

Crossing Disciplines and Scales to Understand the Critical Zone

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A soil profile developed in Quaternary volcanoclastic debris in Basse Terre Island, Guadeloupe. PHOTO BY P. SAK (DICKINSON COLLEGE)

The Critical Zone (CZ) is the system of coupled chemical, biological, physical, and geological processes operating together to support life at the Earth's surface. While our understanding of this zone has increased over the last hundred years, further advance requires scientists to cross disciplines and scales to integrate understanding of processes in the CZ, ranging in scale from the mineral-water interface to the globe. Despite the extreme heterogeneities manifest in the CZ, patterns are observed at all scales. Explanations require the use of new computational and analytical tools, inventive interdisciplinary approaches, and growing networks of sites and people.

KEYWORDS: weathering, soils, Critical Zone, regolith

INTRODUCTION

All life on Earth is supported by the fragile skin of the planet defined from the outer extent of vegetation down to the lower limits of groundwater (Fig. 1). This volume has become known as the *Critical Zone* (CZ) because of its essential role in natural and managed ecosystems (Brantley et al. 2006). The CZ is a complex mixture of air, water, biota, organic matter, and Earth materials. Throughout this zone, chemical reactions proceed both abiotically and through catalysis by organisms, providing nutrients and energy for the sustenance of terrestrial ecosystems. As rocks containing high-temperature mineral assemblages reequilibrate with fluids at the surface, environmental gradients develop. These gradients characterize the CZ both by nurturing life and by simultaneously responding to life.

Importantly, the environmental gradients within the CZ provide energy and resources that sustain humans. Nourishment of the current population (6.7 billion) requires several tens of millions of square kilometers of land in cultivation (Buringh 1989). Today, about 0.23 ha (2.3×10^{-3} km², equivalent to about 50 m \times 50 m) of arable land is available per capita, but roughly twice this area is needed to provide the diverse diet essential for human health (Lal 1989). If we extrapolate the current erosion rate of about 12 million metric tonnes per year over the next 40 years to the point when the population will reach 9 billion, only 20% of the

arable land needed for adequate nutrition will be available. Furthermore, desertification has already caused severe degradation of land in up to 10–20% of drylands worldwide through a variety of factors, including climate change and human activity (Millennium Ecosystem Assessment 2005). Such observations and calculations have led many policy makers to conclude that loss of soil and declining soil fertility threaten sustainable development.

How might we treat and understand the CZ as a sustainable system—a system “that lasts” (Chesworth 2002)? At the longest timescales, geologists conceptualize the CZ as a *weathering engine* or *reactor* (Fig. 2), in which rocks at depth are fractured, ground, dissolved, and bioturbated into transportable materials (Anderson et al. 2007 this issue). At the shortest timescales, geochemists investigate the rates and mechanisms of reactions at mineral-water and organism-

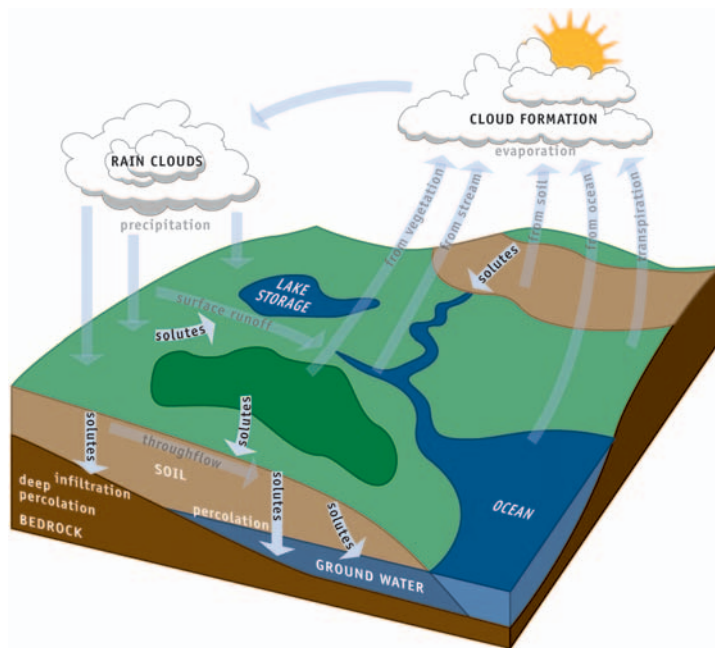


FIGURE 1 Schematic of fluxes and processes in the Critical Zone. The CZ is defined as the volume extending from the upper limit of vegetation down to the lower limit of groundwater. Heterogeneities within the CZ present a challenge to researchers developing models to predict these fluxes and processes. Understanding the CZ requires that scientists cross disciplines and work at all scales (AFTER ANDERSON ET AL. 2004).

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water interfaces (Chorover et al. 2007 this issue). All of these important and coupled chemical, physical, and biological processes are combined in our definition of the weathering process. Quantitative models of these coupled processes and how they respond to tectonic, climatic, and anthropogenic forcings are needed to truly understand the evolution of the CZ (FIG. 3).

