# Application of the Critical Zone Concept to the Deep-Time Sedimentary Record

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## ABSTRACT

In 2006 the US National Science Foundation (NSF) created a national Critical Zone Observatory (CZO) program. As defined in that report, the Critical Zone (CZ) extends from the top of the vegetation canopy to the groundwater table, and integrates interactions of the atmosphere, lithosphere, pedosphere, biosphere, and hydrosphere. Following themes of two recent discussions presented in the *Sedimentary Record*, we propose to extend the CZ concept to deep-time Critical Zones (DTCZ), arbitrarily defined as pre-Quaternary (>2 Ma). Because of recent advances in the study of paleosols (termed paleopedology), especially refined geochemical paleoclimate proxies and pedotransfer functions, it is now possible to reconstruct biogeochemical cycles from paleosols preserved in the sedimentary record in deep-time. We present a case study of a DTCZ as investigated within the framework of a deep-time Critical Zone observatory (DTCZO). Additional advances in interpretations derived from mining of a modern geochemical data base derived from a broad array of Critical Zone environments will improve our understanding of the geochemistry of weathering, and strengthen the veracity of the records of the paleo-atmosphere, biosphere, and hydrosphere.

## INTRODUCTION

As originally proposed by the NSF, invoking the "Critical Zone" concept provided a framework challenging the Earth sciences community to expand its capability for predicting future changes in the Earth climate system (National Science Foundation 2000). The National Research Council (NRC) subsequently identified integrative studies of the "Critical Zone" as one of the six compelling opportunities for earth scientists in the next decade (National Research Council 2001, 2003); a report that was recently updated and reinforced (National Research Council 2012). In 2006 the NSF created and funded a national Critical Zone Observatory (CZO) program, now consisting of 6 observatories stationed throughout the U.S. and Puerto Rico (http://criticalzone.org/).

Why is the "Critical Zone" so important to the Earth sciences? The Critical Zone (CZ) is an actualistic environmental laboratory designed to study the biogeochemical by-products of the interactions of the atmosphere (energy, gases) and hydrosphere (water flux, mineral weathering) acting on the lithosphere (chemical elements, physical substrate) to produce the pedosphere (weathered lithosphere, nutrient storage) and biosphere (floral/faunal, nutrient cycling). Critical Zone observatories (CZO) are designed to study quantitatively the interface of the Earth systems within a defined area to better understand the current structure and function of the CZ and to predict its future response to tectonic, climatic and anthropogenic forcing (Brantley et al., 2007).

However, the sedimentary geology community, and the smaller subset community interested in paleosols, has largely been excluded from the CZ discussion. The recent *Transitions* (2011) document (http://www.nsf.gov/pubs/2012/nsf12608/nsf12608.pdf) argues that the deep-time critical zone concept is important because the climate state of the last 2 Ma years (glacial epoch) is a non-analog to a future world without glaciers. Furthermore, climates of the past are often examined using general circulation models (GCMs) where the validity of any proposed GCM depends on actual data obtained from ancient geologic records of climate that are preserved in rocks, including ancient soil deposits known as paleosols.

Following themes of two recent discussions presented in the *Sedimentary Record* (Montañez and Isaacson 2013, Parrish and Soreghan 2013), we propose to extend the CZ concept to deep-time (DTCZ), arbitrarily defined as pre-Quaternary (>2 Ma). To preserve the integrity of the CZ concept, a DTCZ must be recognized as a snapshot in time - a land surface that extends laterally across a continent, region, or local landscape (Fig. 1). A DTCZ can be studied in the context of a deep-time critical interval (DTCI) recognized, for example, as an intense greenhouse episode or faunal turnover. Sediment cores might expose a DTCI within which to identify and study a DTCZ and even offer complementary interpretive information (Retallack and Dilcher, 2011). At the local scale, however, an outcrop exposure would be the

