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Vertic Features

Irina Kovda[1,*], Ahmet R. Mermut[2]

[1] INSTITUTE OF GEOGRAPHY, RUSSIAN ACADEMY OF SCIENCES, MOSCOW, RUSSIA
[2] FACULTY OF AGRICULTURE, HARRAN UNIVERSITY, SANLIURFA, TURKEY

1. Introduction

Vertic features result from shrink-swell processes, pedoturbation (or churning) and lateral shearing due to the alternating water regime in clayey materials. They are recognized in Vertisols and in various vertic soils that do not meet the requirements for this soil group or order. Cracking and pedoturbation are now believed not to be the most important but concomitant processes in the formation of vertic features by lateral shearing.

The World Reference Base for Soil Resources (IUSS Working Group WRB, 2006) defines Vertisols as churning heavy clay soils with high proportion of swelling clays, deep cracks and a vertic horizon, the latter being a clayey subsurface horizon that, as a result of shrinking and swelling, has slickensides and wedge-shaped peds. In Soil Taxonomy (Soil Survey Staff, 1999), similar criteria are used, with mention of slickensides, pedality, clay content and cracks in the soil order definition.

Vertic features occur worldwide in swelling clay soils, from boreal to tropical environments, with alternating wet and dry periods. They occur under a variety of moisture and temperature regimes, landforms, ecosystems and crops, which influence and transform their macro- and micromorphological, physical and chemical attributes, but retain the diagnostic features.

The major morphological markers of Vertisols are slickensides and wedge-shaped peds (e.g. Mermut et al., 1996a). Other relevant characteristics are a clayey texture, high density when dry, granular structure in surface horizons, blocky structure at subsurface levels, deep wide cracks, monotonous colour coupled with weak horizonation or discontinuous cyclic sequences interrupted by diapiric intrusions (or "chimneys") of underlying material, gilgai, and pedogenic carbonate, iron–manganese oxide and gypsum segregations. Except for the slickensides, wedge-shaped aggregates and clayey texture, the mentioned characteristics may not all be present in Vertisols.

Vertic behaviour results in the development of specific micromorphological features that are observed in thin sections. Jongerius and Bonfils (1964) were the first to describe

* Corresponding Author:
Tel.: +7 495 9390564
E-mail: ikovda@mail.ru

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Table 1 Selected publications reporting Vertisol micromorphology

Region	Publication
America	Mermut and St. Arnaud, 1983; Yerima et al., 1987; Nordt et al., 2004
Africa	Fedoroff and Fies, 1968; De Vos and Virgo, 1969; Blokhuis et al., 1970; Labib and Stoops, 1970; Buursink, 1971; Rodriguez Hernandez et al., 1979; Acquaye et al., 1992; Blokhuis, 1993
Europe	Krupenikov et al., 1966; Yarilova et al., 1969; Ghitulescu, 1971; Kabakchiev and Galeva, 1973; Bellinfante et al., 1974; de Olmedo Pujol and Perez, 1975; Stephan, 1979; Tulpanov and Makeeva, 1984; Bystritzkaya et al., 1988; Fedorov and Solianik, 1991; Kovda et al., 1992
Asia	Kooistra, 1982a, 1982b; Rao et al., 1986; Dasog et al., 1988
Australia	Sleeman and Brewer, 1984

in detail the micromorphology of a Vertisol. Micromorphological investigations were subsequently performed worldwide as part of studies on Vertisol genesis, and commonly presented at international meetings on Vertisols or soil micromorphology. Selected examples of papers describing vertic features in tropical, subtropical and boreal Vertisols are listed in Table 1. Over the last two decades, studies focused mainly on classification issues and on the understanding of stress phenomena.

A number of papers present an overview of the micromorphological characteristics of Vertisols and vertic features, and their pedogenic interpretation (Nettleton & Sleeman, 1985; Mermut et al., 1988, 1996b; Blokhuis et al., 1990). Illustrations of vertic features in thin sections can also be found in the G.D. Smith Memorial Slide Collection (Eswaran et al., 1999).

The purpose of this chapter is to review and summarize available micromorphological information on vertic features, in Vertisols and in the vertic intergrades of other soil groups. The specificity of these soils is largely related to shrink-swell, churning and shearing processes, which strongly influence all aspects of the microfabric.

2. Microstructure

At subsurface levels, an angular blocky microstructure (Fig. 1) with prismatic peds is typical for vertic horizons and corresponds to the wedge-shaped or prismatic pedality observed in the field. Subangular blocky (Fig. 1, 2), massive and complex microstructures also occur.

The surface (1–5 cm) horizon of Vertisols may have fine granular microstructure produced by repeated self-mulching, i.e. cracking and swelling (Nettleton et al., 1983; Mermut et al., 1996b). Mermut et al. (1988) noted the importance of rapid desiccation in the formation of a granular structure. Experiments have shown that in the course of successive wet and dry cycles the structure of the surface of a Vertisol gradually changes from massive to complex crumb, blocky and platy and that the size of the peds progressively decreases (Hussein & Adey, 1998). Development of a granular microstructure may contribute to the appearance of other vertic features. For instance, granular peds falling down cracks may

