafer and Singer (1976). For the estimation of water-dispersible clay (WDC), 10g soil was added to distilled water in a bottle. The suspension was shaken for 8 hours, transferred to a cylinder and the volume made up to 1000 ml. Aliquots were taken to determine the clay content following the international pipette method.

Blocks of undisturbed soil were collected from the B-horizons and their sections prepared (Jongerius and Heintzberger 1975). They were then studied in plain and polarized light, using a Leitz Ortholux Pol microscope, and the features were described according to Bullock *et al.* (1985).

Results

Morphological properties

The soils are deep (>100 cm), very dark grayish brown (10YR 3/2 M) in colour and fine textured throughout the depth. The structure is subangular blocky in the A horizon and angular blocky in the B horizons. Consistency is friable, sticky and plastic in the A horizon and firm to very firm in the B horizon where the soil is very sticky and very plastic.

These soils are calcareous as evident from violent effervescence with dilute HCl. Roots are distributed to a depth of 75 cm. Morphological examination did not indicate any sign of stratification in the parent material. Clay skins were absent. Cracks >5 mm wide at the surface do not extend beyond the A horizons.

Physical and chemical properties

The fine clay dominates the clay fraction. The soils have low to medium organic carbon, are moderately alkaline and calcareous. The CEC is quite high and the soils are highly base saturated. Calcium plus magnesium together dominate the exchange complex. The high CEC and COLE (Table 1b) indicate the dominance of smectite clay minerals in these soils. Despite these properties being similar to those of Vertisols in the basaltic landscape of central Peninsular India, the soils under study do not exhibit slickensides. Instead, few and occasional pressure faces were observed despite the favourable tropical monsoon type climate characterized by mild winters and hot summers for the development of slickensides.

The ratio of clay free sand and silt (Table 1a) indicates the parent material uniformity almost upto 100 cm depth. The total clay shows more than 8% clay in the B horizons than in the A horizon. The ratio of fine clay to total clay in the B horizon is greater by 1.2 times than the ratio in the A horizon. These data support the presence of argillic horizon in clayey material (Soil Survey Staff 2003). The soils lack in clay skins because of their destruction by shrinking and swelling of smectitic clays (Dudal and Eswaran 1988). Following the increase in clays with depth, other properties like WDC, EMP, ESP and $CaCO_3$ (Table 1b) also show an increase with depth whereas exch. Ca/Mg shows a decrease. The depth distribution of these properties point out a fact that dispersion and subsequent movement of clays have been possible in alkaline chemical environment caused by the precipitation of $CaCO_3$ at pH $\geq$ 8.4 (Pal *et al.* 2003b) in semi-arid climatic conditions (Balpande *et al.* 1996; Vaidya and Pal 2002).Due to precipitation of soluble Ca^{2+} ions as $CaCO_3$, concentration of Mg^{2+} and Na^{+} ions increased and this caused the dispersion of clays and their subsequent movement as Mg and Na-clays downward. Thus, both WDC and $CaCO_3$ show an increase with depth (Table 1).

Micromorphological characteristics

The thin sections did not show any distinct boundaries between the horizons. The subsoils show coarse skeletal grains of about 5 to 6%. These are randomly distributed in the fine clayey continuous micromass, creating open porphyric related distribution. Thus the possibility of any inhibition of shrink-swell phenomena by frictional forces due to the interlocking of sand and silt grains (Wilding and Tessier 1988) is discounted.

