

where z_p is the top of the emission plume, L is the distance between up- and downwind measurement towers and c_u and c_d are the up- and downwind concentrations, respectively. For more details of this method, see Denmead (1995).

Recently, some workers have also tried a large-scale mass-balance approach using the atmospheric boundary layer as a sort of chamber. During the day time, the convective boundary layer can grow to 1–2 km, while at nighttime a stable boundary on the order of 100 m often forms. Use of this method necessitates tethered balloons or aircraft to obtain concentration measurements throughout the boundary layer. Regionally averaged fluxes are then estimated from the changing concentrations in the layer. Again, this technique is discussed in more depth by Denmead (1995).

Summary and the future

This article has illustrated the rich theoretical history that allows micrometeorologists to estimate gas exchange between the surface and the atmosphere. It has also indicated how the theory is practically applied to make flux measurements. Though it is still common practice to search for homogeneous sites with good fetch, increasingly researchers are attempting to adapt these techniques to complex terrain. Much of this work currently relates to footprint analysis, but we can also expect to see more measurements of horizontal advection (Staebler and Fitzjarrald, 2004) as well as increasing use of new techniques such as backwards Lagrangian analysis (Flesch et al., 1995).

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MICROMORPHOLOGY

Definition and history

Micropedology is a method of studying undisturbed soil- and regolith samples with the aid of microscopic and ultramicroscopic techniques in order to identify the different constituents and to determine their mutual relations, in space and time, as far as the latter is possible. This means that the investigations should be carried out on undisturbed (and mostly naturally oriented) soil samples, in contrast to the other analytical methods used in soil science (e.g., mineralogical, chemical and physical analyses) requiring mostly a mixing, crushing, solubilization or fractionation of the samples.

The term micromorphology was originally used to refer to that field of micropedology dealing with fabric analysis only, but soon both were used as synonyms. Micromorphology, as a general term, comprises both the qualitative and the quantitative analysis of the soil; the latter is commonly referred to as micromorphometry.

The publication of W. L. Kubiěna’s “*Micropedology*” (1938) is considered as the official birth of this discipline. It contains the basic philosophy, some techniques (among others on the preparation of thin sections of unconsolidated materials) and a first terminology to describe soil microfabrics in a morphoanalytical way, i.e., by giving an enumeration of the morphologically distinguishable units present. The basic fabric types described by Kubiěna were the basis for the later classifications of related distributions patterns by Brewer (1964) and Stoops and Jongerius (1975). The first technical basis for

the consolidation of friable materials, necessary for preparing thin sections, was laid by Ross (1924).

Systematic studies of soils from Central Europe and Spain inspired Kubiěna to a new, morphogenetic approach on soil fabric, which he published first in “*Entwicklungslehre des Bodens*” (1948) and later rephrased in “*The Soils of Europe*” (1956). In this system the microscopic observation of soil materials (mainly in thin sections) leads directly towards the classification of the soil and its genetic interpretation. A same terminology therefore is used for both the type of microfabric and the type of soil or humus (e.g., Braunlehm, Braunerde, Mor).

This system, extended later with a few soil/fabric types from the semi-humid and humid tropics (e.g., Roterde, lateritic Roterde) was in general use till the end of the sixties. Main problems were caused by the fact that it could be used only for describing soil fabrics recognized and described as such by Kubiěna, and that it implied an implicit agreement of the scientist with the genetic considerations of Kubiěna on these materials (Kubiěna, 1970). The system moreover considers only soil *sensu stricto*, not the other regolith material.

Early in the sixties R. Brewer and J. Sleeman from CSIRO, Australia, published several papers on a new, morphoanalytical approach towards soil fabrics. They resulted in Brewer’s “*Fabric and Mineral Analysis of Soils*” (1964 and 1976). This was the first system fit for a systematic analysis and description of any soil or regolith material; the terminology consists for a large part of new coined words. By applying systematically this description technique to a large variety of soils from all over the world, micromorphologists gained a better insight in soil fabric in general, which in turn draw the attention to some weaker points in the system, giving rise to a common effort of a working group of the International Society of Soil Science to develop a new, more comprehensive system, published by Bullock et al. (1985), recently adapted and completed by Stoops (2003). Other important contributions to methodology of thin section analysis, not proposing a specific terminology, are the works of Altemüller (1974) and FitzPatrick (1984 and 1993). Also the fundamental contributions of Babel (e.g., 1975) to the micromorphology of organic soil components have to be mentioned. In the Soviet Union micromorphological research developed in several institutes, partially based on a long tradition in sediment petrography from which many terms (e.g., scaly and fibrous microtextures) were borrowed (Parfenova and Yarilova, 1962; Dobrovolski, 1983).

Apart from the morphogenetic approach of Kubiěna (1948 and 1956) all above mentioned systems are dealing with the individual description of the lowest level of organization, that of the basic constituents. Only in few cases these individual features are diagnostic for a given material or pedogenic process; in general a combination of features is necessary for a diagnosis. In order to make descriptions less lengthy and easier to compare, several authors proposed morphosynthetic systems, allowing describing these characteristic combinations in a few terms. Tentatives published by Brewer and Sleeman (1988), Stoops (1994) and Gerasimova (1994 and 2003) got hitherto little attention.

Whereas micromorphology was during the first two decades of its existence mainly used in studies on soil genesis and classification, on a qualitative basis, more and more need was felt for quantitative data. This tendency was first illustrated in Kubiěna’s “*Die mikromorphometrische Bodenanalyse*” (1967). With the introduction of electro-optical equipment end of the sixties, more emphasis was given to the quantification of pores and their

distribution in the frame of studies on soil structure, permeability, compaction, crust formation etc. At present, image analysis is becoming a major technique in micromorphology.

End of the sixties new powerful tools were developed and became commercially available, opening new possibilities for micromorphology: the scanning electron microscope (S.E.M.) and different types of microprobes. S.E.M. gave the possibility to study in great detail and in three dimensions the finest fabric components (e.g., mineral neoformations, alterations); the microprobe opened hitherto unexpected possibilities to determine chemical composition of fabric units (Bisdorf, 1981), stimulating for instance the application of micromorphology in the field of soil pollution studies.

