Chapter 4

SOIL MORPHOLOGY

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"They are ill discoverers that think there is no land, when they can see nothing but sea."
Francis Bacon

4.1. INTRODUCTION

Morphology is the most important feature used to differentiate Vertisols from other soil orders. Indeed, the concept of Vertisols is derived from their morphological manifestations (Simonson, 1954; Eswaran et al., 1988). The major morphological markers of Vertisols are linear and normal gilgai (micro-relief), cyclic horizons, surface cracking upon desiccation, and slickensides (Soil Survey Staff, 1994). Soil structure (Chapter 7) is also peculiar, especially the occurrence of wedge-shaped aggregates. Slickensides between aggregates are the most characteristic feature of Vertisols (Blokhuis, 1982). Other morphological characteristics described in the literature include color, surface mulching (granular structure), thickness, carbonate, Fe and Mn segregations (glaebules), distribution of clay, bulk density (porosity), and characteristics observed under the petrographic microscope, such as basic related distribution pattern, plasma separation, voids, micro-structure, pedo-features, and relict features.

The most striking morphological characteristics are associated with swelling and shrinking on alternate wetting and drying cycles. Vertisols were believed to be remarkably homogeneous, but recent studies (Wilding et al., 1990) showed that morphological and other characteristics are very complex. The differences in degree of expression of any morphological characteristics reflect the differences in chemical, physical, mineralogical and environmental conditions. In this chapter, the morphological characteristics of Vertisols, without giving any reference to their genesis, are discussed. Because of its importance, soil structure is treated in a separate chapter (Chapter 7) and, therefore, excluded from this chapter. For convenience, this chapter is divided into two sections: macromorphology and micromorphology.

4.2. MACROMORPHOLOGY

The characteristics that are discussed here are: gilgai, nature of cyclic horizons, cracking, surface granular structure, slickensides and sphenoids, color, depth, carbonates and Fe and Mn segregations, clay distribution, and bulk density. These characteristics may not be all present in Vertisols, except for slickensides.

4.2.1. Gilgai

One of the features of Vertisols is the surface configuration (micro-relief) called gilgai (Prescott, 1931; Oakes and Thorp, 1950; Hallsworth et al., 1955); this is an aboriginal Australian term (meaning small waterhole) for the ground surface characterized by knolls and depressions (Hubble et al., 1983). This term is now firmly established in world literature (Soil Survey Staff, 1994). This micro-relief has a repetitive pattern of mounds and depressions, and is a common feature of many clay soils in sub-tropical and tropical areas of the world. The term gilgai is not applicable to micro-topography apparently resulting from freeze–thaw cycles, solifluction, or faunal activity (see Chapter 2). Six gilgai types were recorded by Hallsworth et al. (1955); normal (round) lattice, wavy, tank, stony and melonhole. In addition to these, Thompson and Beckmann (1982) also recognize linear gilgai in Australian soils. The genesis of gilgai is discussed in Chapter 2.

The gilgai feature is not found on all Vertisols. Some Vertisols do not have them, and with others they have been removed by man. Several years, without disturbance, are required for gilgai to develop; man's influence would not be conducive to their formation. It is probable that on the frequently and long term cultivated soils of Europe and much of Asia, their re-emergence has been prevented (Hallsworth and Beckmann, 1969). Gilgai features are reported in Vertisols from U.S.A, Sudan, India, Australia and several other countries. In northeastern Turkey, the Vertisols (Grumusols) on native pastures under about 600 mm of annual rainfall have a distinct gilgai of low humps and knolls or pits of several meters across, with distinct color and depth differences between the two micro-relief elements (Oakes, 1954; Akalan, 1976). This kind of gilgai is found on gentle slopes in which knolls and pits are continuous and form regular lines more or less at right angles to the contour (Dudal, 1965). Spectacular gilgai features are reported in Vertisols from Texas (Wilding and Tessier, 1988).

Gilgai do not include features formed due to frost action or animal activity and their development seems to be dependent, at least in part, on the shrinking, cracking, swelling, and heaving characteristics of particular clay types (Probert et al., 1987). For example, gilgai are not prominent in the semiarid southern India, compared to central India with higher rainfall. Sehgal and Bhattacharjee (1988) reported that gilgai were prominent in Linga, Aroli and Sarol series which occur in areas receiving rainfall >1000 mm per year. They also reported gilgai in Torrerts from the shallow basin of the Mesopotamian plain in Iraq, with a shallow ground water table. Wilding and Tessier (1988) suggest that the degree and frequency of desiccation-rewetting cycles enhances the expression of slickensides and gilgai. The gilgai development in Sudan was localized and infrequent and the incidence of micro-relief was only in the wettest areas (de Vos and Virgo, 1969). No gilgai were so far observed in cold Vertisols (Cryert) from Canada (Mermut et al., 1990).

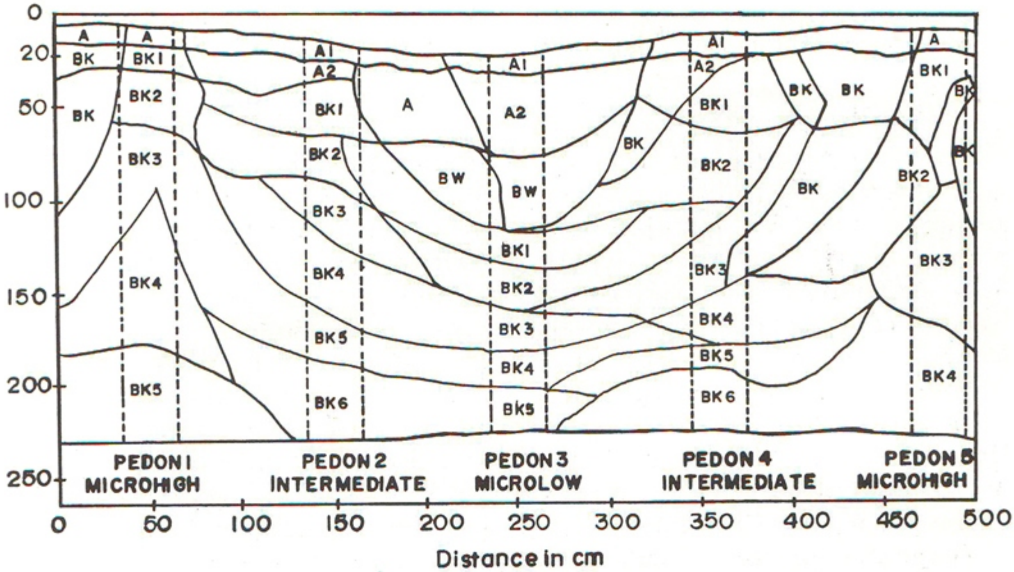

Fig. 4.1. Cross-sectional profile showing the microvariability of Lake Charles clay in Victoria County, Texas (Wilding et al., 1990).

4.2.2. Nature of cyclic horizons

Morphological variations with and without gilgai microtopography are well documented by Beckmann et al. (1971), Spotts (1974), and more recently by Wilding et al. (1990). One of the problems is that horizons are discontinuous. The gilgai complex affects both the soil's physical behavior and the ability to grow crops (Thompson and Beckmann, 1982).

Wilding et al. (1990) have provided an excellent cross sectional profile illustrating the complexity of soil morphology in Vertisols (Fig. 4.1). This presents problems in characterization, sampling and classification of these soils. Striking differences were found in three gilgai positions, namely micro-high, micro-low, and intermediate positions. In the micro-highs, narrow (30–70 cm) "tepee-shaped" structures or diapirs "chimneys" of grayish, calcareous clays extending from the lower Bk horizon to the surface were observed. This portion of soil appears to have been pushed or squeezed up along slickenside planes.