The voids in the B horizons have fine to moderately thick clay coatings of weak orientation (Fig. 1a-f). Thin sections did not indicate any presence of disrupted clay pedofeatures, indicating lack of intense shrink-swell phenomena (Dudal and Eswaran 1988; Mermut *et al.* 1996; Pal *et al.* 2001). As determined by the frequency distribution chart of Bullock *et al.* (1985), the clay coatings occupy an area of more than 5%. The internal boundaries of these features are generally distinct. These pedofeatures under cross-polarised light are yellowish brown to dark yellowish red, mostly without distinct lamination, are poorly oriented and have low birefringence (Fig. 1a-f). These features have hitherto been thought to be the result of rapid translocation of the material. Brewer and Haldane (1957) demonstrated that translocated clays exhibit a lack of lamination and do not show strong and continuous orientation if they are associated with silt size particles. Poor orientation has also been attributed to the presence of fine silt size mica in cutans (Howitt and Pawluk 1985). However, these soils are enriched with fine clay smectite with very low amount of mica in general (Pal and Deshpande 1987). The depth distribution of fine silt (6-2 mm) in many shrink-swell soils of Peninsular India (manuscript under preparation) does not indicate its substantial movement. Thus downward movement of silt in these soils appears to be highly improbable. These impure textural pedofeatures appear to be related to the lack of parallel orientation of clay particles due to alkaline pH condition of soils. A soil with a pH $\geq$8.4 and with high EMP and low ESP, results in deflocculation that will disengage

Table 1a. Physical properties of soils

Horizon	Depth (cm)	Sand (%of < 2mm)	Silt	Clay	Fine clay (%of <2mm)	Fine Clay/ total clay	clay free Sand/ Silt	WDC (%)	COLE
Apk	0-16	7.4	28.9	63.7	30.2	0.47	0.26	2.2	0.25
Bwk1	16-40	10.5	27.6	61.9	33.9	0.55	0.37	2.1	0.25
Bwk2	40-68	7.0	20.6	72.4	43.9	0.61	0.34	4.1	0.26
Btk	68-90	5.6	20.3	74.1	53.5	0.72	0.27	4.5	0.21
Bk	90-110	18.0	21.8	60.2	34.2	0.57	0.82	3.9	0.22

Table 1b. Chemical properties of soils

pH (1:2)	Organic carbon %	$CaCO_3$ (%)	Extractable bases				CEC	Exch. Ca/Mg	EMP	ESP
			Ca	Mg	Na	K				
			cmol(p+) kg^{-1}							
8.5	1.16	16.2	39.6	10.1	0.2	0.6	56.4	3.9	17.9	0.3
8.5	0.81	18.7	34.8	12.9	0.3	0.4	52.3	2.7	24.6	0.5
8.6	1.03	19.1	41.1	14.2	0.4	0.4	65.1	2.8	21.8	0.6
8.5	0.88	25.0	36.7	13.8	0.4	0.4	54.2	2.6	25.4	0.7
8.6	0.66	43.5	21.0	9.2	0.3	0.3	34.7	2.2	26.5	0.9

face-to-face association of clay platelets (Van Olphen 1966). This will lead finally to impairment of parallel orientation of the clay platelets. Thus the textural pedofeatures of the "impure" type can be considered typical in slightly to moderately alkaline and calcareous shrink-swell soils (Pal *et al.* 1994; 2003b).

The plasma separation is not very prominent as the thin sections show only very few patches of porostriated plasmic fabric (Fig. 1g) and the major portions of the section are occupied by poorly separated plasma (Fig. 1h). This clearly suggests that the shrink-swell phenomena have been very less in these highly smectitic soils (Kalbande *et al.* 1992; Pal *et al.* 2001; Pal *et al.* 2003a).

Discussion

The soil has typical physical, chemical and mineralogical properties of Vertisols (Paranjape *et al.* 1997). According to criteria for argillic horizon in clayey soils (Soil Survey Staff 2003), the soils under study have evidence of clay illuviation enriching the B horizons with clay. There are no slickensides or wedge-shaped peds within 100 cm of the soil depth so as to qualify for Vertisols. Thus, they are classified as Vertic Haplustalfs (Soil Survey Staff 2003). The ^{14}C age of soil organic carbon in the Bk horizon was estimated at Birbal Sahni Institute of Paleobotany, Lucknow, India, to be <100 yr BP. This suggests that clay illuviation is a faster pedogenetic process than the formation of slickensides and for the formation of slickensides a time of 100 years appears to be inadequate. Evidences of clay illuviation in terms of depth distribution of clays associated with the typical depth distribution of WDC, EMP, ESP, $CaCO_3$ and organic carbon discount the role of pedoturbation in these soils. The presence of void argillans and absence of disrupted clay pedofeatures further support this. This confirms that pedoturbation if at all operative elsewhere must be a very slow process and may not be sufficient to cause extensive mixing (Wilding and Tessier 1988) and intensive pedoturbation is not at all a major or even a required process to induce typical morphogenetic characters in a Vertisol (Yaalon and Kalmar 1978). In view of this, clay illuviation could be a major pedogenetic process even in a Vertisol and the evidences of it would be reflected only in the depth distribution of total and fine clays (Soil Survey Staff 2003). Other evidences like clay pedofeatures in voids would be disrupted due to intense shrink-swell activities. Research results obtained in this area in the Division of Soil Resource Studies, NBSS & LUP, Nagpur supports this (manuscript

