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CREATING DEEP SOIL CORE MONOLITHS: BEYOND THE SOLUM

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ABSTRACT

Soil monoliths serve as useful teaching aids in the study of the Earth's critical zone where rock, soil, water, air, and organisms interact. Typical monolith preparation has so far been confined to the 1- to 2-m depth of the solum. Critical ecosystem services provided by soils also occur in materials from the deeper soil profile. Soil monolith preparation needs to take this new paradigm into account. Soil cores from such depths can be obtained during site investigations for studies of various engineering and environmental problems. The complexity of soil structure makes the preservation and presentation of cores into monoliths difficult. The wide range of exhibition modes ranging from permanent to mobile displays creates further challenges. We present two methods for monolith preparation suited to soil type and demonstration mode. For permanent horizontal displays, a simple process using floor wax is described. For mobile and vertical displays, a solution of acetone and polyvinylidene chloride (PVDC) at a 5:1 mass ratio can be used to create good structurally sound deep soil core monoliths. In this study soil cores were obtained during installation of monitoring wells at two sites 2.5 km apart in the Piedmont of Georgia in the southeastern United States. To reduce health and safety risk, a well-ventilated location and use of protective gear, while handling and using chemicals, is essential to the process. The finished products are in display at the Geology Department, University of Georgia, Athens, GA in the USA.

INTRODUCTION

There have recently been several high visibility initiatives to raise awareness about the importance of soils. The Smithsonian's National Museum of Natural History, Washington, DC, took eight years to carefully design and hold the successful 18-months "Dig It! The Secrets of Soil" exhibit beginning in 2008, which has since been shown in several other states (Megonigal and others, 2010; Drohan and others, 2010). The year 2015 is being celebrated as International Year of Soils (SSSA, 2015). All the organizers had several objectives including the desire to inspire the public and decision makers to think about soils as an ecosystem of immense importance for humanity. Among the creative approaches that highlighted the centrality and link of the soils ecosystem with many others around us, and at different spatial scale, were 53 soil monoliths, representing every U.S. state and territory, that proved popular. Much earlier, van Baren and Sombroek (1981) made a case for global soil reference collections that included soil monoliths and accompanying soil analytical data and site information to be used for a host of purposes including goals for sustainable use of soils.

Soil monoliths preserve soils at conditions approaching those in the field with consideration to both appearance and structure. A pit is dug, or a core drilled, from which a monolith is extracted, the soil profile described, and samples are collected for analyses. The purposes for creating soil monoliths are many-fold and include such factors as display, instruction, analysis, and transport. Soil monoliths are useful visual aids for teaching soil science, geology, and geochemistry (van Baren and Bomer, 1979). Such monoliths enable large groups to examine soil profiles without the time and financial expense of going into the field.

Soil monoliths were first prepared in Russia during the latter part of the 19th century (van Baren and Bomer, 1979; van Baren and Sombroek, 1981). Early efforts to make soil monoliths resulted in varying degrees of success towards the preservation of soil cores as one massive, permanent structure. After experimenting with several different methods, researchers concluded that the optimum length for monoliths was 100 to 200 cm in length (Borowiec, 1976). Over the years many different chemicals have been used to bind soil particles within a monolith. Sugar was one of the first substances used for impregnating soil cores, which is the introduction of a binding or preservative agent into the pore space surrounding soil grains (van Baren and Bomer, 1979). Since the 1930's, techniques have been refined with the increased availability of different impregnating industrial chemicals (van Baren and Sombroek, 1981) that include nitrocellulose lacquers, vinylite resins, poly-methylmethacrylate, polyethylene glycol, and polyester resins. Monoliths prepared in a laboratory require different impregnating materials compared to profiles impregnated in the field as peels, which are much thinner than monoliths (van Baren and Sombroek, 1981).

Many national and international soil-related organizations have followed the monolith model to create inventories of various soil types. The International Soil Reference and Information Center (ISRIC) in the Netherlands, established in 1966, holds one of the most comprehensive global soil monolith collection, representing units of the 1:5 M FAO-UNESCO Soil Map of the World (ISRIC, 2014). To date some 1000 monoliths have been prepared with detailed descriptions of the full profile, chemical and physical data, and information on the landscape and land use. Some of these are on permanent exhibit at the Center. A typical size of a monolith at the Center is 25 cm wide, 125 to 150 cm long, with impregnated soil thickness varying from 2 to 8 cm (van Baren and Sombroek, 1981). In the United States, similar monoliths are collected as representatives of particular soil series, the lowest hierarchy of the national soil classification system, under the auspices of The National Cooperative Soil Survey Organization. Every state within the United States has a soil series designated as a state soil.

