African Journal of Agriculture and Food Science
ISSN: 2689-5331
Volume 3, Issue 2, 2020 (pp. 11-31) www.abjournals.org

AN OVERVIEW OF SOIL MICROMORPHOLOGY TREND IN THE FIELD OF SOIL SCIENCE

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ABSTRACT: *Over four decades soil micromorphology is considered as a new field of study in soil science agenda. The field is now receiving global attention in the field of research as considered sub-discipline in the field of soil science. However, there are trending views in both scientific and technical challenges regarding the concept of soil micromorphology in terms of its procedures, operational techniques, implications and application in the field of soil sciences. Thus, this paper imperatively overviewed the past and current trends overwhelming the field. The new modern field is basically concerned with the study of micromorphological features of soil under microscopic level, which is useful for evaluating soil mineralogy, genesis, pedogenic and geomorphic processes of soils. The trend in soil micromorphological analysis is quite receiving apparent limitations and constraints which include frequent lack of coordination of both sampling and analyses among the various specialists working on a single site or project, some features are in thin sections are still unidentified or badly understood, climate dynamism, low or lack of petrograhic knowledge among others. To overcome such limitations intensive scientific research should be geared in the field through adoption of standard techniques in its application, using modern microscopic techniques and adequate knowledge on micromorphic features interpretation respectively.*

KEYWORDS: Field, Micromorphology, Overview, Soil, Trend, Soil Science

INTRODUCTION

Soil micromorphology is one of the major subdisciplines within soil science, with sub commission status in the International Society of Soil Science since 1978 (Macphail and Cruise, 2001). Very broadly speaking, soil micromorphologists, like their soil chemist counterparts, are likely to be asked to focus on the on-site and anthropogenic component of a study. One of the first major microscopic investigations was made by Harrison (1933), who used thin sections and other procedures to study the weathering of different rock types under tropical conditions in Guyana. The great pioneer of soil micromorphology was, however, the late Kubiëna (1938), contemporaneously with his work, other techniques were developed for studying soils in greater detail, in particular Transmission (TEM) and Scanning Electron microscopy (SEM). Kubiena (1938) describe the field of studying undisturbed soil in thin sections, soil micromorphology now encompasses a range of ultramicroscopic techniques such as scanning electron microscopy (SEM) that is often linked to microchemical instrumental analyses (e.g., qualitative energy dispersive X-ray analysis or Energy Dispersion X-ray Analysis (EDXRA) and microprobe; e.g., Courty et aI., 1989). Soil micromorphology has now been used in soil science for nearly half a century and may be worthwhile to comment upon a few points of its history. (Coutry, 1990). Site geologists and geo-morphologists, if present, are more likely to take responsibility for the macro geo-morphological setting and the off-site studies. For example, paleosols and colluvium may be identified as macrogeological units, but the soil micromorphologist may confirm these identifications and recognize anthropogenic activities that modified or produced these units. This is not to say that soil micromorphologists cannot also act as competent geomorphologists/geologists, and vice versa. Many workers have been trained in all these fields. As stated as follows, the soil micromorphologist works from the field scale to the microscale, and his/her interpretations may well be of relevance to broad models that reconstruct past landscapes and periods (Macphail, 1992; Whittle et al., 1993). However, there are contemporary views in both scientific and technical challenges regarding the concept of soil micromorphology in terms of its procedures, operational techniques, implications and application in the field of soil sciences. Therefore, there is ardent need to have a general idea on the trend of soil micromorphology as a new sub-discipline in the field of soil science through appraising pertinent literatures. Thus, this paper saddled to overview the trend of soil micromorphology in the field of soil science.

What is Soil Micromorphology?

The term "***Morphe***" is a Greek word which means "*forms or structures*" while "***Logy***" means study. Literally refers to the study of forms or structures. Therefore, in simple term soil micromorphology describe the study of forms and structures of smaller soil particles. Technically, there are scientific definations made by the prominent scholars in the soil agenda. Bullock et al., (1985) define soil micromorphology is the description, interpretation, and measurement of components, features and fabrics in soils, at the microscopic level. According to Courty, (1990) define soil micromorphology as the study under the optical microscope of thin sections prepared from undisturbed and oriented samples after they have been impregnated by synthetic resin. In addition, soil micromorphology is the branch of soil science that is concerned with the description, interpretation and, to an increasing extent, the measurement of components, features and fabrics in undisturbed soils at a microscopic level (Sageidet. 2000). Soil Micromorphology is the study of undisturbed soil samples with the help of microscopic techniques, in order to identify small scale features and interpret how they formed (Stoops,2019).

The method provides information that cannot be obtained by chemical, physical or other methods. Soil micromorphology is based on the same principles as petrography. Samples for soil micromorphology have to be collected with care and normally with the help of metal boxes

Soil micromorphology includes the examination of clods or aggregates of undisturbed soil material with optical microscopes and more high-powered equipment such as scanning electron microscopes, but is usually restricted to the study of thin sections using polarising or petro-graphic microscopes (Kemp 1985).Moreover, soil micromorphology consists of the integrated use of various microscopic techniques for studying the arrangement and the nature of components that form sediments and soils. In the recent years, soil micromorphologists have striven to meet the challenge by demonstrating that the microscope was an essential tool to analyse ancient soils and site formation processes (Courty et al. 1989).

It is essential to establish an intimate connection between the description in the field and the description of the thin section through soil micromorphology. The magnification of a pocket lens as a connecting link in the analysis is very useful and nearly indispensable. The final identification and interpretation are based upon the entire data set. The samples taken in the field as monoliths, with the help of the Kubiena-boxes, have to be air dried to rid the soil of water because of its deleterious reaction with the resin. In the laboratory, the drying of the soil has to be completed with the help of acetone. The soil blocks have to be impregnated with resin under vacuum conditions and then left for at least two months to allow full impregnation by capillarity (Murphy1986).

The Discipline of Soil Micromorphology in the Field of Soil Science

Originally, soil micromorphology was used to study modern soils. Two important directions of research have evolved. The first one is the investigation of palaeosols in order to study the development of regional landscapes and climatic changes. The other direction is the study of Holocene palaeosols focusing on both local and regional interpretations of human influence on pedogenesis (Macphail and Goldberg 1995).

