SOIL PRODUCTION, EARTH'S CRITICAL ZONE, AND THE ANTHROPOCENE

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The great intellectual fascination of pedology derives from its comparative study of the diversity of Earth's soil, its interdisciplinarity required to understand even a single soil, and the many ways in which soil interacts with the natural and cultural environment (Richter and Yaalon, 2012).

Not surprisingly, pedologists have been instrumental to the development of the interdisciplinary Earth science of the critical zone (Jordan et al. 2001; Lin and Wilding, 2005), the critical zone being defined as the life-supporting system of Earth's surficial terrestrial processes. As an integrated body, the Earth's critical zone ("a thing" in the words of W.E. Dietrich, personal communication) extends the conventional definition of ecosystem to include not only the atmosphere, climate, and foliar boundary layer down through the soil to the deepest zone of mineral weathering. Defined by its fluids, the critical zone spans the atmosphere to the deepest aquifers; defined by time, the critical zone spans all biological and geological time scales and history; defined by its slogan, the critical zone extends "from treetop to bedrock". Jordan et al. (2001) when coining the critical zone used the word "critical" for good reason to emphasize the growing concern about human influence on this life-supporting system (Latour 2014). It is no coincidence that at the same moment that a congruence exists in the core concepts of ecology's ecosystem and Earth sciences' critical zone (Richter and Billings 2015), our geological epoch may be renamed the Anthropocene (Waters et al., 2015).

We propose that a paradigm of Earth's critical zones is that of soil production (Figure 1), a brilliant but underutilized framework first proposed by Gilbert (1877). (Note that what Gilbert called "soil" was later called "regolith" (Merrill 1897), although in this piece and others (Richter and Markewitz, 1995), we follow the Gilbert tradition). Here, we suggest that the soil-production paradigm can provide new perspectives of Earth's systems for ecosystem ecologists, critical zone scientists, and pedologists alike. We describe two examples of soil production at the Calhoun Critical Zone Observatory, a 70-year old research station in the Southern Piedmont of North America, a site that provides special insights into these critical zone issues, both over geologic history and during the Anthropocene itself. The first example is a residual soil and weathering profile produced directly from granitic gneiss below, a profile that includes fractured bedrock, saprolite, and argillic Bt horizons; the second example is a profile derived from transported paleo- colluvium from materials previously weathered in place. The comparison of residual and transported materials helps us understand how all soil state factors of climate, biota, geologic substrate, and geomorphology are dynamic over a soil's lifetime. We conclude by considering the role of human forcings as a dynamic and overwhelming new state factor in the Anthropocene (Dudal, 2001, Richter and Yaalon, 2012).

The soil production paradigm

In 1877, Gilbert stated with wonder, "Over nearly the whole of the earth's surface, there is a soil, and wherever this exists we know that conditions are more favorable to weathering than to transportation." Gilbert had realized a fundamental attribute of the planet, that across nearly all landscapes from the tundra to the tropics, weathering's production of soil particles and solutes (W) outpaces transport-related losses via erosion and dissolution (T). The Earth thus soil accumulates (Figure 1). Even in most naturally erosive environments, W keeps pace with T, and soil profiles may be thin but they accumulate. Given liquid water and biogeochemical weathering agents, W liberates mineral particles and inorganic solutes; T removes a fraction of those products but soils accumulate the remainder.

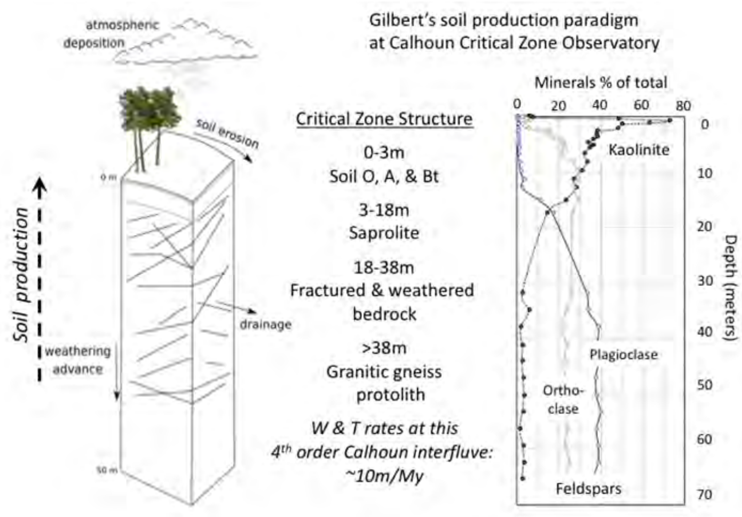

Figure 1. Diagram of Gilbert's soil production treadmill of W > T with structure, mineral, and rate details from a residual soil-weathering profile at Calhoun CZO (Bacon et al. 2012).