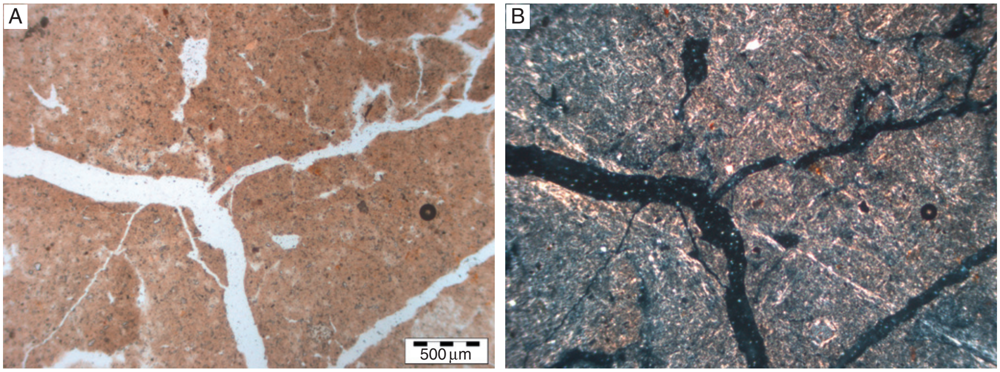

FIG. 1 Angular and subangular blocky microstructure and dense groundmass (B-horizon of a Vertisol, Ecuador). (A) In PPL. (B) Same field in XPL, showing various striated b-fabrics. (Ghent University archive)

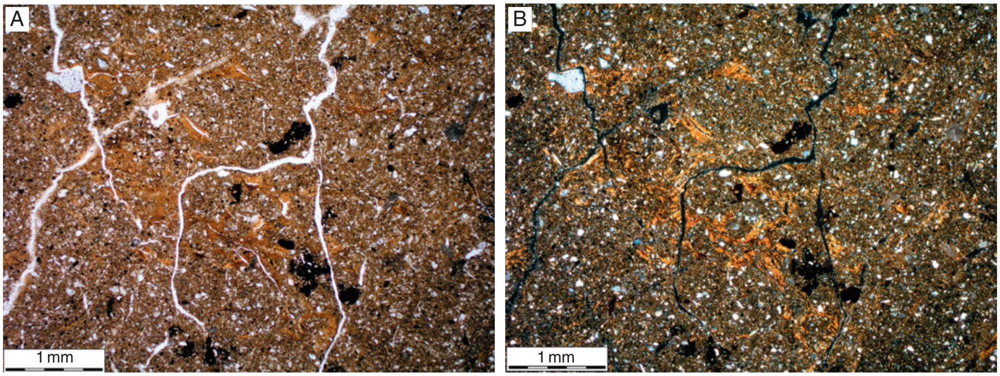

FIG. 2 Subangular blocky microstructure, dense groundmass with open porphyric c/f-related distribution and illuvial clay coatings (2Bkss2b-horizon of a vertic palaeosoil north-western Caucasus, Russia). Note that some clay coatings are related with present pores whereas others have been incorporated into the groundmass. (A) In PPL. (B) Same field in XPL. (Images by I. Kovda)

lead to heterogeneity of the groundmass at the initial stage, which is homogenized in mature Vertisols (Kovda, unpublished work). Rounded microaggregates were described in vertic horizons of Turkish and Israeli Vertisols and linked with an increase of the structural stability index and of hydraulic conductivity (Kapur et al., 1997).

The degree of pedality and ped separation is usually strong in dry field conditions but changes to weak in wet soils. Intra-aggregate microporosity is usually weakly developed, but planar voids separating peds are common. Planar voids (Fig. 3) dominate in the vertic horizon at a depth between 60 and 160 cm (Blokhuis et al., 1990). Bui and Mermut (1989) found that the dominant orientation of planar voids is subhorizontal and oblique. It has been suggested that the frequency and orientation of planar voids could be used to distinguish between Vertisols and vertic subgroups (Mermut et al., 1988, 1996a).

The characteristics and distribution of pores in Vertisols have been studied using image analysis (Puentes et al., 1992; Velde et al., 1996; Cabidoche & Guillaume, 1998;

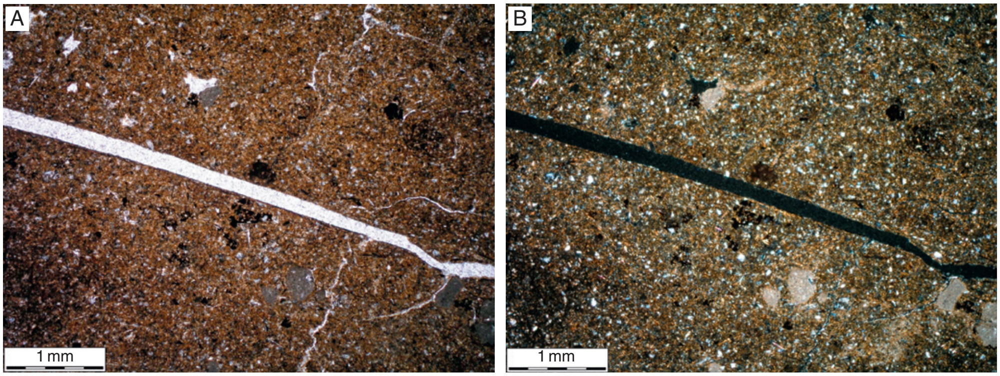

FIG. 3 Large planar void, typical for vertic materials (vertic palaeosoil, north-western Caucasus, Russia). (A) In PPL. (B) Same field in XPL. (Images by I. Kovda)

Moreau et al., 1999), but most of these studies were focused on the evaluation of image analysis techniques rather than on the characterization of Vertisol porosity.