The processes within the weathering engine occurring over this variety of timescales combine to produce patterns at the grain (millimeter), clast (centimeter), pedon (meter), landscape (kilometer), and global (thousands of kilometers) scales. Although often geochemical in nature, interpretation of these processes requires the input of researchers from many scientific disciplines. Despite our 10,000 years of association with soil, we still lack the conceptual and quantitative models needed to predict the outcome of the coupled processes within the CZ, precisely because of their interdisciplinary nature and the variety of scales that are represented.

The challenge to cross disciplines and scales in understanding the CZ is a growing focus for scientists from geology, soil science, hydrology, environmental engineering, chemistry, and ecology (Anderson et al. 2004; Brantley et al. 2006). By way of introduction to the CZ, we discuss in this paper the geochemical story written in the regolith, defined here as the weathered rock material overlying pristine bedrock, as documented by chemical gradients at the pedon scale. We then describe the flux of materials through the CZ, and we conclude with a discussion of issues that transect disciplines and scales of time and space, as we think

about CZ sustainability. In the rest of this issue, our colleagues discuss how geochemical patterns are established through processes occurring at the mineral–water interface (Chorover et al. 2007), as well as how they are affected by biota (Amundson et al. 2007), dust (Derry and Chadwick 2007), and erosion (Anderson et al. 2007).

CHEMICAL GRADIENTS IN THE REGOLITH

Chemical profiles in the regolith—the record of the CZ written at the pedon scale in the language of geochemistry—are similar to the concentration–depth profiles of marine sediments in that biological, chemical, and physical factors are all important (e.g. Goldhaber 2004). This complexity has been categorized successfully for marine sediments by applying simple models. In contrast, only a few researchers have used such simple approaches for regolith profiles, despite their usefulness in understanding the long-term evolution of the CZ (White and Brantley 1995). For example, regolith profiles can sometimes be conceptualized as one-dimensional columns characterized by downward water flow and upward solid flow through the weathering engine (e.g. FIG. 2). Such a simple model can successfully describe regolith developed on ridgetops (White 1995; Murphy et al. 1998).

Using such a conceptualization to consider profiles of concentrations normalized to the parent rock as a function of depth, one can identify five end-member categories of elemental regolith profiles (FIG. 4): (1) *immobile profiles* exhibit parent concentrations at all depths; (2) *depletion profiles* exhibit depletion at the top, grading to parent concentration at depth; (3) *depletion–enrichment profiles* exhibit depletion at the top, enrichment at depth resulting from precipitation or translocation, and a return to parent concentration at greater depth; (4) *addition profiles* show enrichment from external input at the top grading to parent concentration at depth; and (5) *biogenic profiles* exhibit enrichment at the top and a depleted zone that grades downward to parent concentration at depth. These profile

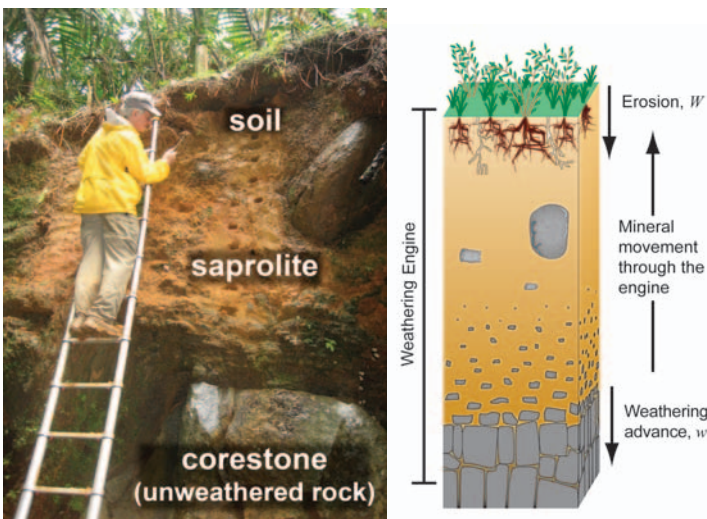


FIGURE 2 Left: a road cut through soil and saprolite developed on the Rio Blanco quartz diorite (Luquillo Mountains, Puerto Rico). Unweathered rock is fractured spheroidally into corestones within the weathering engine at this site. Two corestones appear in the photo, right of the ladder. Once corestones are produced, further fracturing and disintegration produces saprolite grains (Fletcher et al. 2006). At this site, large corestones transform relatively quickly compared to the regolith residence time; therefore, regolith consists mostly of large corestones and saprolite grains. Conceptually, rock flows through the weathering engine at the weathering advance rate, w , and is removed at the top at the erosion rate, W . If $W = w$, then the thickness of the weathering layer remains constant. This one-dimensional model, which describes the weathering engine operative at ridgetops, is being extended to two- and three-dimensions for describing hillslope processes (ANDERSON ET AL. 2007 THIS ISSUE). PHOTOGRAPH BY ERIC PELT