A dark A horizon may be only a few cm thick or even absent on the micro-highs and more than 100 cm thick in the micro-depressions. Organic matter content and depth to carbonates or to a Bk horizon can be equally variable. The micro-lows have little or no carbonate either as nodules, soft segregations or disseminated carbonates and have an A, Bw and Bk horizon sequence. The zone between the micro-lows and micro-highs is generally darker in color than the micro-high, but lighter than the micro-low. The micro-highs have no Bw but a thin A horizon and Bk horizons. Large slickenside planes tend to outline the three gilgai positions

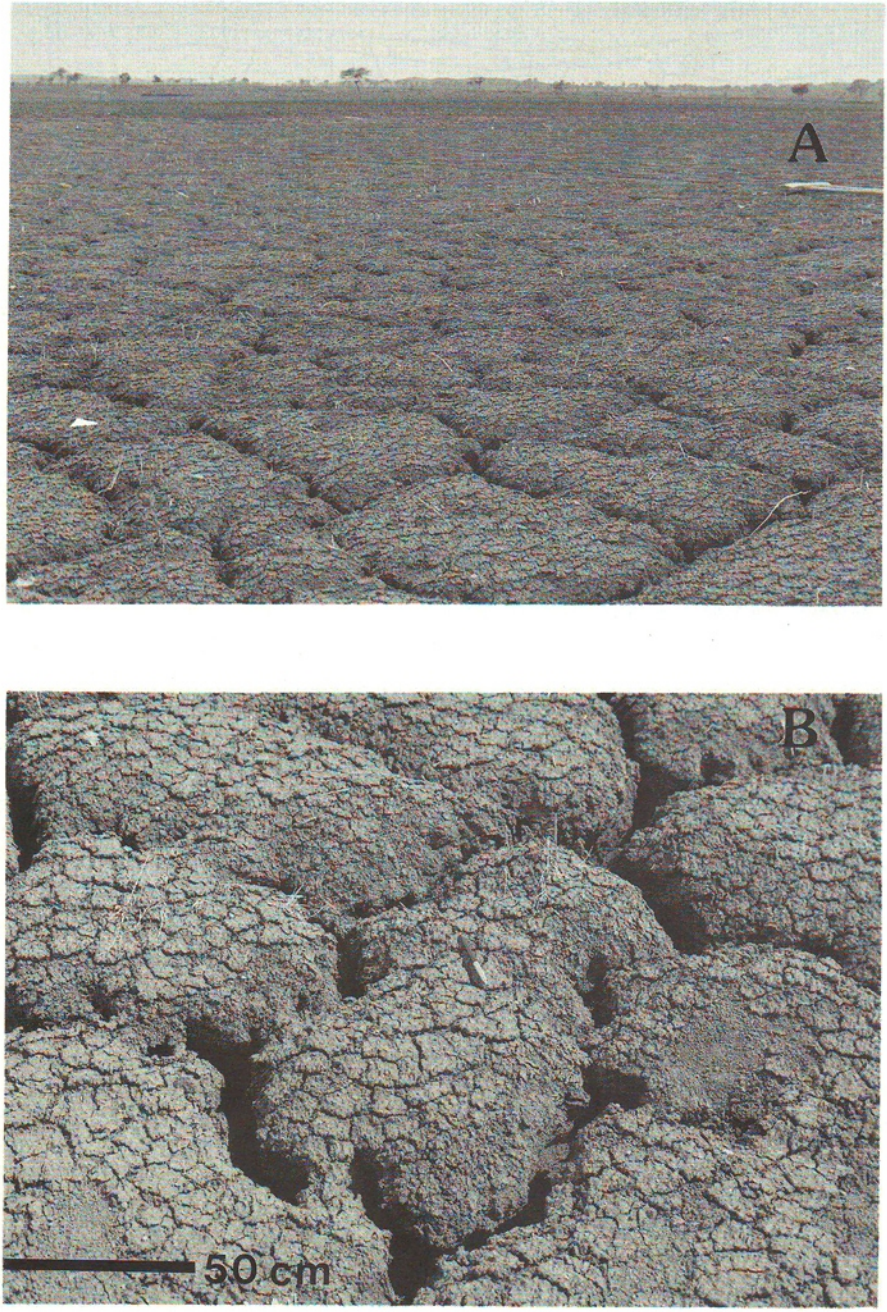

Fig. 4.2. Open cracks: (A) in a Vertisol from Dharwad, India; (B) close up view of cracks, about 5–12 cm wide, showing partial in-filling and formation of thin crust.

as well as the horizons. Wilding et al. (1990) suggested that it is paramount to study close-interval spatial variability so that sampling schemes can be developed for better representation, understanding, and use and management of Vertisols.

4.2.3. Cracking

Cracks are another striking morphological feature of Vertisols (Fig. 4.2) which are used to define this soil order. Partial drying of soil causes the formation of cracks. The open cracks are tortuous and may be 1 cm or more wide at a depth of 50 cm and may extend to a depth of 1 m or more in many Vertisols. Due to cultivation and wetting of the surface (Fig. 4.3), cracks may not be observed in the plow zone, but those below this zone continue to exist. The depth, frequency, size and shape of the cracks are related to the differential moisture status of the cracking zone (El Abidine and Robinson, 1971; Dudal and Eswaran, 1988), and moisture content at the surface and deep in the profile. For example, White (1972) demonstrated that crack outlined polygons were 0.6–0.9 m across when the soil was dried to a depth of 1.0–1.3 m and 1.5–1.8 m across when the subsoil was dried to a depth of 2.5–2.8 m. These crack spacings defined the width of prisms that are described in a vertical section.

The nature of cation-saturation of 2:1 silicate clays tends to affect the size and frequency of cracks. Vertisols in the Ca-saturated clays form wide cracks with

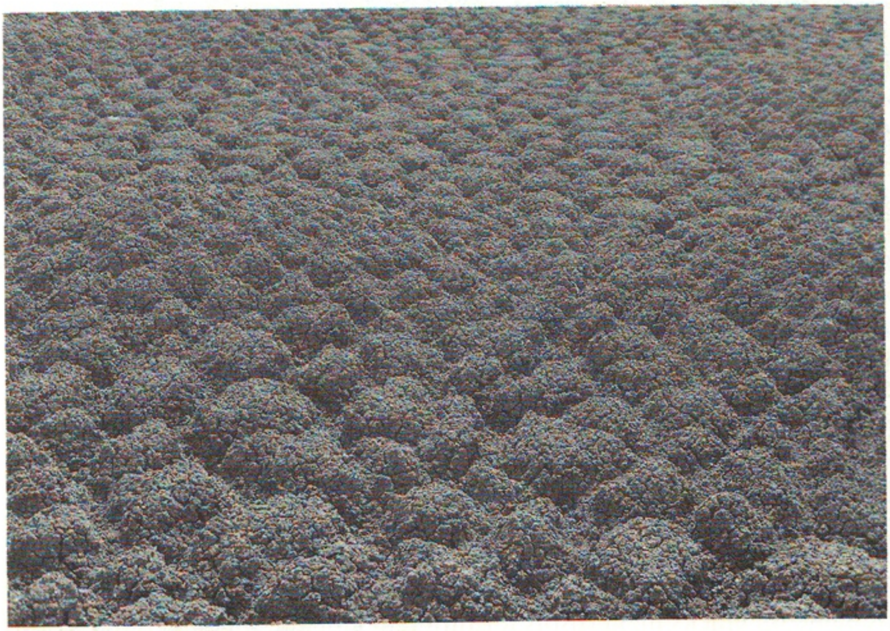

Fig. 4.3. Closed cracks after a short rain shower on a Vertisol, Dharwad, India showing a very interesting pattern of microtopography.

