



## Micromorphological Signatures of Specific Pedogenic Processes

Deepak, Nishitha Reddy, Manisha Ranwa, Tapas Moi and Nisha Sahu

ICAR-Indian Institute of Soil Science, Berasia Road, Nabibagh, Bhopal

### Introduction

**Soil micromorphology** is a specialized field within soil science that investigates the microscopic and submicroscopic structure of soil materials. By analyzing the arrangement, composition, and spatial relationships of soil constituents, micromorphology provides valuable insights into soil formation, development, and properties. Micromorphological studies require undisturbed soil samples to preserve the natural structure and relationships between soil components. Specialized techniques are employed to observe and analyze these samples, allowing researchers to infer genetic and chronological processes influencing soil development. Unlike other soil analysis methods that often involve homogenized samples, micromorphology preserves the micro-heterogeneity and anisotropy of undisturbed materials (Courty et al., 1989).

**Soil Micromorphological Analysis (SMA)** is a sophisticated technique that employs light microscopy and submicroscopic methods to investigate the intricate processes of soil formation and alteration, both natural and human-induced. By meticulously examining the composition and spatial arrangement of soil constituents, SMA offers invaluable insights into soil development, history, and properties. Submicroscopic analysis, which utilizes advanced instruments capable of analyzing radiation beyond the visible spectrum (e.g., scanning electron microscopy and energy dispersive X-ray analysis), complements light microscopy in providing a comprehensive understanding of soil structure (Deneele, 2016).

### Applications of Micromorphology (Ageeb et al., 2019)

Micromorphology has established itself as a valuable analytical tool in diverse fields where soil particles, pores, and organisms play pivotal roles. It offers both descriptive and quantitative insights, often enhanced by chemical, mineralogical, and morphological analyses.

**Soil Genesis:** Micromorphology has been instrumental in defining diagnostic horizons within soil classification systems, such as Cambic, Oxic, Spodic, and Argillic. Additionally, it has contributed significantly to studies on duripan genesis, fragipan degradation, gypsum formation in soils, paleosol interpretation, and clay movement.



**Soil Microstructure:** Micromorphological techniques are employed to characterize soil microstructure by examining the size and shape of soil pores. Thin sections provide valuable information on the impact of factors such as wheel compaction on macro-pore distribution. Furthermore, micromorphology has been used to investigate the influence of soil microstructure on water retention and to characterize structural crusts formed by water erosion.

**Archaeological Studies:** Archaeologists have leveraged micromorphology to analyze artifacts like pottery fragments, charcoal, and bone, identifying their characteristics and the effects of processes such as burning and physical disturbance. Micromorphological features can also offer insights into furnace firing techniques and the preparation of raw materials for construction. Moreover, micromorphology aids in integrating interpretations among artifacts, climate, geomorphology, and soils excavated in archaeological sites.

**Biological Materials in Soil:** Micromorphological techniques have been employed to quantify the effects of earthworm activity on soil aggregation, compaction, structure, and decalcification. Researchers have also utilized micromorphological methods to identify and quantify bacterial populations and void space in grassland soils.

**Hydraulic Conductivity and Water Movement:** Micromorphology can be used to estimate hydraulic conductivity and water movement in soils by visualizing water-conducting pores using dyes or fluorescence microspheres. This technique has been applied to determine the water-conducting properties of quartz veins in saprolite, a weathered bedrock material.

**Micromorphological Signatures:** Micromorphological signatures are distinctive microscopic features observed in soil thin sections that reflect specific soil-forming processes, environmental conditions, or soil management practices. These signatures provide valuable information about the history, development, and functioning of soils, enabling soil scientists to interpret the physical, chemical, and biological processes that have shaped the soil over time.

**Types of Micromorphological Signatures** (Karkanias and Goldberg, 2023; Zickel et al., 2024)

Micromorphological signatures are distinctive microscopic features observed in soil thin sections that provide valuable insights into various soil processes. They can be categorized based on the specific pedogenic processes they indicate:

### 1. Fabric-Related Signatures:

- **B-Fabric:** The arrangement and orientation of fine soil particles, indicative of soil development, clay illuviation, and structural stability. Examples include porphyric, chitonic, and grano striated fabrics.