Thin section preparation procedures may lead to structural changes in the clayey material. Freeze drying and critical point drying were compared, using SEM control, to find out which method of dehydration leads to more significant alteration of the microstructure (Bruand & Tessier, 1987; Tessier, 1987). It was observed that freeze drying gives rise to numerous microscopic cracks (1 m wide). The critical point drying method modifies the microstructure less significantly, but leads to a decrease in specimen volume.

3. Groundmass

Vertic horizons are mainly composed of clay with few coarse constituents. They usually have a dense groundmass with a double-spaced or open porphyric c/f-related distribution pattern.

Material from the surface horizons falls down the open cracks and is incorporated in deep horizons of the subsoil. In thin sections, this process can be recognized by a heterogeneous groundmass with incorporated dark aggregates (Fig. 4) or with materials of contrasting colour and composition occurring side by side (Fig. 5) (Mermut et al., 1996a; Kovda et al., 1999). Lateral shearing may lead to the lateral heterogeneity of the groundmass. These processes explain the complex morphology and soil cover pattern of some Vertisols (Wilding et al., 1990), especially in more wet conditions, and the strongly contrasting colours at the surface and in depth.

3.1 Coarse Fraction

Coarse material generally occurs in small amounts and rarely show relevant micromorphological features. Coarse grains can become fragmented by swell-shrink behaviour of the soil, showing an increase in the degree of fragmentation with decreasing depth

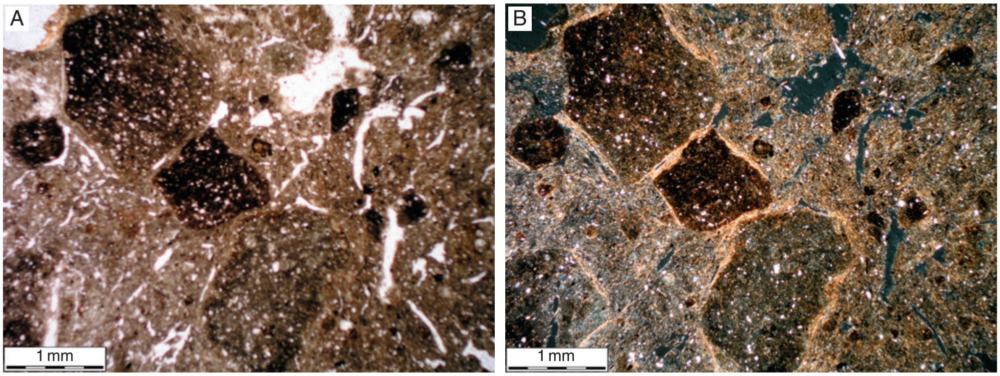

FIG. 4 Heterogeneous groundmass (Bkss-horizon of a Vertisol, Northern Caucasus, Russia). Dark aggregates of material originated from the surface horizon are incorporated in the groundmass. (A) In PPL. (B) Same field in XPL. Note the strongly developed granostriated b-fabric. (Images by I. Kovda)

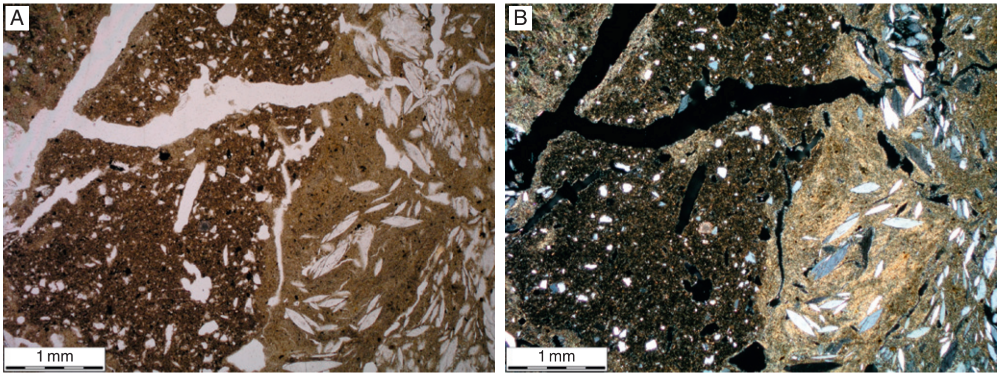

FIG. 5 Heterogeneous groundmass with material rich in organic matter and with an undifferentiated to weakly developed stipple-speckled b-fabric occurring next to clayey material with random striated b-fabric and coarse gypsum grains (BCkssy-horizon of a Vertisol, Northern Caucasus, Russia). (A) In PPL. (B) Same field in XPL. Note the well-developed porostriated b-fabric in the left upper corner. (Images by I. Kovda)

(Rodriguez-Hernandez et al., 1979). Phytoliths in deep subsurface horizons can be an indication of the incorporation of surface-derived material through the vertical cracks (Fig. 6) (Boettinger, 1994; Kovda et al., 1999).