TABLE 4.1

Data on soil cracks in Vertisols from different regions of the world

Sl. No.	Soil/Site	Crop	Crack parameters				Source
			Width	Depth	Spacing	Volume (m^3/ha)	
	Sudan						
1.	GRF	Fallow	4.2	51	28	867	El Abedine and Robinson (1971)
2.	OUH	Natural forest	5.1	42	51	450	
3.	GHAT5	Cotton	3.4	60	39	609	
4.	GHAT7	Fallow	3.7	60	62	392	
	Canada						
1.	Regina	Forage grasses	1.5	34.8	91	82	Dasog et al. (1988a)
2.	Sceptre	Natural grassland	0.9	28.2	70	43	
3.	Sceptre	Wheat	2.0	40.1	111	89	
4.	Tisdale	Wheat	1.6	36.5	154	39	
	Israel						
1.	Measured in 1973 and 1974 at maximum opening					325–287	Yaalon and Kalmar (1978)
	India						
1.	Dharwad	Different crops	1.3	26.9	—	234	Dasog and Shashidhara (1993)

rather low frequency on drying (Smith, 1959; Sleeman, 1963). On the other hand, a higher intensity of fine cracks develops when the clays are Na-saturated.

Characterization of cracks is done as part of the profile description and wider and deeper cracks are emphasized. Systematic measurements of crack width, depth and other parameters for an area greater than that of the pedon is very limited and the techniques used are inconsistent. Soil Survey Staff (1994) requires information on duration of opening of cracks at a specified depth for soil taxonomy, but does not specify their detailed description.

Cracks are formed due to drying of a moist soil when tensile strength exceeds the cohesive strength of the soil (Blokhuis, 1982). Studies on evolution of cracks have revealed two stages in the shrinkage process (Hallaire, 1984). At first, thin cracks (less than 5 mm wide) appear with about 3 cm spacings. Later in the drying process, some of these cracks open wider (more than 1 cm) with about 20 cm spacings while the remaining cracks are partially or even totally closed. On a field scale, it is only the latter types that are measurable. However, progress made in image analysis now provides an opportunity to rapidly quantify, in two dimensions, any type of cracks in Vertisols (Bui and Mermut, 1989; Moran et al., 1989).

Data available on cracks in Vertisols for different climatic regions of the world are limited (Table 4.1). It is obvious that no single parameter can adequately explain cracking intensity. The crack volume per unit area is the best index of the intensity of cracking as it takes width, depth and spacing of cracks into account. Cracking intensity as measured by a direct sand filling technique utilized by Dasog and Shashidhara (1993) for a Vertisol from Dharwad, India was found closely related to moisture depletion due to evapotranspiration and crop removal. The cracking in fallowed areas was less than in cropped fields. Cracking intensity, in general, is the least in cool temperate areas compared to warm tropical regions (e.g. the Sudan) and intermediate in Mediterranean regions (e.g. Israel) (Table 4.1).

Thompson and Beckmann (1982) observed a network of cracks developed mainly in the depressions during a prolonged drying season in Australia. Cracks were less on the mounds and were apparently much finer and shallower than in depressions. Similar observations were made by Stirk (1954). As suggested by Wilding et al. (1990), cracking patterns, crack closure hysteresis and cracking depths as a function of seasonal soil moisture changes, especially in Vertisols with gilgai microtopography have been little explored, and require further attention.

4.2.4. Surface granular structure

In several Vertisols, the surface 2–10 cm layer is a loose mulch consisting of medium to fine granular aggregates (Blokhuis, 1982). It is commonly known that the surface structure of Vertisols ranges from fine granular to massive (Hubble, 1984). There are a few authors who suggest that all Vertisols have finely-aggregated surface layers. The surface mulch provides a fine seed bed and partly or fully fills the cracks. Chapter 7 fully and critically reviews the mechanism of formation of the surface mulch. It is reported that the thickness of the mulch decreases in passing through semiarid to humid areas of Sudan (de Vos and Virgo, 1969; Blokhuis, 1982). In the Sudan, the surface mulch is not well developed where rainfall exceeds 500 mm (Jewitt et al., 1979). Similarly, in India, Sehgal and Bhattacharjee (1988) noted that Vertisols of the semiarid regions had 20–30 mm thick pulverized granular surface mulch.

As defined by Wenke and Grant (1994) mulching is the ability of a dry remolded soil material to form aggregates (<5 mm size) after only a few cycles of drying and gentle wetting. When the soil structure is damaged the self mulching ability facilitates the amelioration of soil structure (Dexter, 1991). Attempts were made to determine self-mulching ability of the soils in different geographic regions by using an index. A laboratory-based numerical index of self-mulching (I_{sm}) developed by Grant and Blackmore (1991) is given below:

$$I_{\mathrm{sm}} = (f_{\mathrm{ns}} + S/P)^{-1}\ (T/35)$$

where P is the percentage clay released by puddling of natural aggregates, S is the percentage clay released from a <5 g sample by shaking after air drying (45°C, for 24 h) and slaking of the puddled soil, T is the total percentage clay and f_{ns} is the fraction of the puddled and dried soils that, after swelling and slacking for up to several hours, does not fall unaided through a 5 mm sieve in free water. Attempts were made to determine the self-mulching ability of the soils in different geographic regions (Grant and Blackmore, 1991; Grant et al., 1993).

Vertisols with finely aggregated surface soil provide a much better medium for plant growth, because the granular topsoil has more porosity, acts as a barrier to vapor transfer from the subsoil and decreases the effect of contraction cracks (Duchafour, 1977; Warkentin, 1982). On the other hand, those in the subhumid regions often have 5–10 mm thick brittle crust which breaks up under the impact of rain. This surface granular mulch may fill cracks during the dry season. Upon wetting, the mulch in the cracks may provide somewhat lower bulk density than the surrounding soil, depending upon the strength of the granules. These cracks, therefore, may become a more ideal site for root growth. For further discussion on this feature the readers are referred to Chapter 7.

4.2.5. Slickensides

The term "slickenside" refers to a surface that has a polished and shiny appearance and that also may be striated or grooved (Dudal and Eswaran, 1988). All Vertisols have slickensides (Fig. 4.4) and the soils that do not have slickensides are excluded from the Vertisol order. The term was first identified by geologists and is now utilized to describe these surfaces. They are characteristic not only of the large wedge surfaces, but also those that can be observed by a hand lens or microscope (de Vos and Virgo, 1969). The term slickenside does not refer to a structural element.

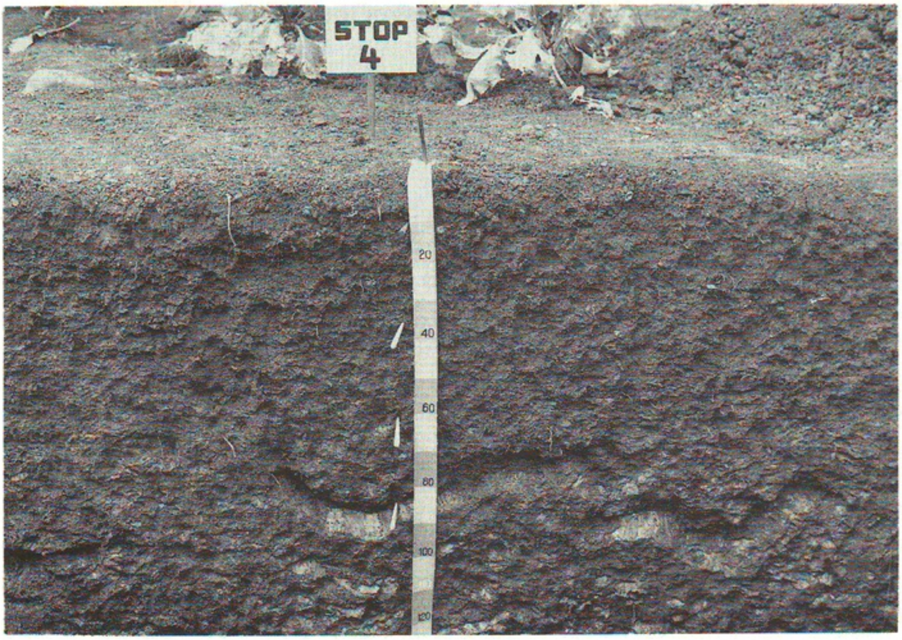

Fig. 4.4. Sets of slickensides that occur below 25 cm and extend to the C horizon in a Vertisol from Central India. The arrows show the tilt angle of the slickensides.

