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# Formation and persistence of Mollisols on zeolitic Deccan basalt of humid tropical India

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## Abstract

In contrast to generally observed non-acidic and less weathered Mollisols in temperate semi-arid and humid climate, acidic and fairly weathered Mollisols on Deccan basalt are observed in hills of central (Satpura Range, Madhya Pradesh) and Western India (Western Ghats, Maharashtra) under forest in the present tropical humid climatic conditions. The detailed morphological, chemical and mineralogical investigations of these Mollisols of central and western India indicates that due to the presence of zeolites in the Deccan basalt, the transformation of smectite to kaolinite was prevented and the retention of adequate amount of smectite and continuous supply of calcium ions from zeolites made the formation of Mollisols in forest even under tropical humid climate.

The formation and the persistence of these Mollisols in association with acidic Alfisols under sparse forest in the basaltic landscape of millions of years in central and western India demonstrates the primary importance of the quality of parent material rich in expanding clay mineral and bases in their formation. This unique example thus expands the basic knowledge on the formation of Mollisols in the humid tropical part of the world.

*Keywords:* Mollisols; Tropical humid climate; Zeolite

## 1. Introduction

Mollisols represent dark coloured, base-rich (*mollic* epipedon) soils of the steppes and cover extensive subhumid to semi-arid areas of north and south America, Europe and Asia. Most of these soils have a grass vegetation after they were deforested. By and large Mollisols occur in landscapes covered by grasslands but they also occur in forested areas. In high altitudes, Mollisols have formed in late Pleistocene or Holocene deposits. Beyond the limits of glaciation, Mollisols may be in older deposits or on older surfaces dating back perhaps to mid-Pleistocene or earlier (Soil Survey Staff, 1999). Mollisols in the USA have formed mostly in Quaternary materials on gentle or moderate slopes. They occur in a wide range of landscapes ranging from flat alluvial plains to undulating plains and mountains (Fenton, 1983).

The major intention of defining Mollic epipedon (of Mollisols) was to provide a differentia to distinguish the soils that have traditionally been used to produce grain, from those that are too dry to cultivate without irrigation (Smith, 1983). The examples of the soils reported from the temperate world even in agricultural land use system may contain high organic matter with soft (*mollus*) soil structure to be termed as Mollisols due to cold climate

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preventing loss of organic matter. But in the humid tropics, the soils under agricultural lands are subjected to high atmospheric temperature and therefore can not store enough organic matter to be grouped under Mollisols. Interestingly, Mollisols have been reported under subtropical part of northern India developed in micaceous alluvium of the Indo-Gangetic Plains (Deshpande et al., 1971; Murthy et al., 1982). These soils are formed under environments similar to temperate climate of the USA and Europe. More recently Mollisols have been reported from hilly mountains of southern Peninsular and north-eastern India (Krishnan et al., 1996; Das et al., 1996; Shivaprasad et al., 1998).

On the high altitude plateau surfaces of central and western India under humid tropical climate, highly weathered ferruginous soils (Ultisols/or Oxisols) are expected to form; but in reality these ferruginous soils are base-rich Alfisols. A positive role of zeolites of amygdoloidal Deccan basalt in the persistence of these non-kaolinitic and/or non-oxidic Alfisols in this climate since the early Tertiary was demonstrated by Bhattacharyya et al. (1999). In addition, instead of commonly reported neutral to alkaline Mollisols, occurrence of acidic Mollisols under forest associated with Alfisols and Vertisols in the humid tropics of central and western India are common. Thus, a research attempt to elucidate

Fig. 1. Location of pedons (P1 and P2) in the study area.

the genesis of these Mollisols is warranted. Accordingly, the present study was attempted to find out the probable reasons for the formation and persistence of Mollisols in the humid tropical climate of India. It is hoped that this addition of knowledge may help in expanding the understanding of the factors of formation of Mollisols.

## 2. Materials and methods

### 2.1. Materials

For the present investigation two Mollisols were selected from the representative catena consisting of Mollisols-Alfisols-Vertisols from Central and Western India (Fig. 1).

Pedon 1 was from the Satpura ranges of the Central India. This area is characterized by humid subtropical climate with mean annual rainfall of 1422 mm and cool temperature from November to February (mean minimum winter temperature of 8.9 °C). Majority of rainfall (~88%) occurs during four wet months with a mean air temperature of 24.4 °C (Table 1). Pedon 1, on the Deccan basalt, occurs on the side slopes at an elevation of 850 m above mean sea level (msl). These areas are under thick forest vegetations of teak (*Tectona grandis*), mahua (*Madhuca indica*) and shrubs and grasses for centuries. The pedon has more than 150 cm thick solum with clay loam texture. The soils have COLE values of 0.1 and mollic epipedon which is 20 cm thick to qualify for *Vertic Haplustoll* subgroup in Soil Taxonomy (Soil Survey Staff, 2003). The morphological description of the soils is given in Table 2.

Pedon 2, also on the Deccan basalt, is located in the Western Ghats of India. This area is characterized by humid tropical climate with mean annual rainfall of 3287 mm and warm winter months of November, December, January and February (mean minimum winter temperature of 14.2 °C). Most of the rainfall (~91%) occurs during four wet months with mean air temperature of 27.0 °C (Table 1). The Mollisols occur on the side slopes of the plateau at an elevation of 1150 m above msl and are under mixed forest (deciduous) vegetation. The soils have more than 200 cm thick solum with clay texture. They have patchy clay cutans between 40 and 100 cm depth. The dark coloured mollic epipedon, cracks and COLE (>0.06) justify grouping this pedon into *Vertic Argiustoll* (Soil Survey Staff, 2003). The morphological description of Pedon 2 is given in Table 2.