The solum, defined as that uppermost part of the earth's surface comprising the O, A, E and B horizons, has for a long period been considered the typical soil model (Richter and Yaalon, 2012). The overarching influence of soil use in agriculture has overshadowed considerations for depth of sampling. The C horizon, which may vary from shallow to very deep (i.e. 10's of meters), was considered the unconsolidated parent material directly above the unweathered bedrock, and with little ongoing pedogenic processes, although its function in other disciplines have been explored (Richter and Yaalon, 2012). Such works have highlighted the shortcomings of the "shallow" soil concept, and given rise to the notion that the lower limit of the soil is at greater depth than currently considered (Richter and Yaalon, 2012). Generally, soil monolith preparation has followed the shallow soil model, probably due to the sheer volume and weight putting limits on what can safely and effectively be extracted and transported. Suggested herein is the need to embrace a 'new' soil model going

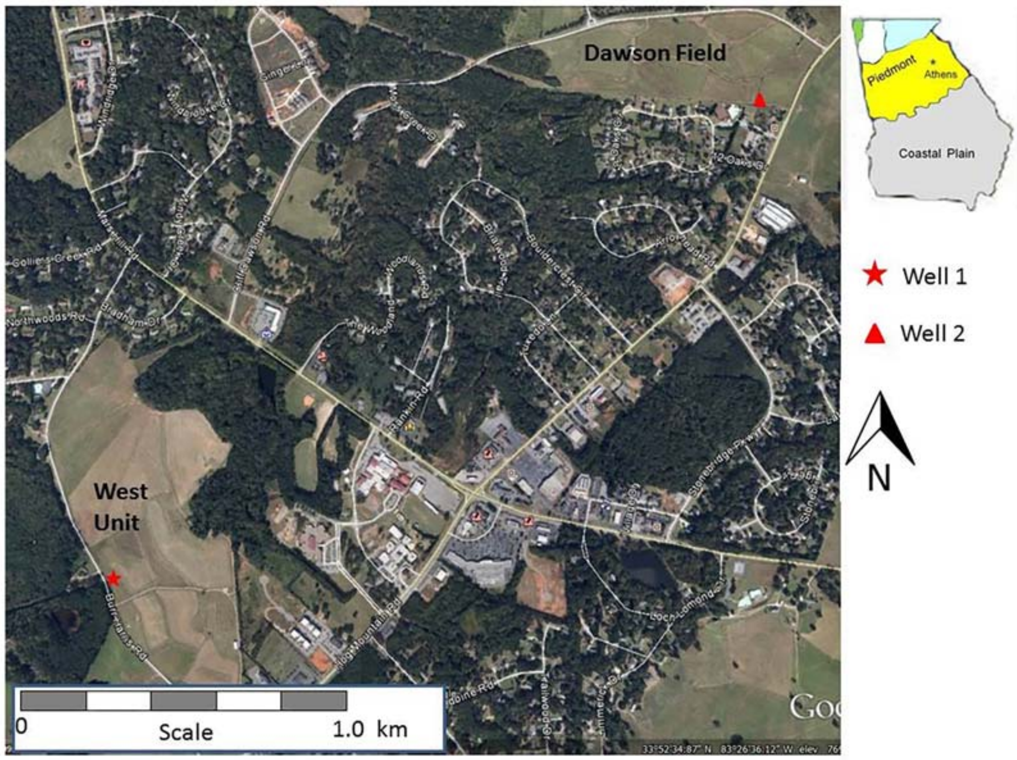

Figure 1. Locations where soil cores were extracted from for installation of monitoring well 1, at the West Unit, and 2, at Dawson Field, within the USDA-ARS Research Center, near Watkinsville, GA (33°52'N, 83°26'W). Wells are approximately 2.5 km apart. Map source is Google Maps (http://maps.google.com).

to depths to and beyond the C horizon into bedrock.