Technical difficulties in the preparation of high quality and large sized thin sections have limited for a long while the development of soil micro-morphology in many soil departments, although others had considerably improved the technique more than fifteen years ago. Technical problems cannot thus explain why soil micromorphology is used in soil science in a non-systematic manner when utilisation of routine soil analyses has been standardised for more than 50 years. Scientific difficulties have been, and still are, probably more limiting because soil scientists often have a basic training in agronomical sciences (especially in France and the USA {and particularly Nigeria}) which includes only a limited background in geology and generally no knowledge of petrography. Soil micromorphology in soil science is taught in a large number of soil science and earth science departments, but this basic knowledge is apparently insufficient and intensive courses in soil micromorphology have recently been created. Soil scientists have commonly escaped their knowledge deficiencies in two ways;

i) Those with a sufficient background in petrography have focused on the weathering of mineral constituents and have paid little attention to the overall organisation of soil constituents.

ii) Others have been using only scanning electron microscopes, and related microprobe techniques, without investigating the intermediate levels of organisation between the field and the ultramicroscopic level.

A large number of soils micromorphologists have, however, overcome the inherent difficulties of thin sections and have been able to handle properly a multi-scale approach, both through time and through spatial scales. For many years, soil micromorphology has been essentially promoted in studies dealing with soil genesis.

In this field a few experts have achieved world-wide experience and are considered to possess the key to interpretation. Unfortunately, most of the available textbooks are essentially devoted to the description of thin sections (Bullock et al. 1985; Brewer and Sleeman 1988; Fitzpatrick 1984) whereas there is a lack of a general textbook dealing with the interpretation of pedological features recognised at the microscopic scales in modern and ancient soils.

Moreover, soil micromorphologists have performed few experiments which could help to corroborate their conclusions (see, for example, Mucher and de Ploey 1990).

On the other hand, in the numerous regional studies of soil-landscapes, soil micromorphology has been commonly used, but only as one of many techniques. Soil micromorphology has suffered a clear decline in this field since the 1970's because the understanding of soil genesis is not at present predominant objective of soil science.

In the recent years, soil micromorphology has however largely expanded its field of application to biological, physical and chemical aspects of soils (e.g., structural modification under farming practises, deterioration of the soil ecosystem by man, behaviour of heavy metals in soils, etc.), (see, for example, Bresson and Boiffin 1990; Thompson et al. 1990). Because in these cases soil micromorphology is combined with other methods to answer specific questions, the logic of the micromorphological investigation can be more efficiently evidenced. It seems that through this direction, soil micro-morphology is progressing successfully in soil science.

Role of Soil Micromorphology Trend in Soil Science

There can be no doubt that soil micromorphology has considerably contributed to our understanding of soil genesis, evolution and functioning. Several processes could not have been understood correctly on the basis of bulk analysis, without the micro-spatial approach of micromorphology. Examples are some podzolisation processes, plinthite formation and polygenesis. Moreover, micromorphology frequently acted as a corrector when interpretation of bulk data alone gave rise to results not in agreement with the truth in the field or landscape, e.g., when results of fine earth analyses are in conflict with reality, and where micromorphologists can explain the contradictions by their observations on the nature and position of the coarser fraction in the soils (Stoops, 2019).

The bibliometric analysis of papers dealing with, or using micromorphology, shows a rise of the number of papers till the period 1986 – 90, followed by a, still continuing, global decline. This decline is strongly expressed for "soil" micromorphology, whereas a considerable increase in papers on "archaeological" and, although less, "palaeopedological" micromorphology is noticed. This rise and decline for "soil" micromorphology goes partly parallel with the interest for soil genesis and classification. In the 1960's till the 1990's studies on soil genesis and classification were strongly encouraged by USDA, FAO and local soil survey institutes. Discovering and naming new soil types/contexts all over the world prompted pedogenic research, and was an excellent occasion for micromorphologists to contribute to the understanding of processes. However, at the end of the century the more "agronomic" view (mainly in departments of agriculture) on soil science overruled the more "naturalistic" vision (including pedogenesis and classification) (mainly in departments of earth sciences), following the economic context. Public and private sponsors became more interested in exploiting soils than in understanding them, and funding for genetic and micromorphological studies was no priority. Parallel, the success of computerization and the "sand syndrome", as it was called by Bouma (1977) appeared, interested more in easily quantifiable data of uniform samples that can easily be stored in databases and treated statistically, rather than in the complex multi-anisotropic reality of soils.

1. Useful, for evaluating soil mineralogy, genesis, and diagenetic processes (Cady et al., 1986).
2. Inexpensive, simple: the cost of a thin-section and a petrographic microscope.
3. Essential precursor for followup analytical procedures (e.g., geochemistry, isotopes).

Soil micromorphology has traditionally been rather qualitative and descriptive. We tried to circumvent that disadvantage by using a semiqualitative approach, with classification of 22 micromorphological characteristics on a scale of 0–3, varying from not detected to abundant, and multivariate analysis of all of them with principal component analysis. (Kooijman, et al., 2009).

The first step in micromorphology concerned the characterization of humus forms, organic matter and peds in the thin sections. (Kooijman, et al., 2009).

This is not the case in micromorphology, which allows the interpretation of exceptional features, which frequently have a clear genetic meaning (Stoops 1998). The normal size of a thin section is 6 x 7.5 cm. The thickness of a thin section should not be more than 20-30 mm to fit on a polarising microscope. Different types of light are used for analysis: plane polarized light (PPL), cross-polarised light (XPL) and oblique incident light (OIL). A further possibility is the use of ultra-violet light (UV). The systematic description of the thin sections follows a universal standard, published as a «Handbook for soil thin section description» by Bullock et al. 1985. The technique of description and interpretat- ion is to a high degree based upon data from pedogenic studies and from agricultural experiments. Some available microscopic techniques are used for the microphological analysis which include but not limited to the following;

Electron Microscopy:

- Secondary Electron
- Back Scattered Electron
- Cathodoluminescence
- X-Ray Maps.

