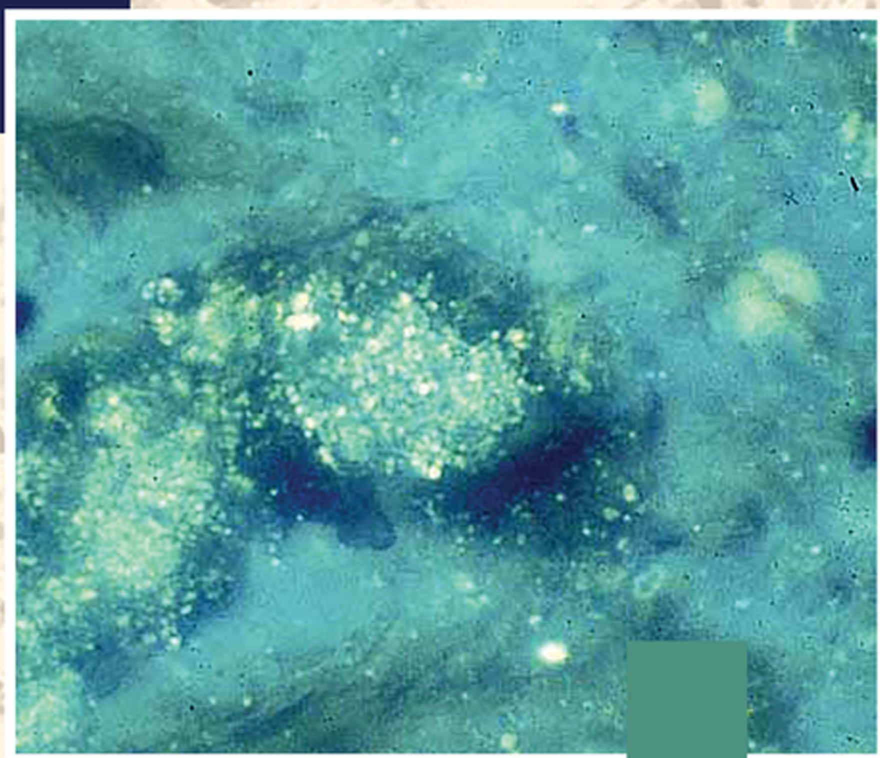
Guidelines for
Analysis and Description of Soil and Regolith Thin Sections

Second Edition



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Soil Science Society of America

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Guidelines for Analysis and Description of Soil and Regolith Thin Sections

Second Edition

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partially based upon the

"Handbook for Soil Thin Section Description" by Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T. and Babel, U.

Soil Science Society of America

WILEY

Editorial Correspondence:
American Society of Agronomy, Inc.
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Library of Congress Cataloging-in-Publication Data

Names: Stoops, Georges, author.
Title: Guidelines for analysis and description of soil and regolith thin sections / Georges Stoops, University of Ghent (Belgium), Faculty of Sciences, Department of Geology, Research Unit Mineralogy and Petrography.
Other titles: Guidelines for analysis and description of soil and regolith thin sections
Description: Second edition. | Hoboken, NJ : Wiley-ACSESS, [2021] | Series: ASA, CSSA, and SSSA books | Revised edition of: Guidelines for analysis and description of soil and regolith thin sections. Georges Stoops, Michael J. Vepraskas. 2003. | Includes bibliographical references and index.
Identifiers: LCCN 2020030573 | ISBN 9780891189756 (paperback)
Subjects: LCSH: Soil micromorphology. | Regolith.
Classification: LCC S593.2 .S76 2021 | DDC 631.4/3—dc23
LC record available at https://lccn.loc.gov/2020030573

doi:10.2136/guidelinesforanalysis2

Cover Design: Wiley
Cover Image: © Georges Stoops

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

To my wife Marthe for her patience during the many hours, days, weeks of writing, and for her continuous moral support. As a souvenir to the many "holidays" in the mountains and seaside during which piece by piece, year by year most of these notes were prepared.