International Working Meetings on Soil Micromorphology are organized every four years since end of the fifties. Their transactions are a main source of micromorphological information. An annotated bibliography of micromorphology covering the period 1968–1986 was prepared by Miedema and Mermut (1990).

Micromorphological research has to follow three subsequent steps: (i) sampling and sample preparation, (ii) fabric analysis and (iii) interpretation. They will be discussed systematically below.

Sampling and sample preparation

Because of the very nature of micromorphology, undisturbed and oriented samples are needed. This requires specific sampling techniques and precautions. Non-coherent soils are mostly sampled with the help of “Kubiěna boxes”, i.e., metal boxes with two loose covers and a body that can be opened, so that samples easily can be removed in the laboratory without disturbance (Figure M4). Pressing the box in a vertical or horizontal section of the profile does sampling. In many cases it is important to preserve the original moisture content during transport, in order to prevent formation of shrinkage cracks, dehydration of colloids or hydration of hygroscopic salts, e.g., by wrapping the boxes in plastic sheets. In case of very loose or brittle materials, the samples have to be pre-impregnated in the field, before transport, with a colorless varnish, such as cellulose acetate solution in acetone (Murphy, 1986).

For the preparation of thin sections, soil materials have to be made coherent by impregnation with a cold setting resin (Murphy, 1986) such as polystyrene, as first recommended by Altemüller (1962) or epoxy. Since these resins are not compatible with water, the latter should be removed. Because air-drying results mostly in the formation of shrinkage cracks and transformation of amorphous organic components, replacement

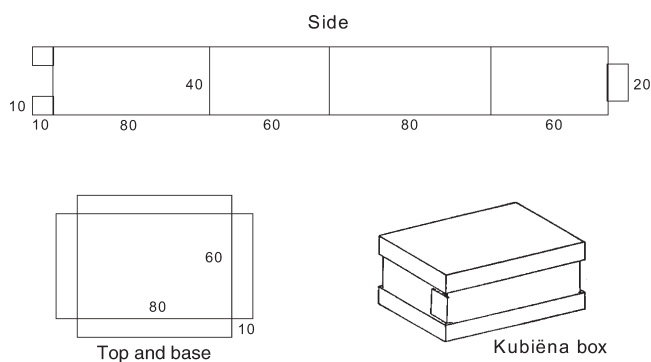


Figure M4 Kubiěna box.

of the water by acetone (Miedema et al., 1974; FitzPatrick, 1984; Chartres et al., 1989) is recommended. This can happen by immersing the sample in acetone, and replacing the latter daily, until all water is removed, or by the vapor phase method, in which the moist samples are put in a hermetically closed container over an acetone/water solution, which is every day replaced by a more concentrated solution, finally by pure acetone, until all water is removed (the first day a 2% acetone/water solution is used, which is doubled every day).

After impregnation with, and hardening of the resin, a slab is sawn from the block, grounded and lapped at one side, mounted on an object glass (1 mm thick), thinned by lapping until a maximum thickness of 20–30 μm , and covered by a cover glass (0.17 mm thick). During all these treatments only oil should be used as lubricating and cleaning agent instead of water, in order to prevent swelling of clays and dissolution of salts. Sizes of the thin sections range between 28 \times 48 mm (petrographic size) and 120 \times 180 mm (mammoth size), depending upon the type of research: the study of microstructure for instance requires large thin sections; detailed mineralogical identifications are easier to do on petrographic size sections. Preparation of thin sections of a sufficient large size and good quality has been, and still often is, one of the problems hindering a more general use of micromorphological techniques.

For S.E.M., undisturbed and dry micro samples are mounted with special glue on stubs and covered with a conductive coating (e.g., C, Au or Pd). Microprobe analyses require highly polished surfaces (e.g., specially polished, uncovered thin sections) and a conductive coating, preferentially of C.

Observation techniques

Soil thin sections are mostly studied with the help of an optical polarizing microscope (petrographic microscope), using transmitted light. In some cases circular polarized light is used, especially to study the fabric of the fine material (Pape, 1974) or to enhance the image of the porosity (Ruark et al., 1982). Identification of opaque materials (e.g., charcoal, pyrite, Mn-oxyhydrates) requires the help of oblique incident or dark ground incident light (Stoops, 2003). Phase contrast microscopy has been used by Altemüller (1964) on very thin (10 μm) thin sections to study the composition of the colloidal fraction of the soil.

UV or blue light fluorescence microscopy is an important tool for the study of organic matter, Al-colloids and some other mineral components (Babel, 1972; Altemüller and Van Vliet, 1990). Fresh organic matter can be stained with fluorochromes and studied with fluorescence techniques (Altemüller and Van Vliet, 1990; Tippkötter, 1990). More recently, cathodoluminescence has been used (on uncovered thin sections) to distinguish calcite grains and nodules of different origins.

Selective extraction of amorphous and free iron (Arocena et al., 1989; Curmi et al., 1994) on uncovered thin section proved to be of great help both in the study of iron components in soils and of the fabric of the groundmass, no longer masked by iron; staining tests for carbonates, feldspars and clays are used in some cases. For more details on optical methods the reader is referred to Drees and Ransom (1994), FitzPatrick (1993), and Stoops (2003).

Fabric analysis: concepts and terminology

In the following paragraphs the concepts of fabric analysis and terminology as proposed by Bullock et al. (1985) and completed by Stoops (2003) are explained. Corresponding terms according to Brewer (1964) or to Russian authors are indicated

in italic. It should be realized however that they are not synonyms, as the basic concepts are different.

The most crucial part of micromorphological research is the detailed analysis of the fabric. Soil fabric “*deals with the total organization of a soil, expressed by the spatial arrangement of the soil constituents (solid, liquid, gaseous), their shape, size and frequency, considered from a configurational, functional and genetic viewpoint*” (Bullock et al., 1985).