3.2 Micromass

3.2.1 Colour

A dark colour of the micromass is typical for many Vertisols and other soils with vertic properties. It has mainly been attributed to strong complexation between clay and organic matter (Singh, 1956). Bornand et al. (1984) considered the localization of organic matter in relation to smectite layers and particles (quasi-crystals), whereby a small part

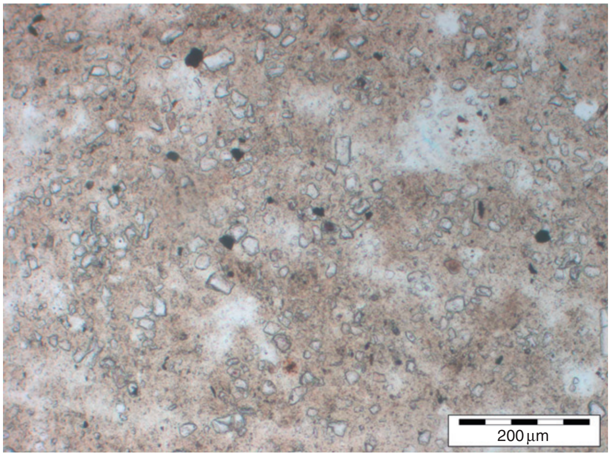

FIG. 6 Numerous phytoliths incorporated into the groundmass (C-horizon of an orthic-eutric Vertisol), (Gigantones, Ecuador) (PPL). (Ghent University archive)

of the organic matter was found to have an external position and the main part has intraparticle localization.

The colour of the fine material is strongly influenced by climate, parent material and carbonate content. Vertisols and vertic soils in arid and semi-arid environments generally have a red-brown colour. In temperate or wet environments, they are often darker due to higher biological activity and higher organic matter content (Dudal, 1965; Nordt et al., 2004). Vertisols derived from basalt are usually dark. More than half of all grey, brown and red clayey soils in Australia are dominated by illite and kaolinite (Norrish & Pickering, 1983).

3.2.2 b-fabric

Shrink and swell processes in soils result in microshearing, which leads to reorientation of the individual clay plates into planar zones with face-to-face alignment of clay domains (Wilding & Tessier, 1988). These zones correspond to streaks with striated b-fabrics, characteristic of vertic materials (McCormack & Wilding, 1974; Mermut et al, 1996a). Mono-, parallel, cross-, poro- and granostriated b-fabrics (Figs. 1B, 4B) occur together with speckled b-fabrics (Fig. 5B). Strial b-fabrics can characterize Vertisols at depth, where these soils developed on sedimentary parent materials (e.g. Mees, 2001). The local occurrence of materials with this b-fabric in BC- and C-horizons can be used to estimate the amount of sediment already converted to soil material (Dasog et al., 1987).

SEM studies have shown strong orientation of clay particles in vertic horizons and, on the other hand, a decrease of the size of oriented clay domains due to their breakdown by high pressures under swelling (Tessier et al., 1992).

Calcitic crystallitic b-fabrics are predominant in calcareous vertic horizons from arid and semi-arid environments (e.g. Blokhuis et al., 1970; Bellinfante et al., 1974; Kalbande et al., 1992; Pal et al., 2001). In these soils, the presence of calcite in the groundmass masks the occurrence of striation (Wilding, 1985; Kalbande, 1988; Mermut et al., 1996b;

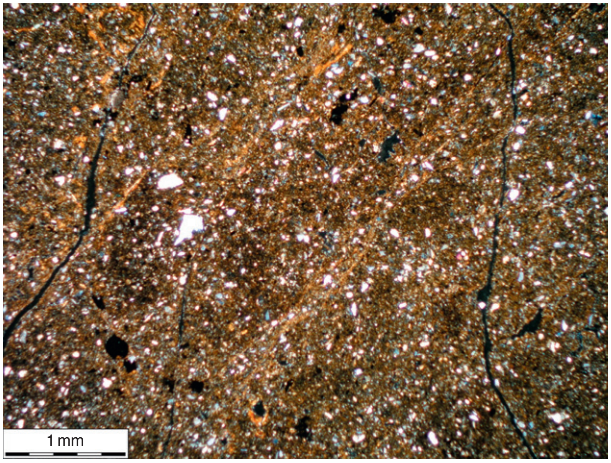

FIG. 7 Parallel-striated b-fabric (2Bkss2b-horizon of a vertic palaeosoil, north-western Caucasus, Russia). Note the striations corresponding to former slickensides, crossing present-day planar voids (XPL). (Image by I. Kovda)

Aydemir et al., 2004). This is demonstrated by the better recognition of striated b-fabrics in decalcified thin sections (Wilding & Drees, 1990). The expression of b-fabrics can also be obscured by the dark colour of the micromass related to a high organic matter content (Yerima et al., 1987; Eswaran et al., 1988; Kovda et al., 1992) or by a poor orientation resulting from a small size of the clay particles (Eswaran et al., 1988).

Vertic horizons with distinct slickensides show well-developed striated b-fabrics (Fig. 7) (Mermut et al., 1996a). In SEM images, slickensides are recognized as bright, smooth surfaces with microgrooves approximately 0.3–20 μm wide, which are believed to be caused by the movement of coarse grains (Morgun Nobles et al., 2004). The thickness of the oriented clay along the slickenside surface is about 3–4 μm. A decrease in shrink-swell and shearing intensity is reflected by weakening of the expression of striated b-fabrics in thin sections and by lowering of the brightness of surfaces in SEM images.

The degree of development of striated b-fabrics is affected by several factors. It seems to be greater in areas with high rainfall than in dry areas and to increase with increasing depth (Blokhuis et al., 1970). The same study indicates that the development of granostriated b-fabrics is influenced by the intensity of the churning process and by the size of the coarse grains.