The Basic Techniques and Stages in Soil Micromorphological Features Analysis Using Thin Sections Method

Three (3) basic stages are involved in soil micromorphology analysis which are

1. Pre-field operation
2. Field operation and
3. Post-field operation.

The stages are briefly described in figure 1 below;

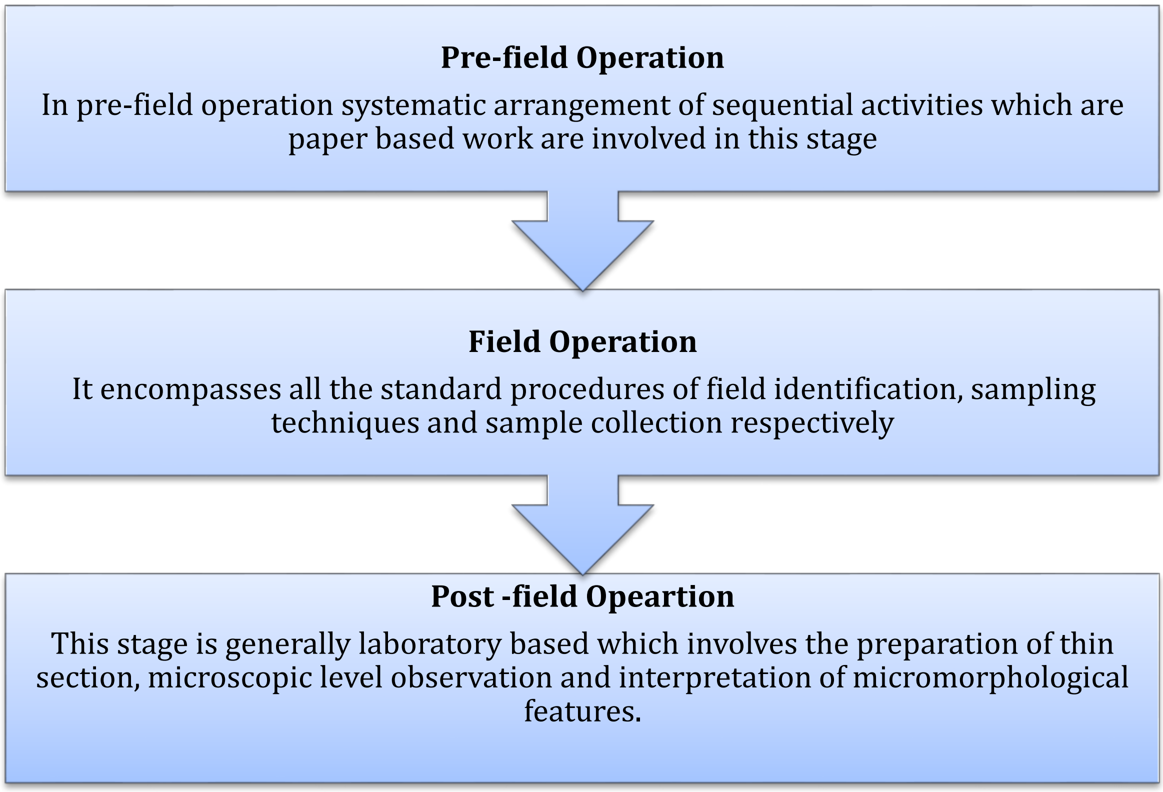

Figure 1: The Technical Stages Involved in Soil Micromorphological Analysis

Fieldwork is essential for the understanding and interpretation of the sampled soils. Observe the landscape and characterize it as much as possible. Take note of the shape of the hills, presence of terraces, raised beach, slopes' gradient and length, type of vegetation and level of coverage, boulders, stones. A pH kit will help you measure soil acidity which in turn will help you for human, mammal and fish bones preservation and seeds.

The quality of micromorphological samples for site interpretation depends largely on the field strategy. Choosing the profile or area to be sampled is key in the geo-archaeology of any site. The sampling strategy must be discussed ahead of sampling with site's directors or PI. A survey of the site should allow you to identify the best place to sample. The technique consists of sampling undisturbed soils from archaeological profiles with metal containers known as Kubïena tins or if not available, an 'electrical socket metal back box'. *[Should you opt for the electrical box, do not forget to put a thin aluminium sheet on the bottom of (to cover the holes) as well as on the top to perfectly seal the sample].* Bearing in mind that one wants to capture as much data as possible, one of the best way to do that is by overlapping sampling tins as shown in the below (fig.2). This prevents to miss horizon even if not clearly visible in the field. It also provides more data per horizons overlapped. If time and money allow, it is a good idea to double the most important samples as depicted in fig. 2 (Dufeu, 2007).

Figure 2: Overlapping Sampling Methods

For an efficient coordination between field observations and microscopic investigations, soil thin sections have to be larger. (ca. 12 x 7 cm or more) than the standard petrographic ones, but have the same thickness (25 pm).

A continuous observation from the field scale down to high magnification, permitted by scanning electron microscopes, allows an exhaustive characterization (nature, shape, size, frequency, etc.) of elementary components and the study of their arrangement. A high level of significance is given to specific attributes, which are subdivided according to their origin into three well-defined groups:

i. Sedimentary features which are diagnostic of the source of the sediments, the mode of transport and depositional conditions.

ii. Pedological features that give information about the dynamics of each soil-forming process and about the interaction of these processes through time.

iii. Anthropogenic features related to human activities, which can be identified at various scales, such as mineral or organic components of human origin or which may correspond to specific fabrics induced by human trans-formations. Both human-induced fabrics and anthropogenic com-ponents can have been produced intentionally or accidentally.