These Mollisols, although under forest, are prone to erosion due to slope factor. This may perhaps justify the thinner mollic epipedon even in soils under forest. The recent modifications of mollic epipedon have been proposed for soils under eroded conditions. The eroded conditions have been explained as a pre-requisite for the cultivated soils (Olson et al., 2005).

Table 1
Climatic datasets of the study area

| Months | Mean temperature (°C) | Rainfall (mm) |
|---|---|---|
| *Satpura Ranges* | | |
| Pedon 1: *Vertic Haplustoll* | | |
| January | 17.4 | 28.7 |
| February | 19.7 | 15.3 |
| March | 23.9 | 27.6 |
| April | 28.5 | 13.2 |
| May | 32.8 | 10.0 |
| June | 31.4 | 131.7 |
| July | 26.7 | 480.4 |
| August | 26.1 | 419.5 |
| September | 26.2 | 213.7 |
| October | 24.0 | 70.6 |
| November | 19.0 | 8.3 |
| December | 16.9 | 2.8 |
| Average | 24.4 | |
| Total | | 1421.8 |
| *Western Ghats* | | |
| Pedon 2: *Vertic Argiudoll* | | |
| January | 25.1 | 2.3 |
| February | 25.3 | 1.0 |
| March | 27.0 | 0.5 |
| April | 28.9 | 5.6 |
| May | 29.8 | 27.9 |
| June | 27.9 | 803.4 |
| July | 26.7 | 1247.1 |
| August | 26.2 | 715.8 |
| September | 26.5 | 364.0 |
| October | 27.2 | 92.7 |
| November | 26.9 | 24.4 |
| December | 26.0 | 2.5 |
| Average | 27.0 | – |
| Total | | 3287.2 |

### 2.2. Methods

The profiles were examined and described following the methods laid down in Soil Survey Manual (Soil Survey Division Staff, 1995) and Keys to Soil Taxonomy (Soil Survey Staff, 2003). The international pipette method was followed for the determination of particle-size distribution. Sand (2000–50 μm), silt (50–2 μm) and clay (<2 and <0.2 μm) fractions were separated from the samples after removing carbonates, organic matter and oxides of Fe and Al and then dispersing the soils according to the size segregation procedure of Jackson (1979). Available water content (AWC) was calculated using the water retained between 33 kPa and 1500 kPa of less than 2 mm size soil samples

Table 2
Morphological characteristics of Mollisols

| Horizon | Depth (cm) | Elevation (m above msl)[a] | Slope (%) | Geology (parent material) | Drainage | Texture[b] | Structure[c] | Munsell colour[d] (moist) | Other features | Land use | Physiographic or topographic position |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Pedon 1: Village Gunjhari, district Mandla, Madhya Pradesh, India (Fine-loamy, smectitic, hyperthermic Vertic Haplustoll)* | | | | | | | | | | | |
| A1 | 0–6 | 850 | 15–30 | Basalt (weathered basalt) | Very well drained | cl | 1f gr | 5YR 2.5/1 | Cracks ~0.5 cm wide | Forest (*Tectona grandis, Madhuca indica*) | Hill slope |
| A2 | 6–20 | | | | | cl | 1f gr | 5YR 2.5/1 | | | |
| Bw1 | 20–37 | | | | | cl | 1f sbk | 5YR 2.5/2 | | | |
| Bw2 | 37–74 | | | | | cl | 2 m sbk | 5YR 2.5/2 | | | |
| Bw3 | 74–106 | | | | | cl | 2 m sbk | 5YR 4/3 | | | |
| Bw4 | 106–150 | | | | | cl | 2 m sbk | 5YR 4/3 | | | |
| *Pedon 2: Village Nigdale, district Pune, Maharashtra, India (Very fine, mixed, isohyperthermic Vertic Argiudoll)* | | | | | | | | | | | |
| A1 | 0–15 | 1150 | ~40 | Basalt (weathered basalt) | Very well drained | c | 1 f gr | 7.5YR 3/2 | Cracks ~0.5 cm wide | Forest (*Syzgium cuminii, Terminalia chebula, Carissa caranadas, Ficus glomerata*) | Hill slope |
| Bw | 15–40 | | | | | c | 1 f gr | 7.5 YR 3/2 | | | |
| Bt1 | 40–74 | | | | | c | 2 m sbk | 5 YR 3/3 | Clay cutans | | |
| Bt2 | 74–108 | | | | | c | 3 c sbk | 2.5YR 3/4 | Clay cutans | | |
| Bt3 | 108–146 | | | | | c | 2 m sbk | 2.5YR 3/4 | Clay cutans | | |
| BC1 | 146–175 | | | | | c | 2 m sbk | 2.5YR 3/4 | | | |
| BC2 | 175–190 | | | | | c | 2 m sbk | 2.5 YR 3/4 | | | |

[a] msl = mean sea level.

[b] cl = clay loam; c = clay.

[c] 1f gr = weak fine granular; 1f sbk = weak fine subangular blocky; 2 m sbk = moderate medium subangular blocky; 3c sbk = strong coarse subangular blocky.

[d] 5YR 2.5/1 = Black; 5YR 2.5/2 = Dark reddish brown; 5YR 4/3 = Reddish brown; 7.5YR 3/2 = Dark brown; 5YR 3/3 = Dark reddish brown; 2.5YR 3/4 = Dark reddish brown (Also see Soil Survey Division Staff, 1995).

