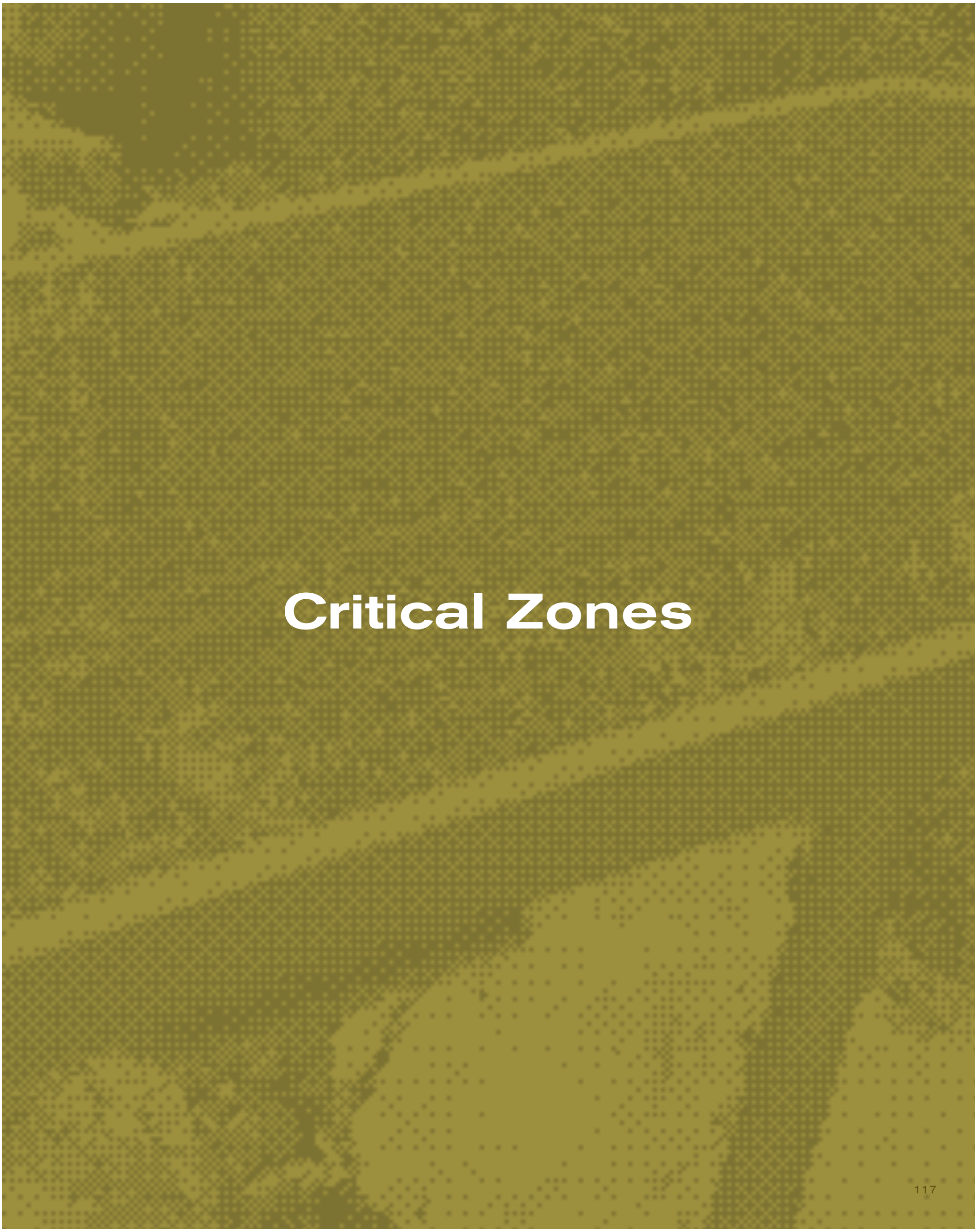


Critical Zones

Yu Hsin Su, *Frame of Reference*, 2020. Video installation, 15 min., loop. Film still.

CRITICAL ZONES

If the disconnection between the world we live *in* and the world we live *from* is really the cause of the disorientation mentioned above, then the remedy is clear: We should find ways to *decrease* the distance between the two worlds, so as to begin our landing on Earth — without crashing.

In this section, we begin the first of three steps leading down to Earth by having its main protagonists present the scientific domain called the Critical Zone. The paradox is that what should be utterly familiar to us is also the least understood, what Jérôme Gaillardet calls for this reason a *terra incognita*: "This pulverulent layer, colonized by living organisms, is the thin coat of varnish upon which humanity has established itself, the precious layer which we cultivate and build upon, and it is the sponge from which we draw our water and in which we store our waste products … It does not include the rocks or the air; it is the permeable zone on the Earth's surface with many different shapes and features: soil, groundwater, river, trees, swamps, glaciers, and so on." There is a clear tension between viewing the Earth as a planetary body floating in space and considering such a tiny biofilm from the inside. If this new science is so important, it is because it tries to bridge the gap in between those two scientific world views: that of the planet and that of the Critical Zone. No wonder that we might feel lost in it, even though this is the only world we have ever experienced.