The depth at which slickensides start appearing in the profile varies widely. Based on the data for a number of soil profiles from India, Vadivelu and Challa (1985) stated that slickensides occur deeper in regions of high rainfall and at a shallower depth in the drier regions. In semiarid areas, the slickensides occurred at depths ranging from 22 to 65 cm (average 47 cm) and in the subhumid to humid regions it varied from 31 to 105 cm (average 60 cm). This is related to depth of cracking in these soils. In humid areas, the wetting of the soil is expected to be deeper and during summer, drying is severe and cracks are expected to be deeper. In the zone below the depth of cracking, because of differential wetting, slickenside formation is favored. Yaalon and Kalmar (1978) observed that slickenside development was strongest below the depth of cracking. Slickensides were, however, noticed at much shallower depths in cold Vertisols where cracks were shallow (Dasog et al., 1987).

In Australian clay soils, slickensides on shear planes are distributed from 0.3 m below the surface to a projected limit of 1.3–1.8 m (Knight, 1980), although they extend deeper in Vertisols of Israel (Yaalon and Kalmar, 1978). Those in Fig. 4.4 start at 25 cm and stop at the upper boundary of the calcareous C horizon. The figure clearly shows that the very frequent slickenside planes appear to be like ripples in the vertical cut with a wide variety of tilt angles. The frequency in this particular soil was more than one in 1 cm vertical distance, which would be qualified as extremely high. Knight (1980) states that the ratio of depth of maximum number of slickensides to maximum depth of occurrence is about half in all the cases, an observation that has to be confirmed and explained. The slickensides occurring in a soil profile from the Akot soil series from Central India depicted in Fig. 4.4, do not follow Knight's rule.

Large slickenside planes tend to outline the micro-low and micro-high gilgai elements in soils from Texas (Wilding et al., 1990) (Fig. 4.1). These slickensides form a "bowl" structure or cone of revolution in the micro-low. Their dip angle perpendicular to the pit face was only about 15° and along upward-tending diapirs of the micro-high, the angle of dip was about 60–75°. The angle of major slickensides ranged from 25 to 60°, but was commonly 50–55°. In these soils, slickenside planes were 2–5 cm apart as they approached the diapirs of the micro-high, but 4–10 cm apart in the intermediate and micro-low pedons. Root growth and development tended to follow slickenside faces; however, some were through the faces. Large slickensides were also found in cold Vertisols without a distinct gilgai micro-topography (Mermut and Acton, 1985; Dasog et al., 1987).

When slickensides intersect, they may form ortho-rhombic structural elements (wedge-shaped natural structural elements or sphenoids) that have their long axis tilted 10–60° from the horizontal. Slickensides form the surfaces of these structural elements. The slickenside, therefore, remains the most significant feature for the identification of Vertisols. Because of insufficient knowledge, slickensides and associated sphenoids are often not adequately recognized and described during the profile description (Eswaran et al., 1988).

4.2.6. Color

Vertisols are generally dark-colored (most frequently 2.5 Y and 10 YR), although they may have a brownish or even brownish-reddish color depending on their composition, moisture, and associated parent material. Despite the fact that the total organic matter content of Vertisols is not different from other soils occurring under similar environmental conditions, their dark color is attributed to the complexation or chelation of organic colloids with smectite (Chapter 5).

4.2.7. Depth

Many Vertisols are deep or very deep. There has been discussion about the minimum thickness that may be used in the definition of Vertisols. Dudal and Eswaran (1988) suggest that this attribute may not be critical as long as the soil develops the full expression of the vertic attributes. For the 39 profiles from the different parts of the world discussed by Dudal (1965) the average thickness was 60 cm and two thirds of the profiles had solum thickness between 30 and 90 cm. It seems that less than 30 cm thick soils do not provide sufficient overburden pressure to form the vertic properties. If this effective depth is absent, the soils are placed in vertic subgroups (Chapter 3).

4.2.8. Carbonates and Fe, Mn segregations

Indurated secondary carbonate segregations, and rounded ferro-manganese nodules and segregations are common features of many Vertisols (Singh and Lal, 1946; Simonson, 1954; Wieder and Yaalon, 1974; Ahmad, 1983). Two distinct morphological groups of carbonate nodules were identified by Mermut and Dasog (1986) in some Vertisols in India. The larger ones were white with irregular surfaces, whereas the smaller ones were black with smooth surfaces. The black ones were also more rounded, compact, and homogeneous in size. Inorganic radiocarbon dating (Table 4.2) indicated that both morphological types were formed as a result of supergene processes. Mean residence time of the glaebules was found to increase with depth. Black glaebules from the Bijapur profile yielded radiocarbon ages of 25,000 and 27,050 yr BP which were much older than the white glaebules from the Sultanpur profile. They were also well over the ages of carbonate glaebules reported by Magaritz et al. (1981). The ages in Table 4.2 indicate the average values of the nodules, but not necessarily the real ages of the nodules. However, these suggest that Vertisols with only white glaebules are considerably younger than those dominated by the black group. Mermut and Dasog (1986) suggest a more detailed study on O and C stable isotopes and ^{14}C radiogenic isotope to understand the mechanism of the carbonate segregation in Vertisols.

Wilding et al. (1990) found that the micro-lows had a few hard carbonate nodules and no soft segregations. Along the concave bowl edges of the micro-lows, hard carbonate nodules occurred in a 20–30 cm wide band in the shape of a concave upward arc. This is believed to have been pushed upward from the lower Bk (Fig. 4.1) between two bordering slickenside planes.

TABLE 4.2

Inorganic radiocarbon ages of selected carbonate glaebules in the Sultanpur and the Bijapur soils, India

Profile	Morphologic group	Horizon	Depth (cm)	Age (MRT)[a] (yr BP)
Sultanpur	White	$Ap + A_1$	0–79	4085 ± 135
Sultanpur	White	AC	79–130	7705 ± 210
Bijapur	Black	Ap	0–35	25,000 ± 1150
Bijapur	Black	A_1	35–55	27,050 ± 1500
Bijapur	White	Ap	0–35	14,770 ± 790

[a] MRT = mean residence time.

The Vertisols developed in the sedimentary plains of Sudan are of two types: soft diffuse, and hard discrete carbonate nodules (Blokhuis et al., 1968/69). In the substratum, segregations consist of both soft with diffuse boundary and hard and discrete. In the solum, however, only the hard ones were found; these increased in size and abundance towards the surface. As in the Vertisols of India, mentioned above, part of the carbonate segregations studied in Sudan were also coated with iron manganese.

Blokhuis (1982) suggested that non-calcareous Fe–Mn nodules may be formed below the zone of pedoturbation, when hydromorphic conditions prevail in the substratum. In a recent study, Acquaye et al. (1992) found that rounded Fe–Mn nodules were present throughout the Vertisols in the Accra Plains of Ghana. Wilding et al. (1990) indicate that Fe–Mn nodules were more pronounced in the strongly calcareous lower Bk horizon (Fig. 4.1). According to these workers, it was difficult to suggest whether these segregations represent contemporaneous alternating redox states or are a relic from a wetter paleo-environment.

Further information about carbonates and Fe–Mn segregations are provided in the micromorphology section of this chapter.

4.2.9. Clay distribution

The clay content of Vertisols of India ranges between 40 and 60%, but it may be as high as 80% (Murthy et al., 1982). Acquaye et al. (1992) give a figure as low as 30 percent which coincides with the marginal range of total clay requirement for Vertisols (Soil Survey Staff, 1994). Those occurring in cryic temperature regimes (Cryerts) have a clay content >60 percent (Mermut et al., 1990). Surface layers generally have less clay contents than the subsoils. Thompson and Beckmann (1982) found no consistent pattern in clay content or clay depth functions between gilgai elements. Yule and Ritchie (1980) found only slightly higher clay contents in micro-lows than in micro-highs in the Vertisols from Texas.