A special type of soil fabric is microstructure. It “*is concerned with the size, shape and arrangement of primary particles and voids in both aggregated and non-aggregated material, and the size, shape and arrangement of any aggregates present*” (Bullock et al., 1985). Analysis of microstructure is still mainly an extension of that of the structure in the field, but performed at higher magnification. The same types of aggregates or peds as described in the field are recognized in thin sections giving rise to several pedal microstructures such as granular, (sub)angular blocky, crumb, lenticular, etc. In apedal soil materials the type of voids present determines the microstructure: channels (Figure M9), chambers, (spherical) vesicles, (irregular) vughs or planar voids (Figure M5). Efforts have been made to determine microstructure on the basis of parameters obtained by image analysis (e.g., Jongerius et al., 1972; Mermut and Norton, 1992), but till now without satisfying result.

The study of the fabric of the solid material was strongly influenced by concepts of (sediment) petrography. Fabric analyses require first the recognition of units, which can be distinguished on basis of composition, relative size, shape, etc., followed by a study of their mutual arrangement.

A first important step in all descriptive systems is to make a distinction between *coarse material* and *fine material* or *micro-mass* (Stoops and Jongerius, 1975; Bullock et al., 1985; Stoops, 2003), respectively called *skeleton grains* and *plasma* by Kubiěna (1938) and Brewer (1964), or *F (framework)-members* and *F-matrix* by Brewer and Sleeman (1988). The limit between *skeleton grains* and *plasma* is generally situated at about 2 μm . Sometimes additional criteria are added (e.g., for Brewer, 1964, *skeleton grains* represent the stable material, *plasma* the colloidal and/or soluble material). The limit between coarse and fine material *sensu* Stoops and Jongerius (1975) is not fixed.

The *relative distribution* of these coarser and finer constituents (c/f) is often characteristic for given soil materials. Five basic patterns of c/f-related distributions are recognized by Stoops and Jongerius (1975) and additional subdivisions proposed by Stoops (2003): (1) *monic* (only one size group is present, either the coarser one (coarse monic), e.g., in pure sand, or the finer one (fine monic), e.g., in pure clay); (2) *chitonic* (fine material forms coatings around coarser material, e.g., in sandy spodic or argillic horizons); (3) *gefuric* (fine material forms concave or convex bridges between coarser grains, e.g., in some cambic horizons); (4) *enaulic* (fine material occurs as micro aggregates between coarser components, e.g., in loose spodic horizons) (5) *porphyric* (coarser grains are embedded in a dense mass of fine material, e.g., in Vertisols) (Figure M6). Depending upon the relative distance between the coarser grains following types of enaulic and porphyric are recognized: close (coarse grains are in touch), single spaced (spacing between coarser grains less than their mean diameter), double spaced (spacing intermediate between once and twice the mean diameters) and open (spacing larger than twice the diameter). Further subtypes of enaulic are determined by the size relation between the coarser grains and the aggregates of fine material (Figure M7). Correlations with other systems are given in Table M6.

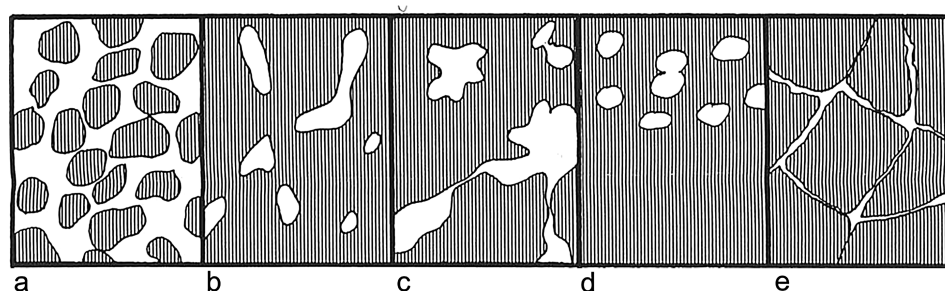


Figure M5 Some types of microstructures and voids: (a) granular microstructure with packing voids, (b) channel microstructure, (c) vughy microstructure with irregular smooth vughs, (d) vesicular microstructure, (e) angular blocky microstructure with accommodating planes.

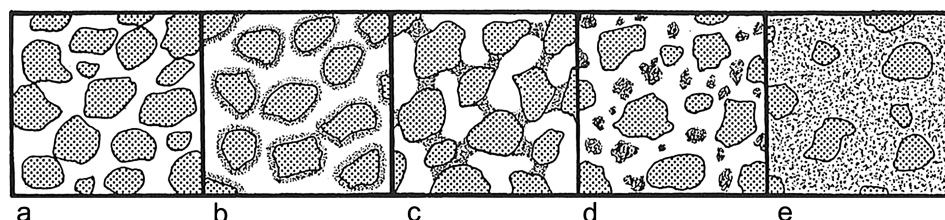


Figure M6 C/f-related distribution patterns: (a) monic, (b) chitonic, (c) gefuric, (d) enaulic, (e) porphyric.

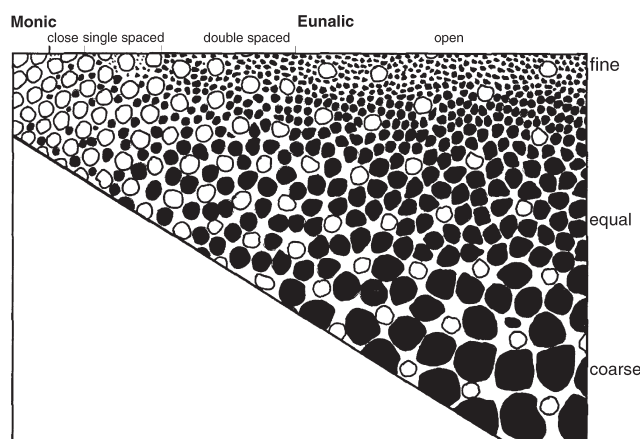


Figure M7 Gradual transition from coarse monic (left) c/f-related distribution pattern over single and double spaced enaulic to open enaulic. From top to bottom transition from fine over equal to coarse enaulic.