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About the Second Edition

Since its publication, fifteen years ago, the "*Guidelines for Analysis and Description of Soil and Regolith Thin Sections*" are internationally considered as a standard for micromorphological studies, as a follow-up of the famous "*Handbook for Thin Section Description*", developed by the International Working Group on Soil Micromorphology of the International Society of Soil Science (Bullock et al., 1985). As the first edition is out of print since a few years, and second-hand copies only available at exaggerated prices, that students surely cannot afford, I took the initiative to prepare a second, updated version.

Since the publication of the first edition, much progress was made in the interpretation of micromorphological features, especially in the fields of archaeology and paleopedology. However, new publications on methods, theoretical concepts and terminology are very rare. The study of many papers applying the concepts of the Guidelines, and especially by refereeing many manuscripts, learned me which concepts and definitions were not clear or insufficiently explained. Also the discussion with students during several intensive courses on micromorphology helped me to discover what had to be remediated.

In this second edition, the text is updated, not only with new references, but also with some older that were overlooked before. Some chapters are rearranged, part of the appendixes integrated as tables in the corresponding chapters, other deleted. A new appendix, containing the translation of 220 terms in 19 languages is added.

I want to extend my thanks for useful comments and suggesting to several colleagues, especially Dr. D. Itkin (Ben-Gurion University of the Negev), Dr. Vera Marcelino (Ghent University, Belgium) and Dr. Florias Mees (Africamuseum and Ghent University, Belgium), and for the interesting comments of many referees, especially of Dr. M. Gerasimova (Moscow Lomonosov University), Dr. R. Heck (University of Guelph), Dr. F. Khormali (Gorgan University of Agriculture and Natural Resources), Dr. P. Kühn (University of Tübingen), Dr. V. Marcelino (Ghent University), Dr. H. Morrás (University of Buenos Aires), Dr. R. Poch (University of Lleida), L. Trombino (University of Milano), E. Van Ranst (Ghent University), Dr. M. Vepraskas (North Carolina State University), Dr. E. Verrecchia (University of Lausanne), and anonymous referees.

My gratitude goes also to Prof. Dr. J. De Grave, head of the Research Unit Mineralogy and Petrology of the Department of Geology of the Ghent University (Belgium) for giving me the opportunity to make use of the infrastructure and thin section collections.

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Acknowledgements to the First Edition

While preparing the texts and illustrations, the author has often recalled all the individuals which have contributed in one way or another over many years to the final production of this book through their works, discussions, support, or advise.

My thanks go in the first place to the members of the former "Working Group on Soil Micromorphology", who regularly assisted at the meetings, and soon became dear friends. The long, sometimes seemingly endless discussions we had on concepts and their formulation were an excellent school where I learned the value of clear, unambiguously expressed ideas and where I became aware that cultural diversity, as small as it might seem within Western Europe, can lead to completely different approaches of scientific subjects, particularly when abstract ideas are involved. Discussions by Dr. H.J. Altemüller and the late Dr. A. Jongerius contributed much to the understanding of the micromorphological concepts needed, but every member of the Working Group had input, not only in a scientific way, but also in a human one. To say it with the words of the popular German singer Reinhard Mey: "Denn eigentlich ging keiner fort: in einer Geste, einem Wort, in irgend einer Redensart lebt Ihr in meiner Gegenwart" (Then in fact none [of my former friends] left. They all live close to me, in a gesture, a word, an expression).

I also want to acknowledge the contributions of numerous students to which I have taught micromorphology over the last 30 years, at the International Training Centre for Post-Graduate Soil Scientists, University of Gent, or as a visiting professor in Europe and overseas. Their remarks and questions helped me a lot to rephrase, reshape and complete definitions, subdivisions and comments. Looking to the *Handbook for Soil Thin Section Description* with the eyes of the student was very instructive, although, as a co-author, not always a very satisfactory experience.