The basic Technique in Soil Micromorphology Involves;

- ✓ Preparation of thin sections of undisturbed soil materials, the sample being collected in Kubeina's boxes with double lids to avoid disturbance
- ✓ Inclusion of synthetic resins for improved impregnation and the increase in size of the section
- ✓ Introducing acetone as diluents of the resins in order to remove water from the samples due to acetone exchange. Thus, reducing shrinkage.
- ✓ Then subject the prepared thin section to the below stages;

1) Examine the slide with the naked eye. (Note: generally, scan the entire thin section on a standard flatbed scanner at 600 dpi resolution, and print the image to help navigate through the thin section and mark where photomicrographs were obtained).
2) Delimit areas of relative uniformity (the whole slide may be uniform)
3) Examine each area with a large hand lens at x 10 magnification.
4) Subdivide into further areas if necessary
5) Examine each uniform area with plane-polarized light at x 20-25 magnification
6) Examine each uniform area with cross-polarized light at x 20-25 magnification
7) Examine each uniform area with plane-polarized light at x 100 magnification
8) Examine each uniform area with cross-polarized light at x 100 magnification
9) Identify and describe the following features (not all present in all thin sections): mineral material, matrix, structure and pores, faunal features, particle size distribution, rock types, organic matter, roots traces, coatings and other surface features, segregations, concretions, nodules and concentrations, weathering features, microorganisms, other features.
10) Then record your observation on the observation sheet and take a photo-micromorphic pictures of the depicted features as diagrams for documentation and recommendation **(FitzPatrick, 1993).**

Basic Features of Micromorphological Features Under Microscopic Level

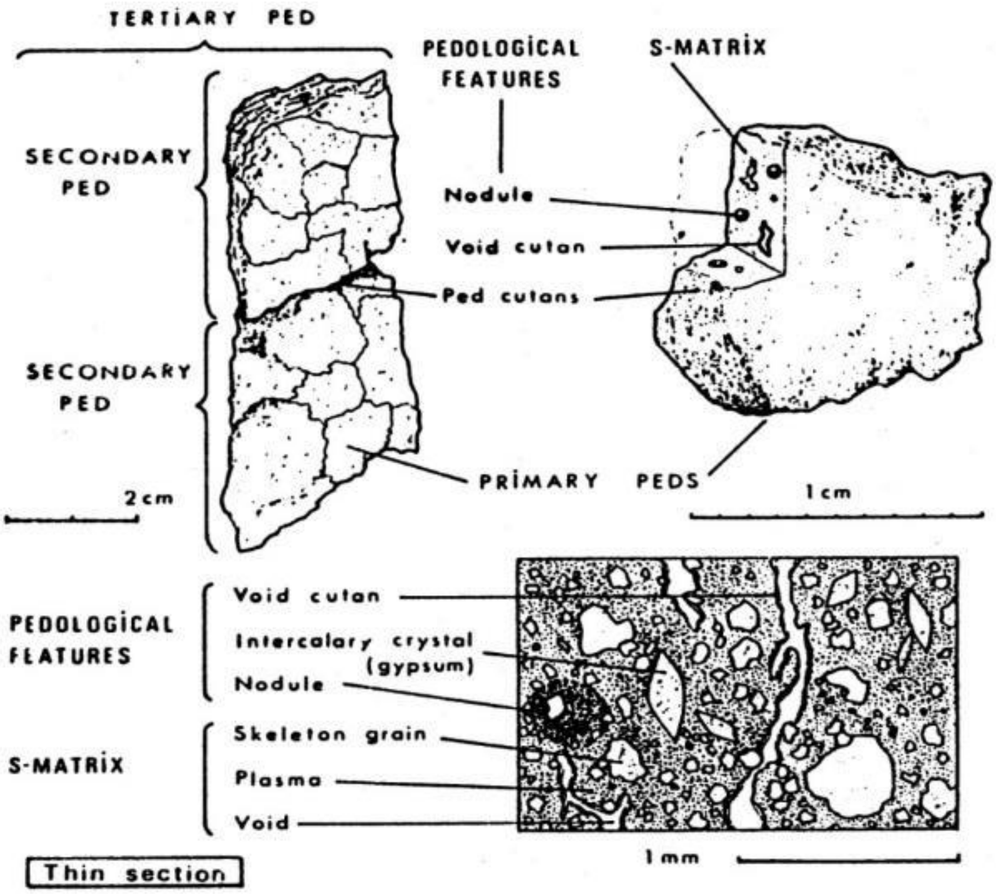

Figure 3: Thin Section Description Under Electronic Microscope.

Source: Brewer (1976): Soil Matrix.

1. Plasma, mainly fine clay-sized mineral particles, but also including organic material of colloid size, which may be soluble,
2. Skeleton grains, chiefly silicate sand and silt grains embedded in the plasma, which are generally stable, and
3. Soil voids, which are pore spaces occupied by air or water, and include: (A) Macropores (>1-2 µm) such as root pores, animal burrows, interpedal and fracture pores, and (B) Micropores (< 1-2 µm) as depicted in figure 3 above respectively.

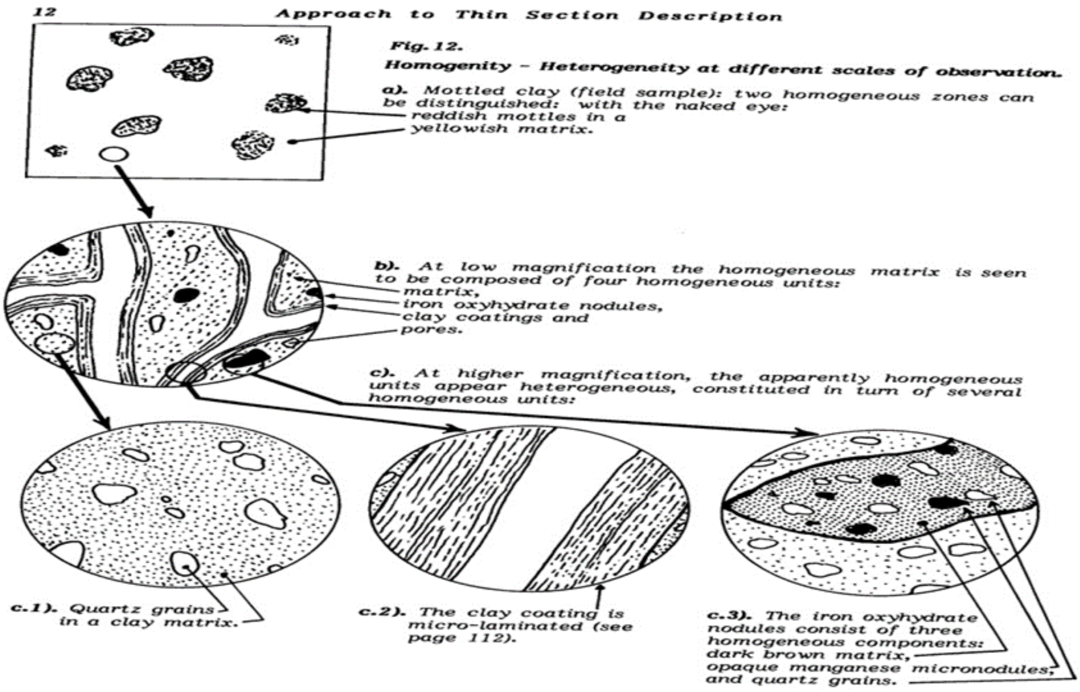

Figure 3: An Approach to Thin Section Description Under Electronic Microscope.