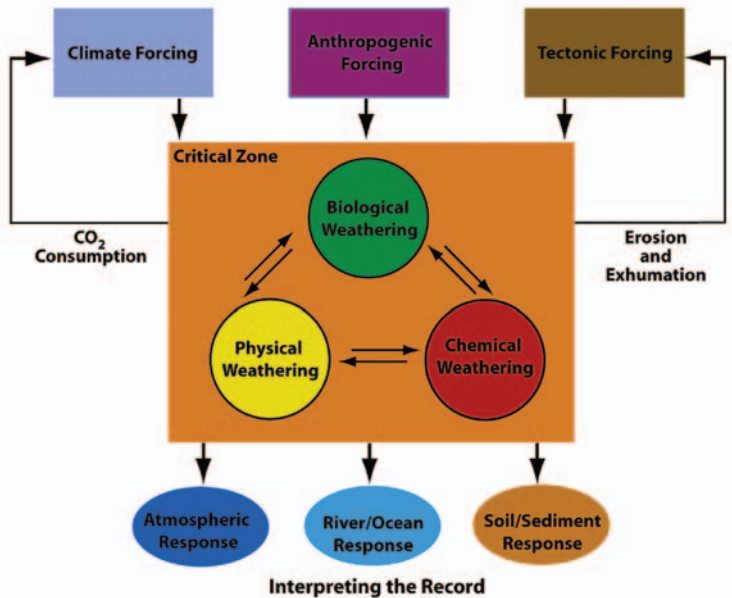


FIGURE 3 Coupled chemical, physical, and biological weathering processes in the Critical Zone are affected by climate and by anthropogenic and tectonic forcing over vastly different timescales. The output from the CZ weathering engine is documented in the response of the atmosphere, rivers and oceans, and soils and sediments, which can be read in the geological record.

types are end-members; any individual profile may be some mixture of end-members. These end-member models can often be used to interpret the story of the CZ.

To see these characteristic types of profiles requires that the elemental concentrations of regolith are first normalized to the concentration of an immobile element (Brimhall and Dietrich 1987; White 1995). Normalization corrects for contraction or expansion of soil and for apparent dilution or enrichment effects that occur when multiple elements in a system react (FIG. 4). For example, relatively unreactive elements, such as Zr (found in zircon), Ti (rutile, anatase), and Nb (columbite, tantalite), commonly become enriched in regolith as more soluble constituents are depleted. When the concentration of an immobile element is normalized to that of another immobile element, the concentration–depth curve exhibits the characteristics of an *immobile profile* (FIG. 4A).

In contrast, *depletion profiles* (FIG. 4B) document loss of elements from the surface, often from mineral dissolution. For example, FIGURE 4B shows a reaction front caused by leaching of Cu from Rose Hill Shale (central Pennsylvania) during soil development. Almost 50% of the Cu has been lost from this soil at the top of the profile. The high affinity of Cu for organic ligands may explain Cu leaching from this soil developed on the relatively non-reactive shale parent. As another example, geochemists often analyze the depletion profile of Na to interpret the dissolution of plagioclase (White 1995).

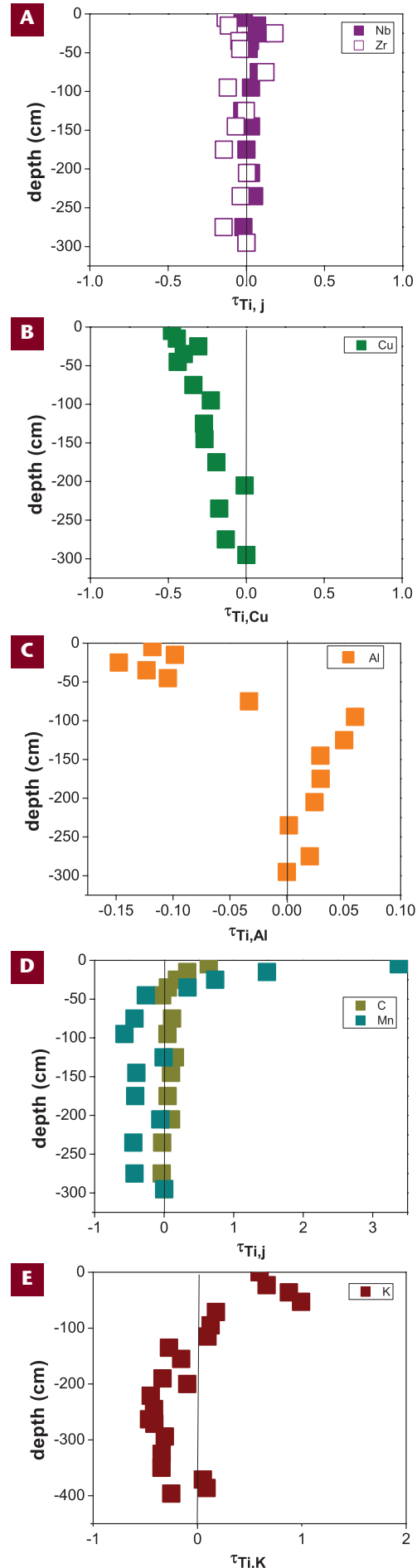
An element that is leached at the surface may reprecipitate at depth in the regolith, resulting in a *depletion–enrichment profile* (FIG. 4C). An example is the soil sequence E-Bs, E-Bt commonly observed in forests where conditions at the top of the profile favor Al dissolution, and less acidic conditions with lower organic ligand concentration deeper in the profile favor formation of secondary Al precipitates. Depletion–enrichment profiles may also be exhibited by Fe, as well as by other elements, including those that are affected by the chemistry of Fe and Al.