4.2.10. Bulk density

A wide variety of bulk density ranges for Vertisols are given in the literature. Dudal (1965) indicates that Vertisols are characterized by a high bulk density. It should be mentioned that, as bulk density changes drastically with moisture content (Dasog et al., 1988a), it is rather meaningless to indicate bulk density without giving information about the moisture content of the soil. Dry bulk density will always be higher, as these soils will shrink as much as 40 percent by volume.

4.3. MICROMORPHOLOGY

From the literature it appears that Jongerius and Bonfils (1964) were the first to describe the detailed micromorphology of a Vertisol from Argentina. This was followed by the studies of Vertisols in Sudan (de Vos and Virgo, 1969; Blokhuis et al., 1968/1969; 1970), Australia (Stace et al., 1968; Sleeman and Brewer, 1984), Spain (Bellinfante et al., 1974), India (Kooistra, 1982), and USA (Nettleton et al., 1983). Several other, mostly indirect, studies have also contributed to our current knowledge (Labib and Stoops, 1970; Osman and Eswaran, 1974; Yaalon and Kalmar, 1978; Brewer et al., 1983; Mermut and St Arnaud, 1983; Dasog et al., 1987; Yerima et al., 1987; Wilding and Tessier, 1988). Several review papers are now available (Nettleton and Sleeman, 1985; Mermut et al., 1988; Blokhuis et al., 1990).

Thin sections used in fabric analysis of Vertisols are made after air-drying the soils, and very little attempt was made to represent thin sections at various moisture tensions. This is mainly because it is very difficult to dry the soil without causing any shrinkage (Eswaran et al., 1988). Tessier and Berrier (1979) have observed fabric changes under scanning electron microscope (SEM) with clods which were subjected to various moisture tensions. Due to high clay contents, the fabric of fine material requires more attention. Another aspect that needs to be established is the comparison of the horizontal and vertical variations of properties with the corresponding micromorphological variability.

The characteristics observed under the petrographic microscope include: groundmass, plasma separations (sepic fabrics), voids, pedofeatures (carbonate and Fe–Mn segregations, cutans, animal activity, relic features, and other features).

4.3.1. Groundmass

Groundmass by definition forms the base material of a thin section excluding the pedofeatures (Bullock et al., 1985). A porphyroskelic related distribution in which the plasma occurs as a dense ground mass and skeleton grains are set after the manner of phynocrysts rock (Brewer, 1976) is commonly reported in Vertisols (Table 4.3). However, other kinds of related distribution patterns are also observed. The Suliemi soil, an Entic Chromustert from Sudan, had a granoidic fabric in the granular surface horizon (Nettleton and Sleeman, 1985). Granic and granoidic, sometimes mull-granoidic, fabrics are common in the surface horizons

TABLE 4.3

Related distribution pattern and plasmic fabrics in some Vertisols

Sl. no.	Country	Related distribution	Plasmic fabric	Source
1.	Canada:			
	(a) grassland	Porphyroskelic throughout	Ma-skel-lattisepic	Dasog et al. (1987)
	(b) grassland forest transition	Mull-granoidic to porphyroskelic in the surface to porphyroskelic in the subsurface	Insepic (surface) ma-vo-lattisepic (subsurface)	Dasog et al. (1987)
2.	Australia	Porphyroskelic (argioporphyric)	Some variety of vo-ma-skelsepic throghout the profile	Sleeman and Brewer (1984)
3.	Sudan	Porphyroskelic	Vosepic, skelsepic and masepic	de Vos and Virgo (1969); Blokhuis et al. (1970)
4.	U.S.A.	Porphyroskelic	Skelsepic, masepic and combination of these	Nettleton et al. (1983)
5.	India	Porphyroskelic throughout	Skelsepic, masepic and vosepic	Dasog et al. (1988b)

of many Vertisols with self-mulching. The plasma and skeleton grains occur as a dense mass in the soil aggregates resulting in the formation of porphyroskelic fabric. The granules are separated by packing and compound packing voids. The subsoil is typically porphyroskelic. The granules that fill the cracks may remain intact and may create accommodating peds with lower pore spaces between the peds (Fig. 4.5). If the surface horizon is distinctly darker than the subsoil, then darker colored wedge shaped tongues which occur at a regular interval in the profile, can be observed. In such situations it is easy to recognize the dark colored surface granules in thin sections from the subsoil.

4.3.2. Plasma separations (sepic fabrics, Brewer, 1976; striated b-fabrics, Bullock et al., 1985)

The fabric of the fine materials has received considerable attention. This is determined by the interference color of clay domains under the microscope. Nettleton et al. (1983) have found a distinct difference in groundmass between the Vertisols and vertic subgroup in 14 selected soils from the U.S.A. Despite the presence of cracks, there was neither plasmic fabric development nor intersecting slickensides in the vertic subgroup. Mermut et al. (1988) stated that vertic subgroups lack planar vosepic, skelsepic and especially masepic plasmic fabrics.

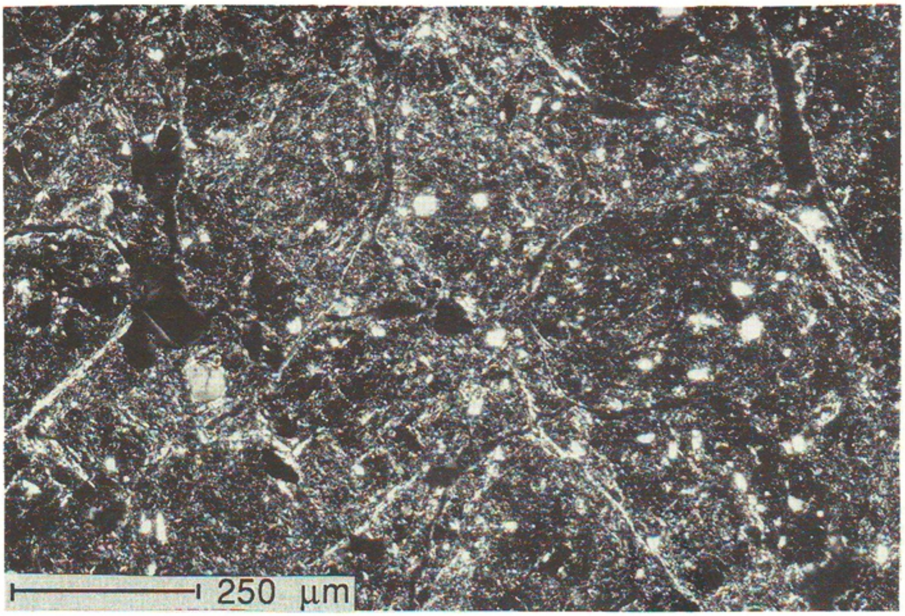

Fig. 4.5. Crack filling surface granules in the subsoil showing a well accommodating related distribution pattern, from the Regina clay plain, Saskatchewan, Canada.

So far no specific widely accepted plasmic fabrics are suggested as diagnostic criteria for Vertisols.

Swelling processes in soils result in micro-shear within the soil fabric. Such stresses reorient the individual clay plates into lineated zones with face to face clay alignment (clay domains, or taktoids) (Wilding and Tessier, 1988). Stress-related fabrics such as masepic, skelsepic, vosepic and maybe lattisepic plasmic fabrics are, therefore, commonly observed in Vertisols. It is known that drying of unconfined soils do not produce reorganization of clay domains, even under irregular drying of remolded clay soils (Nettleton et al., 1983). It requires rather a very strong force to produce even a moderately strong preferred orientation; hence distortion (shear), but not compaction, appear to be the significant cause of preferred orientation (Clark, 1970). Dalrymple and Jim (1984) also concluded that any well-developed masepic fabric in soils is likely to be formed by processes in addition to wetting and drying. Preferred orientation is also controlled by factors such as salt concentration (Clark, 1970), silt content (Dalrymple and Jim, 1984), organic matter (Bellinfante et al., 1974), carbonates (Sleeman and Brewer, 1984) and size, shape and nature of clay minerals (Eswaran et al., 1988).