Site investigation is a critical part of many engineering disciplines (civil, structural, environmental, geotechnical, hazard waste treatment and disposal, etc.) where collection of deep to very deep soil core samples is an integral part of the work. Cores from 2 to 15 cm diameter can be collected in undisturbed or disturbed conditions using augur, direct push, cable-tool, air rotary, or sonic drilling techniques. Similar soil cores can be generated during installation of shallow to deep monitoring wells. These areas offer us opportunities to collect, preserve, display, and use the cores in similar fashion as monoliths. Our objective is to demonstrate approaches for acquiring, preserving, and mounting deep soil cores for use as monoliths representing the 'deep' soil model, for purposes similar to that of monoliths of the 'shallow' soil model. We do so using soil cores from the Georgia Piedmont of southeastern United States.

MATERIALS AND METHODS

Core Collection Site

Soil cores were obtained from two locations taking opportunities of drilling workshops organized by the Science and Ecosystem Support Division, Region 4, US Environmental Protection Agency, in Athens, GA. The workshops were part a regular training course offered to state and federal personnel, and provided detailed instructions on the proper installation and sampling of permanent and temporary ground water monitoring wells. Both sites, approxi-

Figure 2. Drill rig with hollow stem auger used for extraction of soil cores and advancing borehole for installing monitoring wells at site 2, October 11, 2006.

mately 2.5 km apart, were located within the U.S. Department of Agriculture, Agricultural Research Service (ARS) Research Station, near Watkinsville, GA (33°52'N, 83°26'W; Figure 1). The area lies in the Piedmont of the southeastern United States. The site features topography, soils, and land use typical of many sloping fields throughout the Piedmont. Long term mean annual rainfall is 1250 mm and mean annual temperature is 16.5°C.

THE REGION

The Piedmont Province covers approximately 16.7 million ha as foothills east of the Appalachian Mountains, extending 1200 km from southern Virginia to east-central Alabama through large parts of North and South Carolina, Georgia, and parts of Tennessee (Carreker and others, 1977). The topography is gently rolling, generally less than 350 m elevation, with gentle to moderate slopes on ridge tops and steeper slopes near streams. The region is dissected by many streams and valleys are narrow with little alluvial soils. There are abundant surface waters and diverse geological resources (Hendrickson and others, 1963). Average growing seasons vary from 209 to 220 days. Average annual rainfall varies between 1100 and 1400 mm.

The bedrock is composed of a variety of igneous and metamorphic rocks spanning the Precambrian to Late Paleozoic age (Radcliffe and West, 2000). Felsic igneous and metamorphic rocks (granite, granitic gneiss, mica gneiss, and mica schist) dominate (Radcliffe and West, 2000), but large areas of intermediate and mafic rocks occur also (Schroeder and others, 2000; 2002). The felsic rocks are light-colored, acidic, and high in silica, while the mafic ones are dark-color, basic, magnesium- and iron-rich, and low in silica. The humid climate encourages strong weathering, which has resulted in a solum of 1- to 2-m depth, underlain by 1 to over 100 m thick saprolite with mean depth of 15 to 20 m (Buol and Weed, 1991). The saprolite serves as an important aquifer and as water storage zone for the deeper fractured bedrock, which together form an unconfined two-layer ground water system (Radcliffe and West,

Figure 3. (A) Display board for cores from Site 1 showing frame and other components; (B) ready to be moved in place; (C) situated in assigned place; and (D) close up of core sections. In C, the board above holds a poster entitled "CECIL & Related Soils – Precious Resources of the Piedmont. We should understand them and care for them". It summarizes information given in Materials and Methods of this paper. In D are shown distributions of horizons, with the saprolite forming the C horizon and depth from soil surface in meters. The core sections represent a total of 9.15 m depth with the last few centimeters as bedrock (horizon R).

2000).

Ultisols dominate the landscape of the humid-thermic southeastern USA (Perkins and others, 1973). These are strongly leached soils, acidic, low fertility, and typically red to yellow in color. Kanhapludults and Hapludults form the dominant great groups. Approximately 51% of the soils mapped in the Piedmont originate from felsic parent material and comprise of Cecil and related soil series (Radcliffe and West, 2000). Typically, surface horizons are sandy loam over clayey argillic horizons. Solum thickness and the color of the Bt horizon is used to differentiate among these series. Because of the landscape, they are deep, well-drained, and moderately permeable soils. The Cecil soil series is designated as the State Soil of North Carolina.

