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MICROMORPHOLOGY OF LITHIFIED PALEOSOLS

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ABSTRACT

Lithified paleosols show a variety of microscopic fabrics similar to those of the rocks that enclose them. Sedimentary microfabrics are common in soils and paleosols that were weakly developed or waterlogged. Also preserved in many paleosols are soil microfabrics distinct from those of sedimentary rocks.

In clayey paleosols, a variety of bright clay microfabrics (sepic plasmic fabric of R. Brewer) are found. Cavity-lining (vosepic) and grain-coating (skelsepic) bright clay fabrics may form during sedimentation and burial, but other kinds of sepic plasmic fabrics are typical of well drained and developed soils and paleosols. Descriptively similar microfabrics are found in paleosols metamorphosed to lower greenschist facies. At higher metamorphic grades, clays are altered to micas and take on a high birefringence (omnisepic).

Micritic, needle fiber and displacive fabrics are preserved in calcareous paleosols. Their formation as original parts of a soil are especially clear when they are associated with burrows or root traces. Carbonate layers and nodules are less compacted during burial than clayey parts of paleosols, and so preserve microstructures in their original three dimensional arrangement. Recrystallization of limestone during burial can obliterate soil structures. Such destruction is near total in marble.

Soil micromorphological techniques and terminology were not designed for use with paleosols now entirely lithified and metamorphosed, but can clearly be applied to such materials as operational and descriptive schemes. Interpreting original microstructures and what they mean for ancient soil formation remains a significant challenge for the future.

1. INTRODUCTION

Micromorphological studies have proven their worth as an adjunct to field, textural and chemical studies of modern soils (Bullock, 1983). For the study of buried soils whose field character, texture and chemical composition have been altered by compaction, cementation and other diagenetic changes, micromorphological studies are even more vital. For example, it is not possible to disaggregate effectively for grain size analysis paleosols that have been turned into rock by burial and metamorphism. The proportions of sand, silt and clay are best determined from petrographic thin sections, using standard point counting techniques. Compaction and cementation of deeply buried paleosols also alters their base status; a measure important to soil classification and interpretation. Nevertheless, base status can be reconstructed within broad categories by point counting for the abundance of easily weathered base-rich minerals such as calcite, biotite, pyroxene and plagioclase (Retallack, 1983). More important, microscopic features of paleosols, such as clay skins, allow interpretation of similar soil environments and processes as those in which these features form today (Molenaar, 1984; McSweeney and Fastovsky, 1987). A better understanding of the fossil record of soils (Retallack, 1986a), now known as far back as 3300 million years (Lowe, 1983), will depend increasingly on information on the micromorphology of modern soils.

A key question for the application of micromorphological studies to paleosols now lithified and metamorphosed is to what extent are original microstructures preserved ? In our experience, descriptive schemes designed for soil micromorphology, such as those of Brewer (1976) and Bullock et al. (1984), can be applied readily to lithified paleosols. Accurate description and communication of thin section features are no longer serious problems for paleopedology, but their is some question whether described structures were formed originally in a soil, by processes that created the parent material of a paleosol or by its alteration during deep burial. In other words, we want to know what does paleosol micromorphology mean in terms of past environments and soil forming processes ?

2. CLAYEY PALEOSOLS

Almost all the microfabrics described by Brewer (1976), and a few more besides, have now been found in paleosol claystones (Retallack, 1976,1981,1985, 1986b; Retallack and Dilcher, 1981; Molenaar, 1984; McSweeney and Fastovsky, 1987). Paleosols also show a great variety of igneous, metamorphic and sedimentary textures remaining from their parent materials (Gay and Grandstaff, 1980; Grandstaff et al., 1986; Retallack, 1985). Indeed, one of the uses of micromorphology in sequences of lithified paleosols is to distinguish the paleosols from their enclosing rocks. Paleosols differ from most igneous and metamorphic rocks in the presence of clays, in diffuse stains of iron oxides and in corroded or irregular grain boundaries. These features also are found in hydrothermally altered rocks, but these commonly form veins in igneous or volcanic rocks and include a variety of well-crystallized ore minerals, such as pyrrhotite and galena, that are unstable in most weathering regimes. Paleosols within sequences of sedimentary rocks can be difficult to recognize micromorphologically, especially in coal measures and in rapidly deposited coarse-grained sequences. Many fabrics of weakly developed clayey paleosols are similar to those of sediments unmodified by soil formation. Soils of modern peat swamps and paleosols of coal measures show abundant relict bedding (unistrial plasmic fabric of Brewer, 1976) and cloudy (inundulic) and dull (undulic) fabrics (Retallack and Dilcher, 1981;