Attempts have been made to correlate b-fabrics with the shrink-swell potential of a soil measured by COLE values, whereby it was found that higher COLE values corresponded to better developed striated b-fabrics (Yerima et al., 1987). In turn, the shrink-swell potential of a soil is generally negatively correlated with the abundance of organic matter, carbonates, gypsum, iron–manganese oxides and low-activity clays, and with electrolyte concentration (Mermut et al., 1991). Kalbande et al. (1992) found that weak swelling of clays, limited by chloritization of smectite interlayers, was insufficient for the formation of a porostriated b-fabric and only resulted in either mosaic-speckled or granostriated b-fabrics. Based on variations in b-fabric, Kalbande (1988) suggested that shrink-swell processes are less pronounced in the presence of micritic calcite or coarse grains and in conditions with short dry periods.

Changes in b-fabric through wet/dry cycles were studied by Hussein and Adey (1998). They found that these changes were less well defined and more difficult to interpret than microstructure changes developed in the same conditions. The development of b-fabric generally decreased as the soil went through successive wet/dry cycles. B-fabrics were better developed in vertical thin sections than in horizontal thin sections, suggesting that more clay orientation took place parallel to the wetting front. In this study, the b-fabrics were generally mosaic- to stipple speckled with granostriation around large mineral grains and calcium carbonate nodules, and with weakly developed or absent porostriation.

The degree of development of vertic features may decrease in mature soils. Deep black soils on alluvium derived from weathered basalt, with typical properties of Vertisols except for the presence of slickensides, show only weakly developed porostriated b-fabrics (Paranjape et al., 1997). In these soils, shrink and swell processes are operative but their extent is not great enough to reorganize particles and produce b-fabrics typical for vertic horizons. Clayey smectite-dominated soils may need at least 550 years of shrinking and swelling before slickensides and striated b-fabrics can be formed (Paranjape et al., 1997).

Drying of unconfined soils does not produce significant reorganization of clay domains, because this requires a rather strong force. However, some methods of thin section preparation may create artificial stress that could enhance the development of shear-related b-fabrics (Blokhuis et al., 1990). This happens when moist clayey soil is dried quickly and/or when the resin is excessively heated during hardening (60–80˚C). Shear-related b-fabrics can also occur along the edges of a thin section, as a result of friction between the material and the sampling tool.

3.3 Pedofeatures

In comparison with the groundmass features discussed above, the type, distribution, orientation and abundance of pedofeatures in thin sections of vertic materials are much more variable, in function of the temperature and moisture regimes. They therefore provide useful information on environmental conditions.

3.3.1 Fe and Mn Oxide Pedofeatures

Fe and Mn oxide concentrations are very common in vertic horizons and Vertisols as a whole (Sleeman & Brewer, 1984; Blokhuis et al, 1990). The high water retention properties and low permeability of the dense clayey vertic materials are responsible for humid or water-saturated environments and consequently for the reduction and mobilization of Fe and Mn, resulting in the formation of Fe and Mn oxide pedofeatures (see also Lindbo et al., 2010, this book).

The most common Fe and/or Mn oxide features are impregnative and intrusive nodules (Fig. 8) and poorly crystalline coatings and hypocoatings (Rodriguez Hernandez et al., 1979; Sleeman & Brewer, 1984; Blokhuis et al., 1990; Kovda et al., 1992; Nordt et al.,