Sepic fabrics are described by several workers in Vertisols and associated soils (Blokhuis et al., 1970; Kooistra, 1982; Nettleton and Sleeman, 1985; Yerima et al., 1987; Wilding and Tessier, 1988). Brewer (1976) suggested that vosepic plasmic fabric is the result of forces just insufficient to cause shearing, whereas masepic

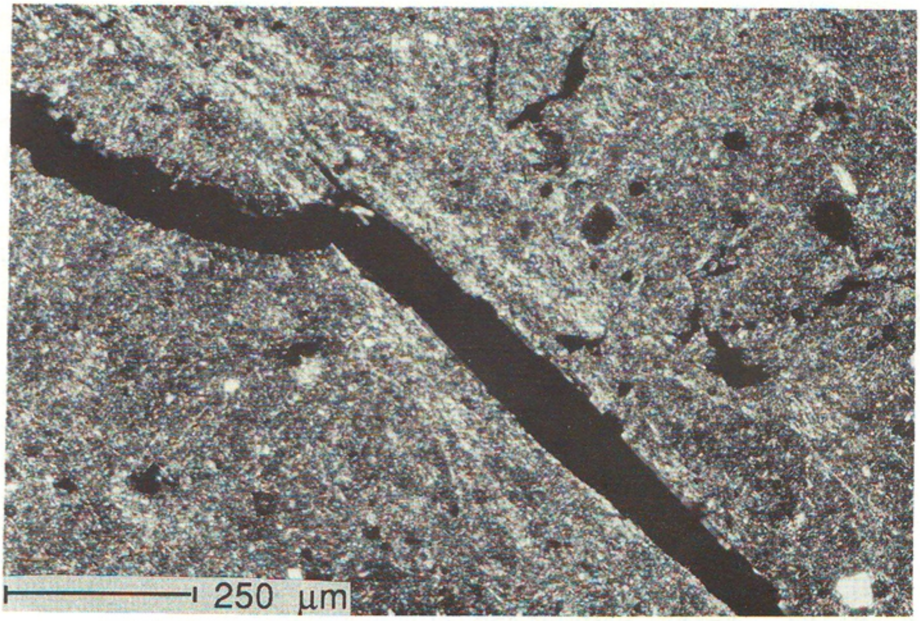

Fig. 4.6. Photomicrograph from a major slickenside surface, showing planar vosepic and masepic (upper left corner) fabrics and planar void (cracks) without plasma separation in the Rouleau subsoil, Saskatchewan, Canada.

plasmic fabric is produced by shearing. Thin sections containing distinct slickensides showed both planar vosepic and masepic and planar voids on the same slickenside surface (Fig. 4.6). If the surfaces are closed, then the resulting fabric is masepic; otherwise, it is planar vosepic fabric. Jim (1986) and Blokhuis et al. (1990) indicated that planar voids and associated vosepic plasmic fabric resulted from shearing, whereas masepic plasmic fabric could be a precursor of vosepic plasmic fabric. Augustinus and Slager (1971) suggested that vosepic and masepic plasmic fabrics in ripening muds from Suriname may be formed by tensile stress, but not by shear stress.

Blokhuis et al. (1990) made the remark that one should realize that some methods of thin section preparation may create artificial stress and could enhance the development of shear-related plasmic fabrics. This may be the case when moist or relatively wet clay soils are dried quickly and/or when impregnating resins are heated up to 60–80°C during the hardening process.

There are other problems. In calcareous Vertisols, it is not possible to observe the plasmic fabrics as they may be masked by fine carbonate particles. After the removal of carbonates by mild acid solution, Wilding and Drees (1990) found that the calcareous subsoil of a Vertisol had mostly masepic plasmic fabrics. Eswaran et al. (1988) indicate that, despite the presence of very obvious and discrete plasmic fabrics, much of the s-matrix is poorly expressed, being insepic or even isotic and, therefore, neglected during the thin section description. The poor appearance of the fabric is attributed to the size of the fundamental clay particles, lack of the orientation of clay platelets and masking by organic matter.

Smectites, which are the predominant clay minerals in most Vertisols, are generally finer than the other phyllosilicates and electron microscope studies indicate the incomplete face to face arrangement of the platelets within the clay domains. Plasmic fabrics were indeed more visible in Vertisols that had higher vermiculite contents than their counterparts in the same region (Mermut et al., 1990). In a detailed study using a transmission electron microscope (TEM), Wilding and Tessier (1988) demonstrated that the type of cation(s) on the exchange site, type and concentration of electrolyte and charge characteristics play an important role in the arrangements and behavior of the fundamental clay particles. As the layer charge increases, the water content of the clay decreases and the number of clay layers in fundamental particles increases. This results in less flexible and more rigid particles, and likely the formation of more distinct clay domains. Much is yet to be learned in this area.

A number of clay soils are known to have micro-fabrics similar to Vertisols in failing to crack sufficiently or in failing to meet one or more of the other criteria for Vertisols (Sleeman and Brewer, 1984; Nettleton and Sleeman, 1985; Blokhuis et al., 1990). Microfabrics of Vertisols and vertic intergrades may overlap and an attempt to classify soils on micromorphological considerations alone may not be appropriate.

The interpretation of different plasmic fabrics in terms of magnitude of stress has not been consistent in the literature. For example, Brewer (1976) considers omnisepic fabric as being formed under extreme pressure, but Nettleton et al. (1983) observed such a fabric in vertic intergrades which undergo less severe stress than in Vertisols. Lattisepic fabric was observed in vertic intergrades by McCormack and Wilding (1974) and Dasog et al. (1987); however, Brewer (1976) considers it a modification of masepic fabric, which is a characteristic of Vertisols. Many workers suggested that masepic fabrics are the main micromorphological characteristics which may occur together with vosepic, skelsepic and lattisepic plasmic fabrics and these are rare or absent in vertic subgroups. Other observations show that these fabrics are also found in soils recognized as a vertic subgroup (Blokhuis et al., 1990). Blokhuis et al. (1970) used the proportion of masepic fabric as a micromorphological parameter to denote the magnitude of stress in Sudanese Vertisols, but they hinted also that the thickness of plasma separation around skeleton grains in a skelsepic fabric may be influenced by grain size or intensity of churning process or both.

As pointed out by Wilding and Flach (1985), micromorphology is used to determine the direction of pedogenic processes rather than quantify the magnitude of such expressions. They also suggested that micromorphology is most useful when set in context with observations that span the continuum from visible to submicroscopic levels of resolution and when integrated with studies using chemical and physical methods. Such attempts are few in the literature.

The above discussions on plasma separations suggest the need for further research in this area. Seasonal or regular sampling of the same soil might help to establish the degree and permanence of stress related plasmic fabrics. Eswaran et al. (1988) also suggest detailed studies on microvariability of soil properties, both horizontally across a pedon and vertically within a pedon.

4.3.3. Voids

Most of the Vertisols are reported to have packing voids, vughs and interconnected vughs, and channels in Brewer's terminology. The void type that dominates the subsoil is planar, part of which may be planar vosepic, with a major preferred orientation direction similar to the orientation of slickensides (Bui and Mermut, 1989). Planar voids are interconnected (Fig. 4.7) and they play a very important role regarding the water distribution in Vertisols.