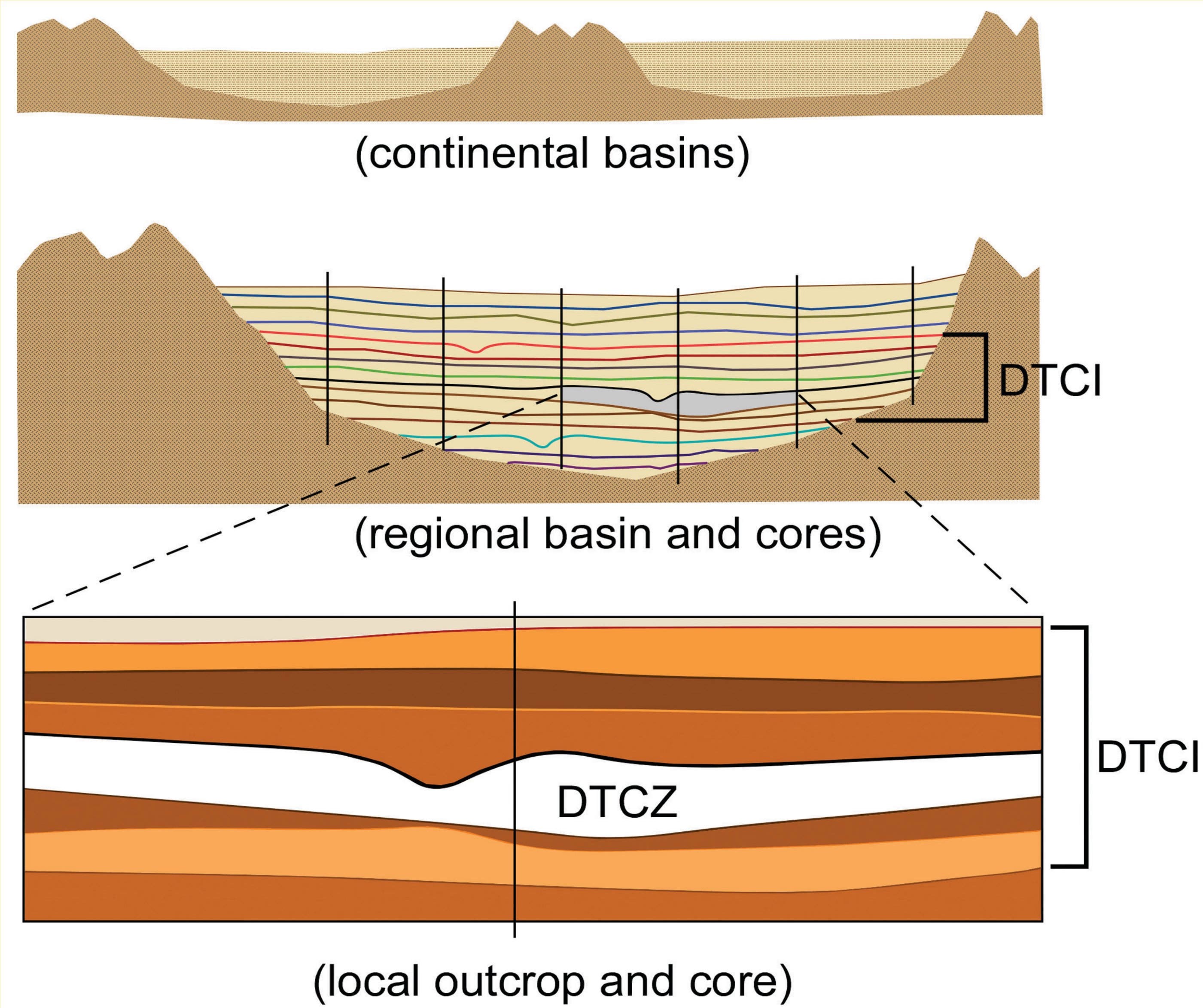


*Figure 1: Top panel - Schematic cross section of two continental-scale structural basins (each ~40 km wide and 100 m deep) containing a succession of alluvial deposits. Middle panel - regional view of a basin accessed by 6 sediment cores penetrating 14 demarcated DTCZ's (color coded lines) through a DTCI. Lower panel - Local outcrop (~6 km wide and 20 m thick) of an alluvial succession illustrating a DTCZ (gray) within the designated DTCI. Note that the single sediment core through this alluvial section would provide limited CZ information. The upper part of each DTCZ is assumed to have been weathered to a paleosol.*

ideal environmental laboratory for studying a specific DTCZ and all associated facies (Fig. 1). Creation of a deep-time Critical Zone observatory (DTCZO) would require a team of scientists studying the structure and function of a DTCZ (http://www.nsf.gov/pubs/2012/nsf12608/nsf12608.pdf).