The dynamism of all soil state factors

At the Calhoun Critical Zone Observatory, many soil and weathering profiles have formed over several million years, and on sites that are geomorphically stable, soil accumulates in residual profiles that are 10s of meters deep (Richter and Markewitz, 1995, 2001; Bacon et al. 2012, St. Clair et al. 2016). One upland soil-weathering profile that is studied in detail has formed on nearly level terrane and has unweathered protolith below 38 m, fractured and weathered granitic bedrock between 38 to 18 m, saprolite C horizon from 18 to 3 m, and a well recognizable Ultisol with Bt, E, and A horizons in the upper 3 m. Plagioclase which composes ~38% by mass of the parent rock, weathers completely to kaolinite between 38 and 12 m; the primary mineral orthoclase weathers to form more kaolinite between about 10 to 1 m (Figure 1). Rates of weathering and transport are are on the order of 10m per million years, and the ^{10}Be residence time of the profile is at least 2 to 3 million years old (Bacon et al. 2012).

Viewed from the soil production paradigm, weathering in this residual profile has liberated inorganic particles (mainly quartz and feldspars) from the granitic gneiss at a more rapid rate than erosion and dissolution transport has been able to remove them. Remarkably, transport is dominated by dissolution rather than erosion, and nearly all feldspars have been dissolved and reformed as kaolinite by the time the soil particles arrive at the soil's surface to become part of the active root zone and are finally subject to erosion. Given the long residence time of the profile, the rate of soil production has experienced many significant changes in climatic and biotic forcings.

The soil production paradigm thus describes the treadmill on which mineral particles liberated from underlying geologic substrate are subject to biogeochemical processes of acid dissolution and hydrolysis on their ride to the soil surface. The mineral particles that compose the A and B horizons are survivors in the soil production system.

An Ultisol profile derived from ancient colluvium has been recently sampled and is used here to contrast with the residual profile described above. The second profile gives us an appreciation for the dynamic nature of landscape evolution and of all soil-state factors (not just climate and biota), and of the fact that most soils are now understood to be polygenetic. The second profile is also in the uplands and in fact lies <100m horizontal from the upper elevations of the contemporary landscape. The A, E, and Bt horizons of the soil profile developed in >5-m of colluvium that lacks rock fabric structure and which is completely exhausted of its original plagioclase. What is more, the colluvium buries a 2-m thick sandy layer with 14C-dead charcoal and wood fragments of unknown age, and this organic matter overlies a saprolite of unknown depth. A granitic gneiss is the ultimate parent below the saprolite. We hypothesize the organic deposits, many dozens of which have been identified across the region, to be at least 100s of thousands of years in age. Given the organic deposits and the age of the system, the contemporary Ultisol has formed in a colluvium that is much reduced in thickness due to erosion and dissolution. The profile has many wonderful mysteries, especially that it clearly indicates that the Piedmont is old enough to have had paleo-landscapes of unknown ages.

Viewed with the soil production paradigm, this colluvially derived Ultisol is related to the residual Ultisol profile of Figure 1, but it also has many contrasts. Whereas the first profile is derived directly from the weathering bedrock below, the second profile is derived from colluvium and illustrates clearly that soil production is not only controlled by the dynamic state factors of climate and biota but also the dynamic state factors of geomorphology and geologic substrata. Many soils have lifetimes sufficiently long that the parent materials that feed via Gilbert's soil production treadmill the soil's C, B, E, and A horizons *change* over soil time. In this ancient landscape, geomorphology and even the geologic substrates are clearly seen to be highly dynamic through time.

The polygenetic wave of human forcings

A major soil problem for the Anthropocene is that human activities are accelerating T relative to W, a shift that has enormous consequences for soils, ecosystems, water, the atmosphere, and the critical zone. In the Anthropocene, humanity has become the Earth's primary geomorphic agent (Hooke 2000), and natural soil profiles are disappearing rapidly (Amundson et al. 2003; Galbraith, 2006). Understanding how contemporary soils evolve as human-natural bodies is as important to pedology today as was the evolution of soils as natural bodies first articulated by Hilgard, Darwin, and Dokuschaev in the 19th century (Yaalon and Yaron, 1965). Recognizing humanity as "a fully fledged factor of soil formation" (Dudal et al., 2002) not only enriches pedology, but reinforces the vital role to be played by soil science in resource and environmental problem solving of the 21st century (Grunwald et al., 2011).

At the Calhoun CZO for example, farming has accelerated T via erosion over about 150 years (1800 to 1950), removed more than 15-cm of soil from the Piedmont region's crop fields, pastures, and gullies (Trimble, 2008). Because Piedmont uplands exceed bottomlands by about 10:1 in area, the legacy sediment deposits (James 2014) have entierely transformed Piedmont valley morphology and floodplain functioning. The novel legacy-sediment soils often amount to a meter or more in depth and are forming in mixtures of eroded A, B, and C horizons materials that have been lost from the uplands. Such human forcings are taking pedology well outside our previous experience with soil as a natural body, given our impact on the balance of T and W. As our land uses are transforming the physical, chemical, and biological properties and processes of soils across the landscape, soil scientists are challenged to develop a pedology with broad purview and decades' time scale that can fully support the science and managment of soils, ecosystems, and critical zones as well. How challenging for pedology that the contemporary polygenetic wave of human forcing involves new climates, biota, geomorphologies, *and* parent materials (Richter and Yaalon 2012).

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