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Soil micromorphology and the anthropocene—Cross-scale connections and technology trends

Micromorfología de suelos y el Antropoceno-Conexiones cruzadas y tendencias tecnológicas
Micromorfologia dos solos e o antropoceno-Ligações à escala cruzada e tendencias tecnológicas

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ABSTRACT

The Anthropocene is a proposed geologic time period used to convey the profound influence humanity is having on the Earth. The term is controversial because of uncertainties about when to designate its beginning and whether a diagnostic feature of this era can survive millions of years into the future. Still, the Anthropocene has captured the imagination of many scientists and provides a framework for analyzing the broad-scale impacts of humanity. The purpose of this paper is to explore how soil micromorphology can contribute to a deeper understanding of the Anthropocene. We approached this issue by systematically examining how data gathered at the micromorphology scale is connected to data obtained at the soil profile, landscape, and global scales. In particular we look at world food production, climate change, groundwater pollution, and plastic decomposition. From this cross-scale analysis it becomes apparent that micromorphology (1) contributes to an understanding of ***feedbacks*** operating in complex adaptive systems and (2) provides evidence otherwise invisible for making ***inferences*** about climate change. As the human footprint increases, soil micromorphology, using both traditional and emerging technologies, can make a unique contribution to understanding the Anthropocene.

RESUMEN

El Antropoceno es un periodo de tiempo geológico que se ha propuesto para explicar la gran influencia que el ser humano está teniendo en los sistemas medioambientales terrestres. Se trata de un término controvertido debido a los problemas en establecer el comienzo de este periodo y a que se desconoce si algún rasgo diagnóstico de esta era sobrevivirá en el futuro dentro de millones de años. No obstante, el Antropoceno ha llamado la atención de numerosos científicos y constituye un marco para el análisis de los impactos de la humanidad a gran escala. El objetivo de este trabajo es explorar cómo la micromorfología de suelos puede contribuir a profundizar en el conocimiento del Antropoceno. Para ello se ha examinado de forma sistemática las conexiones entre los datos recogidos a escala micromorfológica y los datos obtenidos del perfil del suelo, del paisaje y a escalas globales. En particular, se ha prestado atención a la producción mundial de alimentos, el cambio climático, la contaminación del agua subterránea y la descomposición de plásticos. De este análisis cruzado se deduce que la micromorfología (1) contribuye a la comprensión de las ***retroalimentaciones*** *que operan en sistemas adaptativos complejos y (2) proporciona evidencias que de otra forma permanecerían invisibles para realizar* ***inferencias*** *sobre el cambio climático. A medida que la huella humana se hace más evidente, la micromorfología de suelos, utilizando tecnologías tanto tradicionales como emergentes, puede representar una contribución indispensable para comprender el Antropoceno.*

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RESUMO

O Antropoceno é uma era geológica utilizada para transmitir a profunda influência que a humanidade tem tido nos sistemas ambientais do planeta Terra. O termo é controverso porque existem dúvidas acerca do seu início bem como se o diagnóstico desta era sobreviverá a milhões de anos no futuro. Ainda assim, o Antropoceno captou a imaginação de muitos cientistas e fornece um meio para analisar os impactos de larga escala da humanidade. O objetivo deste estudo é explorar como a micromorfologia pode contribuir para um conhecimento mais profundo do Antropoceno. Abordámos esta questão fazendo um exame sistemático de como os dados associados à escala micromorfológica estão relacionados com os dados obtidos no perfil do solo, paisagem, e escalas globais. Debruçamo-nos em particular sobre a produção mundial de alimentos, alterações climáticas, poluição das águas subterrâneas, e degradação dos plásticos. A partir da análise desta escala cruzada aparentemente a micromorfologia (1) contribui para a compreensão de ***feedbacks****, operando em sistemas adaptativos complexos e (2) torna evidentes* ***inferências*** *sobre alterações climáticas não detetáveis de outra forma. À medida que aumenta a pegada humana, a micromorfologia do solo, utilizando as tecnologias tradicionais e emergentes, pode dar uma contribuição única para a compreensão do Antropoceno.*

KEY WORDS
Complex adaptive systems, soil memory, world food supply, climate change, groundwater pollution, plastic decomposition

PALABRAS CLAVE
Sistemas adaptativos complejos, memoria del suelo, suministro mundial de alimentos, cambio climático, contaminación de agua subterránea, descomposición de plásticos