Input to soils through dust deposition and fixation from the atmosphere can create distinctive *addition profiles*. FIGURE 4D shows profiles for Mn and C developed on weathered Rose Hill Shale. Such profiles commonly document the effect of wet or dry deposition (e.g. Mn in FIG. 4D) or input of elements resulting from biological fixation (C in FIG. 4D). Addition profiles demonstrate both addition at the surface and redistribution by downward transport or bioturbation. These profiles are therefore characterized by concentrations

FIGURE 4 Plots of normalized concentration, τ , versus depth for a soil developed in the Shale Hills watershed on the Rose Hill Shale (A–D) and on the Gettysburg Diabase (E), both in central Pennsylvania, USA. The parameter $\tau_{i,j}$ represents elemental concentration normalized to account for volume changes and relative loss or gain of elements (Brimhall and Dietrich 1987).

$$\tau_{i,j} \equiv \frac{C_{j,w} C_{i,p}}{C_{j,p} C_{i,w}} - 1$$

Where C represents concentration (mol/m³) of immobile (i) or mobile (j) elements in weathered (w) or parent (p) material. When $\tau = 0$, concentration is identical to that of the parent; when $\tau < 0$ or > 0 , there is elemental loss or gain, respectively; where $\tau = -1$ for 100% loss of the element. (A) τ for Nb and τ for Zr, plotted versus depth in regolith, document *immobile profiles*. (B) τ for Cu is an example of a *depletion profile*. Cu-organic complexes formed at the surface enhance the loss of Cu from this soil. (C) τ for Al documents an *addition–depletion profile*. Al-organic complexes at the surface deplete Al, releasing it for reprecipitation at depth. (D) τ for Mn and τ for C portray *addition profiles*. Mn and C have been added to the soil as dust and through biological fixation, respectively. (E) τ calculated for K within regolith overlying the Gettysburg diabase documents a *biogenic profile*. K has been removed by roots at depth, then enriched at the surface by biological processes.



that are highest at the surface, reaching parent concentrations at depth. Prediction or modeling of concentration–depth profiles for biologically fixed elements such as C are especially difficult because of their dependence on many biological and non-biological factors (Schimel et al. 1994).

Biogenic profiles are of great importance from the perspective of soil sustainability. They characterize elements such as K that, although released from parent material, are redistributed in the CZ because of their role as nutrients (FIG. 4E). In biogenic profiles, elements characteristically show depletion at depth and enrichment at the surface. These profiles are much more difficult to predict quantitatively than the profiles of non-nutrient elements because of the need for understanding biological fluxes (Amundson et al. 2007). Biogenic profiles document the secretion of organic acids by plants or fungi through roots at depth and the consequent dissolution of primary minerals. If the released nutrients are taken up by roots, transferred to biomass, and recycled in the upper layers of the soil, then a biogenic profile results (Jobbágy and Jackson 2001).

Time Evolution of Profiles

Our discussion so far has largely ignored the evolution through time of these concentration–depth profiles. In regolith not experiencing significant erosion, a reaction front such as that shown in FIGURE 4B moves downward with time at a rate we term the *weathering advance rate* (FIG. 2). Once the normalized elemental or mineralogical concentrations at the top of the profile no longer change with time (perhaps because of total depletion of a mineral or the formation of a stable mineral assemblage), the profile becomes quasi-stationary (Lichtner 1988). At this time, the shape of the reaction front remains constant while the entire profile moves downward. In contrast, in systems where erosion is significant, a true steady-state profile can develop where the concentration–depth curve remains constant with time. In such a system, the rate of erosion equals the rate of weathering advance.

In a steady-state profile, movement of parent material through the weathering engine is ongoing. Such a profile can support ecosystems with constant nutrient delivery. In contrast, in a quasi-stationary profile that moves downward with time and is not significantly eroded, regolith at the surface may become nutrient-poor. In such regimes, dust addition (e.g. FIG. 4D) may be essential for nutrients required to support biota (Derry and Chadwick 2007). In such cases, erosion can rejuvenate the weathering-derived nutrient supply (Porder et al. 2005). Currently, many researchers are attempting to predict such processes at the scale of the mineral interface, clast, pedon, catchment, and globe (e.g. Lichtner 1988; Sak et al. 2004; Goddérís et al. 2006; Navarre-Sitchler and Brantley 2007; Chorover et al. 2007). At present, however, it is impossible to predict these processes in the full context of biological uptake and erosional loss over time and space. The development of fully coupled models will require interdisciplinary teams of CZ scientists.