Our expertise is in the area of paleopedology (study of paleosol morphology, genesis, and interpretation) and as such the purpose of this paper is to present many of the interpretations possible from studying paleosols within the DTCZ concept. In a 2010 SEPM-NSF jointly sponsored Workshop *"Paleosols and Soil Surface System Analogs"*, the paleopedology community was able to assess its role in deep-time climate reconstructions, propose methodological approaches to the characterization of ancient Critical Zones, and voice its desire for increased involvement and support through NSF (Driese and Nordt, 2013).

## IMPORTANT ADVANCES IN PALEOPEDOLOGY

In the absence of monitoring stations, the paleopedologist must study vestiges of once functioning critical zones using a variety of forensic field morphological and laboratory investigative methods (Nordt and Driese 2010a, Nordt et al., 2012, Nordt et al. 2013). Once a paleosol is characterized a number of important interpretations related to the Earth systems are strengthened.

Advances in paleo-atmospheric sciences based on a more robust reconstruction of ancient pedospheres are summarized in Sheldon and Tabor (2009). Whole-rock molecular oxides, especially the Chemical Index of Alteration Minus Potassium (CIA-K), have been

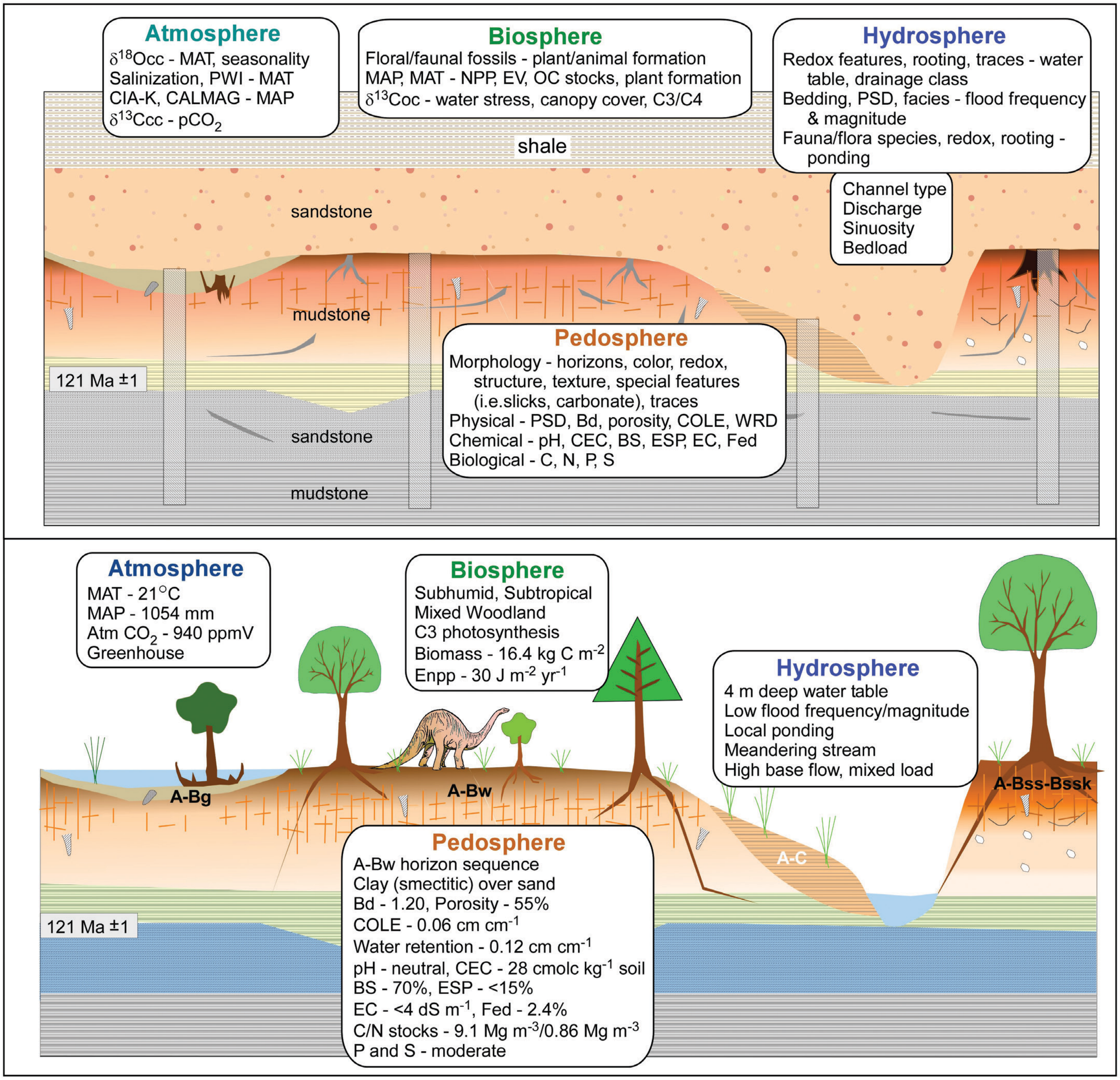


*Figure 2: Illustration of a 2 km wide and 10 m thick cross section of a Cretaceous DTCZ in outcrop before (top panel) and after (bottom panel) reconstruction (refer to Figure 1). Reconstruction was performed from field descriptions and geochemical characterization analysis of 4 fluvial facies (vertical cross-hatched