McSweeney and Fastovsky, 1987). It is fortunate, then, that root traces are so beautifully preserved under soil conditions of rapid burial or waterlogging, because fossil roots provide clear evidence for paleosols in coal measures. In petrographic thin sections, cellular structure of plant roots sometimes is visible, especially in paleosols that have been permineralized with silica or carbonate (Kidston and Lang, 1921; Klappa, 1980; Basinger, 1981). In other cases only traces remain of decay-resistant parts of roots, such as the epidermis and central woody tissues. Other parts of roots commonly decay and are replaced by clay (Retallack, 1976).

Certain kinds of bright clay (sepic plasmic) fabric are diagnostic of paleosols, as opposed to other kinds of rocks. This is a general class of microstructure in which streaks of highly oriented, and thus highly birefringent clays are arranged in a matrix of flecked, unoriented clay (Fig. 1). The abundance of birefringent clay is thought to increase with proportion of swelling clays (smectites), with periodicity of wetting and drying and with age, in soils that are generally well drained (Brewer and Sleeman, 1969). The three dimensional arrangement of oriented clay is unlikely to be matched by depositional or burial processes because it calls for a complex, oscillating and multidirectional pattern of stresses. Not all sepic plasmic fabrics are good

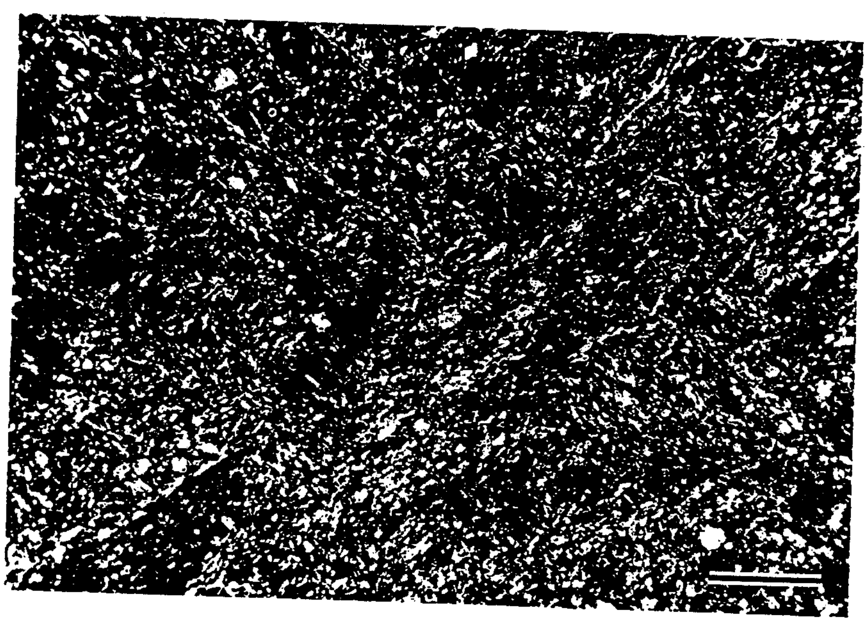

Fig. 1. Intersecting bright clay (clinobimasepic plasmic) fabric in the clayey subsurface (C) horizon of a paleosol (Sulfaquept) in the mid-Cretaceous (94Ma), upper Dakota Formation, near Fairbury, Nebraska, U.S.A. Scale bar is 0.1 mm.

indications of pedogenic processes. Grain-coating bright clay fabric (skelsepic) can form by rolling of grains during deposition or by compaction of clayey matrix around them during burial, as well as by stresses generated around grains during soil formation (Fig. 2). Another exception is void-filling bright clay fabric (vosepic) in which oriented clay may fill cracks that formed in the original soil or that were opened by dissolution at depth. Voids formed during deep burial are called secondary porosity in the terminology of the petroleum business (Schmidt and McDonald, 1979). Voids and fissures of secondary porosity filled with clay can in some cases appear similar to clay skins and other cutanic features, but they lack the lateral extent of banding patterns seen even in disrupted fragments of soil clay skins. Thus most (insepic, mosepic and masepic), but not all, kinds of bright clay fabric may be diagnostic of paleosols.