Soil material can be split up in a more or less undifferentiated *groundmass* or matrix and in distinct *pedofeatures* (respectively *s-matrix* and *pedological features* sensu Brewer, 1964). Pedofeatures are larger than 20 μm and can be distinguished from the groundmass on basis of difference in composition or internal arrangement.

Fabric analysis of the groundmass comprises the description of (i) nature, shape, size, degree and type of weathering (Delvigne, 1998) of the coarse material (Figure M9b), (ii) characteristics of the fine material or micromass, such as color, limpidity and interference colors, if any and (iii) the c/f-related distribution pattern. Randomly oriented clay sized phyllosilicates do not show

interference colors in thin sections, because superposition of many randomly arranged particles gives rise to a statistical isotropy. Phyllosilicate clay particles occur however practically always as small (about 20 μm) aggregates (called domains). Because of this parallel orientation the domains behave as small single anisotropic crystals – called *pseudocrystals* by the Russian micromorphologists (Dobrovolski, 1983) – and display therefore interference colors in thin sections.

Patterns of these interference colors determine the (*birefringence*)-fabric (partially equivalent to Brewer's (1964) *plasmic fabric* and the Russian *microtexture*). An *undifferentiated b-fabric* (i.e., no interference colors visible; *isotopic* according to Brewer, 1964) points to the presence of amorphous clays (e.g. allophane in Andosols) or to high amounts of organic colloids (in many humic horizons) or sesquioxides (oxic horizons) in the clay fraction, masking the interference colors. Parallel arrangement of the clay domains in the micromass is realized by (shear) stress, e.g., in Vertisols. This becomes visible in thin sections as elongated patterns of interference colors (*striated b-fabrics*, partially corresponding to the *sepic plasmic fabrics* according to Brewer (1964), or *fibrous microtextures* according to the Russian micromorphologists), e.g., *porostriated b-fabric* along fissures (slickensides in Vertisols), *granostriated b-fabric* around grains (Figures M9d and M9f), etc. Less developed random patterns of short (20–50 μm) domains are called *speckled b-fabrics* (partially the *asepic plasmic fabric* sensu Brewer (1964) or *scaly microtextures* according to the Russian micromorphologists). When the micromass contains numerous crystallites (e.g., of calcite) or mineral splitters (e.g., sericite flakes) determining the interference pattern, a *crystallitic b-fabric* (*crystic* according to Brewer, 1964) results (Figure M9f).

Apart from the mineral components, also the organic ones are described. Special attention is given to the degree of fragmentation and humification of plant fragments. A distinction

Table M6 Comparative table of types of related distribution of coarse and fine material

Kubiěna (1938)	Brewer (1964)	Stoops and Jongerius (1975)	Eswaran and Baños (1976)	Brewer and Sleeman (1988)
Elementary fabric	related distribution of plasma and skeleton	c/f related distribution	normal and specific related distribution	fabrics of f-members/f-matrix
bleached sand	granular	monic	granitic phytic	granitic
intertextic	intertextic	gefuric	intertextic	iunctic
plectoamictic p.p.	agglomeroplasmic	enaulic	congelic p.p.	agglomeric enaulic
chlamydomorphic	—	chitonic	dermatic	chlamydic
porphyropeptic	porphyroskelic	porphyric	plasmic	porphyric
porphyropeptic			porphyric	

Note. The equivalence between the terms is not absolute, as the concepts of coarse/fine, f-members/f-matrix and plasma/skeleton grains are not identical. For Kubiěna (1938), Brewer (1964) and Eswaran and Baños (1976) the limit between coarse and fine is situated at 2 μm , for Stoops and Jongerius (1975) and Brewer and Sleeman (1988) the limit is not fixed.

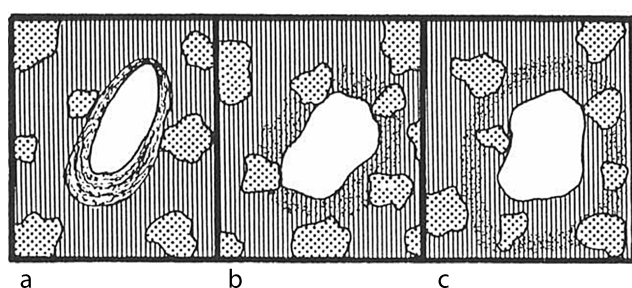


Figure M8 Pedofeatures related to surfaces: (a) coating in a, (b) hypocoating in the groundmass surrounding a channel, (c) quasicointing in the matrix.

is made between *organ residues* (Figure M10a) (containing more than 5 cells belonging to different types of tissue, e.g., root residues), *tissue residues* (containing more than 5 cells of a same type, e.g., paranchymatic residues), *cell residues* (containing less than 5 coherent cells) and *fine organic material* (colloidal fraction) (Figure M10a) (Bullock et al., 1985).

Stoops (2003) subdivided *pedofeatures* at the highest level into matrix pedofeatures and intrusive pedofeatures. Whereas *matrix pedofeatures* represent a change in the groundmass by impregnation with a component (Figure M9a), depletion of a component (Figure M9e) or change of the fabric, *intrusive pedofeatures* (Figure M9a) such as clay coatings (Figure M10c) or gypsum crystals (Figure M9c) occur outside the groundmass.

According to their morphology and fabric following types of pedofeatures are distinguished (Bullock et al., 1985):

1. *Coatings*, *hypocoatings* and *quasicointings* (Figure M8). These are pedofeatures related to surfaces of pores, aggregates or grains. In most cases they can be correlated with Brewer's (1964) *cutans*, *neocutans* and *quasicutans* respectively.