- **Argillans:** Clay coatings on pore walls and mineral grains, suggesting clay illuviation.
- **Fe/Mn Oxide Coatings:** Iron and manganese oxide films, indicating redox processes, Gleying, or waterlogging.

## 2. Pore-Related Signatures:

- **Channels and Voids:** Various types of pores, indicative of biological activity or physical processes like shrink-swell behavior.

## 3. Pedofeatures:

- **Microlaminations:** Thin layers of different materials, suggesting episodic deposition, seasonal variations, or specific pedogenic processes.
- **Calcium Carbonate Nodules (Calcans):** Accumulations of calcium carbonate, commonly associated with calcification in arid and semi-arid regions.

## 4. Microstructure-Related Signatures:

- **Plasmic Microstructure:** The arrangement and distribution of the fine fraction of the soil, indicative of crystallization processes, organic matter distribution, and mineral weathering.

## 5. Organic Matter-Related Signatures:

- **Humus Forms:** Presence of amorphous or particulate organic matter, indicating decomposition rates, humification processes, and organic carbon sequestration.
- **Charcoal Fragments:** Microscopic pieces of charred organic material, suggesting fire history, human activity, or natural wildfires.

## 6. Mineral-Related Signatures:

- **Quartz Grain Coatings:** Silica or iron coatings on quartz grains, indicating weathering processes, silica leaching, or podzolization.
- **Gypsum Crystals:** Presence of gypsum crystals, suggesting salinization or arid soil conditions.

## 7. Biogenic Signatures:

- **Faunal Excrements:** Dung pellets or earthworm granules, indicating biological activity and soil turnover.



- **Root Channels and Residues:** Evidence of plant roots and associated organic residues, indicating root growth patterns, plant-soil interactions, and nutrient cycling.

## 8. Redox-Related Signatures:

- **Mottling:** Irregular patches of color, indicating fluctuating water tables and alternating oxidation and reduction conditions.
- **Gleying:** Gray or blue-green colors due to reduced iron under waterlogged conditions.

## Micromorphological Signatures of Different Specific Pedogenic Process

### A. Podzolization (Stoops, 2021)

It is a process of soil formation resulting in the formation of podzols and podzolic soils. It is the process of accumulation of silica and eluviation of sesquioxide. It is almost a reverse of calcification process due to leaching of all bases including calcium.

#### 1. Eluvial Horizon

The eluvial horizon, typically characterized by its pale color, is depleted of iron, aluminum, and organic matter due to leaching. This process often results in a platy structure that can impede water infiltration and root growth.

#### Micromorphological Features:

- **Absence of Fe and Al Oxides:** Microscopic examination reveals a scarcity of iron and aluminum oxides, resulting in a lack of reddish or yellowish coatings or nodules.
- **Dominance of Quartz Grains:** Quartz grains are prevalent and appear clean, reflecting the removal of iron and aluminum oxides.
- **Skeletal Organic Residues:** While some organic residues may remain, they are often bleached and fragmented, indicative of organic matter leaching.
- **Siliceous Cementation:** In certain cases, the eluvial horizon may exhibit siliceous cementation, characterized by the precipitation of silica as a thin coating on soil particles, contributing to its rigidity.

#### 2. Illuvial Horizon (B Horizon or Spodic Horizon)

The illuvial, or Spodic, horizon is distinguished by its darker color, typically reddish-brown, due to the accumulation of iron, aluminum oxides, and organic matter. This horizon often

exhibits a blocky or subangular blocky structure, indicative of the deposition of illuviated materials.

### **Micromorphological Features:**

- **Fe and Al Coatings:** Iron and aluminum oxides are visible as reddish or yellowish coatings on mineral grains and pore walls, suggesting their movement and deposition.
- **Organic-Aluminum Complexes:** Dark organic matter, often complexed with aluminum, is deposited in this horizon, appearing as dark, amorphous coatings or infillings.
- **Iron and Aluminum Nodules:** Small nodules or concentrations of iron and aluminum oxides may form within the illuvial horizon.
- **Humus Infillings:** The spodic horizon often contains dark, humic infillings within pores and along root channels, resulting from the downward movement of organic matter.
- **Fibrous Organic Material:** The organic material in the illuvial horizon is more fibrous and less decomposed than in the eluvial horizon.