Blokhuis et al. (1970) have observed that planar voids were dominant in high rainfall areas and vughs and interconnected vughs in low rainfall areas. Examination of the micromorphological description of many Vertisols showed that this may not be valid for other Vertisols. Both cracking and soil displacement produce planar voids. Micromorphology provides an excellent opportunity to differentiate and maybe quantify the voids that are produced by stress from those formed by desiccation. To do this, there is a need to quantify the planar voids.

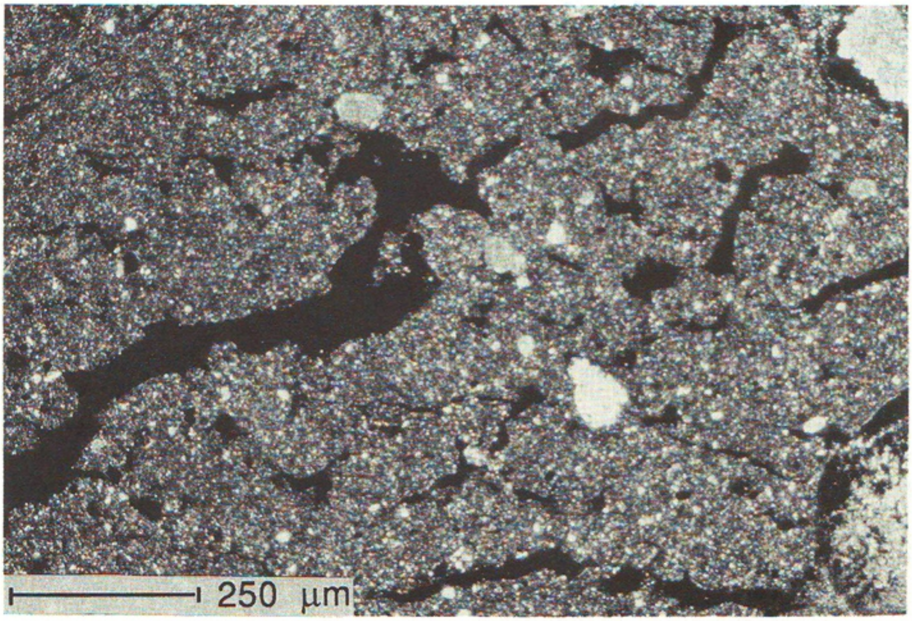

Fig. 4.7. Several subparallel sets of interconnected planar voids without plasma separation from the subsoil, just above the slickenside zone of the Bijapur Vertisol from Karnataka State, India.

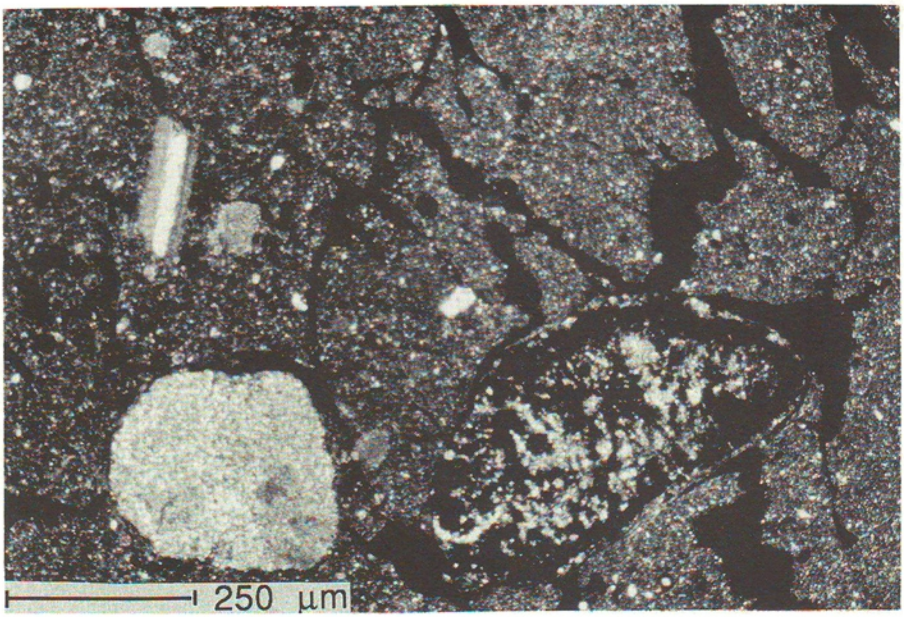

Fig. 4.8. Two carbonate nodules one without and the other with Fe–Mn oxyhydroxide occurring around the glaebule. The lath–shaped particle at the upper left corner is a piece of snail or shell fragment.

Bui and Mermut (1989) have attempted to measure the length of the planar voids per unit area and determine their major preferred orientation directions, using the image analysis technique. They found that in Vertisols the dominant orientation of planar voids was sub-horizontal and oblique vertically. Bui and Mermut (1989) have further reported that the frequency (cm/cm^2) of total planar voids was found to be much higher in Vertisols that occur in the tropics, than their counterparts in the temperate regions. It appears that image analysis techniques can help to determine whether a soil has been subjected to stress–strain processes. Further studies may help to prove that Vertisols and vertic subgroups can be separated on the basis of frequency and orientation of planar voids.

4.3.4. Pedofeatures

Pedofeatures reported for Vertisols include carbonate and Fe–Mn nodules, clay cutans, animal activity, relict features and other neoformations such as gypsum and barite.

(1) Carbonate nodules

The micromorphology of carbonate nodules, especially in non-calcareous Vertisols has been reported by many workers (Blokhuis et al., 1968/1969, 1970; Rajan et al., 1972; Abdel-Kader and Abdel-Hamid, 1974; Wieder and Yaalon, 1974; Olmedo Pujol, 1980; Mermut and Dasog, 1986; Dasog et al., 1988b). They are one of the distinct macro-and micro-pedofeatures of the Vertisols, and may contain different amounts of X-ray amorphous Fe–Mn oxyhydroxide (Fig. 4.8).

According to their mode of origin and micromorphology, Wieder and Yaalon (1974) have distinguished three kinds of calcite nodules. These are:

(1) orthic, which contains skeleton grains similar to the surrounding soil, and formed *in situ*;

(2) disortic, which is transported by pedoturbation within the profile; and

(3) allotic, which have a non-carbonatic internal fabric that differs in composition from the soil fabric.

In their detailed studies, Mermut and Dasog (1986) indicated that the amount of impurities which controls the internal fabric of the carbonate nodules may be useful in understanding the type of environment under which they occur. They found that those occurring in the soils under subhumid climatic conditions had higher engulfed soil materials than in that of lower rainfall areas. More engulfing of soil matrix by the nodules was attributed to the result of relatively high dissolution in the wet season coupled with rapid precipitation during the dry season.

The size, shape, distribution and orientation of carbonate nodules were also studied in two dimensional thin sections from India by Mermut and Dasog (1986). They found that nodules have a clustered and semi-banded basic distribution pattern (Fig. 4.9). Some bands were about 45° from horizontal. The orientation pattern of the nodules corresponded with the major preferred orientation direction of planar voids and slickensides. This was interpreted as a sign of soil displacement through shear failure.

Four Indian Vertisols from four different rainfall regions studied by Dasog et al. (1988b) showed that a considerable proportion of calcitic nodules were impregnated with Fe–Mn oxyhydroxides in the soils from low rainfall regions; however, they were rare or absent in the soil from the high rainfall region. The presence of Fe–Mn oxyhydroxides in calcite nodules was attributed to past hydromorphic conditions.

(2) Cutans

Illuviation processes in Vertisols are either nonoperative or obliterated by the pedoturbation or by soil displacement (Dudal and Eswaran, 1988). The amount of cutans found in Vertisols is not enough to consider the process as significant. Some insignificant cutans are observed in the subsoil in Vertisols with evidence of leaching and pH lower than 6.5. With advanced leaching and formation of cutans, the soil may then be transformed to other soils such as Alfisols.