Coatings are intrusive pedofeatures lining the walls of pores or surrounding grains or aggregates, such as clay coatings in argillic horizons (Figure M10c and M10d), calcite pedents (beards) below pebbles in semi-arid soils, silt cappings on aggregates in frozen soils or due to agriculture (Figure M10b), gibbsite coatings around quartz grains in oxisols. *Hypocoatings* are matrix pedofeatures related to, and immediately adjoining natural surfaces, such as impregnations of cryptocrystalline iron oxyhydrates along voids in temporarily wet soils, microcrystalline calcite impregnations around channels

(pseudomycelium), calcite depletions around root channels in calcareous soils or groundmass compactions around animal burrows. *Quasicointings* are also matrix pedofeatures related to surfaces, but at some distance of the latter ones, e.g., cryptocrystalline goethite around channels in hydromorphic soils (cf. the so called Liesegang-rings in geology).

2. *Infillings* consist of materials filling, or partially filling voids, such as excrements filling a channel, illuviated clay filling a fissure, or loose gypsum crystals in a void. A partial equivalent in Brewer (1964) are the *pedotubules*; but these are restricted to infillings of channels or chambers with soil material, mainly of biological origin, with exclusion of pure plasma (clay or soluble material). Also some of his *crystal-laria* cover the concept of infillings.
3. *Crystals* and *crystal intergrowths* are intrusive pedofeatures consisting of single crystals, or intergrowths of crystals, larger than 20 μm , euhedral or subhedral in shape and embedded in the groundmass. They correspond to Kubiěna's (1938) and Brewer's (1964) *intercalary crystals*. It are mainly crystals of the more soluble fraction of the soil, such as gypsum (Figures M9c and M9d), calcite and goethite, but also more exotic pedogenic minerals such as barite, celestite and vivianite do occur.
4. *Nodules* are three-dimensional bodies occurring in the groundmass, i.e., not related to surfaces or pores. They correspond in general to Brewer's (1964) *glauabules*. According to their internal fabric different types are distinguished, such as *typic nodules* (with an undifferentiated internal fabric) (Figures M9c and M9d), *concentric nodules* (*concretions* according to Brewer, 1964), *nucleic nodules* (with a foreign core). Nodules may be intrusive pedofeatures (e.g., pure calcite nodules in Vertisols) or may be matrix pedofeatures, i.e., corresponding to zones of groundmass more or less strongly impregnated with or depleted of one or other component, such as iron oxyhydrates (rusty flecks) in hydromorphic soils or microcrystalline calcite (in arid soils). Pure nodules have sharp boundaries, whereas impregnative ones may have diffuse boundaries when formed in situ, or sharp ones when transported. Nodules formed in situ and not disturbed are said to be *orthic*, but when they were subject to translocations they are *disorthic*; inherited nodules are called *anorthic* (Wieder and Yaalon, 1974).
5. *Intercalations* are elongated, undulating pedofeatures not associated with pores or surfaces, embedded in the groundmass. They are mainly related to differences in texture, but little is known about their genesis. There is no equivalent in Brewer's (1964) terminology.