Another important exception to the use of bright clay fabrics as diagnostic of paleosols is the formation of woven bright clay fabric (omnisepic) at high grades of metamorphism (greenschist facies and beyond). Metamorphic reactions serve to alter clay minerals into more highly birefringent micas. At moderate depths of burial (only a km or so) and temperatures (a few hundred degrees C),

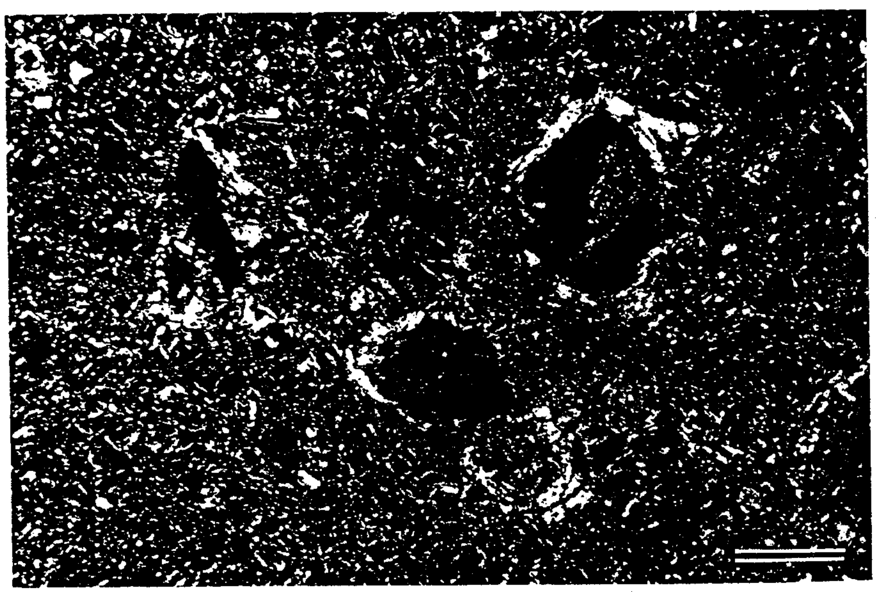

Fig. 2. Grain-coating bright clay (skelsepic plasmic) fabric around partly plucked clay clasts in the clayey subsurface (C) horizon of the Ogi silty clay loam paleosol (Fluvaquentic Eutrochrept) in the Oligocene (30 Ma) Brule Formation, Badlands National Park, South Dakota, U.S.A. Scale bar is 0.1 mm.

smectite is converted to illite with addition of potash and losses of silica, lime and soda (Bethke and Altaner, 1986; and references therein). Paleosols that have suffered illitization at metamorphic grades as high as prehnite-pumpellyite and zeolite facies still show an array of bright clay fabrics similar to those of modern soils. It could be that illitization selectively affects already oriented clay along which fluids can migrate more readily. This idea, suggested by simple observation of paleosol micromorphology affected by moderate grades of metamorphism, needs experimental testing. Paleosols with pervasive metamorphic chlorite, biotite and muscovite formed at high temperatures and pressures (greenschist facies and beyond) have a uniformly high birefringence that is similar to woven bright clay fabric (omnisepic) in soils. Even in such altered paleosols, variations in brightness of micas are suggestive of original less pervasively bright clay fabrics (masepic to insepic), but these features are subtle and difficult to quantify (Retallack, 1986b). Comparisons with modern soils may be limited for such metamorphosed paleosols, but their microscopic study is no less important.

3. CALCAREOUS PALEOSOLS

Lithified paleosols formed on limestone or by calcification of other sediments in climates with seasonal aridity also show a range of microstructures comparable to those of modern calcareous soils. Much of what is known about the micromorphology of calcareous paleosols has been reported by sedimentary petrographers under the term "vadose alteration fabrics," which have proven important for recognizing ancient exposure and sea level changes in the geological record (Estaban and Klappa, 1983). Another reason so much is known about them is their sheer abundance in the rock record (Allen, 1986; James and Choquette, 1988; Wright, this volume).