Many individuals have contributed to the final result of this book. Mentioning every contribution would be impossible. Among those that sent in the past opinions on the *Handbook* I want to acknowledge especially Dr. H. Morras (INTA, Argentina) for his detailed and well-considered comments. Several colleagues improved the manuscript of the "Key to the ISSS Handbook for Soil Thin Section Description", which forms an essential part of this manual, determining the way in which several concepts were modified and interrelated. Amongst them I want to acknowledge the contributions of Dr. J. Arocena (UBC, Canada) and Dr. A. Ringrose-Voase (CSIRO, Australia). A great help to me were the comments of Dr. L. Drees (Texas A&M University, USA) on the first manuscript of this book, both with respect to the content and the redaction. Thanks go also to the members of the Editorial Committee who reviewed the manuscript. I really appreciate their comments and corrections. Following scientists were involved: Prof. A. Busacca (Washington State University), Dr. L. Drees (Texas A&M University), Prof. Dr. P. Goldberg (Boston University), Prof. Dr. R.W. Griffin (Prairie View A & M University, Texas), Dr. A. Jongmans (Wageningen Agricultural University, The Netherlands), Prof. Dr. D.L. Lindbo (North Carolina State University), Dr. W.D. Nettleton (USDA), Dr. F.E. Rhoton (USDA), Prof. Dr. H. Stolt (University of Rhode Island), Prof. Dr. L.T. West (The University of Georgia), Prof. Dr. L.P. Wilding (Texas A & M University) and Dr. M. Wilson (USDA).

Special thanks go to Dr. F. Mees (University of Gent, Belgium) for his comments on the first draft and his digitizing all the micrographs shown in the CD. Final formatting of the CD was done by Matthew Vepraskas (Virgin Tech. University) and Matthew Kirk (North Carolina State University). Thanks also to Mrs. Martine Bogaert (University of Gent, Belgium) for making the drawings.

Many colleagues kindly and spontaneously helped me with providing advises, information and illustrations. Not being able to thank everybody who gave some help, I want to mention especially following persons: Dr. F. Runge (Paderborn, Germany) and L. Vrijdaghs (Tervuren, Belgium) (phytoliths), Dr. J. Delvigne (Marseille, France) (weathering).

Although the collection of thin sections of the Laboratory for Mineralogy, Petrology and Micropedology of the Ghent University (Belgium) is very rich, some specific examples were missing, or not sufficiently didactic. The author is indebted to several friends and colleagues that send micrographs, especially Dr. J. van de Meer (University of Amsterdam, The Netherlands) (Micrographs 4.22 and 7.28), Dr. B. Van Vliet-Lanoë (University of Lille, France) (Micrographs 3.27 and 3.28), or gave the opportunity to make micrographs of their thin sections: Dr. J. Aguilar (University of Granada, Spain), Dr. C. Ampe and Dr. V. Marcelino (Ghent University, Belgium), Dr. P Kühn (Greifswald, Germany), Dr. R. Poch (University of Lleida, Spain), Dr. L. Trombino (University of Milano, Italy).

Thanks go also to Dr. C.V. Waine, publisher of the *Handbook for Soil Thin Section Description* for the permission to reproduce several figures.

Last, but not least, many thanks go to Dr. M. J. Vepraskas (North Carolina State University, USA), who urged me to write this book and who started and continued the timeconsuming and sometimes difficult administrative publishing procedures, including the editing. Without his help and continuous support this work would not have been realized.

GEORGES STOOPS

List of Abbreviations

BLF	blue-light fluorescence microscopy
CL	cathodoluminescence microscopy
CPL	circular polarized light
CT	X-ray computerized tomography
EDS	energy-dispersive spectroscopy
FTIR	Fourier-transformed infrared spectroscopy
OIL	oblique incident light
PPL	plane-polarized light
SEM	scanning electron microscopy
TDFI	transmitted dark field illumination
TEM	transmission electron microscopy
UVF	ultraviolet fluorescence microscopy
WDS	wavelength-dispersive spectroscopy
XPL	cross-polarized light
XPLλ	cross-polarized light and 1λ-retardation plate (gypsum compensator) inserted

1. Introduction

Precise descriptions of the features seen in soils or regoliths as examined under the microscope require a specific set of concepts and terms because the microscope reveals features that simply cannot be seen with the naked eye. Microscopic features can of course be described using common words, but this would lead to very tedious and lengthy descriptive texts that are time consuming both to write and to read and not always unambiguous. Moreover, it would be difficult to translate such descriptions without losing information or committing errors. By using a comprehensive terminology, descriptions would be not only shorter, but also easier to compare and to store in databases.