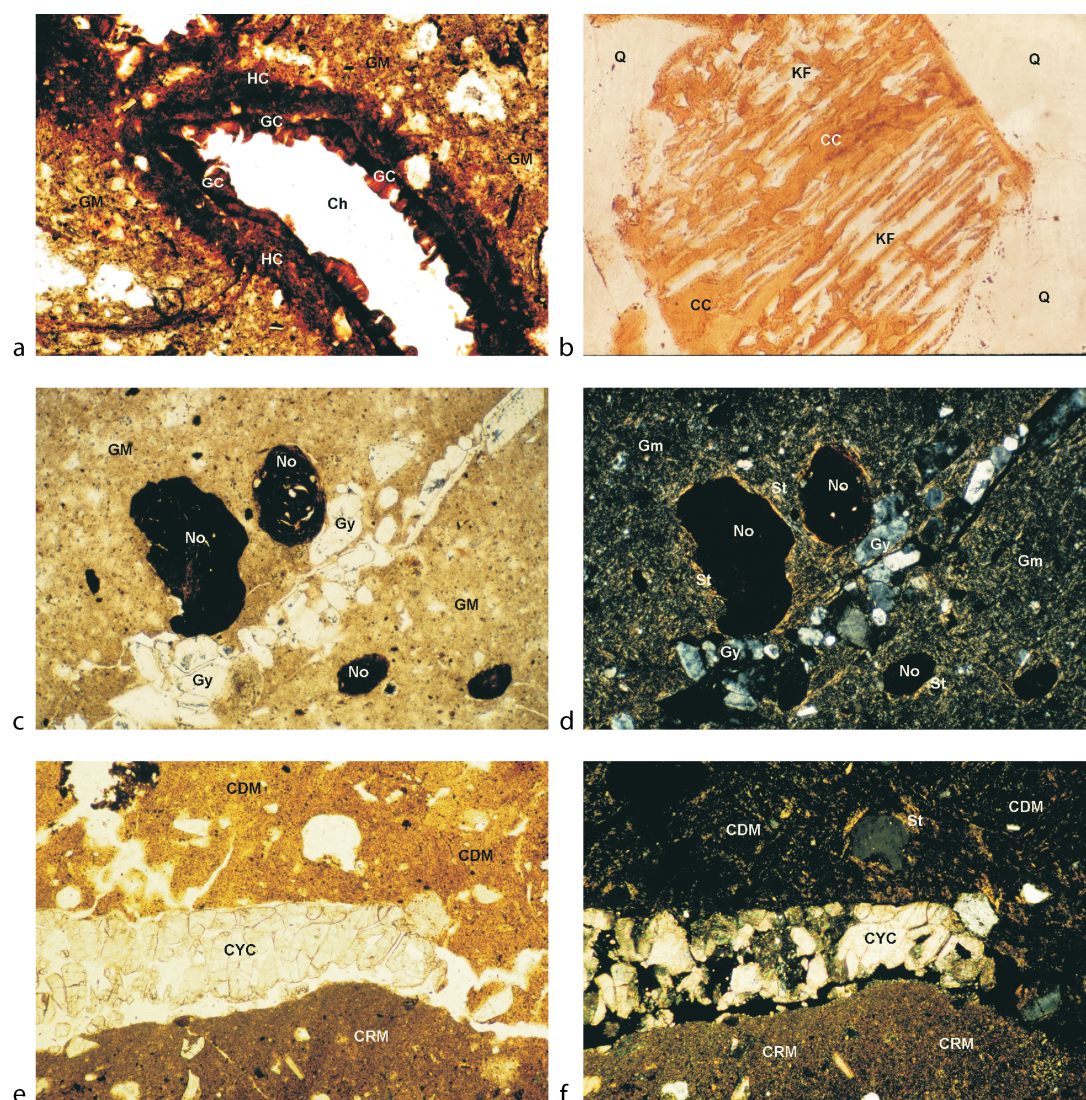


Figure M9 (a) Hypocoating (HC) of iron hydroxide in groundmass (GM) around channel Ch (impregnative pedofeature), and goethite coating (GC) covering the walls of the channel (intrusive pedofeature) Plain light. (b) Weathering of perthite (intergrowth of lamellae of Na- and K-feldspar) in granite. The Na-feldspar is completely weathered and replaced by illuviated yellowish clay (CC), only the K-feldspar lamellae are still intact (KF). The grain is surrounded by quartz (Q). (c) Grayish groundmass (GM) of a clayey soil with nodules of Fe and Mn hydroxide (No), and gypsum crystals (Gy) infilling a former void. Plain light. (d) Same as (c), but crossed polarizers. Note striations (St) around nodules, due to orientation of clay particles (granostriated b-fabric). (e) Quera. Cytomorphonic calcite (CYC) in root channel. The groundmass below is rich in fine calcite (CRM), the part above the channel has been calcite depleted (CDM). Plain light. (f) Same as (e) but crossed polarizers. Notice striations (St) around quartz grain (granostriated b-fabric) due to clay orientation (CDM), and interference colors of fine calcite throughout CRM (crystallitic b-fabric).

6. *Excrements* of the soil mesofauna are common in many soils, especially in the surface horizons. They can be purely organic, or mixed organic and mineral. They are subdivided according to their external shape (Figures 10a, 10c and 10d). Aging gives rise to disintegration or coalescence. Excrements correspond to Brewer's (1964) *fecal pellets*.
7. *Compound and complex pedofeatures*: Compound pedofeatures are those that consist of a mixture of two or more pedofeatures, for instance superposed coatings of clay and goethite, or impregnative iron nodules containing clay coatings. Complex pedofeatures (Stoops, 2003) are specific associations

of pedofeatures with a diagnostic genetic relationship, such as cytomorphonic calcite crystals in root channels, surrounded by calcite depletion hypocoatings (Figures M9e and M9f) in Mediterranean (*queras*, as defined by Herrero and Porta, 1987).

Quantitative analyses

The fundament of the quantitative analysis of thin sections is the Law of Delesse which states that proportions of areas measured on a surface correspond to the proportions of volumes of the three dimensional body.