### **3. Translocation Evidence**

- **Illuvial Clay Films:** Although less prominent in podzols than in some other soils, illuvial clay films may be present in the illuvial horizon, indicating the movement of finer particles from the upper horizons.
- **Micro aggregation:** The accumulation of organic matter, iron, and aluminum in the spodic horizon often leads to the formation of microaggregates, which are visible as small, stable clusters of soil particles under the microscope.

### **B. Salinization (Abdel and Ibrahim, 2013)**

Salinization, the accumulation of soluble salts in soil, is a common occurrence in arid and semi-arid regions or areas affected by improper irrigation practices. Micromorphology, the study of soil microstructure, offers valuable insights into the physical and chemical processes associated with salinization.

Key micromorphological signatures of salinization include:

- **Salt Crystals and Efflorescence:** These are the most prominent features, appearing as white or pale-colored crystalline formations on the soil surface or within the matrix. Salt crystals, composed of soluble salts such as sodium chloride, calcium

sulfate, and magnesium sulfate, exhibit various morphologies such as cubic, prismatic, or needle-like shapes.

- **Vesicular Pores:** These small, rounded voids form due to the displacement of soil particles by salt crystals or the entrapment of air bubbles during the drying of salt-rich solutions. They are often abundant in upper soil horizons and contribute to a puffy or vesicular soil structure.
- **Salt Crusts and Cementation:** Salt crusts form on the soil surface due to the evaporation of saline groundwater or the accumulation of salts from irrigation water. These crusts can range from thin, friable layers to thick, hard, cemented formations. Under the microscope, they appear as dense, compact layers with a massive or platy structure.
- **Salt Coatings and Infillings:** Salt coatings form on the surfaces of soil particles, roots, or organic matter fragments, appearing as thin, whitish layers under the microscope. Salt crystals can also infill pores, cracks, or channels within the soil matrix, obstructing water movement and reducing soil permeability.
- **Biological Indicators:** Salinization can negatively impact soil microbial communities and plant growth. Reduced microbial activity and diversity can be observed through the decreased presence of fungal hyphae, bacterial colonies, or other microbial features. Plants may also exhibit morphological and anatomical changes, such as the thickening of leaf cuticles, the development of salt glands, or the accumulation of compatible solutes.

### C. Gleization (McKeague et al., 1986)

Gleization is a pedogenic process characteristic of waterlogged soils, where anaerobic conditions result in the reduction of iron and other elements. This process leaves distinctive micromorphological traces that can be used to identify gleyed soils.

Key micromorphological signatures of gleization include:

1. **Gleyed Matrix:** The soil matrix typically exhibits a gray, bluish-gray, or greenish-gray hue due to the reduction of ferric ( $\text{Fe}^{3+}$ ) to ferrous ( $\text{Fe}^{2+}$ ) iron. The matrix often has a fine texture and a homogenous appearance, indicative of a stable waterlogged environment.
- **Reduced Iron Compounds:** Microscopic examination reveals a predominance of reduced iron compounds, lacking the characteristic red or yellow colors of oxidized iron.
  - **Homogeneity:** The matrix generally appears uniform, with minimal mottling or color variation.