Source: Brewer (1976): Soil Matrix

The Soil Micromorphology Scale and Global Food Production

A cascade of linkages and feedbacks can be traced between the global scale and micromorphology scale (Figure 4). There is a vertical flow of matter between all scales and a substantial horizontal flow of matter across the landscape and global scales. World food production is an example of these vertical and horizontal flows that are intensifying during the Anthropocene. First, supply and demand forces at the global scale cause farmers to grow specific crops at the landscape scale. This involves industrial agriculture that relies on fossil fuel, crop monocultures, synthetic chemicals, heavy machinery, and large-scale irrigation. At the micromorphology scale, these processes are seen as pore collapse, pore clogging, crust sealing, and microstructure dispersion (figure 5 and 6) (FitzPatrick 1993; Adderly et al. 2010; Pagliai and Stoops 2010).

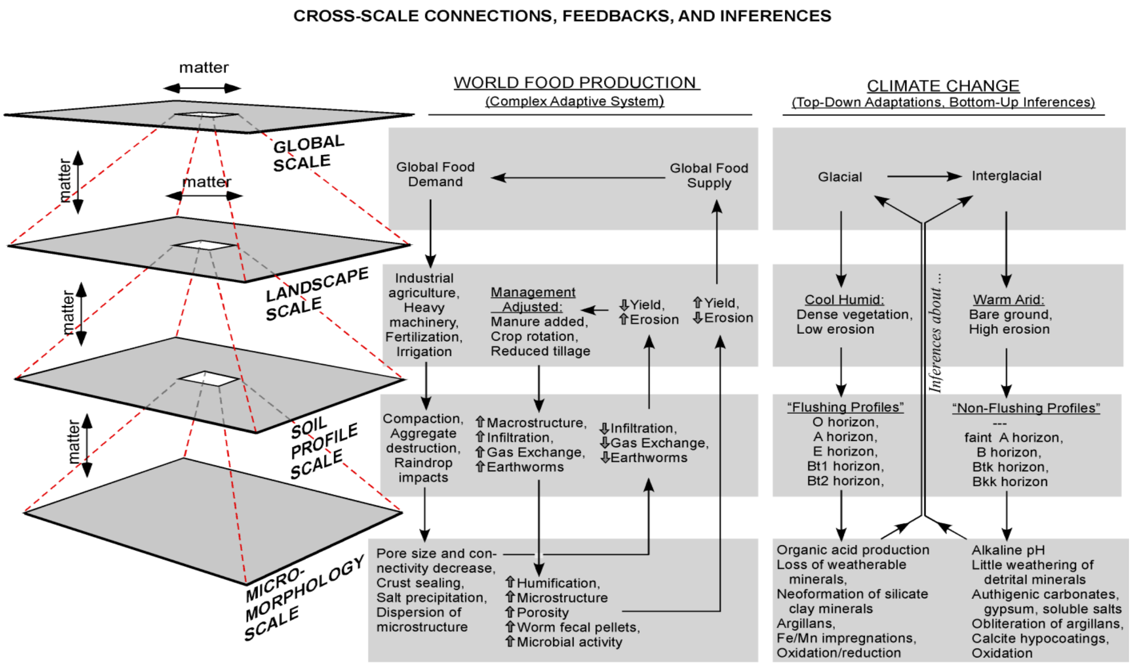

Figure 4: Depicted the Linkages and Feedbacks can be Traced Between the Global Scale and Micromorphology Scale

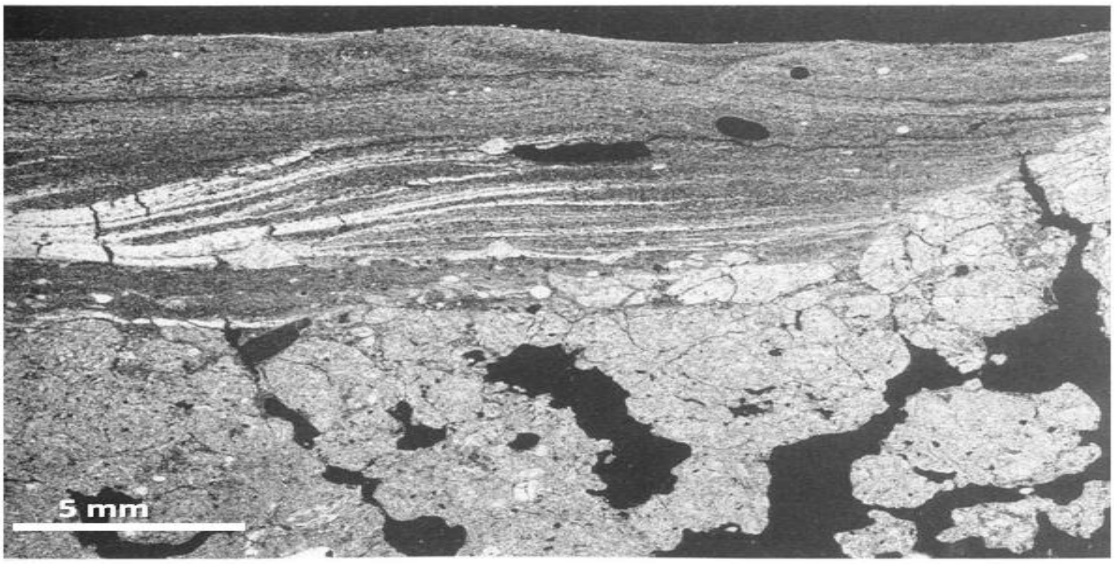

Figure 5: Crust Resulting from Cultivation Overlying a Porous Soil Illustrating how Insights Gained at the Micromorphology Scale can Increase Understanding of the System at Broader Scales.