PALAVRAS-CHAVE
Sistemas adaptativos complexos, memória do solo, fornecimento mundial de alimentos, alteração climática, poluição das águas subterrâneas, degradação de plásticos

1. Introduction

Human populations have progressively spread across the continents and emerged as a major driver of environmental change (King 2004), with agriculture being the greatest impact of humans on Earth (Ellis et al. 2010; Ellis 2011). When compared with short-term geologic processes, humans move more sediment than rivers, glaciers, or wind (Hooke 2000; Wilkinson 2006). Humans have also become a significant intercontinental transporting agent of organic matter (e.g., food and fiber) and metals (e.g., electronic appliances and vehicles). The major terrestrial repository for these transported materials is soil.

In addition to moving matter, humans have chemically transformed matter from their natural geochemical states to synthetic states, some of which are very stable in the soil environment, such as stainless steel, aluminum, and plastic (Weisman 2007). By transforming and moving matter, including the release of industrial carbon dioxide, humans have altered the chemical composition of the atmosphere, oceans, and soils (Zalasiewicz et al. 2008, 2011; Richter et al. 2011; Richter and Yaalon 2012). Therefore, a term is needed —the Anthropocene— to provide a way to depict humanity's growing influence on the environment (Crutzen 2002).

The Anthropocene has gripped the interests of many scientists based on recent professional meetings, such as the “Archean to Anthropocene” (2011 Geological Society of America), “How is the Anthropocene Transforming Pedology?” (2012 Soil Science Society of America), and “Ecological Science in the Anthropocene” (2012 NSF-LTER Meeting). As a formal geologic time period, however, the Anthropocene is problematic (Vince 2011). When did it begin? Is there a stratigraphic marker for the Anthropocene that will endure far into the geologic future?.

The purpose of this paper is to explore how soil micromorphology (the study of soil in its undisturbed state at the microscopic level) can provide a deeper understanding of the Anthropocene. Our approach is to systematically examine links between micromorphology and larger scales. Thus, we have divided the spatial continuum into four scales: (1) the *micromorphology scale*—mm^2 to μm^2, (2) the *soil profile scale*—m^2 to cm^2, (3) the *landscape scale*, which, roughly speaking, refers to an area visible from a hill—a few thousand to a few km^2, and (4) the *global scale*. We use examples from the published micromorphology literature dealing with world food production, climate change, and environmental science to examine cross-scale connections that shed light on links between micromorphology and the Anthropocene.

2. Discussion

2.1. World Food Production

A cascade of linkages and feedbacks can be traced between the global scale and micromorphology scale (**Figure 1**). 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 (Withgott and Laposata 2012). These landscape-scale practices lead to compaction, aggregate destruction, and the effects of raindrop impacts on