Terminology is in the first place a means of communication and, in the second place, a means of education- people more easily recognize objects, features, or situations for which they know a name. Features or combinations of features without a name are often not consciously observed! For instance, Inuits have many words for snow, while speakers of English have only one and can barely differentiate between wet and dry snow. Eunologues can distinguish and name many types of wines, based on the variety of grapes, fermentation and storing, whereas people not acquainted with this terminology can merely recognize red, white, and rosé wines.

To put an end to the proliferation of overlapping or contradictory concepts and terms in micromorphological publications, an international working group was created in 1969, under the auspices of the International Society of Soil Sciences, to establish a simple, comprehensive terminology for the description of soil thin sections. The result of this work was published in the Handbook for Soil Thin Section Description by P. Bullock, N. Fedoroff, A. Jongerius, G. Stoops, T. Tursina and U. Babel in 1985 (hereafter referred to as the Handbook). The book was highly appreciated by the micromorphological community, as it helped solve several problems of description inherent to the then existing systems. It became widely used, both for scientific research and as a teaching aid.

Since the early 1990s the Handbook had been out of print, but the original publisher was not interested in the publication of a second edition.

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doi:10.2136/guidelinesforanalysis2

Because of the demand for a new edition and to have the opportunity to amend several errors, contradictions and inconsistencies in the original text, I agreed to prepare a new revised text. The *Guidelines for Analysis and Description of Soil and Regolith Thin Sections* (hereafter referred to as the Guidelines) appeared in 2003. The text of this book was essentially based on the Handbook (Bullock et al., 1985), and on the author's own series of lecture notes and his experience in research and teaching at the International Training Centre for Post-Graduate Soil Scientists (Ghent University, Belgium) and during several intensive courses on micropedology in Europe and abroad. For some definitions and concepts, different approaches by other soil micromorphologists, which were discussed by Bullock et al. (1985), were not repeated in the Guidelines. Decisions then made, were adopted without arguments or references. In several places, however, definitions and schemes were discussed in more detail, as experience has shown that students are often puzzled why specific decisions were made.

Not all concepts of the Handbook were as user-friendly as intended by its authors. Especially in those cases where the distinction between features was partly based on common experience of the authors, some concepts were left unclear (Stoops and Tursina, 1992). Stoops (1998) suggested, therefore, the introduction of a key, which would probably not enhance the scientific level of the system much but would surely contribute to the use of unambiguous concepts and to a higher reproducibility of the descriptions, making it easier to store them in a database.

Almost 15 yr after its publication in 2003 the Guidelines was out of print, and a second, updated edition was urgently needed, as the system of concepts and terms became internationally the standard for micromorphological studies. In this second edition some concepts, giving rise to misunderstanding, are clarified and references to literature updated and extended. Almost no new ideas on description or concepts and terms were published in the last two decades. The concepts of the Guidelines were meanwhile also explained in two manuals: Loaiza et al., (2015) and Simões de Castro and Cooper (2019).

In the 1960s and the 1970s, micromorphology was often related to soil classification and/or related genetic studies. Since that time, application has gone beyond the bounds of traditional soil science as other disciplines discovered the utility of micromorphology. Other frequent users of micromorphology include: Quaternary geologists (e.g., Catt, 1989; Kemp, 1999; Cremaschi et al., 2018), sedimentologists (e.g., Zimmerle, 1991; van der Meer and Menzies, 2011; Menzies and van der Meer, 2018), weathering specialists (e.g., Nahon, 1991; Tardy, 1993; Delvigne, 1998), and especially archaeologists (e.g., Courty et al., 1989; Macphail et al., 1990; Davidson et al., 1992; Goldberg and Macphail, 2006; Macphail, 2008, 2014; Nicosia and Stoops, 2017; Goldberg and Aldeias, 2018; Macphail and Goldberg, 2018).