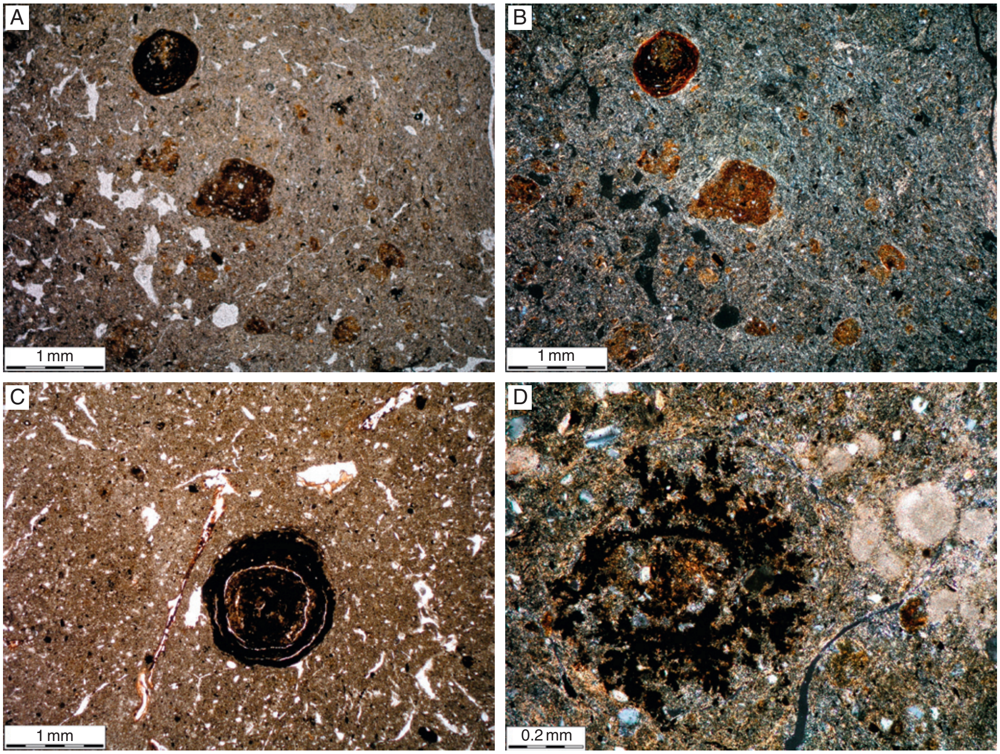

FIG. 8 Impregnative Fe/Mn oxide nodules (Vertisols, Northern Caucasus, Russia). (A) Typic Fe/Mn oxide nodules (Bkss-horizon) (PPL). (B) Idem in XPL. Note granostriation around nodules. (C) Concentric Fe/Mn oxide nodule (Bss-horizon) (PPL). (D) Dendritic Fe/Mn oxide nodule (Bk-horizon). Note also the calcite nodules (PPL). (Images by I. Kovda)

2004). Concentric nodules (Fig. 8C) are typical and are believed to reflect moisture regimes with repeated seasonal wet/dry cycles (Brewer, 1964; Stoops, personal communication). Image analysis and mapping with SEM/EDS analysis of these nodules in a young Vertisol from Texas have shown clear banding for Fe and Mn, and no banding for Al, Si, K, Ca or Ba in any of the studied nodules (White & Dixon, 1996). Typic, aggregate or dendritic nodules (Fig. 8A, 8B, 8D), partly with gradual boundaries, have also often been described in vertic materials (Labib & Stoops, 1970; Buursink, 1971; Sleeman & Brewer, 1984). An upward increase in degree of fragmentation and dispersion of these pedofeatures has been reported (Rodriguez Hernandez et al., 1979).

The occurrence of abundant Fe and Mn oxide pedofeatures of various morphologies has been interpreted as evidence for prevailing wet conditions in the past (Blokhuis et al., 1969; Kabakchiev & Galeva, 1973).

3.3.2 Carbonate Pedofeatures

Vertic horizons may be free of carbonates or may have soft (powdery) or hard (concretionary) carbonate segregations. In thin sections, hard carbonate nodules are generally

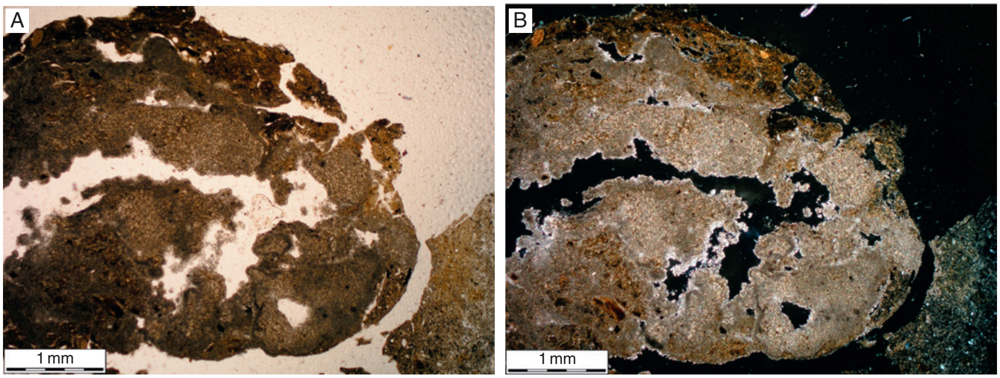

FIG. 9 Geodic disorthic complex microsparitic carbonate nodule with Fe and Mn oxide impregnations (Bkss-horizon of a Vertisol, Northern Caucasus, Russia). (A) In PPL. (B) Same field in XPL. (Images by I. Kovda)

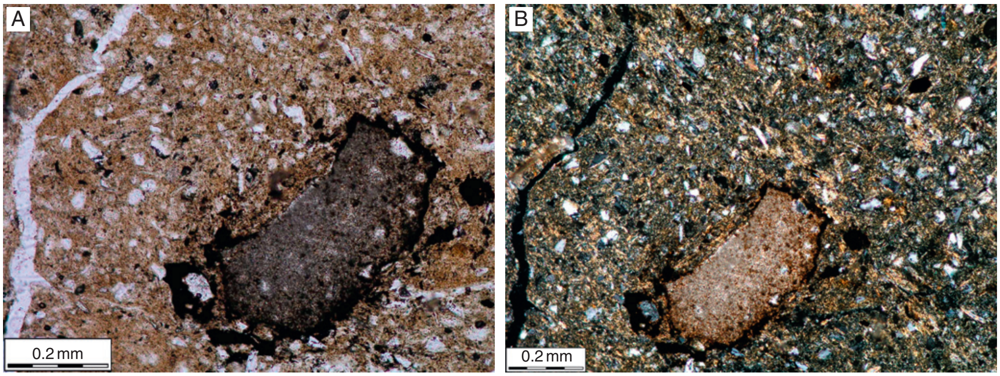

FIG. 10 Typic disorthic calcite nodule with external and internal Fe oxide hypocoating (3Bkss1b-horizon of a vertic palaeosoil, north-western Caucasus, Russia). (A) In PPL. (B) Same feature in XPL. (Images by I. Kovda)

micritic or microsparitic and usually have sharp boundaries. Calcite nodules can be orthic, disorthic or anorthic (Wieder & Yaalon, 1974).