The soil series at the two sampling sites is also Cecil (fine, kaolinitic, thermic Typic Kanhapludults). These soils typically have a well-developed, extensive, iron oxide rich Bt horizon. The C horizon (saprolite) accurately captures aspects of the original parent textures. The soil core parent rock is the Athens gneiss metamorphosed from plagioclase and biotite rich granites. The cores have retained the characteristic physical features of these basement rocks altered by a humid, temperate environment. Cecil and related soil series have been extensively investigated over the past 30 years (Bruce and others, 1983; Schroeder and West, 2005; Austin, 2011, Austin and Schroeder, 2011).

SOIL CORE EXTRACTION

Soil cores were extracted on November 13, 2004 at site 1 (Well 1, Figure 1) and October 11, 2006 at site 2 (Well 2, Figure 1). A drill rig (Figure 2) using a 20-cm diameter hollow stem continuous flight auger and a 10- cm diameter split spoon sampler was used to obtain soil cores, while at the same time advancing boreholes for installation of monitoring wells. At site 1, bedrock was reached at 9.2 m. At site 2, drilling stopped at 12.2 m before refusal, after encountering a water bearing strata starting at 6.1 m. In both cases, 13-cm diameter aluminum irrigation pipes, cut lengthwise in half, were laid on the ground to receive core samples as they were extracted in sections of approximately 153 cm. The core sections were then transported to the laboratory for temporary storage until the monolith making process was started. Core sections from site 1 went to the ARS Research Station and those from site 2 went to the Department of Geology, University of Georgia, in Athens, GA, approximately 15 km northeast of the site.

MAKING OF MONOLITH AND DISPLAY BOARD FOR SOIL CORE FROM SITE 1

Before monolith preparation began for the 9.2 m core from site 1, a discussion was held about how best to display and locate the core sections. The ARS Research Station routinely hosted customers and stakeholders from students and professors to local, state and federal researchers and extension personnel, as well as international visitors, throughout the year. After assessment of potential spaces, a small recess space with good lighting from three directions in one of the foyers, but too small for much other use, was identified. After the dimensions of the space were measured, it was decided to display the core sections horizontally in equal length sections one below the other on an incline starting with the uppermost section at the top.

The frame of the board was built from 5 cm thick by 10 cm wide (2" x 4") lumber. Wheels were installed at the four corners of the frame base to allow easy steering of the whole unit into the tight space. Plywood was used to cover the front and sides (Figure 3A). After smoothing with sand paper, the plywood was varnished. Skirting was used to add character to the otherwise bland plywood face. To hold the core sections in place, aluminum irrigation pipes available at the Research Station were cut in to 1.83 m (6 ft) sections, and then cut lengthwise in half, and fixed in place with nuts and bolts (Figure 3B). The board was then taken to the assigned spot and rolled into the tight space. The core sections were transferred to the open tubes. A mixture of the clear floor wax "Future" from Johnson Wax (Racine, Wisconsin), which is a clear acrylic paint, and ordinary glue diluted with water, was sprayed and poured across the core sections over a period of several weeks until they hardened. This was based on experience on earlier similar cores. There was minimal 'picking' of core sections with sharp objects toward a flat finish as would normally be done in standard monolith preparation. This left the core sections intact as found *in situ* during extraction with either curvature (most part of the solum), or flattish surface (parts of the C horizon). It was decided that this would work fine for the intended purpose. Since the display was designed to be permanent, a poster was hung above the finished work titled "CECIL & Related Soils - Precious Resources of the Piedmont. We should understand them and care for them" (Figure 3C and Figure 3D). A few brief paragraphs tell viewers how soils form in the Piedmont, give the geologic context with some details for the Georgia Piedmont, and show the makeup of Piedmont rocks and minerals. Several brightly colored images of the watershed and regional soil types are also included.

MAKING OF MONOLITH AND DISPLAY BOARD FOR SOIL CORE FROM SITE 2

Core Characterization and Materials

The core sections from site 2 are shown as extracted in Figure 4A. Monolith preparation

Table 1. Core horizon and color characterization of nine core sections from Site 2.