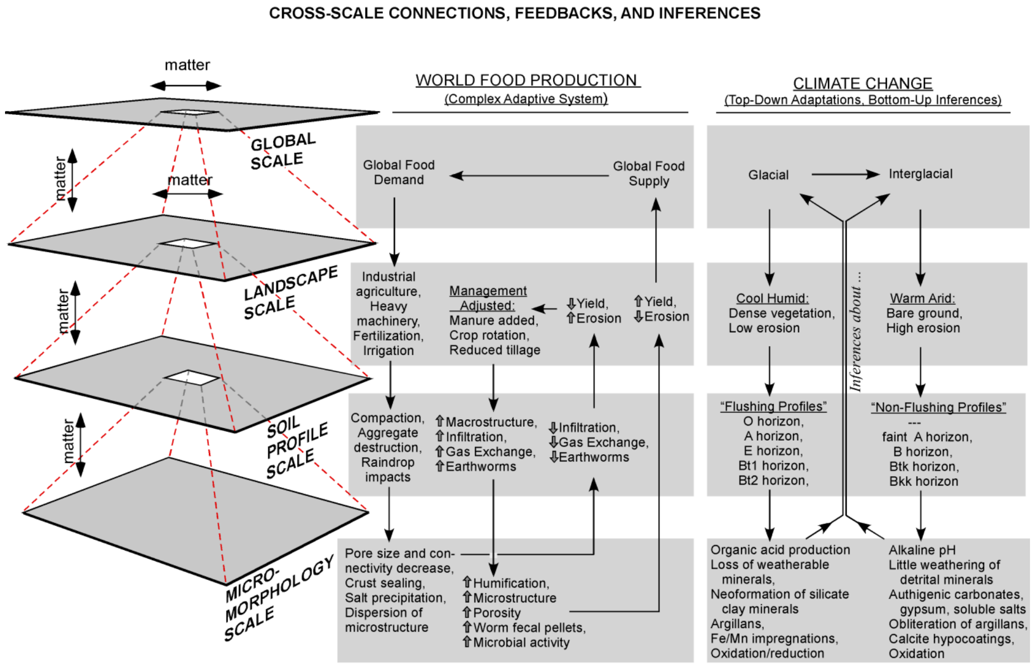

Figure 1. Illustration of cross-scale connections, feedbacks, and inferences involving micromorphology in world food production (shown as a complex adaptive system) and climate change studies (shown as inferences scaled-up from the micromorphic scale to the global scale).

bare soil at the soil profile scale. At the micromorphology scale, these processes are seen as pore collapse, pore clogging, crust sealing, and microstructure dispersion (Figure 2) (FitzPatrick 1993; Adderly et al. 2010; Pagliai and Stoops 2010).

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.

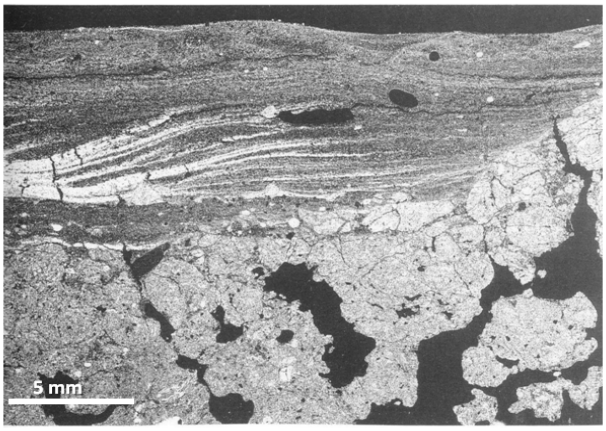

Figure 2. Crust resulting from cultivation overlying a porous soil illustrating how insights gained at the micromorphology scale can increase understanding of the system at broader scales. From FitzPatrick (1993) with permission from Wiley Publishers.

2.2. Climate Change

To determine if humans are causing climate change in the Anthropocene, it is necessary to understand climate change before the Anthropocene. Paleosols and archaeology sites, both of which are investigated with micromorphology, can contribute evidence about climate change (Courty et al. 1989; Fedoroff et al. 2010).

Paleosols, including their micromorphology features, carry a "soil memory" of climate (Targulian and Goryachkin 2004). Some types of soil memory, such as thermodynamically stable minerals or dissolution pipes in petrocalcic horizons, represent a durable memory of past climates, while other soil memory types, like soluble salts, organic matter, and structure in topsoils, are easily altered and represent an evanescent memory (Yaalon 1971; Gerasimova and Lebedeva 2008). If micromorphology features survive lithification, they can be preserved in the rock record and provide evidence of climate change spanning millions of years (Retallack and Wright 1990).

If we take a mid-latitude location which had a cool humid climate during the last glacial maximum, but has since shifted to a warmer arid climate during Holocene deglaciation, such as many locations in the American Southwest (Hawley et al. 1976), then the following scenario may serve as an illustration of cross-scale connections between micromorphology and global climate change. First, based on modern analogs, we can assume that under a cool humid climate the landscape was densely vegetated, had little erosion, and produced a soil profile with a sequence of O-A-E-Bt1-Bt2 horizons (**Figure 1**). 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 nonflushing, a micro-stratigraphy can accumulate and preserve a memory of climate change as carbon isotopes in the laminae in of petrocalcic horizons at the micromorphology scale (**Figure 3**).