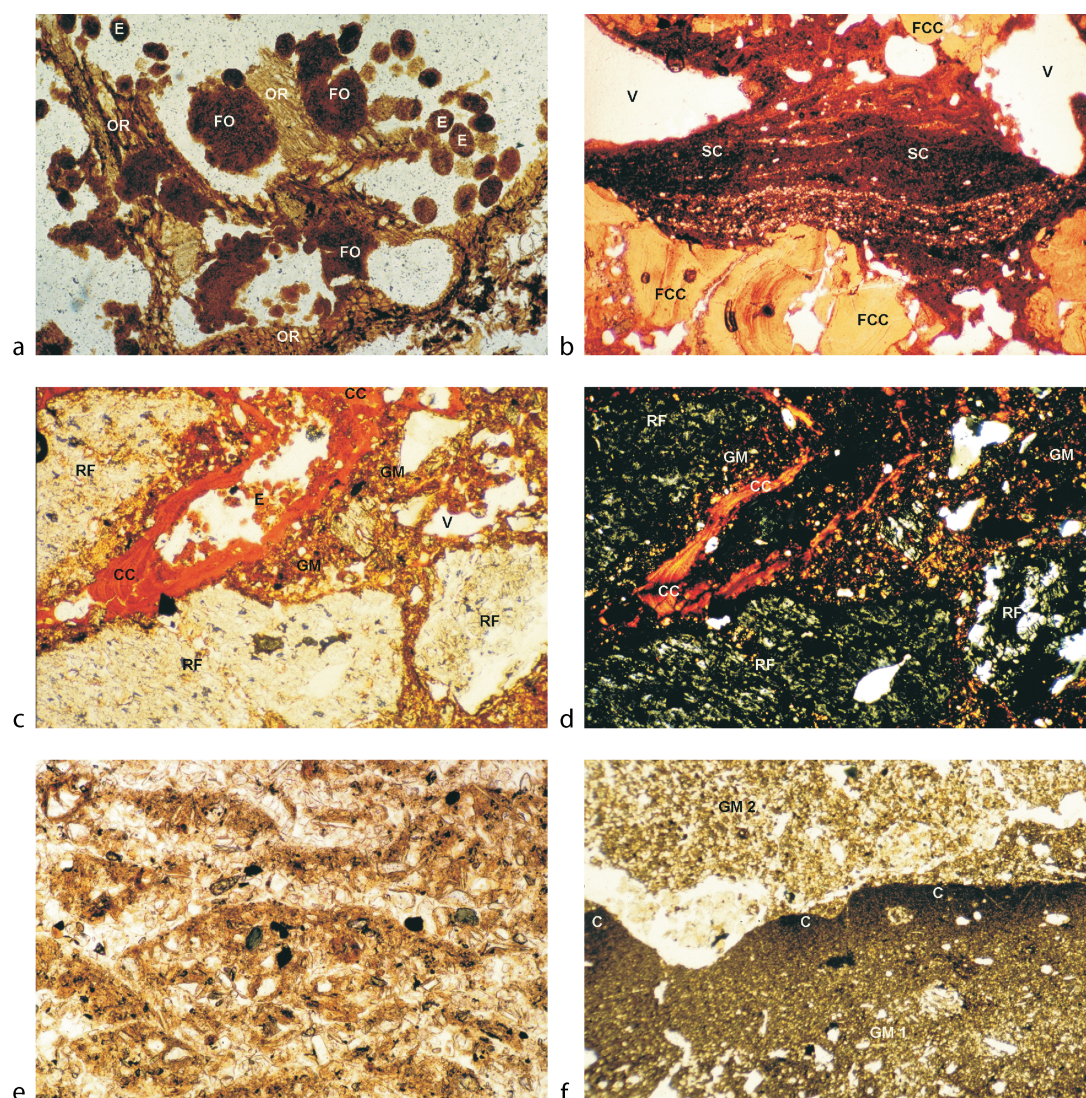


Figure M10 (a) Organ residues (OR) with large excrements of fine organic material (FO) and smaller excrements (E) (plain light). (b) Horizontal coating of clay and silt (SC), partially filling a void (V), in material consisting almost only of fragments of clay coatings (FCC) in clay with flint deposit (plain light). (c) Close packing of rock fragments (RF), interstitial groundmass (GM) and orange illuvial clay coating (CC), some excrements (E) and voids (V) (plain light). (d) Same as (c), but between crossed polarizers. Note interference colors of the clay coating. (e) Lenticular microstructure. In each aggregate the fine material is concentrated on top, whereas the lower part is depleted of clay. Microstructure formed as a result of repeated cycles of freezing and thawing (plain light). (f) Buried surface crust. GM1: groundmass of the old loess; C crust showing fining up, GM2: groundmass of the younger loess (plain light). Note depressions in crust due to local erosion.

A distinction has to be made between the quantitative analyses of the solid material (groundmass and pedofeatures) and that of the porosity (voids).

For the quantification of the solid components the classical petrographic techniques of point counting (Eswaran, 1968) and line counting are still the most popular and in most cases the only that can be used. The aim is to quantify indirectly pedogenic processes. Not all fabric elements or units can be quantified: the area of matrix pedofeatures does not yield any information that can be interpreted in an unequivocal way (Stoops, 1978). Therefore pure fabric units, such as inherited or pedogenic minerals or clay illuviation features are the most commonly quantified. The aim of such studies is for

instance the quantification of clay illuviation processes (Ducloux, 1973; Miedema and Slager, 1972), of ratios of inherited to pedogenic carbonates or sulfates, the relative increase or decrease of weatherable and stable minerals through a profile. Quantification of orientations (especially of phyllosilicates) can be used to determine pedoplasation processes.

Image analysis is becoming more and more important (Mermut and Norton, 1992; Moran, 1994) in analyzing quantitatively soil fabric, especially microstructures and porosity. In this way not only pore volumes, but also their shapes and orientations can be determined quantitatively. For quantitative studies of porosity, a fluorescent dye is often added to the

resin: observed under UV-light pores will appear as bright features. Comparison of micromorphometric data with results of physical analyses yields good results. Comparing data of different authors however remains difficult, as no agreement exists on standardization of methodology and parameters to be used.

Interpretation and applications

Introduction

Interpretation of micromorphological descriptions is partially based on deduction, partially on comparison with known materials and for a small extend on results of experiments. Advantage is taken particularly of the potentiality to deduce from spatial relationships chronological or genetic ones, for instance to conclude in which order pedogenic features were formed (e.g., yellowish clay coatings on pores traversing red mottles indicate that the illuviation postdates hydromorphism), and which processes are still active.

Applications in pedogenesis

Coatings, hypocoatings, quasicoatings and infillings are practically always the result of in situ formation (pedogenic in soil materials). The juxtaposition of (hypo)coatings gives a relative chronology. Nodules can be pedogenic or inherited from the parent material or from older soils (orthic versus anorthic).

Combination of fabric analysis and determination of the nature of the constituents enables a micromorphologist in most cases to determine the origin of the parent material, or to distinguish between clay accumulations formed by in situ weathering or by illuviation. From a genetic point of view the possibility of determining for each feature its position in a sequence of events (chronology), as mentioned earlier, is of uttermost importance.

The transformation of saprolite to a soil material, called pedoplasmatation (Flach et al., 1968), is another topic that can be studied only by micromorphology, as it concerns in the first place the transformation of fabrics, initially without mineralogical or chemical changes.

Alteration and weathering

Micromorphological methods are more and more used in studies of rock weathering, as they allow to follow the different weathering stages of each component individually, and to estimate their interactions (Delvigne, 1998). Sometimes micromorphology is the only technique to give an exact insight in the material studied: e.g., the parallel arrangement of orthoclase lamellae in thin sections of undisturbed material points to perthites or antiperthites in the original rock, due to a preferential weathering of the albite lamellae (Figure M9b). Grain mounts or XRD would only reveal the presence of K-feldspars.

Soil classification

Soil classifications, except that of Kubišna (1956) do in general not use micromorphological data as differentiating criteria, although Soil Taxonomy (Soil Survey Staff, 1975) mentions micromorphological characteristics in the description of some diagnostic horizons. Nevertheless this technique may be useful, or even indispensable to recognize some diagnostic features such as clay illuviation (clay coatings versus pressure faces), calcite translocation, in situ weathering, etc. (Douglas and Thompson, 1985). Systematic applications of micromorphology would, without doubt, be of great help to classification,

as for instance it would allow to subdivide cambic horizons on a sense full basis.

Paleopedology, Quaternary geology and archeology

Palaeosols are often difficult to identify as many physical and chemical characteristics have changed as a result of overburden, weathering and seepage of solutions. Micromorphological characteristics however are mostly well preserved and allow then the determination of the soil type, the palaeoclimate and environment. In this way micromorphology became an important tool in Global Change studies.