columns). Climate reconstruction from data from the A-Bss-Bssk paleosol profile, biosphere and pedosphere reconstruction from the A-Bw profile, and hydrosphere reconstruction from characteristics of both the fluvial system and paleosols. Note slight color changes and transformation of root traces to drab halos during diagenesis. gray - iron reduction zones in mass or after roots, white ovals - pedogenic carbonate nodules, cross-hatched cylinders - faunal traces, dark features in subsurface - tree stumps, Bd - bulk density, COLE - coefficient of linear extensibility, WRD - water retention difference (AWC – available water capacity), PSD - particle size distribution, ExC - exchangeable cations, CEC - cation exchange capacity, BS – base saturation, ESP - exchangeable sodium percentage, pH - hydrogen ion activity in solution, EC - electrical conductivity, Fed - citrate dithionite extractable iron, cc and oc - calcium carbonate and organic carbon for isotopic analysis, PWI – paleosol weathering index, EV - evapotranspiration, Enpp - net primary productivity expressed in units of energy.*

popularly used in the paleosol community for reconstructing climate, especially mean annual precipitation (MAP) (Sheldon et al. 2002). However, because CIA-K, defined as ($Al_2O_3$/($Al_2O_3$+CaO+$Na_2O$)*100), is fundamentally an index of clay formation and base loss related to feldspar weathering, it is inappropriate for one soil order that is well-represented in the rock record as paleosols, namely, the Vertisols. These soils have high clay-content and high shrink-swell potential, and commonly form from alluvium that has been "pre-weathered"