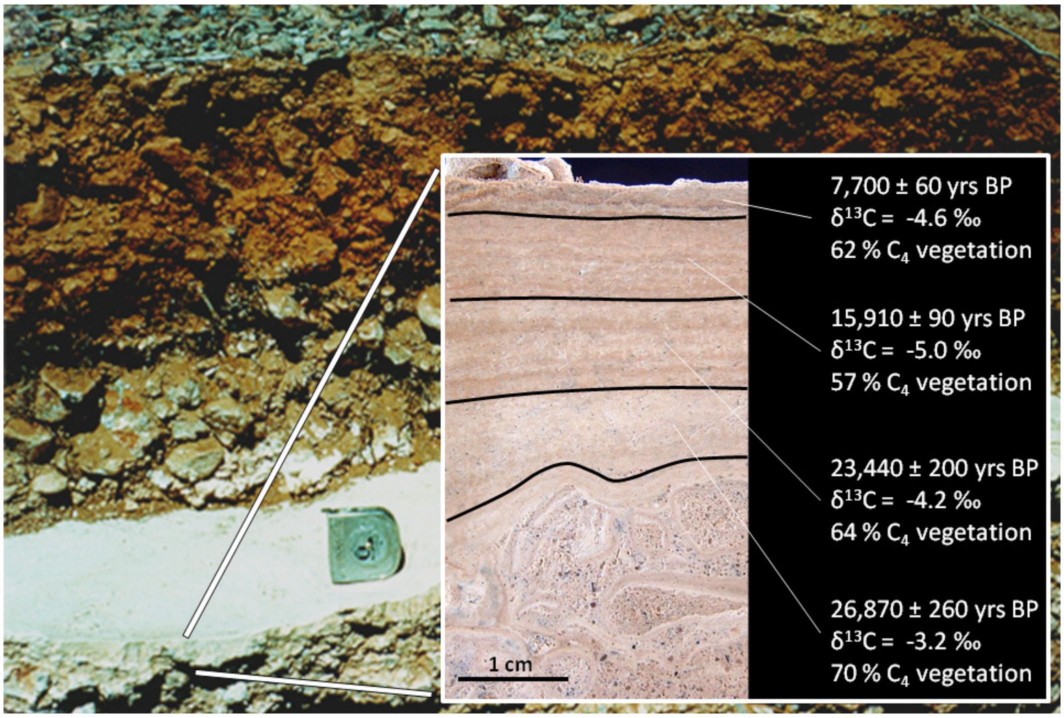

Figure 3. Radiocarbon-dated laminae of the upper zone of a petrocalcic horizon illustrating how "memory" at the micromorphology scale can be used to make inferences about paleoclimate at the global scale (after Monger et al. 1998, 2009).

All micromorphology features are not necessarily indicators of past 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).

Climate change can also be inferred from archaeology sites (Kooistra and Kooistra 2003). Evidence for a certain type of prehistoric agriculture, for example, can be derived from diagnostic strata that are observed at the profile scale. Further evidence can then be obtained from microscopic fragments of burned wood, bone, feathers, calcitic ashes, dung, and rock flakes at the micromorphology scale (Wattez et al. 1990; Macphail and Goldburg 2010).

2.3. Environmental Science

Environmental science is a huge category of scientific disciplines dealing with how humans interact with abiotic and biotic factors. We herein provide two examples —groundwater pollution and plastic— to illustrate how micromorphology and cross-scale connections provide increased understanding of environmental issues related to the Anthropocene.

Groundwater pollution from agricultural chemicals or septic systems impacts drinking water and human health across the globe. At the landscape scale, pathways connecting pollutants from aboveground activity to regional aquifers are typically studied at the profile scale using dyes to reveal flow routes along ped faces, slickensides, and root channels (Nobles et al. 2003). At the micromorphology scale, colored-epoxies and fluorescent-epoxies have been used to embed soil and preserve its natural pore architecture to study conducting versus non-conducting pores and microvoids in ped interiors (Bouma et al. 1977; Vepraskas et al. 1991). 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.

Plastic is a term for organic polymers, such as polyethylene, polyurethane, nylon, polyester, and polypropylene, which are cast or drawn into various containers, films, or textile fibers. Plastic had its beginning as Bakelite in 1909 and has since, especially since World War II, burst forth upon the world as a cheap material with a thousand uses. Plastic, in contrast to natural organic polymers, such as chitin, lignin, or collagen, is not easily broken down when it enters soil, or when it enters the oceans where it has significant environmental consequences for marine animals (Weisman 2007).