EROSION AND WEATHERING ADVANCE RATES

As discussed in the previous section, the rate at which a weathering front propagates (FIG. 2) is defined as the weathering advance rate, w (White 1995). In a steady-state system, the erosion rate, W , must equal w . If the CZ system is truly operating at steady state, the thickness of any layer in that weathering system (incipiently weathered bedrock, saprolite, soil), as well as the rate of transformation of each layer into material of the overlying layer, must be constant in time (FIG. 2). For example, it is often assumed that on

average the rates of soil formation and soil loss in forested land are roughly at steady state. Most estimates for these rates vary between 7 (Troeh and Thompson 1993) and 80 mm per 100 years, but these rates might be an order of magnitude higher under extreme conditions. Testing whether such rates are indeed equal for natural systems is of current interest because they place constraints on the patterns manifest in the CZ at the pedon and landscape scales.

How can CZ scientists quantify these rates to characterize the weathering engine? The erosion rate is easier to measure than the weathering advance rate. For example, the erosion rate can be estimated by measuring the riverine sediment + dissolved load or by estimating soil loss at a given location (TABLE 1). In addition, interpretation of cosmogenic isotope concentrations in soil or sediment can reveal the duration of exposure to cosmic rays (e.g. Bierman and Steig 1996). Erosion rates are inferred from these exposure ages using model calculations based on penetration depths of cosmic rays and the assumption that layers penetrated by cosmic radiation maintain steady-state thickness.

Erosion estimates made using these various techniques do not necessarily agree. Riverine estimates are lower by a factor of about 5 than estimates based on soil loss, at least partly because eroded soils are redeposited and stored on land before transport to the ocean (e.g. Lerman and Wu 2007). Furthermore, sediment studies commonly report suspended loads and neglect bedloads. In addition, the temporal and spatial scales for measuring erosion affect the estimate of erosive flux (e.g. von Blanckenburg 2005).

While many researchers have estimated rates of erosive loss, W (TABLE 1), our understanding of regolith formation processes and rates, i.e. the value of w , is limited. We need to understand how to compare weathering advance rate estimates, such as those in TABLE 2 for transformation of bedrock to regolith (ranging from 0.05 to 10 mm per 100 years), to erosion rate estimates, such as those in TABLE 1, reported at the continental and global scales (ranging from 7 to 80 mm per 100 years). Weathering advance rates have been derived from approaches based on mass balance, cosmogenic isotopes (^{10}Be), slope curvature, and dissolved-solute loss from catchments. In fact, although it would be very interesting to compare w to W quantitatively to determine if steady state exists, often the estimates of regolith production are based on the assumption that regolith thickness is at steady state. Estimates of weathering advance rates have been shown to vary over 7 orders of magnitude when compared across laboratory to watershed spatial scales (Navarre-Sitchler and Brantley 2007). Clearly, understanding the CZ as a weathering engine will require many observations, new conceptual models, and powerful numerical models.

SCALING TO PREDICT CZ PROCESSES

Quantification of the rates of processes occurring within the CZ is a challenge, at least partially because of the extremely large ranges in scales of space and time. The processes that control the development of regolith profiles (FIG. 4) occur over periods ranging from less than microseconds to more than millions of years (FIG. 3). At the same time, variations in Earth's orbit cause climate change on timescales of tens of thousands to hundreds of thousands of years, and these changes also affect the geochemical patterns that define, and are observable in, the CZ. Furthermore, the geochemical profiles are manifestations of the coupled processes of weathering, erosion, and uplift that define landscape evolution over much longer geological timescales (Anderson et al. 2007). Fortunately, paleosols

and sediments preserve evidence of the responses to these perturbations over timescales greater than that of human history.

No less troublesome than temporal scales, spatial scales within the CZ vary over 16 or more orders of magnitude, from the atomic to the global scale. To characterize the important chemical and physical properties (e.g. from the scale of an individual soil grain up to regional lithologic variations) and processes (e.g. fluid movement along a grain boundary up to large-scale flow in major hydrologic basins), observations must be made ranging in scale from that of individual atomic layers, where atomic force microscopy is used, to that of entire continents, where satellite remote-sensing tools are required.

A useful approach to these scaling issues is to study processes from both ends of the time and distance spectra. For example, measurement of the rates of weathering in the laboratory can be compared to rates measured in the field. Thus, the study of chronosequences—regolith systems developed within the same climate on the same lithology but characterized by variations in duration of weathering exposure—yields rates for CZ processes over timescales of 10^3 to 10^6 years. When such comparisons are made (Fig. 2, Anderson et al. 2007 this issue), we generally observe that field rates are slower than laboratory rates by up to five orders of magnitude and that apparent weathering rates decrease with duration of exposure to weathering (White and Brantley 2003). Variations in weathering rates as a function of the duration of measurement may be related to how we conceptualize and parameterize the reactive surface area over time and the approach to equilibrium of weathering systems. However, weathering rates have also been observed to change with anthropogenic impact (Raymond and Cole 2003).