Pedogenic carbonates have a high preservation potential in the rock record for two main reasons. First, the precipitation of carbonate results in early cementation and so resists later mechanical compaction on burial. The solubility of calcite during deep burial makes it susceptible to pressure solution, but the effects of this process can be easily recognized from stylolites and other features. Second, most pedogenic carbonates are either dolomite or low magnesium calcite (less than 4 mole % Mg). Both forms are mineralogically stable during diagenesis. However, other common forms of calcite, aragonite and high magnesium calcite (more than 4 mole % Mg) are readily converted to low magnesium calcite during diagenesis, typically with some loss of microfabric detail. Although these latter forms do occur in present day calcretes (Watts, 1980), they appear to be volumetrically minor.

Two broad groupings of pedogenic carbonates can be defined, each with different diagenetic susceptibilities. One group (beta calcretes of Wright, this volume) consists of biogenic soil carbonates such as rhizoconcretions and related features. Actual roots are relatively rarely permineralized to preserve ultrastructure, but more commonly occur as calcified tubes (Bown, 1982; Cohen, 1982). A common form recognized mainly in post-Jurassic calcretes is the structure known as *Microcodium*, which consists of small (under 2 mm) radial aggregates of petal-like calcite crystals. Klappa (1978) has compared this form, which is uncommon in Holocene soils, to fungal sclerotia, possibly endomycorrhizae. Its absence in paleosols older than Jurassic may reflect a geologically late appearance or its loss by diagenesis. Needle fiber calcite (lublinite) is a major contributor to modern calcareous soils and has been recognized in paleosols as old as early Carboniferous (Wright, 1984, 1986). It forms in association with fungal mycelia, but has a relatively low preservation potential (Calvet and Julia, 1983) because the fibers are syntaxially overgrown with micrite-sized rhombs and the acicular form is destroyed (Phillips and Self, 1987). Certainly fossil examples of this structure typically show much alteration (Fig. 3). Finally, many laminar calcretes are biological in origin, due to cyanobacteria (Krumbein and Giele, 1979) or lichens (Klappa, 1979), or to calcified root mats (Wright et al., 1988).

The other suite of pedogenic carbonates (alpha calcretes of Wright, this

Fig. 3. Needle fiber calcite in a tubular void remaining from a root trace in the Heatherslade Geosol of the Early Carboniferous (345 Ma) Gully Oolite at Three Cliffs Bay, South Wales. Scale bar is 50 μm long.

volume) consists of abiogenic fabrics, typically resulting from the growth of carbonate. Caliche nodules, for example, commonly show replacive crystic fabrics (Wright, 1982), in which mineral grains appear etched (caries texture) and floating in a micritic to microcrystalline matrix that has replaced an earlier less calcareous matrix (Fig. 4). In some cases, fossil caliche nodules preserve concentric bands of (seasonal?) ferruginization (Retallack, 1985). To this list of original caliche microtextures can be added displacive calcite texture. This has been considered controversial because there is some doubt that crystallization pressure can force apart soil matrix (Watts, 1979). However, displacive fabrics can form by precipitation of calcite in cracks in the soil. This kind of displacive fabric is unlikely to form under load of burial, but could form during forcible injections of fluids or magma, as in the boxwork textures of many hydrothermal ores (Edwards and Atkinson, 1986). In this particular case, associated volcanic rocks and ore minerals should be a clue to the non-pedogenic nature of displacive fabrics. There is more danger in mistaking fossil caliche for algal or lacustrine limestone, which is what it has been called in some geological reports. In thin section, truly aquatic carbonates are distinctive