The objective of this book is to provide a system of analysis and description of soil and regolith materials as seen in thin sections. It is not intended as a manual of micropedology; topics such as sampling, thin section preparation, and interpretation of thin sections are therefore not discussed. Also, no attempt has been made to present proposals for higher levels of classification of microfabrics, as no sufficient agreement exists in the international micromorphological community on how to handle this problem.

In the past, many authors mixed the terminologies of Bullock et al. (1985) with those of Brewer (1964a and 1976), Brewer and Pawluk (1975) and others, without realizing the differences (e.g., differences in basic concepts) and especially without being aware of the false interpretations that might result. It is indeed scientifically incorrect to use a mixture of concepts and terms of different systems, which are not compatible. Is there any soil scientist that would accept a classification proposal for a soil profile, expressed in a mixture of U.S. Soil Taxonomy and WRB criteria and terms? Experience has shown that such a mixture of terms is dangerous and often leads to false statements.

To avoid confusion, some micromorphological concepts, definitions, and terms used by other systems are set off in separate explanatory paragraphs "Background", as complementary information to the reader, but not as a suggestion for its use as part of the proposed terminology. Where appropriate, concepts and terms are compared with those of other authors, without going into detail. The reader is referred to the original papers, or to Stoops and Eswaran (1986) or Jongerius and Rutherford (1979) for additional information. A complete glossary of existing micromorphological terms is beyond the scope of this textbook.

Terminology and/or classification reflect the state of the art in a given field of science and can therefore only be an approximation. The author is aware that this book is only a next approximation to a completer and more rational micropedological terminology.

2. Definitions and Historical Review

2.1 WHAT IS SOIL MICROMORPHOLOGY?

Soil micromorphology is a method of studying undisturbed soil and regolith samples with microscopic and ultramicroscopic techniques to identify their different constituents and to determine their mutual relations, in space and time. Its aim is to search for the processes responsible for the formation or transformation of soil in general, or of specific features, whether natural (e.g., clay skins, nodules) or artificial (e.g., irrigation crusts, plow pans), and their chronology. Consequently it is an important tool for investigations of soil genesis, classification, or management of soils and regoliths. The technique has also proven its usefulness in other domains, especially paleopedology and archeology.

A bibliometric study by Stoops (2014, 2018) shows that from 1950s onwards the number of micromorphological papers published increased, reaching a maximum of almost 700 during the period 1986 to 1990, decreasing slightly from then on. This decrease, explained mainly by the loss of interest in soil genesis and classification topics (due to shortage of funding) and the fact that discussions on new methods and concepts stabilized, was partly compensated by a gradual increase in the fields of paleopedology and archeology (see also Courty et al., 1989; Nicosia and Stoops, 2017; Adderley et al., 2018; Cremaschi et al., 2018; Fedoroff et al., 2018; Macphail and Goldberg, 2018).

Micromorphological investigations are based on the principles of (i) preservation of the fabric and structure, and (ii) functional investigation. Hence, the investigations should be performed on undisturbed and mostly naturally-oriented samples (in view of the characteristic vertical anisotropy of the soil), in contrast to the other analytical methods used in soil science. Chemical, physical, and mineralogical analyses usually require mixing, grinding, solubilization, or fractionation of representative soil samples and therefore yield average data. This is not the case for micromorphology, which often allows the examination of specific features in soils. According to the principle of functional investigation, all

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doi:10.2136/guidelinesforanalysis2

observations should be directed to the understanding of the function of each soil constituent or fabric within the soil as a whole.