(Richards, 1954). Extractable bases ($Ca^{2+}$, $Mg^{2+}$, $Na^+$ and $K^+$) were determined following the standard method (Jackson, 1973). Cation exchange capacity (CEC) was determined by saturating soils with 1 N NaOAc (pH 7) and leaching the Na-saturated soils by $Mg(NO_3)_2$ to eliminate the influence of $Na^+$ ion from zeolites and feldspathoid minerals (Gupta et al., 1985; Pal et al., 1994). The $Na^+$ ions were measured in atomic absorption spectrophotometer to calculate the CEC. Soil organic carbon was determined following the procedure of Walkley and Black (1934). The coefficient of linear extensibility (COLE) was determined following the method of Schafer and Singer (1976). The silt and clay fractions were subjected to examination of X-ray diffraction (XRD) analyses of parallel oriented slide mounts after Mg- and K-saturation, Mg-glycolation using ethylene glycol, heat treatment of K-saturated samples at 25, 110, 300 and 550 °C, and HCl treatment (Jackson, 1979) using a Philips diffractometer and Ni-filtered CuKα radiation at a scanning speed of 1°2$\theta$/min. The powdered sand samples were also examined by XRD after box mounting. Minerals were identified following various diagnostic methods (Jackson, 1979; Brown, 1984). The semi-quantitative estimates of clay minerals in the clay fractions were carried out following the method of Gjems (1967).

## 3. Results

### 3.1. Physical and chemical properties

The Mollisol of the Western Ghats (Pedon 2) contains less amount of sand (10–16%) than Pedon 1 (23–52%), whereas total clay content was higher (51–61%) throughout the depth of Pedon 2 than Pedon 1 (28–39%). Pedon 1 has also more fine clay in the clay fractions (46–76%) than Pedon 2 (39–59%). Higher proportion of fine clay fractions as well as higher content of smectites indicates more available reactive surface of Pedon 1 per unit weight of clay than Pedon 2. Pedon 2 had Bt horizon which was not identified in Pedon 1. Both the soils have a considerable amount of AWC for biological activities and litter decomposition (Table 3).

Both the pedons have acidic reaction; however, Mollisol (Pedon 1) of the Satpura are marginally more

Table 3
Particle-size distribution, textural class and AWC of Mollisols

| Horizon | Depth (cm) | Particle-size distribution (%) | | | | Textural[a] class (CS) | Available water content (%) |
|---|---|---|---|---|---|---|---|
| | | Sand (2000–50 μm) | Silt (50–2 μm) | Clay (<2 μm) | Fine clay (<0.2 μm) | | |
| *Satpura Ranges* | | | | | | | |
| Pedon 1: *Vertic Haplustoll* | | | | | | | |
| A1 | 0–6 | 31 | 39 | 30 | 22 (73)[b] | Clay loam | 15 |
| A2 | 6–20 | 23 | 38 | 39 | 19 (46) | | 16 |
| Bw1 | 20–37 | 30 | 41 | 29 | 22 (76) | | 18 |
| Bw2 | 37–74 | 38 | 31 | 31 | 22 (71) | | 18 |
| Bw3 | 74–106 | 42 | 27 | 31 | 20 (64) | | 19 |
| Bw4 | 106–150 | 52 | 20 | 28 | 16 (57) | | 19 |
| CS[a] | 20–150 | 38 | 31 | 31 | – | | – |
| *Western Ghats* | | | | | | | |
| Pedon 2: *Vertic Argiudoll* | | | | | | | |
| A1 | 0–15 | 16 | 33 | 51 | 29 (57) | Clay | 15 |
| Bw | 15–40 | 12 | 35 | 53 | 31 (58) | | 17 |
| Bt1 | 40–74 | 10 | 29 | 61 | 36 (59) | | 18 |
| Bt2 | 74–108 | 11 | 28 | 61 | 35 (57) | | 17 |
| Bt3 | 108–146 | 13 | 34 | 59 | 31 (51) | | 18 |
| BC1 | 146–175 | 13 | 36 | 53 | 25 (47) | | 18 |
| BC2 | 175–190 | 13 | 34 | 51 | 20 (39) | | 15 |
| CS[a] | 40–146 | 11 | 30 | 59 | – | – | |

[a] CS : Control section; CS is defined by a depth of 150 cm from the soil surface, since the bottom of the deepest diagnostic horizon (cambic for Pedon 1: thickness 150–20 = 130 cm and argillic for Pedon 2: thickness 146–40 = 106 cm) is less than 150 cm (Soil Survey Staff, 2003).

[b] Parentheses ( ) indicate % of fine clay.