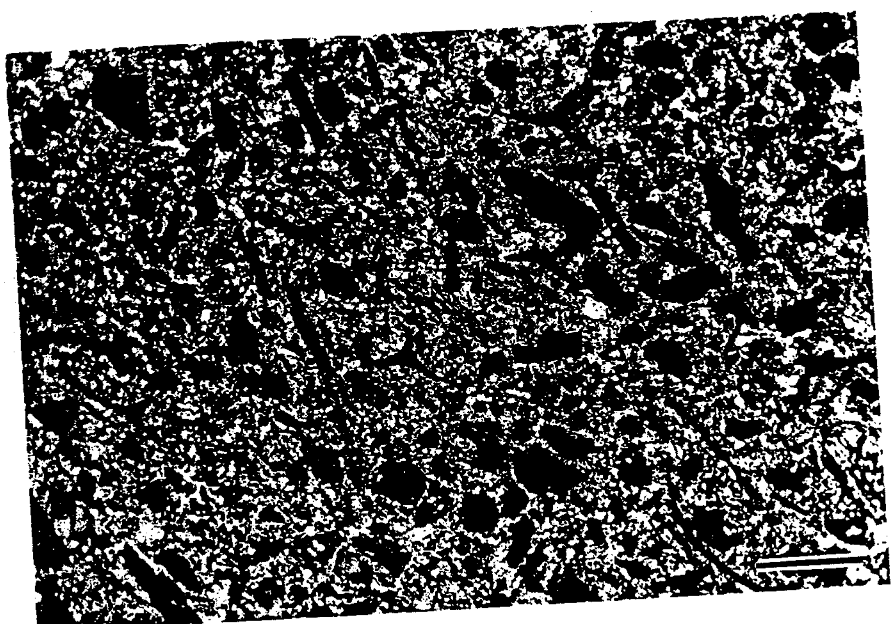

Fig. 4. Microcrystalline lime mud (crystic fabric) with incipient development of caries texture (replacive embayments) into surprisingly well preserved volcanic shards, in caliche nodule of a calcic (Bk) horizon of the type Samna silty clay loam paleosol (Ustollic Eutrandept) in the Late Oligocene (29 Ma) Sharps Formation, Badlands National Park, South Dakota, U.S.A. Scale bar is 0.1 mm.

in their chambered or otherwise complex algal structures and their fossil ostracods, diatoms, clams and snails that may be recognizable even in small fragments (Scholle, 1978). Associated fossil root traces, much less weathered mafic minerals within (compared to beyond) the nodules and evidence of nodules resorted into associated paleochannel sandstones are just a few of the lines of evidence that can be used to identify caliche-bearing paleosols in rock sequences.

Carbonate paleosols and parts of paleosols are of special value because they preserve soil textures in their original three dimensional arrangement (Fig. 5), without the crushing that affects associated clayey soil material or sediments after burial (Wright, 1983, 1987). The carbonates themselves are subject to a variety of diagenetic alterations, but only dolomitization and recrystallization will be discussed here. Dolostone, a carbonate rock of the mineral dolomite, is thought to form in modern hypersaline lakes, coastal lagoons and oceans (Zenger et al., 1980) as well as in soils of high base status (Doner and Lynn, 1977). In most cases, originally formed dolomite is micritic or (rarely) microacicular, unlike sugary dolomite of sand-to-silt-sized rhombs that form during burial alteration of non-dolomitic carbonates. Distinguishing between original and burial dolomite is a thorny problem for the history of soils. It remains to be seen whether the abundant dolomitic caliche of Precambrian and Paleozoic paleo-

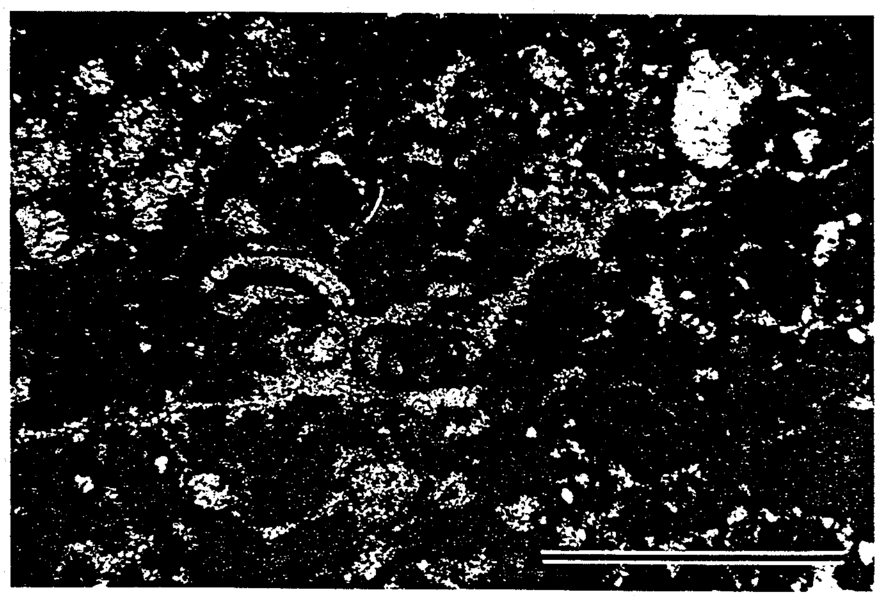

Fig. 5. Uncrushed marine foraminifer (chambered), brachiopod (curved shell) and fecal pellets (dark) in the surface (A) horizon of the Darrenfelen Geosol of the Early Carboniferous (350 Ma) Cheltenham Limestone, near Llanelly, South Wales. Scale bar is 1 mm.

sols is a result of their burial alteration, or a signal of changing conditions of soil formation through geological time (Retallack, 1986a).