In Quaternary geology and geomorphology the interpretation of buried palaeosols can be carried out by comparing them with present-day soil formations in various climatic zones (Figure 10f). The use of micromorphological indexes (e.g., Magaldi and Tallini, 2000) helps correlating and dating palaeosols. Also for the interpretation of (peri)glacial deposits and deformations a comparison can be made with micromorphological analysis of sediments and deformation features observed in (peri)glacial areas of today (Dumanski and St. Arnaud, 1966; Harris, 1985; Van Vliet-Lanoë, 1985; van der Meer, 1996). Another source of information is experimental work in combination with thin section analysis. Laboratory experiments made it possible, for example, to identify redeposited loess by splash, rainwash and afterflow processes (Mücher et al., 1981), and to make a distinction between structural modifications by repeated freezing and thawing cycles (Coutard and Mûcher, 1985) (Figure M10e).

Applications of micromorphology in archeology are manifold. Apart from those based on the determination of soil genesis and palaeosols, the identification of old living floors, pedoturbations, industrial sites and other traces of human activity is a more and more common practice (Courty et al., 1989; Davidson et al., 1992). More recently micromorphology got also applied in technical geology, soil biology and landscape ecology.

Soil physics, soil degradation

Soil micromorphology is used to study and solve practical problems of soil degradation, water percolation, soil management, etc. One of the most successful applications has been the study of different types of surface crusts (depositional, structural and vesicular crusts) and their formation conditions, both under natural and experimental conditions (Callebaut et al., 1986) (Figure M10f). Problems of soil physics, e.g., the calculation of saturated hydraulic conductivity in heavy soils (Bouma et al., 1979) have been successfully solved using micromorphometric approaches. An increasing attention is given to the evolution of porosity and microstructure under different management practices, where micromorphology and image analyses proved to be sensitive techniques to monitor changes in an early stage. The problem arising in these applications however is the need of a large number of thin sections and measurements to obtain statistically valuable results (Murphy and Banfield, 1978).

Control of analyses

One of the most important applications of micromorphology is to help the interpretation and critical evaluation of results of other analytical techniques. E.g., the knowledge that textural microlaminations are present in a material will influence the sedimentological interpretation of its grain size analyses; when

a soil scientist wonders why unstable minerals are present in the silt fraction of an oxisol, the micromorphologist may tell him that they were protected in an iron hydroxide nodule, and liberated during dithionite treatment.

Georges Stoops

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Cross-references

Cutans
Microhabitats
Microstructure, Engineering Aspects
Soil Engineering

MICRONUTRIENTS

Micronutrients are chemical elements required by plants in relatively small quantities OUP (2000). Table M7 provides context for this definition. The current article is an expanded version of Chesworth (1991), where the original references will be found.

Micronutrients are typically found as constituents of cofactors and coenzymes in living organisms. For the purposes of this article, the micronutrients are taken to be those recognized by the Soil Science Society of America (see Mortvedt et al., 1991): copper, zinc, molybdenum, manganese, cobalt, boron and chlorine (Figure M11). Whitehead (2000) also includes I and Se, which are not considered here.

Basic chemistry

p block elements

Boron

Boron is a group IIIA element, together with Al, Ga, In, and Tl. Atomic size increases in the vertical sequence B to Tl, as with similar groups in the periodic table. Because of the lanthanide contraction, Tl is smaller than would have been predicted. All atoms in group IIIA contain s^2p^1 electrons. Additionally Ga, In and Tl have d electrons, while Tl also has f electrons.

Consequently B and Al exhibit simpler chemical behavior than other members of the group.

Boron, in particular, shows little similarity to the others. It is the only element whose outer-shell vacancies outnumber the valence electrons without imparting metallic properties. Yet, it is not a typical nonmetal, since its electrons are not localized in covalent bonds in the elemental state. As a result, B is usually designated a metalloid, a classification borne out by its electronegativity, which, at 2.04, is close to the borderline between metallic and nonmetallic elements. The energy needed to remove its three outer electrons is too high to be compensated by lattice or hydration energies so that B is always covalent in compounds. The quoted ionic radius for B has little meaning, therefore.

The other elements of the group can form trivalent ions, and Tl is also capable of losing the single p electron to form a uni-positive ion. The three valence electrons of B can be delocalized between 3 or 4 orbitals to form triangular sp^2 or tetrahedral sp^3 hybrids. These occur as structural units in all the common borate minerals. B is a weak Lewis acid, having the ability to accept an electron pair. The rest of the group is either amphoteric (e.g., Al) or basic (e.g., Tl).

Because the size of atoms or ions in the periodic table increases downwards, and from left to right, atoms or ions that lie diagonally, one beneath the other, tend to be approximately the same size, and to show similar geochemical behavior in instances in which that behavior depends on size. For this reason, the crystal chemistry of borates is generally similar to that of silicates, and B can substitute for Si in silicates and aluminosilicates. It does so especially in sheet silicates. However, because of its ability to assume a three-fold as well as a four-fold coordination, its chemistry is more complex than that of Si.

Chlorine

The halogens, F, Cl, Br, I, and At (astatine) are Group VII elements. All have an outer electron configuration of s^2p^5 and so require only one more electron to achieve a stable inert gas configuration. All, therefore, have a high affinity for electrons and all form ions with a single negative charge. The state of condensation increases downwards in the group with F and Cl existing as gases under low temperature, low pressure, conditions, Br as a liquid and I as a solid. All of the foregoing are non-metallic. At is semi-metallic and radioactive, occurring as a daughter product in uranium ores. Its longest lived isotope has a half life of 8.3 hours, so at any one time, the total amount of At in the planet is less than 30 gm. This makes it the rarest of all naturally occurring elements on Earth.

Chlorine gas does not occur in nature; neither do the elemental forms of the other halogens. After F, Ozone and O, Cl has the third highest affinity for electrons in the periodic table. Chloride ion (Cl^-) is the only form in which Cl occurs commonly in nature.

d block elements

Manganese, Fe, Cu, Zn, and Mo all have electronic configurations with d orbitals (Figure M11) and all but Zn are correctly called transition elements. In Zn the d orbitals are completely filled so that it is not technically a transition element, though it is sometimes given that designation. It invariably shows an oxidation state of II in its compounds, whereas the other elements display the multiple oxidation states that are characteristic of elements with incompletely filled d orbitals.

The presence of incompletely filled d orbitals has the further consequence that elements and ions in solids and solutions



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