Table 4
Physical and chemical properties of the Mollisols

| Horizon | Depth (cm) | pH (1:2) | | OC[a] (g kg$^{-1}$) | Extractable bases (cmol (+) kg$^{-1}$) | | | | CEC[b] (cmol (+) kg$^{-1}$) | BS (%)[c] | COLE[d] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Water | KCl | | Ca | Mg | Na | K | | | |
| *Satpura Ranges* | | | | | | | | | | | |
| Pedon 1: *Vertic Haplustoll* | | | | | | | | | | | |
| A1 | 0–6 | 5.9 | 5.1 | 35 | 29.6 | 14.4 | 1.0 | 2.3 | 52.2 | 91 | 0.11 |
| A2 | 6–20 | 5.8 | 4.8 | 30 | 32.8 | 16.4 | 1.0 | 2.0 | 59.8 | 87 | 0.12 |
| Bw1 | 20–37 | 5.8 | 4.6 | 20 | 33.2 | 18.8 | 1.1 | 1.8 | 59.8 | 92 | 0.11 |
| Bw2 | 37–74 | 5.9 | 4.3 | 12 | 36.8 | 19.2 | 1.1 | 1.4 | 67.4 | 87 | 0.14 |
| Bw3 | 74–106 | 5.6 | 4.2 | 8 | 45.4 | 18.4 | 1.2 | 0.8 | 71.7 | 92 | 0.16 |
| Bw4 | 106–150 | 5.5 | 4.0 | 5 | 45.2 | 17.6 | 1.1 | 1.0 | 73.9 | 88 | 0.16 |
| *Western Ghats* | | | | | | | | | | | |
| Pedon 2: *Vertic Argiudoll* | | | | | | | | | | | |
| A1 | 0–15 | 5.7 | 5.0 | 20 | 9.2 | 2.5 | 0.4 | 0.5 | 18.6 | 68 | 0.10 |
| Bw | 15–40 | 5.7 | 5.1 | 12 | 10.3 | 2.7 | 0.4 | 0.4 | 18.5 | 75 | 0.14 |
| Bt1 | 40–74 | 5.7 | 5.2 | 7 | 10.3 | 2.8 | 0.4 | 0.2 | 18.7 | 73 | 0.16 |
| Bt2 | 74–108 | 6.1 | 5.3 | 4 | 12.0 | 3.9 | 0.4 | 0.2 | 18.6 | 89 | 0.17 |
| Bt3 | 108–146 | 6.1 | 5.0 | 3 | 12.0 | 4.6 | 0.5 | 0.2 | 18.7 | 92 | 0.15 |
| BC1 | 146–175 | 6.1 | 5.0 | 1 | 11.9 | 5.7 | 0.4 | 0.2 | 20.0 | 91 | 0.13 |
| BC2 | 175–190 | 6.1 | 5.4 | 1 | 11.7 | 5.9 | 0.5 | 0.3 | 19.5 | 94 | 0.13 |

[a] OC = organic carbon.

[b] CEC = cation exchange capacity.

[c] BS = base saturation.

[d] COLE = coefficient of linear extensibility.

acidic than that (Pedon 2) of the Western Ghats. Organic carbon content is more in Pedon 1 than Pedon 2. The CEC of soils on the Satpura (Pedon 1) was higher than those of the Western Ghats (Table 4). Higher CEC of Pedon 1 is due to more amounts of smectites. It is interesting to note that despite their acidic reaction and non-calcareous nature both the Mollisols have very high base saturation (Table 4). This is due to the presence of zeolites as confirmed by XRD studies.

### 3.2. Mineralogy of sand-size fractions

The sand fractions (2000–50 μm) of Pedon 1 contained quartz, feldspars and zeolites. The XRD analysis indicated a strong peak at 0.90 nm of zeolites. Various thermal treatments indicated that the zeolite peak at 0.90 nm remained unchanged up to 300 °C and it disappeared at 450 °C (Fig. 2). This suggests that these zeolites belong to Si-poor heulandite type (Brown, 1984; Ming and Dixon, 1986; Bhattacharyya et al., 1993, 1999). The sand fractions of Pedon 2 showed a strong peak at 0.90 nm of zeolite with other accessory minerals such as mica, feldspars, quartz and anatase (figure not shown). The zeolite present in both the Mollisols is similar (Fig. 2).

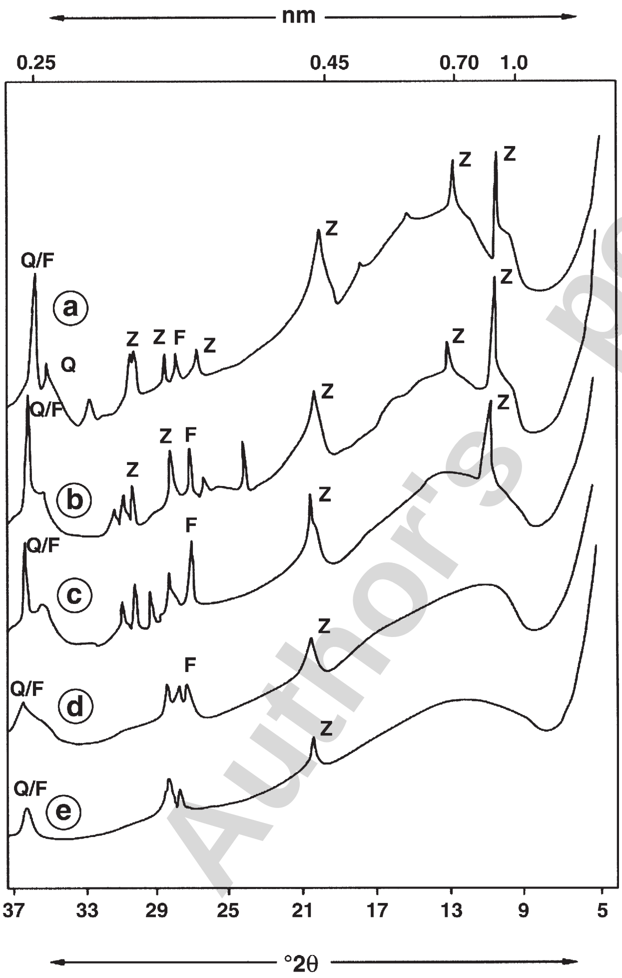

Fig. 2. X-ray diffractograms of sand fractions in Mollisols as representative in terms of behaviour of zeolite mineral towards thermal treatments: (a) room temperature; (b) 210 °C; (c) 300 °C; (d) 450 °C; (e) 550 °C. Z, Zeolite; F, Feldspars; Q, Quartz.