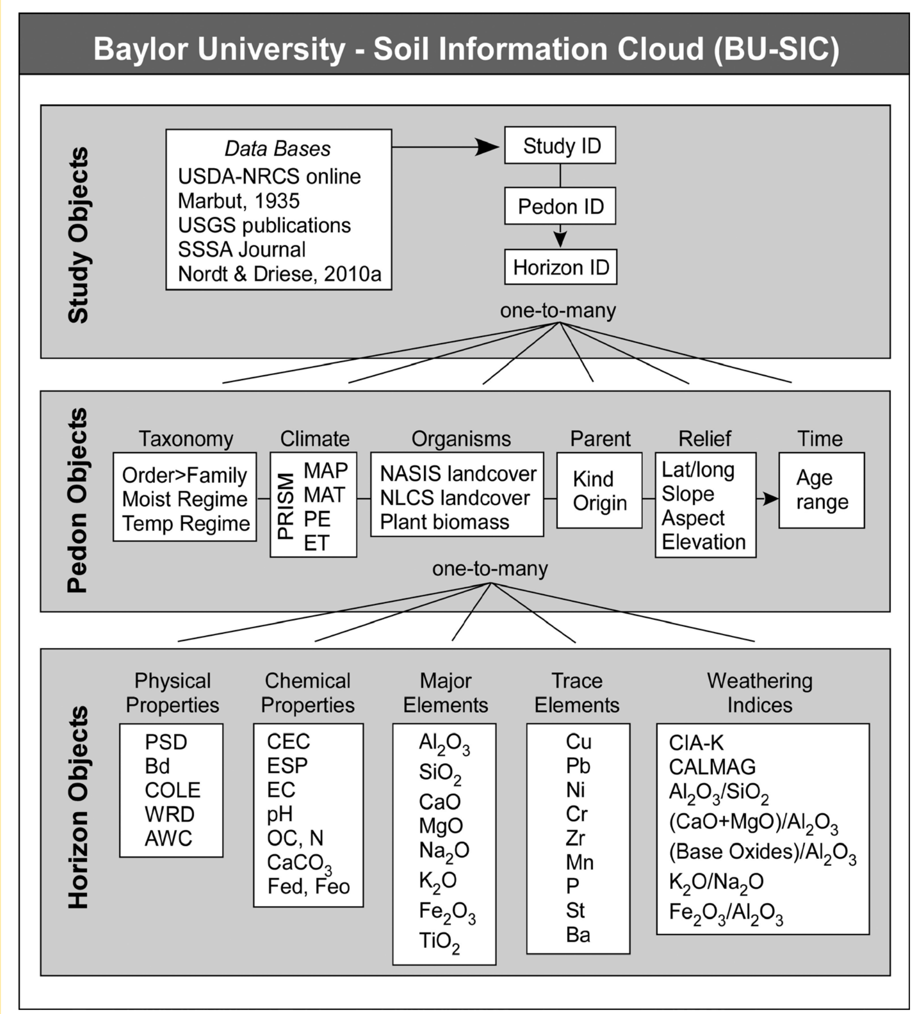


***Figure 3: Baylor University-Soil Information Cloud (BU-SIC) for database management of information sources scaled from study objects to pedon objects to horizon objects. The hierarchical structure permits many different types of queries depending on the needs of the researcher. The database is currently being queried for correlations between bulk soil oxides (major and trace elements, and weathering indexes) and climate parameters, and between bulk soil oxides and physical and chemical properties for establishing pedotransfer functions. NASIS – National Soil Information System, NLCS – National Landscape Conservation System, PRISM – Parameter-elevation Regressions on Independent Slopes Model, PSD – particle-size distribution, Bd – bulk density, COLE – coefficient of linear extensibility, WRD – water retention difference, AWC – available water capacity, CEC – cation exchange capacity, ESP – exchangeable sodium percentage, EC – electrical conductivity, OC – organic carbon, N – nitrogen, P – phosphorous, S-Sulfur, Fed – citrate dithionite extractable iron (crystalline, pedogenic), Feo – ammonium oxalate extractable iron (amorphous, pedogenic).***

(Nordt and Driese 2010a). Recent advances developing MAP proxies specific to Vertisols, such as CALMAG, defined as ($Al_2O_3$/($Al_2O_3$+CaO+MgO)*100), have improved MAP estimates (Nordt and Driese 2010b). Estimating paleo-temperatures has been problematic because the $\delta^{18}O$ of pedogenic carbonate nodules involves many uncontrained assumptions (Dworkin et al., 2005). However, the wide error bar in the original geochemical salinization equation for temperature proposed by Sheldon et al. (2002) was recently improved by developing the paleosol weathering index (PWI) designed specifically for forested paleosols (Gallagher and Sheldon, 2013). The stable C composition of paleosol carbonate has had long standing success helping to reconstruct long-term trends in atmospheric $CO_2$ (see Ekart et al., 1999).

The pedosphere also provides important clues to the paleo-biosphere. For example, Nordt et al. (2012) calculated organic carbon stocks of paleosols using the rationale that as organic materials decompose upon burial certain trace elements remain behind as conservative tracers of the original organic content. Gulbranson et al. (2011), using modern climate (PRISM) and bulk soil geochemistry data, developed energy fields for paleosols in the rock record. As defined in this work, $E_{PPT}$ (energy from precipitation, kJ $m^{-2}$ $yr^{-1}$) and $E_T$ (evapotranspiration, cm) can now help classify Holdrege life zones and associated plant formations. Other studies show that the $\delta^{13}C$ of bulk paleosol organic carbon provide insights into atmospheric $^{13}C$ to potential moisture stress levels of C3 plants and to differences in canopy cover (Kohn 2010). Moreover, Fox and Koch (2003) were one of the first to document the spread of C4 plants from the stable C isotopic composition of paleosol organic materials. Röbler et al. (2012) developed an approach to reconstruct the structure of a plant community across a landscape as a snapshot in time from botanical remains and traces in paleosols.

Reconstructing terrestrial hydrospheres include, in addition to climate parameters from geochemical analysis, information extracted from paleosols and the affiliated environments of deposition (i.e. fluvial). Soil water-holding capacity and hydraulic conductivity can now be measured or inferred in paleosols (Nordt et al. 2013). Drainage class can be inferred from redoximorphic features and faunal traces related to water table levels, ponding, and flooding (Kraus and Hasiotis, 2006). Channel parameters can be related to paleo-discharge, channel type, and even flood magnitudes (Flaig et al. 2011), which in turn controls the stability of the landscape in fluvial settings.