Hard nodules also often contain Fe and Mn oxide impregnations (Fig. 9, 10), including dendritic Mn oxide occurrences (Blokhuis et al., 1969; Labib and Stoops, 1970; Kooistra, 1982a). Their sharp boundary has been attributed to churning processes, i.e. argilloturbation (Blokhuis et al., 1969; Wieder and Yaalon, 1974). The sharp boundary has also been considered an indication that nodules were no longer actively growing (Kovda et al., 2003; Nordt et al., 2004).

White and black carbonate nodules, with and without Fe/Mn oxide coatings, have been described for Indian and Sudanese Vertisols (Blokhuis et al., 1969; Rajan et al., 1972; Mermut & Dasog, 1986; Srivastava et al., 2002). Microsparitic or sparitic carbonate nodules with Fe/Mn oxide coatings and sharp boundaries have been interpreted as having formed elsewhere, followed by transportation and redeposition (Pal et al., 1999, 2001). Fe/Mn oxide coatings on hard carbonate nodules reflect a wetter environment and are often a relict feature (Mermut & Dasog, 1986). These coatings can protect carbonate nodules against recrystallization, preventing rejuvenation of their radiocarbon age and changes in stable isotope geochemistry (Kovda, 2004).

Shrinking-swelling, lateral shearing and vertical churning have an impact on the morphology and location of carbonate pedofeatures. Many hard carbonate nodules are disorthic, whereas micritic soft carbonate masses may be elongated parallel to the shear direction (planar voids or slickensides) (Podwojewski, 1995). Carbonate nodules may have a clustered or semi-banded distribution parallel to planar voids or slickensides. Some bands were reported to be oriented at an angle of 45° with the horizontal, indicating soil displacement through shear failure (Mermut & Dasog, 1986). Blokhuis et al. (1969) explained the peculiarities of hard carbonate nodules in Vertisols by their formation in the substratum and further upwards transport, during which they acquired a subangular to rounded shape and also became harder. The Fe/Mn oxide impregnations and coatings on those carbonate nodules were also inherited from the substratum.

Micritic/microsparitic calcite coatings and hypocoatings in voids have been documented as well in horizons with vertic properties (Blokhuis et al., 1990; Kovda et al., 2003; Heidari et al., 2005).

3.3.3 Gypsum Pedofeatures

Gypsum pedofeatures often occur in deep vertic materials in arid environments (Dudal, 1965; Sehgal & Bhattacharjee, 1988; Ahmad, 1996). Compared with Fe/Mn oxide and carbonate pedofeatures, gypsum pedofeatures are less common. Various gypsum features have been described (Barzanji & Stoops, 1974; Podwojewski & Arnold, 1994; Podwojewski, 1995) with no indications about the relationship between those features and vertic characteristics. Gypsum can be inherited from the parent material or formed by early translocation processes of soluble constituents of the parent material by groundwater or soil solutions and even from ocean source (Barzanji & Stoops, 1974; Parfenova & Yarilova, 1977; Podwojewski & Arnold, 1994; Coulombe et al., 1996a).

3.3.4 Textural Pedofeatures

Textural pedofeatures, in particular illuvial clay coatings, are uncommon in Vertisols and horizons with vertic properties (Blokhuis, 1993). Nevertheless, they have sometimes been described (Osman & Eswaran, 1974; Verheye & Stoops, 1974; Mermut & Jongerius, 1980; Yerima et al., 1987). Osman and Eswaran (1974) combined data on the percentage of clay coatings in thin sections with total clay contents and incipient flocculation ratios, concluding that clay translocation is an active process in Vrtisols but that the evidence of clay translocation is continuously being destroyed by vertic processes. Textural pedofeatures are often fragmented and/or deformed and incorporated in the groundmass by shrink-swell and shearing processes (Fig. 2) (Nettleton & Sleeman, 1985; Yerima et al., 1987; see also Kühn et al., 2010, this book). They are more commonly found in deep horizons, where they are not disturbed by shrink-swell activity (Wilding & Drees, 1990).

Some textural pedofeatures may show a kink-band fabric instead of a continuous orientation (Stoops, 2003).

Textural pedofeatures in Vertisols can be related to a former wetter environment or to a decrease of the activity of vertic processes, with the rate of illuviation exceeding the rate of destruction by churning processes (Nettleton & Sleeman, 1985).

The development of clay coatings can be due to ferrolysis in wet Vertisols that become very acid, because of redox changes under alternating seasonal reduction and oxidation, resulting in clay disintegration in the upper part of the soil (Wilding, personal communication).

Pedofeatures composed of silt, in the form of nodules and intercalations, were occasionally found in some Australian cracking clay soils, generally in the lower part of the profiles (Sleeman & Brewer, 1984).

4. Degradation of Vertic Features in Cultivated Soils

Well-illustrated examples of how structure and porosity of Vertisols are affected by land use were presented by Coulombe et al. (1996b), showing that continuous and intensive cultivation results in the formation of a massive structure, an increase in bulk density and a lowering of continuity and connectivity of macropores. McGarry (1987, 1989) reported that structural degradation may extend to a depth of 65 cm and result in the development of blocky, massive or platy microstructures in various parts of the profile. A comparison of the effects of wet and dry cultivation on soil structure and b-fabric using thin sections shows that cultivation of wet soils leads to better developed striated b-fabrics, mostly at a depth of 5–20 cm (McGarry, 1987, 1989). This is related to the greater incidence, at this depth, of shearing of soil in a plastic state by tillage tools and tractor wheels.