The silt fractions (50–2 μm) of both the pedons contained smectite, mica, smectite-kaolin interstratified (Sm/K) minerals, quartz and feldspars (Fig. 3). The Mollisol on the Satpura (Pedon 1) contained zeolites also. The chloritisation of smectites was indicated by incomplete expansion of the 1.40 nm peak on glycolation and broadening on the low angle side of the 1.0 nm peak of K-saturated sample heated to 550 °C. The 0.90 nm peak of zeolite disappeared at 550 °C indicating Si-poor heulandite type of zeolites. A slight shift and tailing of the 0.7 nm peak on glycolation and gradual reinforcement of the 1.0 nm peak with a corresponding decrease in the 0.7 nm peak intensity on K-saturation and subsequent heating (110–550 °C) suggested that these kaolins are to some extent interstratified with chloritised smectite (Sm/K). The formation of Sm/K is generally associated in soils developed in humid tropical climate, where it forms an important ephemeral stage during the transformation of smectite to kaolin (Pal et al., 1989; Bhattacharyya et al., 1993).

The coarse clay fractions (2–0.2 μm) of both the pedons were similar in mineral suit. The minerals identified were smectite, mica, Sm/K, quartz and feldspars. Zeolites were also identified in Mollisol of the Satpura ranges. These minerals belonged to Si-poor heulandite type. The Sm/K minerals were dominant in Pedon 2. Peak shift analysis (Wilson, 1987) indicates considerable amount of smectites in both the pedons (Table 5).

The fine clay fractions (<0.2 μm) of soils contain smectites and Sm/K in different proportions. Representative XRDs are shown in Fig. 4. The identified mineral at 0.7 nm was not discrete kaolinite but are interstratified minerals of Sm/K. The relative proportion of Sm in these Sm/K interstratified minerals (Table 6) indicates that although the 0.7 nm reflection appears to be a peak of kaolinite (Hajek, 1985; Yerima et al., 1985, 1987) it actually contains little smectite (Bhattacharyya et al., 1997). This type of smectite is primarily responsible for retention of high amount of organic carbon in the Mollisols under study. Total amount of smectite including the smectites of Sm/K after the peak shift analysis (Wilson, 1987) is higher in Pedon 1 (Satpura) than Pedon 2 (Western Ghats) (Table 6). This suggests that the surface area available in Mollisol of Satpura is more than that of

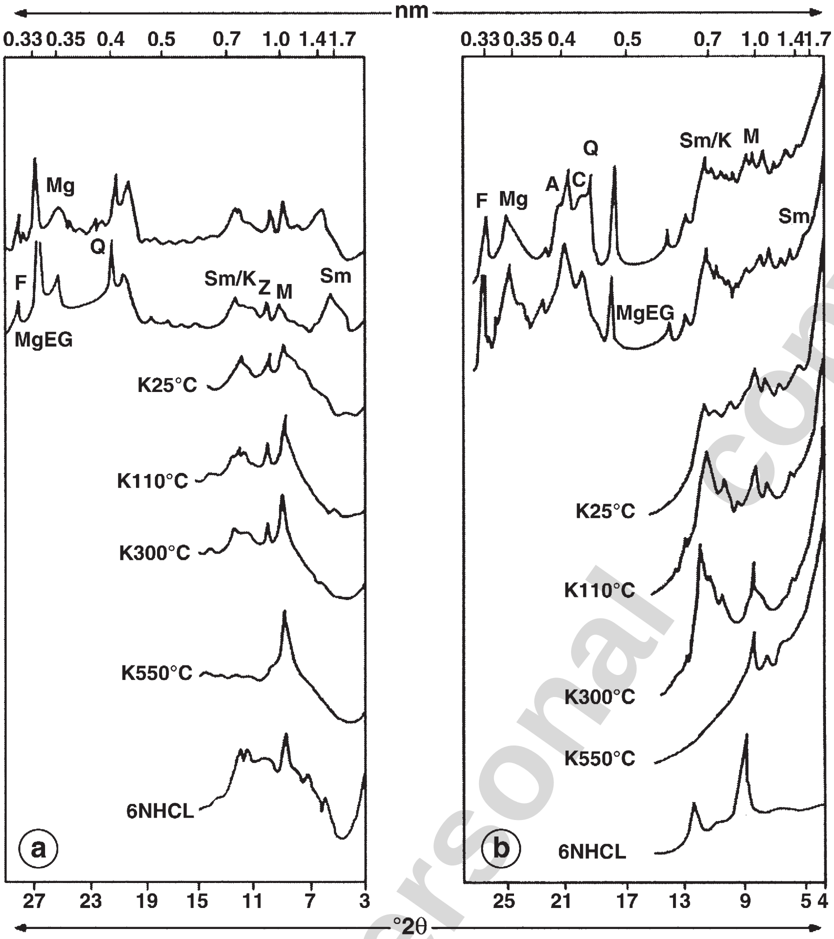

Fig. 3. X-ray diffractograms of representative silt fractions of (a) P1, Bw1 (20–37 cm) and (b) P2, Bt1 (40–74 cm); Mg, Mg saturated; MgEG, Mg saturated and glycolated; K25/110/300/550 °C, K saturated and heated to 25 °C, 110 °C, 300 °C and 550 °C; 6 N HCl, samples boiled in 6 N HCl for 30 min. Sm, Smectite; M, Mica; Z, Zeolite; Sm/K, Smectite–kaolin, Q, Quartz, F, Feldspars, C, Cristobalite, A, Anatase.

the Western Ghats. This has resulted in more soil organic carbon (SOC) in former than the latter (Table 4).