2. **Redoximorphic Features:** Patches of reddish, brown, or yellow tones within the gleyed matrix indicate areas where iron oxidation has occurred, typically due to fluctuating water tables.
  - **Iron Mottles:** Mottled patterns of oxidized iron (reddish-brown or yellow) are visible within the gray matrix, often with diffuse boundaries and irregular shapes.
  - **Pore Linings:** Reddish-brown or yellowish iron oxide linings may be observed around soil pores and root channels, suggesting the penetration of oxygen.
  - **Depletion Zones:** Areas adjacent to iron mottles may exhibit lighter colors or bleaching, indicative of iron and other element depletion.
3. **Iron and Manganese Nodules:** Iron and manganese nodules can form within gleyed soils, often displaying reddish-brown, dark brown, black, or dark gray hues.
  - **Ferruginous Nodules:** Dense concentrations of iron oxides can form nodules scattered throughout the gleyed horizon, frequently with a concentric structure suggesting multiple phases of formation.
  - **Manganese Nodules:** Black manganese nodules or concretions may also form, often in association with iron nodules, and may exhibit a similar concentric internal structure.
  - **Micronodules:** Smaller nodules or aggregates of iron and manganese may be dispersed within the matrix, contributing to localized reddish-brown coloration.
4. **Organic Matter Accumulation:** Organic matter often appears dark brown to black and is frequently poorly decomposed due to anaerobic conditions.
  - **Amorphous Organic Residues:** Dark, amorphous organic matter may coat soil particles or fill pores, often appearing as poorly decomposed fragments.
  - **Organic Coatings:** Fine organic coatings can be observed on mineral grains, contributing to the darker color of certain horizons or areas within the soil.
  - **Partially Decomposed Plant Material:** Plant residues, such as roots or stems, may be preserved due to slow decomposition, often exhibiting minimal alteration.
5. **Reduced Pore Space and Structure:** Gleyed soils typically have fewer and smaller pores due to compaction and limited biological activity in waterlogged conditions.
  - **Reduced Porosity:** Microscopic examination often reveals sparse, small, and irregularly shaped pores, indicating limited air space and poor aeration.
  - **Anoxic Pore Infillings:** Pores may be filled with reduced forms of iron and manganese, appearing as dark, compacted materials.

- **Minimal Bioturbation:** Limited evidence of soil fauna or root channels due to the anaerobic environment results in a more compact and less porous soil structure.

#### **D. Laterization (Diop et al., 2023)**

Laterization, a soil-forming process prevalent in tropical and subtropical regions, involves intense weathering and leaching, leading to the accumulation of iron and aluminum oxides and the depletion of silica. This process results in the formation of laterite soils, which are often rich in iron and aluminum but deficient in nutrients.

Micromorphological analysis of laterite soils reveals distinctive features indicative of this process:

##### **1. Iron Oxide Coatings:**

- **Uniform coatings:** Iron oxides, such as hematite and goethite, often form uniform coatings on soil particles, including quartz grains and mineral fragments.
- **Variable thickness:** The thickness of these coatings can vary, with thicker deposits indicating more intense weathering or longer periods of laterization.
- **Concentric layers:** In some cases, concentric or banded layers of iron oxides may be observed, suggesting multiple phases of precipitation or varying environmental conditions.

##### **2. Iron and Aluminum Nodules (Ferrans):**

- **Reddish-brown color:** Nodules typically exhibit a reddish-brown or yellowish-brown color due to the presence of iron and aluminum oxides.
- **Size and shape:** They can range from microscopic to several centimeters in size and may be rounded, irregular, or elongated.
- **Concentration:** Nodules are often concentrated in specific areas of the soil profile, reflecting zones of intense iron and aluminum accumulation.

##### **3. Gibbsite Crystals:**

- **White to colorless appearance:** Gibbsite crystals, composed of aluminum hydroxide, are typically white to colorless but may be tinted by associated iron oxides.
- **Needle-like or plate-like shape:** Crystals are often small and have a needle-like or plate-like shape.

- **Distribution:** They can be scattered throughout the soil matrix or concentrated in certain horizons.

#### 4. Depletion of Silica:

- **Reduced quartz grains:** The absence of silica is indicated by a reduced presence of quartz grains or a lighter color in areas where silica has been leached out.
- **Rounded or smooth particles:** Soil particles may appear more rounded or smooth due to the removal of silica.

#### 5. Altered Soil Structure:

- **Reddish or yellowish color:** The soil structure may appear more reddish or yellowish due to iron and aluminum oxide accumulation.
- **Dense and less granular texture:** The texture of the soil may be more dense and less granular compared to non-lateritic soils.
- **Blocky structure:** The soil may exhibit a blocky or angular blocky structure due to the accumulation of iron and aluminum oxides and the compaction of soil particles.

### Conclusion

Soil micromorphology is a crucial field in soil science, examining soil at the microscopic level to reveal its structure and formation. Using techniques like light and scanning electron microscopy, Soil Micromorphological Analysis (SMA) preserves the natural soil heterogeneity and provides insights into soil genesis, archaeological contexts, and various soil processes. It identifies distinctive micromorphological signatures, such as fabric patterns and pore structures, which are key to understanding soil history and development. These detailed observations enhance our comprehension of the physical, chemical, and biological factors shaping soil, underscoring the significance of micromorphology in soil science.

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