From FitzPatrick (1993) with permission from Wiley Publishers.

Responses at the micromorphology scale are then linked back to the profile scale as decreased infiltration, decreased gas exchange, and decreased earthworm activity. These responses can then be followed up to the landscape scale where decreased yield and increase erosion can initiate a change in management practices, such as manure additions, crop rotation, or reduced tillage. The consequences of the management changes can then be traced downward through the profile to the micromorphology scale where increased humification, microstructure, porosity, and worm fecal pellets can be documented in thin section as a response to management at the landscape scale (Kooistra et al. 1990; Dobrovol'ski 1991). Once more, adaptations at the micromorphology scale can be traced up through the soil profile to the landscape scale as increased yield and decreased erosion. Subsequently, these responses feed back to the global scale where supply and demand forces again influence world food production.

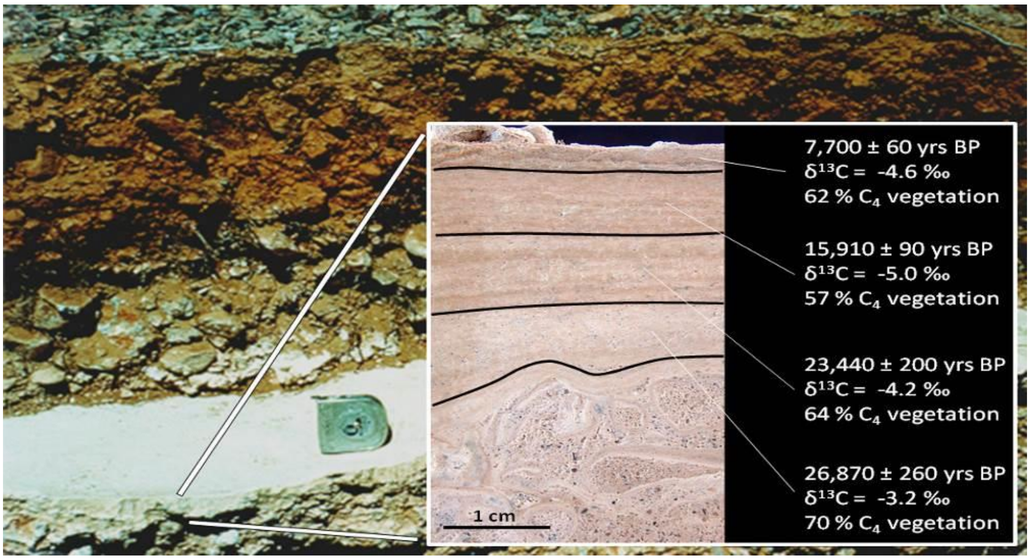

Figure 6: Radiocarbon-Dated Laminae of the Upper Zone of a Petrocalcic Horizon Illustrating how "Memory" at the Micromorphology Scale can be used to make Inferences about Paleoclimate at the Global Scale (after Monger et al. 1998, 2009).

At the micromorphology scale, properties of this soil would include organic acid production, loss of weatherable minerals, neoformed silicate clay, illuvial clay coatings, and, depending on drainage, redoximorphic and Fe/Mn impregnations (Bullock and Thompson 1985; Lindbo et al. 2010). With a shift to greater aridity, diminished vegetative cover, increased bare ground, and increased erosion would occur simultaneously at the landscape scale (Gile and Hawley 1966). At the profile scale, soils would transform from having a "Flushing Profile" to having a "Non-Flushing Profile" accompanied by the formation of A-B-Btk-Bkk horizons (Rode 1962; Monger et al. 2011). Consequently, organic matter decreases, pH increases, and there is little weathering or leaching. Instead, authigenic carbonates, gypsum, or soluble salts precipitate and form hypocoating, nodules, and intercalations (Durand et al. 2010; Poch et al. 2010). These accumulations are capable of obliterating relict argillans which developed in a wetter climate (Allen, 1985). Because arid soils are non-flushing, a micro-stratigraphy can accumulate and preserve a memory of climate change as carbon isotopes in the laminae in of petrocalcic horizoAll micromorphology features are not necessarily indicators of past

ISSN: 2689-5331

Volume 3, Issue 2, 2020 (pp. 11-31)

climates, but some features can be scaled up to make inferences about climate change based on the assumption that ***FACTORS* → *PROCESSES* → *FEATURES***. The challenge is that a soil profile may "remember" more than one climate change and is therefore a palimpsest that, like a parchment that has been written upon several times, contains remnants of imperfectly erased features (Targulian and Goryachkin 2004; Fedoroff et al. 2010). Still, for example, micromorphology features such as cryoturbated and papulized pore ferriargillans, ice-expelled silt cappings, frost-shattered particles, platy and lenticular microstructure in the subsoil, and blocky microstructure caused by ice blades can be useful evidence that a Cryosol once existed in a location that is now occupied by a warmer climate (Van Lliet-Lanoë 1985, 2010)

Insights obtained at the micromorphology scale about how pollutants flow through soil can be scaled up and combined with data gathered at the profile scale to redesign agricultural practices and septic systems, which occurs at the landscape scale. at the micromorphology scale.

Suggested Standard Sheet for Recording Observations

Specimen Designation:
Formation (or Soil Series):
Investigator:
Locality:
Hand specimen description (if applicable):

Skeletal grains / % estimate:
Pedogenic features/ % estimate:
Soil matrix (plasma)/ % estimate:

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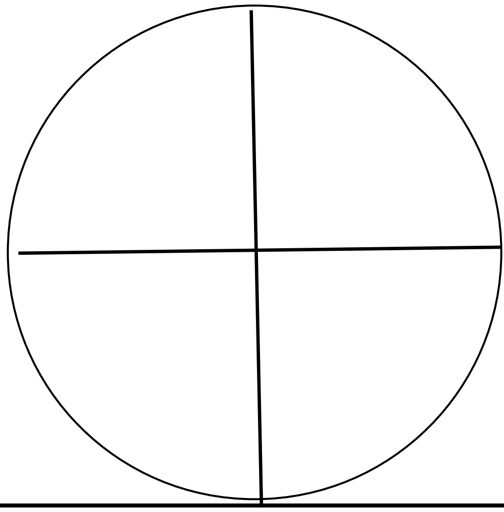
Distinguishing properties:

(Sketches of fields of view at different magnifications)



Cementation and alterations (if lithifiedl):

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Texture……………………………………………………………

Source: (Bullock et al., 1985)

The Essentiality of Soil Micromorphology

The importance of soil micromorphology cannot be overemphasized. The field provides tremendous achievements in soil science agenda of which the following are;

- This is important in or-der to ensure that the various components –sand, silt, clay and organic material and the pores in between –stay undisturbed (Courty et al. 1989).
- Roman and Robertson (1983) were among the first to identify historic tilled fields using soil micromorphology. Later, the method was used to trace ancient agriculture by scientists like Macphail et al. (1990). Langohr (1990) was able to map the soil types that were dominant in Belgium in the Neolithic. He could confirm that the Neolithic people preferred to use loessic soils. Soil micromorphology can support other types of analysis in the reconstruction of prehistoric cultural activities (deforestation, pasturing, clearance, tilling, abandonment and regeneration of natural vegetation).
- Micromorphological analysis is today the most reliable method for identifying and understanding the processes involved in soil formation. Both processes produced by nature as well as those induced by human impact are included. Buried soils (palaeosols) can contribute to Quaternary studies through their use as stratigraphic marker horizons as well as by providing information on Quaternary environments. As to the latter, it is necessary to assume that the pedological features resulting from past pedogenic processes are similar to those produced by the same processes today. It is also necessary to assume that some soil features and processes are uniquely associated with specific environments. On the basis of these assumptions, certain buried horizons can give indications on climatic, vegetational, topographical and hydrological conditions (Birkeland 1984).
- Dufeu (2007) Since the 1980s, micromorphology analysis has become a research tool in and for the study of soils plays an important role in:
    - Geo-archaeology
    - Archaeology
    - Quaternary geology
    - Paleo-pedology
    - Soil management
    - Forensic

Soil Micromorhological Properties.

- ✓ **Soil structure**

Several environmental factors can affect the soil structure and they must be considered in

micromorphological analysis. For instance, soil fauna activities such as feeding, reproduction and protection (burrowing), affect both soil components and therefore soil structure arrangement. It is important to identify and describe the soil structure observed during micromorphological analysis since as to be faunal induced or geogenically formed (see fig. 7). (Dufeu,2007).

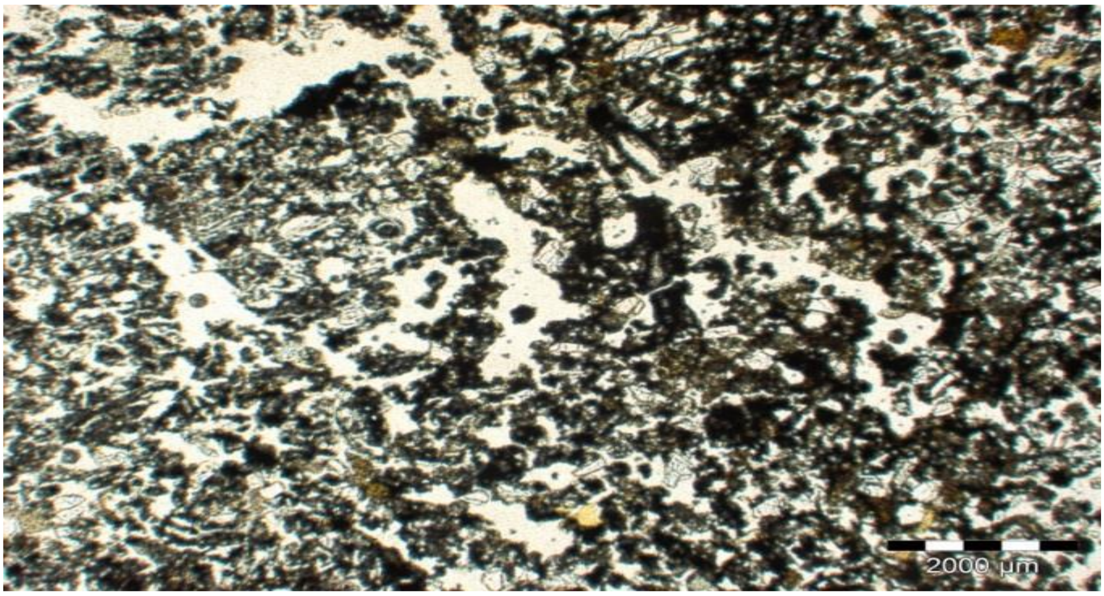

Figure 7: Faunal Activity Exhibiting a Vermicular Structure(left). Lenticular Structure, (right) with a Strongly Expressed Parallel Oriented Coarse Organic Matter. The Channels and Chambers are all due to Faunal Activity.

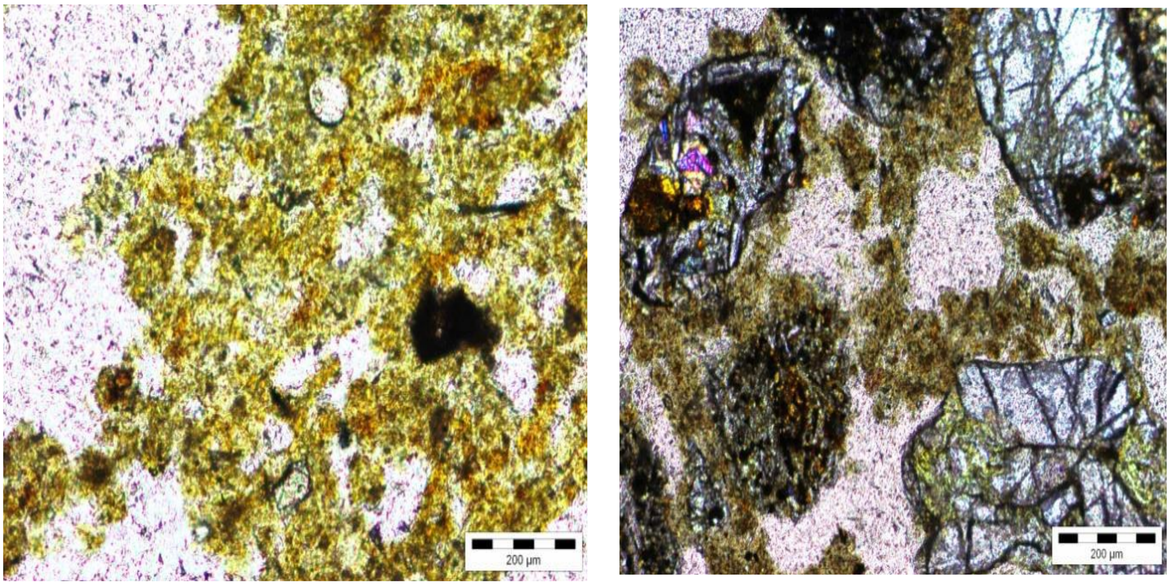

Figure 8: Vughy Microstructures an Irregularly Shaped Void or Pore within a Soil Aggregate.