Most microscopic observations of soil materials are made on thin sections. These are thin (30 µm) slices of a soil or regolith material that has been impregnated with plastic, glued to a glass slide, and then cut and polished to a thickness where the materials become translucent to light.

The research domain of micropedology covers all observations of undisturbed earthy samples under the microscope, including studies of thin sections, micromanipulations, microchemical and microphysical methods, and ultramicroscopic techniques. The best-developed and most popular part of micropedology is fabric analysis of thin sections, also called soil micromorphology, and its quantitative aspect, soil micromorphometry. Micromorphology is often used as a synonym for micropedology.

2.2 BRIEF HISTORICAL REVIEW

Observations made on soil materials using a hand lens, in either the field or laboratory, have probably been performed since the early beginning of soil science. Although the study of soil thin sections dates back to the beginning of the 20th century (Delage and Lagatu, 1904; Agafonoff, 1929, 1936a, 1936b; see also Stoops, 2009a, 2018), the first person to use magnifying instruments in a systematic way to study the soil was the Austrian scientist W.L. Kubiëna, considered therefore the "founding father of micropedology". He reported his first observations in some short papers in the early 1930s (Kubiëna, 1931), but his work received international recognition after the publication of his manual *Micropedology* in 1938, which was prepared during his stay as visiting professor in Iowa (Stoops, 2009b).

The scientific work of Kubiëna can be subdivided into two periods (Stoops and Eswaran 1986). In the first period, Kubiëna analyzed the fabric (internal organization) of the soil according to purely morphological criteria, using a morphoanalytical approach. The genetic interpretation of the morphology then followed. In his book *Micropedology*, Kubiëna (1938) defined different levels of fabric and gave an extensive description of the lowest level, the elementary fabric, as "the arrangement of the constituents of lowest order in soil in relation to each other", in other words the related distribution between stable coarse material (called skeleton grains, e.g., mineral grains, rock fragments) and the mobile fine material (called plasma, composed of colloids or clay). A terminology, partially consisting of newly coined terms, was introduced to name the different fabric types observed. In the second period, a morphogenetic approach prevailed, which means that specific combinations of soil features in soil thin sections were interpreted to explain the genesis of the soil material examined. Micropedology was at the base of Kubiëna's ideas on soil genesis and his new system of soil classification. These approaches were discussed comprehensively for the first time in his book *Entwicklungslehre des Bodens* (1948), and later in *The Soils of Europe* (1953) appearing simultaneously in Spanish, English and German, and in several papers in journals and proceedings. Most of his later ideas were published in his last book *Micromorphological Features in Soil Geography* (1970). The morphogenetic approach differs from the morphoanalytical one in that it is not limited to merely analyzing the fabric, but also directly involves a genetic interpretation of the observations. In fact, this morphogenetic approach of the microfabrics involves a genetic interpretation of the soil studied, right from the descriptive phase of study. No individual features are considered, but all characteristics as a whole are related to a specific soil type, after which the microfabric is named. Well-known terms are Braunlehm, Rotlehm, Braunerde and Roterde, which were presented in a hierarchic sequence, Braunlehm being at the origin of all other types. Also detailed micromorphological descriptions of humus types were given, from the terrestrial Mor to the subaquatic Anmoor. Kubiëna's approach to the soil microfabric was not purely analytical, but rather a personal view on specific aspects of soil formation, as seen under the microscope. A limitation of Kubiëna's system is that it was restricted to the soil types he described, and could not be used for soil materials with a similar fabric but a different genetic evolution. Moreover, his interpretations were generally not supported by other soil analyses (e.g., mineralogical, physical and/or chemical).