(3) Iron–manganese segregations

Formation of Fe–Mn segregation is controlled by oxidation–reduction potential of the soil, and they are reported to be pedogenic (Blokhuis et al. 1968/1969; Ghitulescu, 1971; Kabakchiev and Galeva, 1973; Bellinfante et al., 1974; Mitsuchi, 1976; Sleeman and Brewer, 1984; Stephan and de Petre, 1986). They are common

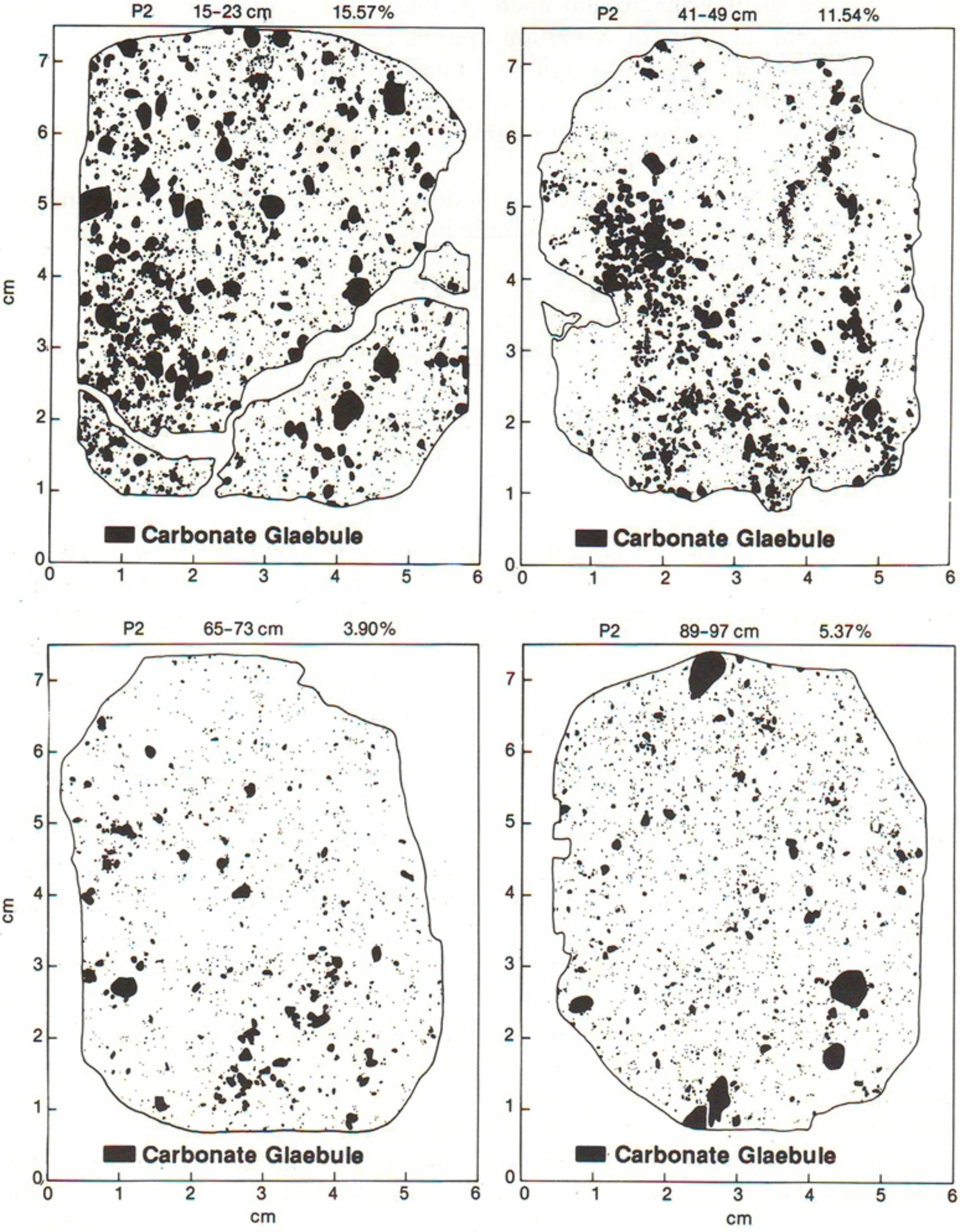

Fig. 4.9. Size, shape, distribution and orientation patterns of the carbonate nodules, >40 μm, at two different depths of the Bijapur profile (after Mermut and Dasog, 1986).

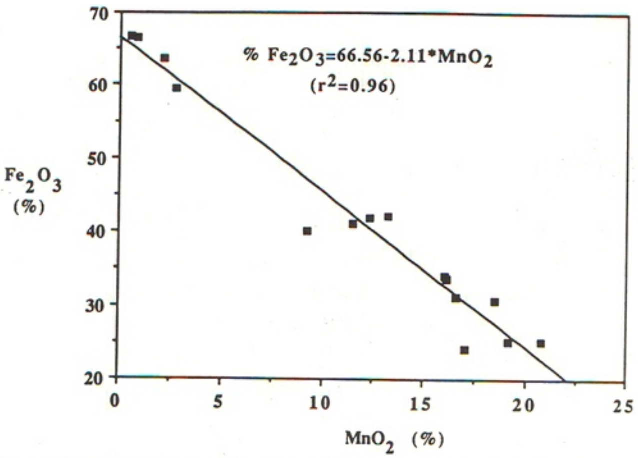

Fig. 4.10. Variations in Fe– and Mn–oxide concentrations of nodules from the Akuse and Prampram soils (Acquaye et al., 1992).

especially in soils from basalt regions. According to the terminology used by Bullock et al. (1985), the major forms described in the literature include typic, concentric and cross concentric. Acquaye et al. (1992) found an inverse relation between Fe and Mn content of nodules occurring in the Vertisols from the Accra plains of Ghana (Fig. 4.10).

(4) Animal activity

Several investigators have reported the occurrence of mineral animal excrements in Vertisols (Kooistra, 1982; Stephan and de Petre, 1986). It is generally agreed that soil fauna do not play a significant role in the genesis of Vertisols. The influence decreases with depth. Sleeman and Brewer (1984) have reported the presence of *milliped modexi* and *termite* fecal pellets in Australian Vertisols. Mineral excrements were present to varying extents in the Vertisols studied by Dasog et al. (1988b), but they were most abundant in the surface horizons. Kooistra (1982) reported minor animal activity in the majority of Vertisols from India. High faunal activity, wherever found, was considered to be of significance in improving the physical conditions of the soil.

(5) Relic features

Sufficient relics of pedogenic or geologic features are found in Vertisols that helps to decipher the genesis of Vertisols (Nettleton and Sleeman, 1985). They include papules, void argillans, carbonate nodules (discussed above), pseudomorphs of biotite and other weatherable minerals, shell fragments of molluscs or gastropods (Fig. 4.8), bones, artifacts (such as bricks and pottery) and fragments of coal, etc.

Nettleton and Sleeman (1985) indicated that papules and illuvial coatings are typical examples of relic features found in the Vertisols. It is hypothesized that some of the Vertisols in the Mediterranean area (Osman and Eswaran, 1974) are derived from Alfisols and the presence of clay coatings are evidence of the early stage of soil development. Available data suggest that the conversion of Alfisols to Vertisols took place under a climate wetter than the present one.

It is believed that clay illuviation is unlikely in Vertisols, and even if it occurs, it may be very difficult to ascertain, because the intense pedoturbation would obliterate it beyond recognition (Blokhuis, 1982). Yerima et al. (1987) found that argillans were preserved in tropical Vertisols in El Salvador. Several other authors reported the presence of illuvial argillans in the C horizon of these soils (Osman and Eswaran, 1974; Verheye and Stoops, 1974; Mermut and Jongerius, 1980).

The above discussion suggests that several morphological characteristics are not completely understood and there is need to further our knowledge in this area.

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