Waterlogging is a major risk in irrigated Vertisols and results in changes of the type, location and abundance of pedofeatures (calcite, gypsum and Fe/Mn oxide occurrences; clay coatings; depletion pedofeatures). Dissolution of calcite and gypsum and their accumulation in deep horizons as calcite nodules and gypsum infillings were described for wet Vertisols (Kovda et al., 2003). Newly formed pedofeatures reflect a wetter soil environment by the larger size of the crystals and by the presence of illuvial clay coatings and iron oxide nodules. Fe oxides occur as impregnative typic nodules and hypocoatings instead of concentric nodules. In irrigated soils, the total porosity and the degree of development of b-fabrics increase, microaggregation and intra-aggregate porosity decrease and the colour of the micromass in the surface horizon changes to lighter brown (Dostovalova & Tursina, 1988).

The reclamation of sodic Vertisols by adding $CaCO_3$ results in a change in aggregation, an increase in clay translocation and the dispersion of fine organic material (Bystritskaya et al., 1988). Experiments with Br and Brilliant Blue FCF dyes have shown that slickensides do not act as significant barriers for the penetration of solutes and chemicals into the groundmass (Morgun Nobles et al., 2004). Solutes penetrate into the soil both vertically along the cracks and laterally through the slickenside surfaces.

5. Vertic Features in Palaeosoils

Diagnostic vertic features are usually well preserved and easily identifiable in palaeosoils. Vertic features in palaeosoils have been recognized in several places worldwide (Matviishina, 1982; Gray & Nickelsen, 1989; Tsatskin & Chizhikova, 1990; Driese & Foreman, 1992; Joeckel, 1994, 1995; Driese et al., 2003; Kovda et al., 2008;).

Vertic palaeosoils commonly have a reddish brown colour and vertic field properties such as a coarse blocky and wedge-shaped structure and slickensides. In thin sections, typical vertic features such as an open porphyric c/f-related distribution, a blocky microstructure and striated b-fabrics (cross-, poro-, grano- and parallel striated) are observed (Driese et al., 2003; Kovda et al., 2008). Voids related to non-active slickensides sometimes show only weakly developed porostriated b-fabrics (Fig. 3) and can be filled with carbonates, gypsum, and silt-sized quartz grains and have Fe/Mn oxide coatings. Typic and complex carbonate nodules with distinct sharp boundaries (disorthic) have been reported (Caudill et al., 1996). Clay coatings were described in some Pleistocene Vertisols (Fig. 2), as well as in a variety of Fe and Mn oxide nodules and carbonate pedofeatures (Kovda, 2004). Several phases of carbonate precipitation and later recrystallization have been documented in vertic palaeosoils of various ages (Caudill et al., 1996; Kovda, 2004). Pal et al. (2001), using micromorphological observations for Bss-horizons, supported the idea of a polygenetic nature of some Vertisols in Central India.

Vertic palaeosoils can provide additional information for environmental reconstructions because they undergo little burial compaction (less than 10%) due to their high original density (Blodgett, 1985; Caudill et al., 1996). This fact was used to correlate the depth to the pedogenic carbonate horizon in Holocene Vertisols with the mean annual precipitation for estimating palaeo-precipitation values (Caudill et al., 1996). The difficulties of this method are depth corrections for erosion and possible microrelief and/or subsurface cycling in the past. The wetter soil environments in the microlows and drier conditions in the microhighs complicate the estimation of mean annual precipitation for the area. Micromorphology could be helpful for identification of erosion and correlation with palaeomicrorelief.

Striated b-fabrics can not be used for the reconstruction of tropical or subtropical environments (with 4–8 dry months), as done by some authors (Tsatskin & Chizhikova, 1990; Driese & Foreman, 1992), because cold boreal Holocene Vertisols may show the same features. Other micromorphological features of vertic materials can help the identification of various stages of palaeopedogenesis (see also Fedoroff et al., 2010, this book).

6. Conclusions

Research on the micromorphology of vertic features has been carried out since the 1960s. Vertic features, resulting from shrink-swell processes, vertical mixing and lateral shearing, due to alternating wetting and drying of clayey materials, are very prominent and rather easy to identify in thin sections.

Vertic materials show a characteristic combination of micromorphological features. The most relevant are striated b-fabrics, an open porphyric c/f-related distribution, a blocky microstructure, a heterogeneous groundmass with incorporated dark aggregates, Fe/Mn oxide pedofeatures and, in more arid regions, carbonate and gypsum pedofeatures. However, classifying Vertisols and vertic subgroups of other soils based exclusively on their micromorphological characteristics is impossible (Blokhuis et al., 1991; Mermut et al., 1991), because other clayey soils may be micromorphologically similar.

The micromorphological study of vertic features in modern soils and palaeosoils can provide reliable information on the genesis and evolution of the soil and on long-term and short-term environmental changes and trends. Good indicators for the recognition of soils with vertic behaviour include the presence of surface-derived granular aggregates preserved in deep cracks or as part of a heterogeneous groundmass, as well as the occurrence of striated b-fabrics and abundant complex nodules. Nevertheless, more micromorphological studies are required for a better understanding of the preservation and diagenetic transformations of vertic features in palaeosoils.

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