In the early 1960s, an expansion of micromorphology in different countries occurred, and it became clear that the morphogenetic approach of Kubiëna and his school was unsatisfactory. As a result, a new morphoanalytical system for micromorphological descriptions of the inorganic part of the soil material was developed in Australia by R. Brewer and J. Sleeman (1960) and later published by Brewer in his book *Fabric and Mineral Analysis of Soils* (1964a) (reprinted in 1976). This was the first attempt ever to establish a comprehensive system for making systematic and detailed micromorphological descriptions of soils. Although partly inspired by the morphoanalytical approach of Kubiëna, Brewer's system was based mainly on the experience of the author, who was interested in soil mineralogy. For this reason, the system was largely restricted to the mineral part of the soil. Barratt (1969) and Bal (1973) made extensions for the organic part.

Brewer's system was intended to be based on purely morphological criteria. However, one of its basic concepts, namely the plasma- skeleton grain concept, has a genetic base. Plasma and skeleton grains are not only defined by their absolute size (respectively smaller and larger than 2 μm), but also by their stability (See also Section 7.1 Background). This creates problems, as for example the case of minerals like calcite or gypsum, which can be stable in arid soils but will dissolve in the humid tropics. In his later publications (Brewer and Pawluk, 1975; Brewer and Sleeman 1988), the author almost abandoned these concepts. A most important contribution was the introduction of the concept of pedological features (Brewer and Sleeman, 1960, Brewer, 1964a), which by definition are those components that form by soil processes, such as clay coatings and Fe–Mn nodules. However, features inherited from the parent material, such as rock fragments or sedimentary structures, were also considered to be pedological features. Especially the fact that only single mineral grains could be part of the skeleton while compound grains (such as a quartzite fragment composed of two or more quartz grains) were considered pedological features, was felt by the users of the Brewer's system as problematic.

One of the merits of Brewer's system is that it made micromorphology more popular in many countries, especially in tropical and arid zones, where Kubiëna's system didn't provide concepts and terms for the description of fabrics. However, the greatest merit of the system is that it obliged micromorphologists to systematically analyze and describe all features of the soil thin section, as opposed to the morphogenetic system of Kubiëna which did not.

The second part of the 1960s showed an important expansion of soil micromorphology. Several new centers were created in Europe (e.g., in Great Britain, France, and Spain) and interest increased in the United States, Africa, South America, and Asia. The Post-Graduate Training Centers of Gent and Wageningen, and later also that of the ORSTOM (Paris), began attracting many students from Africa, Asia, and South-America and influenced this expansion. As a result, the knowledge on the micromorphology of soils increased sharply, forcing scientists to adapt the system, where possible, to new observations, adding new terms or changing or extending some of the concepts. Because this sometimes led to confusion, an international Working Group on Soil Micromorphology was created during the Third International Working Meeting on Soil Micromorphology, held in Wroclaw, Poland, in 1969. The purpose of the Group was to create an internationally acceptable terminology and classification. The result was the publication by Bullock et al. (1985) of the *Handbook for Soil Thin Section Description,* under the auspices of the International Soil Science Society (ISSS, now IUSS). The system of Bullock et al. (1985) became widely used by soil micromorphologists and it was later reworked for the first edition of this book (Stoops, 2003).

In 1984, FitzPatrick published his *Micromorphology of Soils*. It emphasizes the interpretation of soil thin sections, and not terminology. This is also the case for *Soil Microscopy and Micromorphology* by the same author (1993).

Micromorphology, as applied in the United States, is a tool rather than a discipline (Wilding and Flach, 1985; Wilding, 1997). On the contrary, in Europe (including Russia) and in Australia, micromorphology is often considered a discipline, and several research institutes and universities may have had one or more full-time micromorphologists on their staff. In several universities, micromorphology is still a regular part of the curriculum. These different approaches explain why scientists in the United States have contributed relatively less to the formulation of concepts and terms in the field of micromorphology, which is not to say that their work has been less important for the development of a description system. The efforts of a number of American soil scientists (including staff members of USDA and Soil Management Support Service of the USAID) in elaborating and refining U.S. system of soil taxonomy contributed to a better understanding of the distribution and genesis of micromorphological features, and as such to their interpretation and description. This effort is well illustrated in SSSA Special Publication 15, *Soil Micromorphology and Soil Classification* (Douglas and Thompson,