With respect to cross-scale connections, plastic may be viewed in the following manner. Petroleum is harvested at the landscape scale, transported at the global scale, taken back down to the landscape scale where it is refined and converted to plastics, then re-distributed at the global scale, sold at the landscape scale, then finally disposed of in soil, including landfills, at the profile scale. At the micromorphology scale, the rate of plastic decomposition can be viewed in the context of other soil constituents, both aboveground and belowground. Aboveground micromorphology shows how plastic disintegrates when exposed to sunlight by breaking into smaller pieces (**Figure 4**). Belowground micromorphology shows plastic to be less decomposed than aboveground. Even a nylon shirt buried in the A-horizon of a forest soil for 44 years (from 1964 to 2008), shows little evidence of decomposition when view at the micromorphology scale (**Figure 5**).

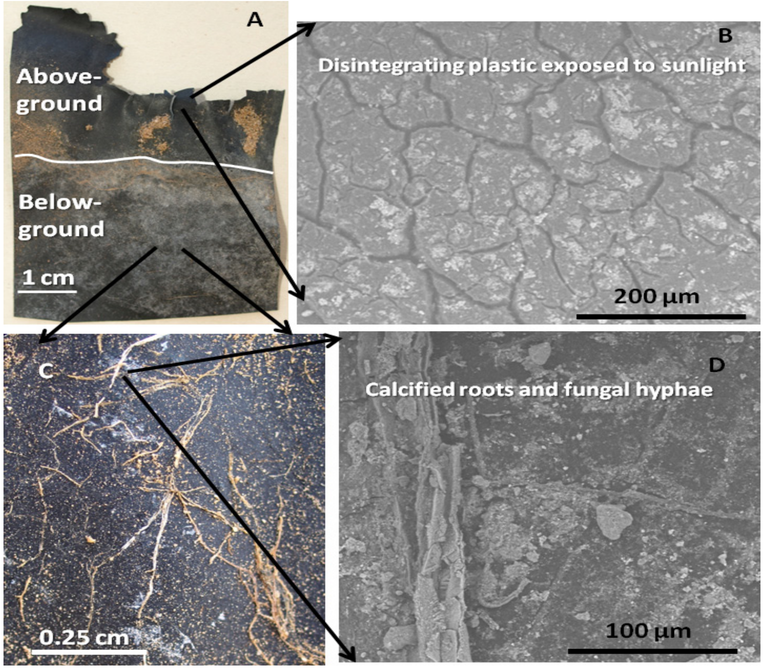

Figure 4. Comparison of the aboveground and belowground plastic decomposition in a desert soil (Typic Torripsamment) after 14 years. (**A**) Piece of black polyethylene plastic left vertically in place from an archaeology excavation in 1994. (**B**) SEM image showing disintegration into smaller pieces when exposed to sunlight. (**C**) Enlargement of belowground zone showing the extent of attached roots. (**D**) SEM of calcified roots and fungal hyphae illustrating the potential of using plastic of known age to quantify rates of pedogenesis.

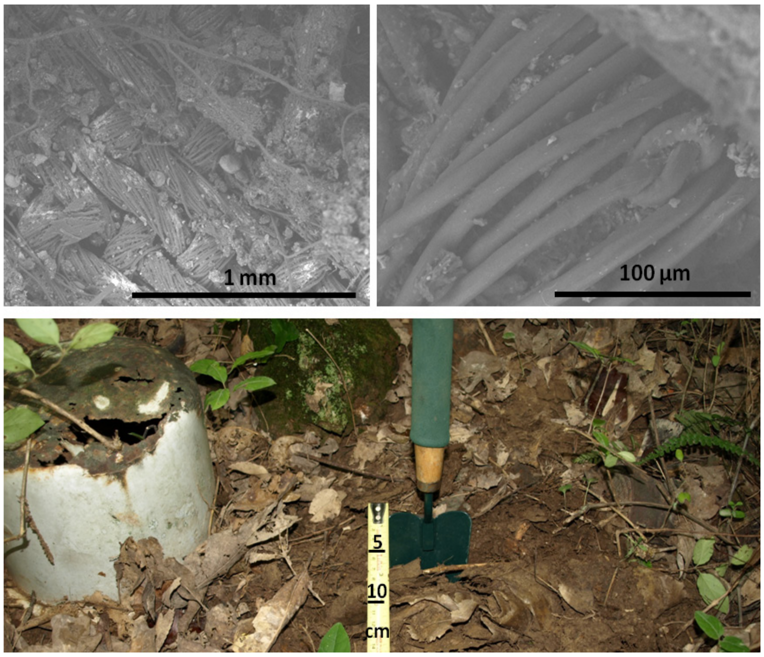

Figure 5. Waste disposal site illustrating the durability of nylon when buried in the A horizon of a forest soil (Typic Hapudult) for 44 years. (**A**) Scanning electron micrograph of the nylon shirt. (**B**) Magnification of the same shirt showing the relatively un-decomposed state of the nylon fibers. (**C**) Photograph of the site showing the much greater state of decomposition of the neighboring pots and cans to left and right of the green hand spade that is inserted into buried plastic.