## CASE STUDY OF THE DTCZ CONCEPT

Figure 2 is a schematic representation of the logic and steps in reconstructing a DTCZ in the sedimentary record at the outcrop scale, beginning with morphological description and laboratory analysis of samples collected from each alluvial facies (cross-hatched columns). The optimal approach would be for a team of geoscience specialists to study the outcrop exposure from varying perspectives.

From these data secular atmospheric conditions were calculated from geochemical and isotopic analysis of the most weathered paleosol, i.e., that most likely in equilibrium with ambient climate conditions (Fig. 2, A-Bss-Bssk profile). The floodbasin facies in Figure 2 (A-Bw profile) is used as an example of studying one facies of the DTCZ in detail. Here, biogeochemical characterization of the paleosol is performed by a combination of field description, direct laboratory analysis, and pedotranfer functions, and the biosphere is reconstructed from atmospheric conditions, paleosol edaphics, and botanical remains. The hydrosphere is recreated from channel dimensions of buried river channels and from the distribution of redoximorphic features in paleosols for extrapolating water table depths.

Reconstruction of the entire schematic cross-section in Figure 2 from the integrated field and laboratory studies discussed herein indicates that this DTCZ formed in a temperate subhumid to humid greenhouse climate (high MAP and $pCO_2$) with soils in the floodbasin facies that were nutrient-rich (neutral pH, high BS, low EC or salinity, and low ESP or sodicity), and that had optimal water holding capacity (strong ped structure, low bulk density, high porosity and water retention), optimal nutrient retention (high clay content and CEC) and nutrient reserves (relatively high C, N, P, Fe), and moderate shrink-swell potential (COLE). Comparatively high NPP and minor water stress and open canopy based on C3 isotopic signatures, suggest that carbon and nitrogen stocks were in plentiful supply in both above- and below ground biomass. The DTCZ formed in an infrequently flooded floodplain of a meandering stream (attached point bars, mixed load, aerial view of channel features), but with variable drainage conditions depending on the affiliated facies (redoximorphic features, Fed content, faunal traces). Immature, wet Entisols (Aquents, A-Bg profile) occurred in what were ponded areas supporting early to midsuccessional swamps (hydrophytes). More mature and better drained Vertisols (Uderts, A-Bw and A-Bss-Bssk profiles) formed across the floodbasin facies supporting mixed woodlands (mesophytes). Variably drained Entisols (Fluvents, A-C) formed on riparian point bars bordering incised river channels (mixed hydrophytes and mesophytes). Comparing these conditions to another DTCZ with different environmental conditions, say in a stratigraphically superposed cool house interval, would strengthen the understanding of ecosystem response to different forcing mechanisms.

## LOOKING TO THE FUTURE

We are currently developing a soil database (BU-SIC) that contains over 1500 pedons and 6000 soil horizon records obtained from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) that can be queried using different soil and geochemical (whole-soil) parameters to (Fig. 3): 1) develop new paleosol bulk geochemical proxies using partial least squares regression (PLSR) for a universal approach to calculating MAP and mean annual temperature (MAT), 2) establish paleosol pedotransfer functions that relate bulk geochemical assays to modern soil characterization properties for all paleosol types, and 3) develop a new paleosol taxonomic system based on a combination of field morphological properties, measured laboratory properties, and pedotransfer functions.

Regarding paleosol classification, there are two competing taxonomic systems employed for the rock record. The Mack et al. (1993) scheme takes the minimalist approach with classification criteria limited to field observations of preserved morphological features. This strength is also its weakness in that it provides limited interpretative value and little in the way of the reasons why any taxonomic system is constructed. In contrast is the modern U.S. soil taxonomic system (Soil Survey Staff 1999). If this system is taken through all six categorical levels for classification it requires so much quantitative and semi-quantitative information as to make it impossible to apply to all fossil soils. Thus a compromise of approaches is needed to improve consistent communication and application.

## CONCLUSION

Even though this paper is not a comprehensive over view of all aspects of the DTCZ concept, it is apparent that the design and implementation of DTCZ observatories will improve our understanding of deep-time sedimentary records. These records will for the first time provide valuable information in a holistic manner about ancient landscapes as opposed to the limitations of studying one-dimensional stratigraphic sections. We recommend the formation of task forces that would work towards developing these various concepts and to form teams of scientists designing DTCZ studies across deep-time critical intervals.

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