While silicate dissolution kinetics have been observed to vary by up to five orders of magnitude across temporal scales, up to seven orders of magnitude variation has been seen in these rates across spatial scales (Navarre-Sitchler and Brantley 2007). Thus, patterns in chemical signals documented at the scale depicted in FIGURE 4 (pedon scale) must be renormalized for comparison to patterns developed at larger spatial scales (FIG. 5). Soil geochemical surveys have been conducted globally to delineate geochemical and textural patterns at scales of approximately 1:10,000,000 (national scale), 1:1,000,000 (state or regional scale), and 1:1000 (local scale) (Jobbágy and Jackson 2001; Reimann 2005). In some cases, for example for isotopic signatures of nitrogen in soils and plants, global patterns can be related to regional variations in mean annual precipitation and temperature (Amundson et al. 2003). In other cases, regional patterns can be related to the distribution of the underlying lithology; for example, chromium in surface soil is related to the distribution of ultramafic rocks (FIG. 5A). We also observe for elements such as mercury that land use variations related to industrialization, urbanization, waste disposal, mining, and agriculture influence continental-scale chemical variations in the regolith (FIG. 5B). Elevated concentrations of mercury in soils of the eastern United States are related to the location of coal-fired power plants. Documenting, understanding, and predicting such regional- to global-scale patterns must be accomplished in the next decade by researchers within all the disciplines of CZ science, as we attempt to make policy decisions to safeguard our planet's ecosystems.

The role of the CZ in global carbon dynamics exemplifies the difficulty of crossing disciplines and scales when attempting to address a globally important policy issue. The planetary carbon cycle is of great concern because the

TABLE 1 ESTIMATED SOIL EROSION RATES

Location	Type of land	Soil erosion rate (mm/100 y)	Reference
Global	World average	7*	Troeh and Thompson (1993)
	Agricultural	60	Wilkinson and McElroy (2007)
Europe	Continent	80 [§]	Yang et al. (2003)
North America	Continent	56 [§]	Yang et al. (2003)
South America	Continent	51 [§]	Yang et al. (2003)
Africa	Continent	29 [§]	Yang et al. (2003)
Australia	Continent	19 [§]	Yang et al. (2003)
Asia	Continent	81 [§]	Yang et al. (2003)

TABLE 2 EXAMPLES OF ESTIMATED REGOLITH FORMATION RATES

Rock type	Location	Rate (mm/100 y)	Method	Reference
Quartz diorite	Puerto Rico	5.8	Mass balance	White et al. (1998)
Basalt	Costa Rica	2.9	Mass balance	Sak et al. (2004)
Greywacke/sandstone/chert/greenstone	San Gabriel Mountains, California, USA	1.5–10.7	¹⁰ Be, ²⁶ Al, and curvature observations	Heimsath et al. (1997)
Granulite/amphibolite	Sri Lanka	0.2–0.7**	¹⁰ Be	von Blanckenburg et al. (2004)
Schist	Coweeta, North Carolina, USA	3.8	Mass balance	Velbel (1986)
World average	Global	7*		Troeh and Thompson (1993)

* This value is calculated by assuming the average density of soil to be 1.4 g/cm³. The value is calculated from the generally assumed average soil erosion rate of agronomists of 1 t/ha/y, which is the soil formation rate under steady state.

** Silicate weathering rate

§ GIS-based RUSLE (Revised Universal Soil Loss Equation). Estimates of soil erosion rate caused by water. Average values for 1900s–1980s

greenhouse gas CO₂ is changing global climate at unprecedented rates (IPCC 2007). Soil is an important player in the global carbon cycle: the pool of soil carbon is about 3.3 times larger than that of atmospheric carbon (Lal 2004). However, carbon concentrations in one soil profile at one geomorphologic position (e.g. FIG. 4D) cannot yet be used to quantitatively predict net soil carbon balance in other locations. To do so requires a watershed-scale approach at the least, because carbon gains and losses change with spatial position (Liu et al. 2003). Furthermore, changes over time, such as the conversion from natural to agricultural ecosystems, cause significant organic carbon loss from soils. By one estimate, land-use conversion in the post-industrial era has resulted in a loss of 136 Gt of carbon (mostly to the atmosphere), compared to the release of 270 Gt of carbon by fossil fuel combustion over the same time period (Lal 2004).

Despite the importance of such studies, few direct estimates of carbon loss or gain in soils over large areas and long timescales are available. Perhaps the best example of direct evidence of large-scale carbon loss from soils is the data from almost 6000 soil sample sites throughout England and Wales. These sites were sampled in 1978 and resampled in 2003. The data document systematic carbon loss of 0.6% per year (relative to the existing soil carbon content) from the upper 15 cm regardless of soil properties and land use (Bellamy et al. 2005). The authors conclude that this loss is linked to climate change. These dramatic data may indicate an important positive feedback between release of CO₂