As an unintended consequence of its inertness, plastic helps reveal rates of pedogenesis by providing surfaces of known age on which biological and pedological features are made visible, such as calcium carbonate deposits laid down by roots and fungal hyphae (Figure 4). Also as the consequence of its slow decomposition, plastic in sediment may make a durable chronostratigraphic marker for the Anthropocene.

3. Technology Trends

Technology increases our understanding of nature, including the Anthropocene. Orbiting satellites, for example, increase our ability to view how humans are altering Earth's surface. Likewise, microscopy increases our ability to view how humans are altering Earth's sub-surface. Technology routinely used in soil micromorphology includes a combination of petrographic thin sections, x-ray diffraction, and electron microscopy with x-ray chemical analysis (e.g., Kovda et al. 2003). These technologies, combined with ongoing digital revolution, continue to improve the resolution and distribution of microscopic images across a broad front (Pool 2012).

Soil micromorphology as traditionally practiced has produced an enormous body of information, but results depend heavily on optical imaging of thin sections which requires elaborate preparation and many days to produce. Confocal microscopy in principle offers a tremendous procedural and temporal shortcut to obtain centimeter-scale, three dimensional (3D) series of focused images at sub-micrometer resolution through confocal reflection and fluorescence of native soil samples. Laser scanning confocal imaging has already been successfully applied in studies of soil microbes for over a decade using specific fluorescent probes for both biological and chemical species (Assmus et al. 1995). Since this type of imaging is essentially non-destructive and dynamic, there is potential to probe events at high temporal and spatial resolution. Other optical methods, such as light sheet imaging (Keller et al. 2008) or orthogonal-plane fluorescence optical sectioning (Buytaert et al. 2010), also offer the advantage of greater sample volumes for 3D imaging. The greater penetrating power of hard x-rays in laboratory scale tomography systems has opened soil micromorphology to quantitative study, where porosity and material composition are accessible to digital image analysis and volume rendering through computer graphics, also in a regime that allows for dynamic analyses at micrometer and submicrometer dimensions (Figure 6).

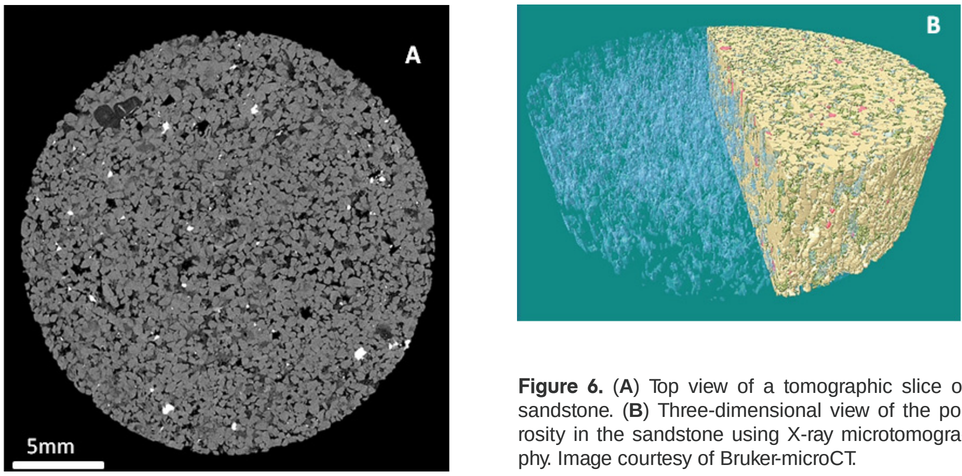

Figure 6. (**A**) Top view of a tomographic slice of sandstone. (**B**) Three-dimensional view of the porosity in the sandstone using X-ray microtomography. Image courtesy of Bruker-microCT.