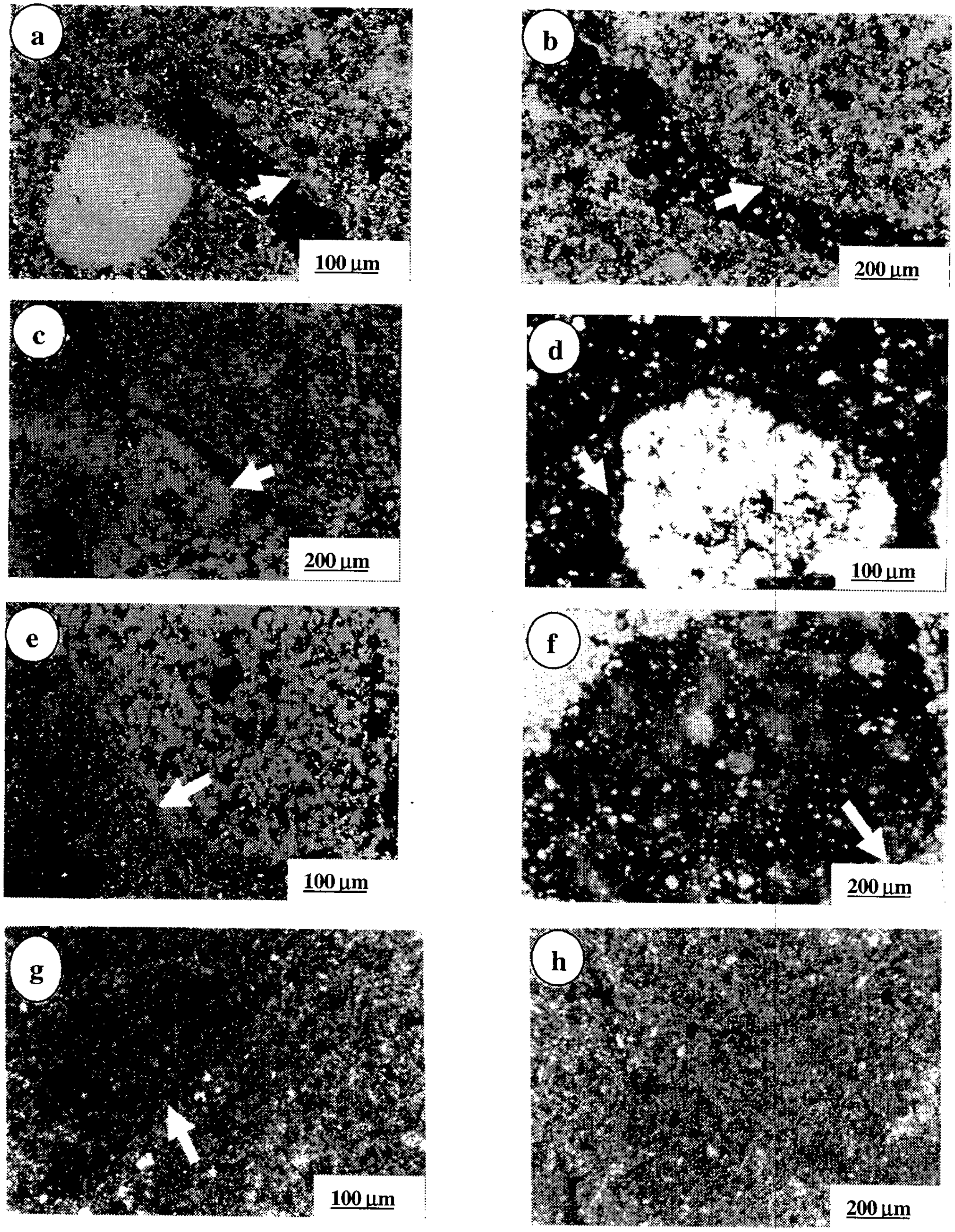

Fig. 1. Representative photomicrographs in cross-polarised light of impure clay coatings shown by arrow along the channel voids (a-c), around PC (d,e), NPC (f), and of very few patches of porostriated *b*-fabric (g) and poorly separated plasma (h).

under preparation). This provides us a strong genetic clue for the formation of Vertisols from Alfisols not only in the Mediterranean area (Osman and Eswaran 1974) but also in subhumid and semi-arid climatic conditions of central India. This climatic conditions induce a slight to moderate alkaline chemical environments conducive for formation of Alfisols with Vertic character initially and finally towards a Vertisol with time.

Many researchers (White 1967, Yaalon 1971, Parsons *et al.* 1973) indicated that slickensides form rapidly. It is clear that they are not formed in 100 year time. The poorly separated plasma separation may be due to the (a) presence of $CaCO_3$ (Rimmer and Greenland, 1976); (b) presence of calcite crystals that cause a state of disorganization in plasma (Bellinfante *et al.* 1974), and (c) decrease in the internal surface area of fine smectite caused by hydroxy-interlayering in smectite interlayers (Kalbande *et al.* 1992). Low amount of soluble Ca^{2+} ions in shrink-swell soils in general (Kalbande *et al.* 1992, Paranjape 1995, Pal *et al.* 2001, Srivastava *et al.* 2002, Pal *et al.* 2003a) is not enough to inhibit the swelling of smectite by contracting the diffuse double layer. Examination of XRD diagram of fine clay smectite indicates a very little amount of hydroxy-interlayering in smectite interlayers (Paranjape 1995), showing no influence in plasma separation.