Carbonates are prone to recrystallization (neomorphism of Folk, 1965) at only moderate depths and temperatures of burial. Much of this alteration is related to the inversion of aragonite and high magnesium calcite to low magnesium calcite. However, low magnesium calcite can also recrystallize from very fine grained calcite (micrite) to coarser crystals (more than 4 µm, but typically 10-15 µm) called microspars. Further burial and metamorphism result in the equigranular mosaic found in marble. The literature on modern and ancient calcretes contains many references to recrystallization because of the presence of calcite crystals in irregular mosaics with irregular crystal boundaries (both characteristic features of recrystallized micrite). However, such fabrics can result from complex series of precipitation and dissolution phases during calcrete growth. Studies of some mosaics using cathodoluminescence show that they are primary and not due to recrystallization (see Wright, this volume). Many Precambrian and Paleozoic calcrete nodules show apparent recrystallization features (Fig. 6) but detailed cathodoluminescence work is required to identify the degree of burial related alteration.

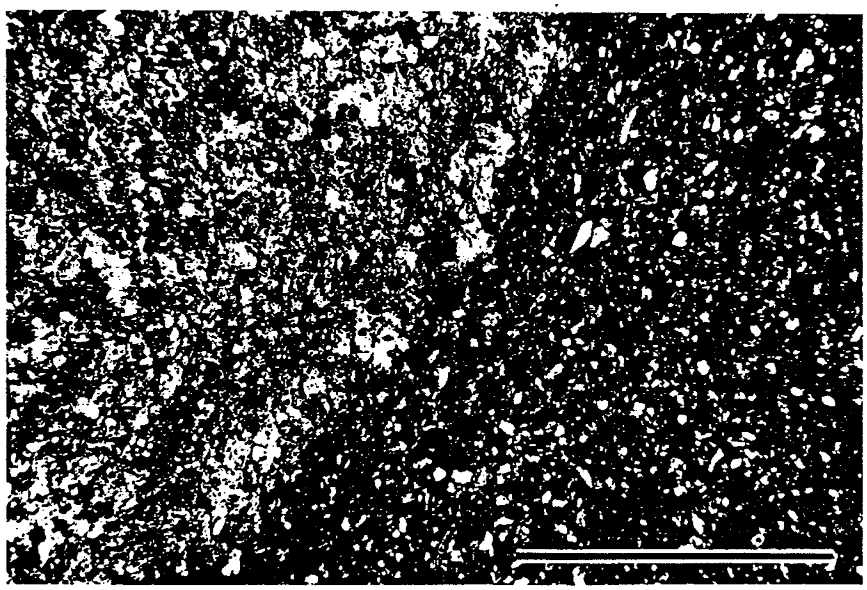

Fig. 6. Recrystallized caliche nodule (upper left) with near-marginal iron stain (neoferran) from the calcic (Bk) horizon of the type Lehigh Gap clay paleosol (Oxic Ustropept) in the Late Silurian (420 Ma) Bloomsburg Formation, near Palmerton, Pennsylvania, U.S.A. Scale bar is 1 mm.

4. CONCLUSIONS

The range of microfabrics now known from lithified paleosols already approaches that of modern soils, despite the small number of scientists that have formally reported their study. It is clear that descriptive classifications of soil micromorphology (such as those of Brewer, 1976 and Bullock et al., 1984) can be used for lithified paleosols as well as modern soils. How these various features are to be interpreted is another matter that is far from solved. A part of the problem is alteration of paleosols during deep burial and metamorphism. Some information on these changes can be gleaned from the extensive literature on sediment diagenesis and metamorphism. How, or if, these changes on burial selectively affect particular parts of paleosols remains to be studied seriously. Once these alterations to micromorphology can be filtered out, the remaining features can be used to assess how similar to modern soil-forming processes were those of the distant geological past. Micromorphology is, and is likely to remain, of critical importance to assessing the fossil record of soils.

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