Topographical imaging and material characterization of soils by scanning electron microscopy coupled with elemental analysis and mapping has been extensively explored over the past few decades in soil micromorphology. At present, quantitative results at high sensitivity and submicrometer resolution are readily achieved by most electron microscopy facilities. With the introduction of field emission electron guns and other instrumental improvements, spatial resolution has increased and is approaching values that are more typical of transmission electron microscopes. The introduction of variable pressure and environmental controls of the sample atmosphere in environmental scanning electron microscopes again introduces the possibility of performing dynamic experiments at high spatial resolution with soils under controlled conditions of hydration under lower vacuum (**Figure 7**). At the high end, modern transmission electron microscopes with improved lenses, reduced aberrations, and field emission guns achieve atomic lattice resolution for extremely thin samples. When coupled with available spectroscopic detectors for X-rays and electrons, transmission electron microscopes provide nanometer scale resolution of chemical composition. Atomic force microscopy also permits the visualizing the dynamic atomic structure of crystalline minerals in fluids (**Figure 8**). Even more rapid developments are occurring with scanning probe microscopes.

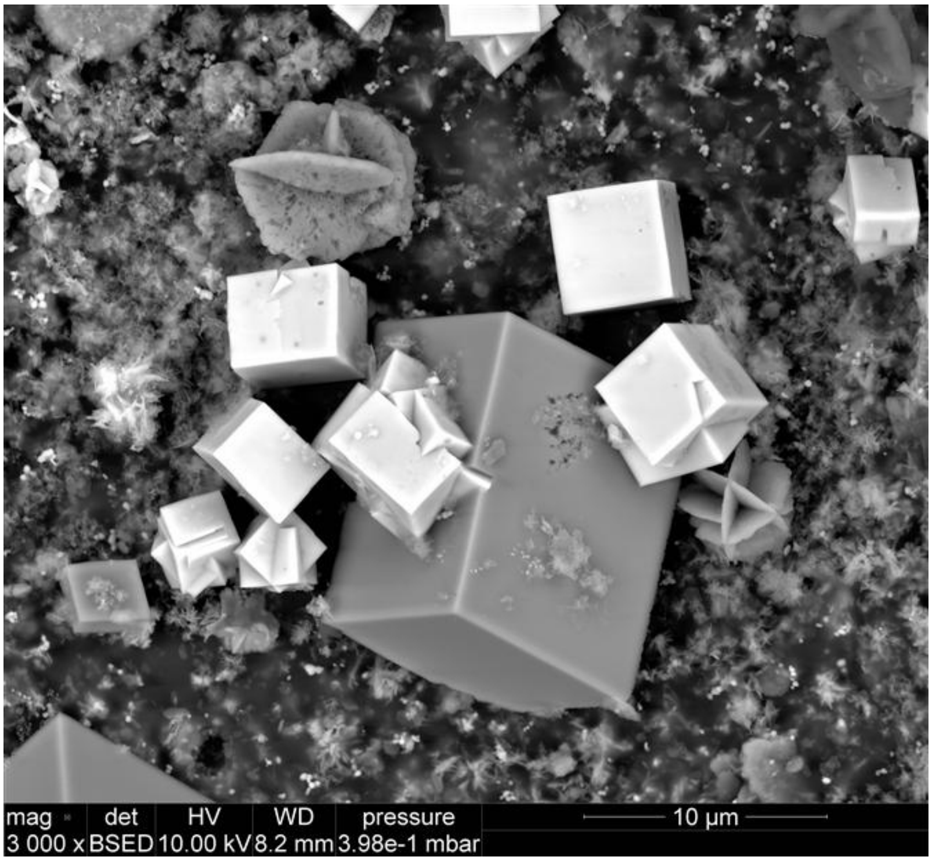

Figure 7. Calcium carbonate (grey cubes) and tin-calcium carbonate on a sealing slurry after artificial weathering under controlled conditions of hydration, representing the increasing ability to obtain high quality images under low vacuum. Image courtesy of FEI and Alexander Kroft.