## 4. Discussion

### *4.1. Formation of Mollisols*

Mollisols are formed abundantly in temperate humid climate, which is conducive for the formation and retention of high organic matter (OM). Mollisols are, by and large, neutral in reaction with more than 50% base saturation and 0.6% SOC and exhibit lower degree of weathering. Some Mollisols are formed in areas where precipitation is sufficient for water to leach the soluble soil constituents and weathering products through the profile (Buol et al., 1973). Other Mollisols are formed in areas where water enters the soil and is held by the soil particles till it is lost by evapotranspiration. Percolation through the profile frequently may not occur in such areas. The soluble constituents and weathering products may not be lost from these soils. Thus, in the environment where Mollisols are formed may have a wide range of leaching environments, stages of weathering and horizon differentiation. These ranges may include soils that have free $CaCO_3$ in the surface horizon to those soils in which the parent material has been leached to a depth of more than 2 m (Fenton, 1983). The process of Mollisol formation has been related to the general pedogenic process of calcification leading to the formation of chernozemic soils (Marbut, 1951; Fanning and Fanning, 1989). Calcification indicates weak eluviation and the formation of secondary calcium carbonate in sub-soil horizons. Due to the process of calcification influenced by such conditions, a stable, black type of humified organic matter forms throughout a typically thick A horizon and often the upper part of the B horizon. The mollic epipedon was thus defined to recognize the dark, high base status zone at the top of mineral soils. The dark colour of A and sometimes the upper B horizon of Mollisols may result largely due to Ca-humate which refers to Ca-

Table 5
Semi-quantitative estimates of minerals in coarse clay fractions (2–0.2 μm) of Mollisols

| Horizon | Depth (cm) | Minerals (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Smectite (Sm)[a] | Mica | Zeolite | Sm/K (Sm:K) (K)[b] | Quartz | Feldspars |
| *Satpura Ranges* | | | | | | | |
| Pedon 1: *Vertic Haplustoll* | | | | | | | |
| A1 | 0–6 | 22 (32) | 9 | 16 | 37 (26:74) (27) | 14 | Trace |
| A2 | 6–20 | 23 (31) | 12 | 22 | 30 (26:74) (22) | 9 | Trace |
| Bw1 | 20–37 | 27 (36) | Trace[c] | 17 | 36 (26:74) (27) | 8 | Trace |
| Bw2 | 37–74 | 20 (31) | 6 | 16 | 41 (26:74) (30) | 15 | Trace |
| Bw3 | 74–106 | 32 (38) | 6 | 18 | 34 (18:82) (28) | 8 | Trace |
| Bw4 | 106–150 | 32 (38) | 6 | 18 | 34 (18:82) (28) | 8 | Trace |
| *Western Ghats* | | | | | | | |
| Pedon 2: *Vertic Argiustoll* | | | | | | | |
| A1 | 0–15 | 13 (29) | 9 | Nil | 62 (26:74) (46) | 9 | 7 |
| Bw | 15–40 | 12 (24) | 9 | Nil | 68 (18:82) (56) | 7 | Trace |
| Bt1 | 40–74 | 11 (20) | 21 | Nil | 59 (15:85) (50) | 8 | Trace |
| Bt2 | 74–108 | 18 (25) | 9 | Nil | 61 (12:88) (54) | 7 | Trace |
| Bt3 | 108–146 | 18 (26) | 9 | Nil | 65 (12:88) (57) | 6 | Trace |
| BC1 | 146–175 | 18 (23) | 10 | Nil | 62 (9:91) (57) | 10 | Nil |
| BC2 | 175–190 | 11 (17) | Trace | Nil | 69 (9:91) (63) | 9 | 9 |

[a] (Sm) = Effective smectite (after peak shift analysis) = % Smectite + % smectite from Sm/K [as an example say for Bw, 15–40 cm horizon of Pedon 2 effective smectite] = 12% + 18% of 68 = (12 + 12)% = 24%.

[b] (K)=Effective kaolinite (K) content (after peak shift analysis) = 82% of 68 = 56% (for 15–40 cm horizon of Pedon 2).

[c] Trace = <5%.

saturated humic acid in the humified organic matter. Ca-ions apparently slow the rate of decomposition of Ca-humate enabling organic matter content of the soils quite high (Fanning and Fanning, 1989). This has been reported due to the formation of bridge-linked compound between inorganic clay colloids and humic acid in presence of polyvalent cations like Ca and Mg (Varadachari et al., 1991; Bhattacharyya and Ghosh, 1994).

In contrast to commonly reported calcareous Mollisols (Fanning and Fanning, 1989), the Mollisols under study are acidic and non-calcareous. Their occurrence in high weathering and leaching environments clearly points out a fact that the parent material must be providing enough of Ca ions and moisture for the formation and persistence of Mollisols.

The presence of Sm/K clay minerals indicates the transformation of smectites to kaolin in tropical humid climate of the study area (Pal et al., 1989). The clay fraction is dominated by smectite and Sm/K in both Pedon 1 and Pedon 2 and the content of smectite in Pedon 1 is more than Sm/K in Pedon 2 (Table 6). The subdominant amount of smectite holds enough moisture (Table 4) to maintain a pedo-environment for the accumulation of organic matter and has made the formation of mollic epipedon possible even in tropical humid climate. This has been possible due to zeolites, which provided continuous supply of bases not only to arrest the complete transformation of smectite to kaolin but also to maintain very high base saturation level of the Mollisols.