The surface horizon of Vertisols have columnar structure due to overburden pressure and the development of cracks due to shrinking of smectite clay under dry conditions. In the subsoils where sphenoids and/or slickensides are formed, the difference between horizontal stress and the vertical stress is quite large. On swelling, a soil is acted upon by these two sets of stresses. When the vertical stresses are confined and the lateral stresses exceed the shear strength of the soils, failure occurs along a grooved shear plane theoretically a 45 degree to the horizontal (Wilding and Tessier 1988) and in practice such shear failure may range from 10 to 60 degrees (Smart 1970, Knight 1980). Thus the shear failure is associated either with porostriated or mosaic speckled to granostriated plasmic fabric (Kalbande *et al.* 1992, Pal *et al.* 2001, 2003a), indicating a prominent surface oriented plasma separation in the slickensided horizons. The plasma separation and slickenside formation appear to be inherently related to each other during the genesis of Vertisols (Dasog *et al.* 1987, Wilding and Tessier 1988, Kalbande *et al.* 1992, Pal *et al.* 2001, 2003a). The presence of pressure faces and few patches of porostriated plasmic fabric confirm that shrink-swell activity has been operative but not to the extent it can produce slickensides with the prominent presence of porostriated plasmic fabric. Thus the results of the study suggests that (a) the formation of slickensides requires atleast a time more than a century and (b) the Vertic Alfisols of sub-humid and semi-arid climates appear to be the precursor of the genesis of Vertisols.

Conclusions

The present study indicates that clay illuviation is more important pedogenetic process in a <100 year clayey shrink-swell soils than the pedoturbation. Pedoturbation appears to be a very slow process or even not a required process in a Vertisol and a time of a century is not adequate for the formation of slickensides. The study also suggests a strong possibility of the formation of Vertisols with time from Alfisols with vertic character in subhumid and semi-arid climatic conditions of central India.

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