A soil whose pore space consists mostly of vughs is said to have a vughy microstructure as shown in figure 8 and 9 respectively. Re-worked soil organic matter by soil animals exhibiting vughs and hypocoating of the grain mineral (partially XPL) (Photo by Dufeu, 2007).

Figure 9: Variation of Soil Structure and Porosity level for Micromorphological Analysis.

Limitations and Constraints in Soil Micromorphology Trends

As in the other field, despite the developmental achievement in soil science through micromorphological analysis there are quite limitations and constraints associated with the field. The following are some of the identified challenges and limitations;

- One of the constraints that emerged since the late 1950s is a frequent lack of coordination of both sampling and analyses among the various specialists working on a single site or project. For example, when the various specialists' sample different parts of the site, conflicting interpretations may result that may be impossible to resolve. This situation is further exacerbated when workers are sampling and analyzing at different scales. Increased dissatisfaction with this situation, which ultimately is a waste of energy.

- One should not think that there are no longer challenges in micromorphology, and that everything is clear and has been explained. Many features in soil thin sections are still unidentified or badly understood, such as the white, yellow or red grains in many soils on volcanic materials, the formation mechanism of pseudomorphs and its interpretation with regard to environment and chronology, the formation of some nodules and the paragenesis of some pedogenic minerals.

- Climate is changing, whether by natural processes, as many earth-scientists think, or by human activities. This means also that soils, as natural bodies, will adapt to the new conditions. Here lies an important challenge for micromorphology: can we predict these changes in soil behaviour, so as to inform policy and decision makers on possible risks or opportunities? For instance, changes in amount and distribution of precipitation will change some soil parameters and behaviour, with impact on agriculture, water quality and supply. Micromorphology and micromorphometry taught us already part of the story of crust formation, but for instance the role of the nature of the clay (size and mineralogy) and its spatial arrangement is still a well-kept secret of nature which has to be disentangled. (Stoops, 2019).

- Several processes could not have been understood correctly on the basis of bulk analysis, without the micro-spatial approach of micromorphology. Soil micromorphology seems slower to apply recent micro-analytical techniques, such as μFTIR, μXRD, μXRF, and gas-chromatography, to name a few. This is remarkable, as in the 1970's and 1980's so called submicroscopic techniques were already a hot item in soil micromorphology (Bisdom and Ducloux, 1983).

- Also, in the field of micromorphometry few progresses have been made, notwithstanding the new techniques for image analysis. A lack of standardisation of techniques here makes comparison between papers of different authors impossible.

- Many features in soil thin sections are still unidentified or badly understood (Cornwall, 1958).

SUMMARY

Soil micromorphology owes it popularity to the late Walter Kubiëna who saw its potential as a tool to investigate some of the properties and processes in soils. His two books "Micropedology" and "Soils of Europe" are landmarks in the development of Soil Science. He did not have the benefits of modern equipment and impregnating ground. His work was followed by other researchers, in particular in the Netherlands and in Germany. Then followed a number of important publications on micromorphology by Brewer, FitzPatrick, Bullock et. al. and Stoops. The technique is now well established globally with investigations into every aspect of soil science including engineering and archaeology. There have been many notable contributions but alas there is no consensus about terminology. There are those that have produced very elaborate terminologies and some like this author that plead for simple language and the use of accepted terms as used in this publication.

The microscopic study of thin sections of soil micromorphological analysis from soils makes it possible to describe and measure components, features and fabrics in undisturbed soils, which cannot be seen by the naked eye. The method provides an important insight into many problems of, for example, soil development, diagenesis, weathering, and soil/plant interactions, and can be used for various activities. The use of micromorphology is increasing in a number of disciplines, particularly in soil science, quaternary geology, and palaeoecology. It was not until the 1970s that the micromorphological analysis of soil thin sections was developed for general application. Today, soil micromorphology has become one of the established scientific techniques like analysis of macrofossils, charcoal, pollen, and bulk chemical, biological, and physical analysis respectively.

CONCLUSION

Since the 17th Century, scientists have been using microscopes to make objects visible that were otherwise invisible. Soil micromorphology, in particular, makes visible the natural architecture and basic mineral and organic components of soil that are otherwise invisible (Kubiëna 1938; Brewer 1964; Bullock et al. 1985; Stoops 2003). By systematically looking at cross-scale connections between micromorphology and the soil profile, landscape, and global scales, patterns have emerged in the field. We can expect environmental change, induced by natural factors or by humans, to have been recorded in sedimentary materials only when the perturbation has been strong enough to modify their singular properties. The recognition in the field of these modifications is essentially limited by the fact that observable properties at this level of organisation are the resultant of complex interactions between elementary components of various sizes (atomic, molecular, nanometre, microscopic, etc.). Observations of thin sections prepared from undisturbed samples provide substantial information about most reactions which have affected the basic constituents of sediments (sand-, silt- and clay-sized mineral particles and organic components). These reactions are characterised by their specific signals which may relate to sedimentary changes, pedological modifications or man-induced transformations.

Therefore, soil micromorphology plays a pivotal role in soil sciences particularly in the field of pedology. To realize optimum performance and overcome the constraints intensive research and publications should be geared towards soil micromorphological perspective through the application of scientific techniques and principles accordingly.

"One should not think that there are no longer challenges in soil micromorphology, and that everything is clear and has be explained"

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