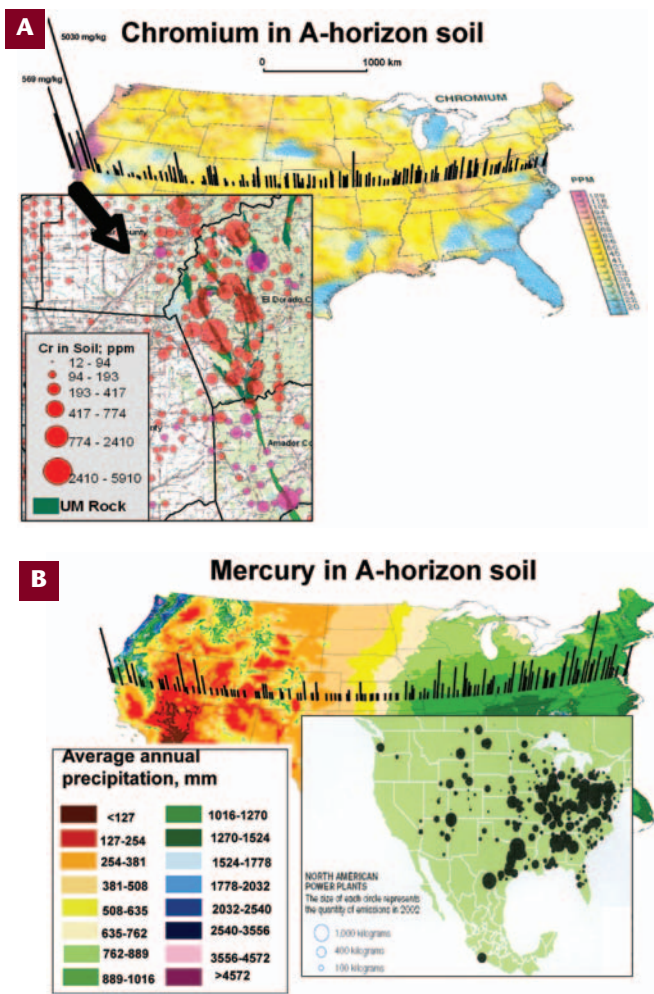


FIGURE 5 (A) Chromium in A-horizon soils across the United States. Vertical bars are proportional to Cr content (maximum = 5030 ppm). The base map depicts gridded Cr content based on 1323 soil samples, where warmer colors indicate higher Cr contents (Gustavsson et al. 2001). Note the elevated Cr in the west (California; data from Smith et al. 2005). The inset shows Cr content in A-horizon soil samples in northern California (Goldhaber M, unpublished data; larger circles represent higher Cr). The highest Cr concentrations occur over ultramafic rocks (shown in green). (B) Mercury in A-horizon soils across the United States (Smith et al. 2005). Vertical bars are proportional to Hg content (maximum = 0.18 ppm). Inset represents Hg emissions from coal-fired power plants for 2002 (Miller and Van Atten 2004). The base map is contoured for precipitation. Note the correspondence between Hg concentration in eastern United States with higher power plant Hg emissions in this part of the country.

from microbial metabolism in soils and average global changes in temperature, soil moisture, and nutrients. Of course, in contrast to this dataset from the UK, soil also has the ability to sequester carbon and aid in removing atmospheric CO₂ (Lal 2004). Many more studies at small and large spatial scales and short and long timescales are needed to document carbon loss and carbon sequestration in soils.

NETWORKS OF PEOPLE AND SITES

Given the importance of the CZ in terms of “pollutants” such as atmospheric CO₂ and with respect to nourishing ecosystems and humans, we need to develop new scientific and societal paradigms that will enable us to understand the full range of CZ processes, from microcosms, through individual landscape features, family farms, and watersheds, to the globe. How might researchers in geochemistry and mineralogy respond to this scientific challenge? Clearly, fundamental geochemical processes in the CZ are

still not fully understood; however, understanding most of these processes will require interdisciplinary teams of scientists who can cross scales of time and space to unravel the important chemical, physical, biological, and geological factors. In a recent meeting convened by the U.S. National Science Foundation to summarize broad research areas of interest for CZ science, the following four overarching questions were identified (Brantley et al. 2006):

- How are the rates of physical and chemical weathering perturbed by environmental forcing?
- How do important biogeochemical processes occurring at Critical Zone interfaces govern long-term sustainability of soil and water resources?
- How do processes in the Critical Zone nourish ecosystems and how do they respond to changes in external forcing?
- What processes in the Critical Zone control biosphere–atmosphere exchanges of important gases and particulates?

Researchers also identified the need for a global network of observatories to investigate CZ processes across gradients in environmental variables (Fig. 6). Scientists envisioned that these observatories would generally be in operation for about five years and that “deployments” of instrumentation and researchers would investigate these sites to answer process-oriented research questions. CZ researchers around the world have begun to build this network and the cyber infrastructure that will provide access to the data (czen.org). These huge endeavours will generate intellectual debate for years to come. Aspects of each of these questions are addressed in the papers presented in this issue.

IS THE CRITICAL ZONE SUSTAINABLE?

Aldo Leopold, one of the great early conservationists, recognized that “the reaction of land to occupancy determines the nature and duration of civilization” (Leopold 1933). Soon thereafter, U.S. President Franklin Roosevelt warned that “a nation that destroys its soils, destroys itself.”

In fact, Carter and Dale (1974) noted that the sites of the earliest civilizations in Mesopotamia and in the Nile and Indus valleys were all characterized by fertile soil, dependable water supplies, low relief, and limited soil erosion. These properties enabled surplus crop production, which supported the development of non-agricultural pursuits. While the fertile valleys and waters of the Tigris and Euphrates rivers in Mesopotamia made this area a cradle for civilization, deforestation and grazing in the Armenian hills to the northwest have now caused massive downstream silt transport and destruction of the irrigation systems that supported early Mesopotamian agriculture (Carter and Dale 1974).