Depth (cm)	Horizon	Color	Depth (cm)	Horizon	Color	Depth (cm)	Horizon	Color
Core Section 1			Core Section 3			Core Section 6		
0-9	Ap	5YR5/4	297-380	BC	7.5YR6/8	741-875	C	saprolite
9-23	A	5YR3/4	380-398	BC	5YR4/3	Core Section 7		
23-45	BA	2.5YR5/4	398-426	BC	7.5YR7/6	875-1031	C	saprolite
45-70	B	2.5YR5/4	426-443	C	7.5YR5/6	Core Section 8		
70-118	Bt	10R5/6	Core Section 4			1031-1189	C	saprolite
Core Section 2			443-596	C	saprolite	Core Section 9		
118-122	Bt	10R5/6	Core Section 5			1189-1313	C	saprolite
122-297	BC	7.5YR6/8	596-741	C	saprolite			

Figure 4. (A) Soil core sections extracted October 11, 2006 at site 2; (B) Monolith preparation at the soil chemistry laboratory, Crop and Soil Sciences Department, University of Georgia, Athens, GA; and (C) Dry soil core sections before soil impregnating process. The differences in coloration seen between A, B, and C are more than likely due to several factors. The core sections were extracted some three years prior to the impregnation process. They were relatively well-cared for within that span of time but transport and time likely had some deteriorative effect on the core sections. This required some careful cleaning prior to being transformed into a series of soil core monoliths.

took place at the soil chemistry laboratory, Crop and Soil Sciences Department, University of Georgia, Athens, GA, which allowed for a continuous, multistage process, ensuring a high-quality final product (Figure 4B). Soil horizon and color characterization was performed on the nine core sections in the laboratory (Table 1). The soil profile featured unconsolidated regolith (C-horizon saprolite) below 426 cm. Several core samples were analyzed using X-ray diffraction (XRD), which confirmed a typical Cecil soil mineralogy. XRD patterns can be displayed next to various horizons.

Polyvinvylidene chloride (PVDC; Solvay Specialty Polymers USA, Alpharetta, Georgia), normally obtained as a fine-powder polymer resin, was chosen as the binding agent to preserve the core sections due to its physical and chemical properties. This product is also widely known as "Saran". It is the chief component of the commercially available food wrapping known as "Saran Wrap", manufactured by Dow Chemicals. It is resistant to various forms of physical and chemical weathering once it has hardened. It is particularly resistant to acidic and alkaline constituents. PVDC is insoluble in hydrocarbons. It has a low permeability to gases and forms an excellent barrier to biological as well as weathering agents.

The PVDC resin was suspended in solution with acetone to allow for impregnation of the soil core sections. Acetone is a liquid at standard pressures and atmospheres that has a lower viscosity than water, which aids in more thorough impregnation of soil. Acetone's high rate of evaporation allows the next step in the monolith preparation process to proceed soon after.

Despite adequate ventilation in the workspace, extra precautions were taken to minimize the health and safety risks posed by working with the combination of acetone and PVDC. Both chemicals pose risks if inhaled: acetone to the nervous system and PVDC to the lungs. To reduce the risk of inhalation, a high-powered fan was placed in the window drawing air out of the workspace. Also a half face-piece respirator was utilized when using large amounts of acetone and PVDC. Gloves were always worn when handling chemicals and the workspace was frequently cleaned. As latex breaks down quickly when exposed to acetone, latex gloves could not be used. Butyl rubber gloves are recommended for handling acetone.

The following materials were assembled prior to construction of a 13.1-m long monolith:

- The original core, divided into ~1.45 m smaller core sections
- 1.36 kg PVDC
- Several reagent bottles
- 38 liters laboratory-grade acetone
- Nine 2.44 m long 5.08 cm x 20.32 cm boards: treated pine
- 18, 1.22 m long 2.54 cm x 5.08 cm boards: treated pine
- Carpentry tools including carpenter's clamps, wood glue, drill, a masonry hammer, and a rubber mallet
- A large gardening pail with a 7.5 cm diameter spigot
- Clear polyurethane
- An assortment of painter's brushes
- Half face-piece respirator
- Butyl rubber gloves
- High-powered box fan

Construction Procedure and Methodology

Prior to construction, solutions made up of several acetone to PVDC mass mixing ratio were tested on a small quantity of soil similar in structure and origin to that of the soil core. Several of these mixing ratios were determined to be suitable for impregnating the soil core. Initially the soil core sections were very dry, had mostly formed into hard blocks because of long term storage (Figure 4C), and needed to be saturated during impregnation. The solution from a 5:1 mixture (acetone: PVDC), which had relatively low viscosity, proved the most suitable for impregnating the core sections with a consistent and complete saturation and with uniform transport within the pore space. Enough volume was prepared for use in subsequent monolith preparation.