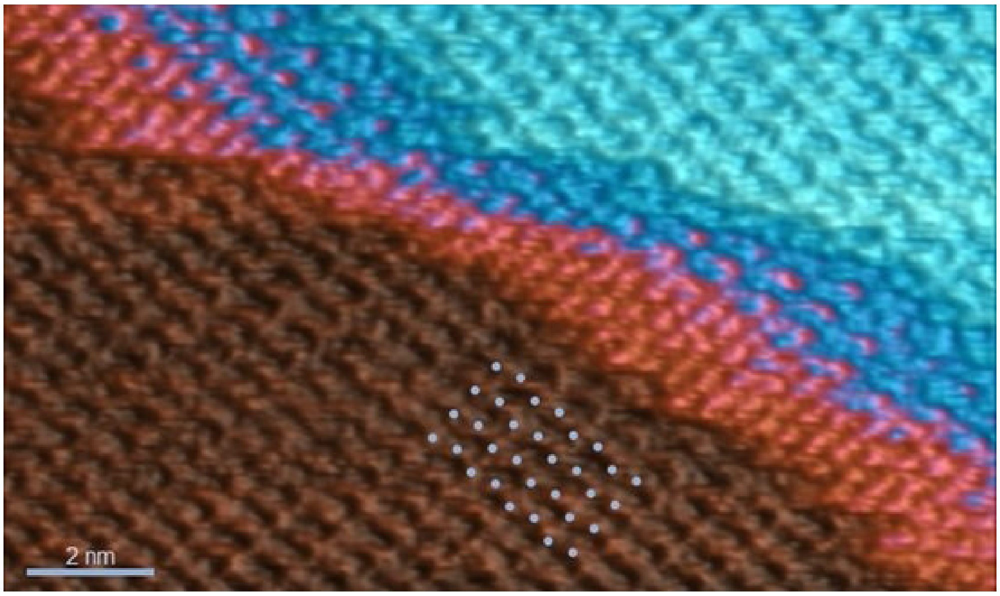

Figure 8. Atomic force micrograph of the surface of a calcite crystal in water. Crystal planes are shown with different colors. The red plane is actively dissolving. Dots show the locations of oxygen atoms in the crystal lattice. Image courtesy of Bruker NanoSurfaces, Santa Barbara, CA.

3. Conclusions

Since the 17th Century, scientists have been using microscopes to make objects visible that were otherwise invisible. This led to an understanding, for example, that blood gets from arteries to veins by flowing through invisible capillaries, that pond water contains organisms too small to see with the unaided eye, that some of these organisms are germs that cause disease, and that the well-developed and specialized Cambrian fossils were preceded by a long evolutionary history of microfossils that extend life back to at least 3.5 billion years (Asimov 1989). 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, two patterns have emerged from this study.

The first pattern deals with ***feedbacks*** operating in a complex adaptive system. A complex adaptive system, by definition, must meet four criteria: (1) the system must contain diverse agents, (2) those agents must be connected, (3) they must be interdependent, and (4) if a perturbation occurs in the system, the entire system adjusts and is adaptive (Page 2011). World food production with its cross-scale links, feedbacks, and adaptations is a complex adaptive system involving processes at the microscopic scale that, when scaled up, affect management adjustments at the landscape scale and supply and demand at the global scale (**Figure 1**). Likewise, groundwater pollution is a complex adaptive system because insights obtained at the micromorphology scale about how pollutants flow through soil can be scaled up and combined with insights gained at the profile scale to redesign (i.e., adjust) agricultural practices and septic systems at the landscape scale. Plastic in soil, which is very symbolic of the Anthropocene, might also be considered a complex adaptive. It consists of numerous connections between diverse agents linked to interdependent adjustments driven by market forces. In addition, the recognition at the profile and micromorphology scale of plastic's extraordinary durability, even in soil where most wastes decompose, might lead to management decisions to produce less plastic or to make plastic that is biodegradable.

The second pattern deals with ***inferences***. Micromorphic features can be used to make inferences about environmental drivers (i.e., climate change) by working backwards through the relationship *FACTORS → PROCESSES → FEATURES* (Targulian and Goryachkin 2004). In addition, archaeological objects too small to be seen with the unaided eye, such as fragments of bone, feathers, or rock flakes, can be scaled up to make inferences about climate change based on human land use.

Technology advancements in microscopy are continuing to enable scientists to see smaller and smaller objects while breakthroughs in low vacuum technology are enabling them to see objects in their aqueous environments. Digital technology continues to make it easier to capture, quantify, and distribute micromorphology information. As technology increases during the Anthropocene, the global human footprint is likely to become progressively larger as world population and affluence simultaneous increase. By providing insights about mechanisms linked to broader scales, soil micromorphology will help us to better understand past and future relationships between humans and soil.

4. Acknowledgments

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