This example is not an anomaly. Human impact on soils has occurred in three main waves. The first started 4000 years ago, when civilizations occupying river basins began moving upslope from the valleys, exposing virgin soils to seasonal rains (McNeill and Winiwarter 2004). The second phase of impact occurred in the 16th to 19th centuries, with the implementation of improved ploughshares to break up soil. The third phase is occurring now, with population pressure leading to the destruction of tropical rainforests. Humans are now a geological force transforming the Earth’s surface. Forty percent of the Earth’s ice-free land is currently cultivated or used as permanent pasture (Richter and Markewitz 2002). This agriculture induces transport of 70% of Holocene sediment (Wilkinson 2005). With industrialization came mining operations, which have also

Critical Zone Exploration Network

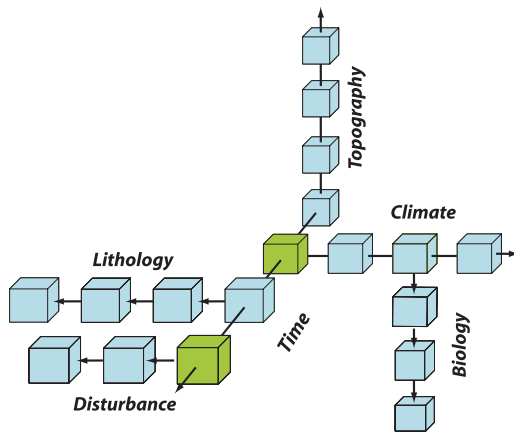


FIGURE 6 Conceptual diagram outlining a model for a network of observatories to investigate Earth surface processes. Each box represents a CZ observatory site or sites. These sites are chosen to span environmental gradients as shown, but other gradients could also be explored. For example, network legs could investigate gradients in pH, water composition, uplift rate, or deformation rate. CZ observatory sites for such a network are envisioned to be instrumented for relatively short periods. Sites (noted in green) located on more than one gradient should be instrumented for longer durations. FIGURE FROM BRANTLEY ET AL. 2006

negatively impacted the landscape. For example, as of 1977, when stricter regulations were implemented, the mining industry alone had disturbed 2.3 Mha in the United States, an area roughly the size of the state of Vermont (Lal et al. 2004). As a result of human activities, the current global rate of erosion is about an order of magnitude higher than the natural erosion rate (Hooke 2000; Wilkinson 2005).

The extent of the planetary transformation brought about by humans has led to the new term “Anthropocene,” which has been defined as “a new geological epoch in which

humankind has emerged as a globally significant, and potentially intelligent, force capable of reshaping the face of the planet” (Clark et al. 2004). While much current interest has focused on the impact of humans on the chemistry of Earth’s envelope of air and the effects of this chemical change on climate (IPCC 2007), our species is rapidly changing the chemistry of the hydrosphere and the regolith as well. Conceptualizing the complex interplay of chemistry, biology, geology, and physics within the skin of the Earth as a system—the Critical Zone—forces scientists to work together across disciplines and scales. In so doing, scientists will learn how to interpret recurrent patterns observed in the CZ and how to protect the CZ for all life. Importantly, heterogeneities in the CZ at all scales require advances in our ability to model the time evolution of the CZ. The list of tools and techniques for moving forward in this area is growing rapidly, enabling strides forward. Whether our species can be truly intelligent, as opposed to just geologically significant with respect to our impact on the planet, remains to be seen.

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GLOSSARY

- Amphiphilic** – describes a chemical compound possessing both hydrophilic and hydrophobic properties
- Autotroph** – organism that uses CO₂ as a carbon source
- Chemotroph** – organism obtaining its energy from the oxidation of compounds that are organic (chemoorganotroph) or inorganic (chemolithotroph)
- Chronosequence** – a series of soil profiles sampled on different-age landforms that are composed of the same underlying parent material (substrate). The presumption is that the soils vary primarily due to differences in their age rather than to differences in parent material, climate, vegetation, or topographic position. Chronosequences are used to infer changes in soil properties and processes as they develop.
- Dissimilatory reduction** – the use of a compound as a terminal electron acceptor for metabolism
- Extracellular metabolites** – compounds released to the exterior of a cell as a result of chemical reactions occurring within the cell
- Heterotroph** – organism that uses organic substrate(s) as a carbon source
- Immobile element** – an element that is not lost from a weathering system due to solubilization
- Neofomed precipitates** – mineral products that form as a result of weathering reactions
- Pedon** – the smallest unit of soil that contains all the horizons of that soil type
- Polar organics** – organic molecules that are hydrophilic and therefore exhibit high solubility in water
- Regolith** – the mantle of weathered material overlying bedrock
- Saprolite** – chemically weathered rock that retains the structure of the original bedrock
- Xenobiotic** – a chemical found in an organism or ecosystem that is not normally produced there but rather derives from an external source (e.g. a pollutant introduced by human activity)