Influence of the quality of parent materials in terms of clay minerals and bases in maintaining the slowly oxidizable pool, very slowly oxidizable pool and the passive or recalcitrant pool of OM has been assessed (Eswaran et al., 1995; Batjes, 2001) and the contribution of mineralogy in sequestration of OM has been recalculated to be as high as 78% (Bhattacharyya and Pal, 2003). Since mollic epipedon represents soils containing high OM content, it is expected that formation of Mollisols should be possible in forest areas with high rainfall and cool climate. The effect of vegetation and climate thus greatly influence the formation of these soils. Among the climatic parameters, rainfall favouring leaching has a dominant influence on soil properties in setting the level of base saturation. And if the rate of weathering of parent materials is high due to high rainfall and relatively warm tropical temperature, the base saturation assumes more importance as realized in Mollisols of the Western Ghats. Reports of Alfisols and Ultisols in high rainfall and cool temperature regions of thickly vegetated Indian Himalaya on poor-base rock systems (Bhattacharyya et al., 1994, 1996; Nayak et al., 1996; Sidhu et al., 1997; Rana et al., 2000) clearly indicate that more rainfall and vegetation with cool temperature do not favour the formation of

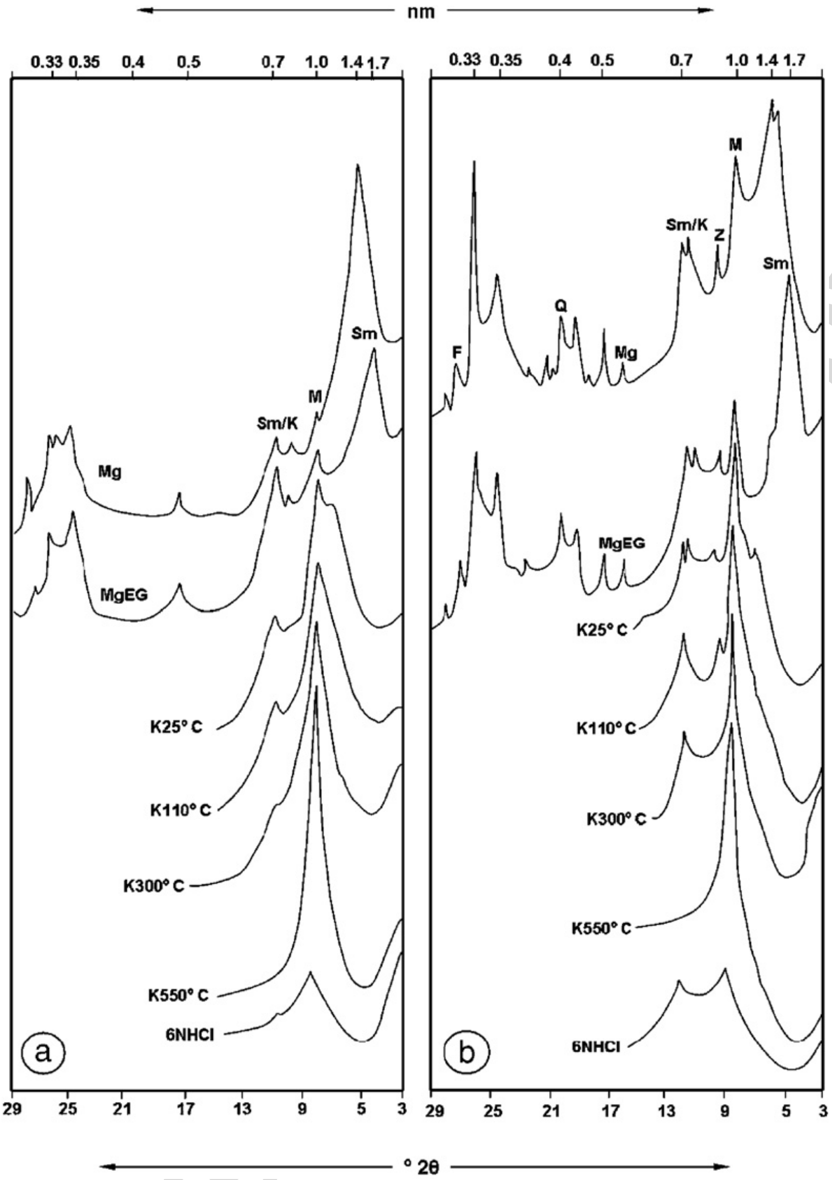

Fig. 4. X-ray diffractograms of representative fine clay fractions of soils: (a) P1, Bw1 (20–37 cm) and (b) P2, Bt1 (40–74 cm); Mg, Mg saturated; MgEG, Mg saturated and glycolated; K25/110/300/550 °C, K saturated and heated to 25 °C, 110 °C, 300 °C and 550 °C; 6 N HCl, samples boiled in 6 N HCl for 30 min. Sm, Smectite; M, Mica; Sm/K, Smectite–kaolin.

Mollisols even when bases are added in soils through forest biocycling. This reaffirms the role of the quality of parent material in terms of clay minerals and bases not only in accumulation of SOC but also in the formation and persistence of Mollisols.

### 4.2. Persistence of Mollisols

Mollisols are abundant in temperate climate with extremely cool temperature in a landscape ranging from mid-Pleistocene to Holocene with less degree of soil weathering. The Mollisols described in the present study represent the humid tropical climate. The presence of zeolites in the coarse clay fractions (2–0.2 μm) indicates a huge source of base-rich heulandites, which still persist. The loss of bases during the leaching of soils has thus been continuously replenished by the steady supply of bases from heulandites. This process develops a chemical environment which prevents the formation of kaolinitic and/or oxidic clay minerals, characteristic of typical advanced stage of soil weathering. In fact these zeolitic minerals, acting as saviours against further soil degradation (Bhattacharyya et al., 2000), maintain a base saturation level (>50%) sufficiently high enough to keep these soils moist, soft and dark even with sub-dominating proportion of smectites in the present day humid tropical climate.