Core Housing Construction and Core Impregnation Methodology

The following sequence was followed:

- Wooden boxes were constructed from plywood to hold the soil core segments. The channels in the box were set at 10-cm wide at the base, per core diameter, and 5-cm deep. The length of boxes varied from 118 to 179 cm to accommodate the different

Figure 5. Preparation of wooden box to house soil core sections.

length core sections. Each box was built approximately 0.5 cm larger in length, width, and depth, than each core section (Figure 5).

- The boxes were first glued together using wood glue, then clamped tightly for a period, followed by reinforcement with nails to provide extra material strength against the stress of holding the core sections.
- When the boxes were completed, the core sections were placed in each box in the following manner:
  - o One by one, core sections, still in the original aluminum casing, were placed on a working table, soil face up.
  - o Each box was placed opening down on top of its respective core section.
  - o Two workers then carefully flipped each box containing the core section over so that each section was contained within a box. It was crucial that the core sections remained sandwiched between the base of the box and the casing during this procedure. It was necessary to press the core casing edges flush with the base of each box in order to make sure that little to no soil particles were lost. Care was also taken to keep the soil faces horizontal throughout the process.
  - o To accommodate the curved core sections into the dimensions of their orthogonal boxes, the soils were carefully redistributed laterally with mild flattening using a rubber mallet or a masonry hammer and smoothed-out with the painter's brush.
  - o The 5:1 solution was distributed throughout the core sections from a metal watering pail. Extreme care was taken to avoid soil particles being washed away over the edges by slowly tipping the watering pail at no more than a 30-40o angle.
  - o The acetone took approximately 30 minutes to evaporate from each core section. Once the core sections had dried, clear lacquer was applied to each box surface, coating both the soil and the wooden box.
  - o Wood stain was applied to each box wood surface once the core sections had dried.

RESULTS AND SUMMARY

The finished products formed a collection of soil core sections with well-preserved structure at greater depth than that of the solum, ending at bedrock at site 1. The features of the soil profile and characteristics of the Cecil soil series are distinctively evident, including the diagnostic epipedons. The features of the top soil, subsoil, and saprolite forming the C horizon are well preserved. Fine roots remaining in the A horizon are preserved. The mosaic of colors and minerals within the saprolite highlight the complex weathering chemistry of primary and secondary minerals. The distinctive physical

Figure 6. The finished core sections from site 2 secured on a wall at the Geology Department of University of Georgia in Athens, GA, for viewing by students, faculty and visitors. Poster to the right provides content about making of exhibit and additional mineralogical information from X-ray diffraction. Left inset shows first segment of core with Munsell ® color chart.

features of the Athens gneiss, especially foliations, are evident at the bottom core section of site 1. The sections overall represent well-preserved profile of a soil that is characteristic of large parts of Piedmont Physiographic Province, particularly in Georgia. They present good visual-teaching tools for representing the results of soil forming processes, extending back through geologic time, through the dynamic interaction of five factors: parent/rock material, topography, climate, biological organisms, and time. The display can also illustrate the recent human contributions to soil alteration. The audience can vary from small school children to adults of all walks of life and discipline.

In May 2012, upon reassignment of the 70-yr ARS Research Center to UGA, the soil core sections and display board for site 1 (Figure 3C) were transferred to the Department of Geology at the UGA-Athens where they are on display. The finished core sections from site 2 have been secured on one of the walls at the Geology Department for viewing by students, faculty and visitors (Figure 6). The display format for core sections from site 1 was custom made and was much less mobile (can be considered static) than that for core sections from site 2 which can easily be transported to any place and audience. The preservation process was rudimentary for core sections of site 1, while for core sections of site 2, it was complex. In both cases, our approach demonstrated that using soil core sections from site investigation or monitoring well installation sites, etc., and using simple to complex preserving and displaying techniques, preparation of soil monoliths going well beyond the solum can become routine for any desired purpose.

The monolith making process should start as soon as cores are obtained to retain the *in situ* soil characteristic and features. When in storage, soil cores tend to accumulate debris, and could dry out or absorb moisture, compromising the structural integrity of core features, especially if storage period is long. Only climate-controlled storage can counter this, which adds unnecessary cost and management. This points to pre-preplanning about where and when cores might become available, where they can be stored and for how long, division of activities among personnel involved in the effort from acquiring materials to fabricating display board, and where and how the finished product might be utilized.

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DISCLAIMER

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