The Mollisol of each of the study area is a member of Mollisol-Alfisol-Vertisol association. The Mollisols of the Western Ghats have argillic horizons unlike those of the Satpura Range. This indicates that the Mollisols and the associated ferruginous Alfisols are formed in a stable (basaltic) landscape. It has been observed that the Alfisols are more acidic, have more clay and kaolinite than the Mollisols (Table 7). This suggests that the Alfisols (under sparse forest) are more weathered than Mollisols due to better water influx in the former. This indicates that even under similar parent material and climate two different groups of soils can be formed due to difference in density of forest vegetation. The associated ferruginous Alfisols were formed in tropical humid climate and are persisting since the early Tertiary (Bhattacharyya et al., 1999). The transformation of smectite to Sm/K during humid tropical weathering began at the end of the Cretaceous and continued during the Tertiary (Kumar, 1986; Tardy et al., 1991). Many of these ferruginous soils date back to the Tertiary and Cretaceous (Idnurm and Schmidt, 1986). In other words, they were formed almost as soon as the Deccan basalt was erupted (Ollier, 1995). This suggests that although the soils in the study area are formed in humid tropical climate for millions of years they have not reached the advanced stage of weathering represented by Ultisols and Oxisols (Soil Survey Staff, 1999). Instead they represent Alfisols and Mollisols.

Table 6
Semi-quantitative estimates of minerals in fine clay fractions (<0.2 µm) of Mollisols

| Horizon | Depth (cm) | Minerals (%) | | |
|---|---|---|---|---|
| | | Smectite (Sm)[a] | Mica | Sm/K (Sm:K) (K)[b] |
| *Satpura Ranges* | | | | |
| Pedon 1 : *Vertic Haplustoll* | | | | |
| A1 | 0–6 | 68 (74) | 8 | 24 (23:77) (18) |
| A2 | 6–20 | 73 (79) | 10 | 17 (33:67) (11) |
| Bw1 | 20–37 | 76 (82) | 9 | 15 (33:67) (9) |
| Bw2 | 37–74 | 76 (85) | Trace[c] | 20(43:57) (11) |
| Bw3 | 74–106 | 72 (82) | Trace | 23 (43:57) (13) |
| Bw4 | 106–150 | 81 (93) | Nil | 19 (65:35) (7) |
| *Western Ghats* | | | | |
| Pedon 2 : *Vertic Argiustoll* | | | | |
| A1 | 0–15 | 12 (29) | 14 | 74 (23:77) (57) |
| Bw | 15–40 | 12 (23) | 14 | 74 (15:85) (63) |
| Bt1 | 40–74 | 16 (26) | 15 | 58 (15:85) (59) |
| Bt2 | 74–108 | 12 (33) | 19 | 69 (31:69) (48) |
| Bt3 | 108–146 | Nil (21) | 8 | 92 (23:77) (71) |
| BC1 | 146–175 | Nil (7) | 8 | 92 (8:92) (85) |
| BC2 | 175–190 | Nil (7) | Trace | 95 (8:92) (88) |

[a] (Sm) = Effective smectite (after peak shift analysis) = % Smectite + % smectite from Sm/K [As an example say for Bw, 15–40 cm horizon of Pedon 2 effective smectite] = 12% + 15% of 74 = (12 + 11)% = 23%.

[b] (K) = Effective kaolinite (K) content (after peak shift analysis) = 85% of 74 = 63% (for 15–40 cm horizon of Pedon 2).

[c] Trace = <5%.

Table 7
Salient properties of Mollisols and associated Alfisols (0–30 cm)

| Soils | Properties | | | |
|---|---|---|---|---|
| | pH (water) | Clay (%) | Minerals (%) in the fine clay fractions | |
| | | | Smectite[a] | Kaolinite[a] |
| *Satpura Ranges* | | | | |
| Mollisol | 5.8 | 33.8 | 79 | 12 (Mica 9%) |
| Alfisol | 5.2 | 50.5 | 37 | 54 (Mica 9%) |
| *Western Ghats* | | | | |
| Mollisol | 5.7 | 52.0 | 26 | 60 (Mica 14%) |
| Alfisol | 5.4 | 56.0 | 18 | 67 (Mica 15%) |

[a] Values after peak shift analysis (Wilson, 1987).

The formation and persistence of the Mollisols, therefore, support that the steady state may exist in soils developed over long periods of time not only a few hundreds to thousands of years (Yaalon, 1971, 1975; Smeck et al., 1983) but also millions of years. The hypothesis of Chesworth (Chesworth, 1973, 1980) for soil formation in humid tropical climate cannot explain the persistence of these Mollisols because the stability of zeolites over time was not considered in his model. Thus the formation and persistence of these Mollisols provide an 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; Bhattacharyya et al., 1999). Due to the presence of zeolites the adverse effect of tropical weathering was overcome and thus the zeolitic Deccan basalt could produce a group of organic matter-rich, dark-coloured, soft, clayey, smectitic but acidic Mollisols.

## 5. Conclusions

The present study provides a unique example of formation and persistence of Mollisols in humid tropical environment. The Mollisols have been formed due to the conditions of better water storage effecting retention of more organic matter in the soil system to maintain the mollic epipedon. Better moisture storage has been due to the presence of smectites having more surface area. The continuous supply of bases from zeolites of amygdoloidal basalts are responsible for the stabilization of smectites in such an environment. The present model on the formation and persistence of Mollisols in the hills of central and western India expands the basic knowledge on the formation of Mollisols in humid tropical environments.

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