The reason for our ignorance is visible when you consider the paradigm at the heart of this new interdisciplinary field: There exists a wide gap between what can be observed in the laboratory and what happens *in situ* and *in vivo*. As Susan Brantley puts it: "When we estimated rates of reactions in nature, we discovered they were always slower, sometimes almost a million times slower, than our measured lab rates. Many people puzzled over this." It really meant, as Brantley argues, devising a new role for "Earth physicians": "In Earth surface science before 2004, we didn't have many GPs [general practitioners]. That's why many of us pushed to create a new type of scientific GP. We created Critical Zone science to focus on studying the Earth's surface – from air to trees to water to rocks to humans." It's about time that land benefits from what patients have in medicine, namely a well instrumented emergency room! "Earthcastings" are as crucial to cope with life-threatening diseases as are prognoses for cancers or strokes.

The reason for this distance between what happens in the laboratory and what happens in the field is, of course, the emergence of life forms which have endlessly complicated the running of chemical processes. As William E. Dietrich puts it: "Suddenly, I saw that the slow workings of geologic processes, that shape hills, weather to a porous stone the underlying bedrock and produce a mobile soil, were driven by biotic processes that enhanced the storage of water (and nutrients) to life itself: a co-evolving system connected from canopy top down to fresh bedrock." And Dietrich expresses again the same surprise as Brantley: "The Critical Zone is where we live and, surprisingly, it is also a frontier area of research."

Why? Because this Earth physiology completely transforms the description of what a landscape is. As Daniel D. Richter, another Critical Zonist, and Sharon A. Billings explain: "The Critical Zone is defined by the slogan 'from tree top to bedrock,' by its fluids 'from the atmosphere to the deepest of circulating groundwaters,' and by its temporality 'across human, biologic, and geologic time.'" This zonal reach is enough to expand collaboration among many established disciplines.

Essential to the collaborative work of the Critical Zonists are long-term and well instrumented research sites. The solution was to choose specific watersheds and to equip them with enough instruments to decrease the distance between lab results and field data. Hence the creation of an international network of Critical Zone Observatories (CZOs). As shown by Alexandra Arènes and then by Marie-Claire Pierret in one specific case, the Strengbach site in Alsace, it is through the careful instrumentation of these sites that people are learning to inhabit them in a new way. And the same is true of the unfortunate trees in Paris as illustrated by Aleksandar Rankovic.

Which gives still another meaning to the adjective "critical": "Thus to study the Critical Zone, scientists study critical places, as Alexander von Humboldt had already understood when he wrote in his famous book *Cosmos* that 'everywhere, in every separate portion of the earth, nature is indeed only a reflex of the whole'" (Jérôme Gaillardet). As Simon Schaffer shows, this link between a network of instruments, the conception of an animated Earth, and worries about the development of the human race, industry, and resources is not new. Critical Zone Science is but one episode in the attempt to build one of those cosmograms that John Tresch proposes in the first section.

It is because these zones are so odd that art is indispensable for giving them a provisional shape as is done magnificently in the sculptures of Sarah Sze discussed by Bruno Latour. Hence the right use of the word "zones" in the plural to describe such *terra incognita*. Jeanne Etelain, in her brief history of the term, from Greek belts to erogenous zones, offers a perfect transition for what comes next, the second step in landing on Earth, namely Gaia.

The Critical Zone, a Buffer Zone, the Human Habitat

Jérôme Gaillardet

The Critical Zone: Using Sun's Energy to Transform Rocks

THE EARTH IS a rocky planet and one of the inner planets of the solar system (third planet from the sun). "Rocky" refers to the fact that it is made of a particular class of minerals called silicates — made of silicon, oxygen, and magnesium. The original atmosphere surrounding it was formed by degassing from the Earth's molten interior during an early stage of the planet's formation. This original atmosphere contained mainly carbon dioxide, nitrogen, and water. While nitrogen is an inert gas, carbon dioxide and water combine to form a very aggressive chemical compound — carbonic acid — which reacts with silicates and destroys them; it dissolves them and transforms them into new, lighter, hydrated minerals. This vast neutralization reaction, in the sense of the nineteenth century French and German chemists who first understood its importance,[1] forms continuously yet almost invisibly new materials that accumulate in a soft and porous film on the surface of continents. This pulverulent layer, colonized by living organisms, is the thin coat of varnish upon which humanity has established itself, the precious layer which we cultivate and build upon, and it is the sponge from which we draw our water and in which we store our waste products. Scientists studying the Earth call this near-surface layer the "Critical Zone." It does not include the rocks or the air; it is the permeable zone on the Earth's surface with many different shapes and features: soil, groundwater, river, trees, swamps, glaciers, and so on.

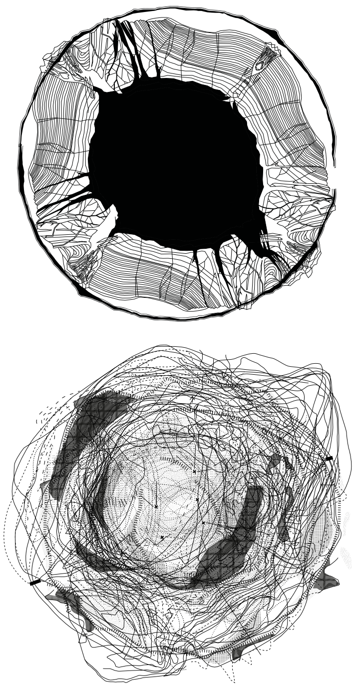


Fig. 1: Alexandra Arènes, Representations of the deep Earth energy at the center of the Earth and the solar energy at the surface of the Earth, two complementary energy sources, 2019. Visualization.

We do not live on Earth, but on a thin film, barely visible on a planetary view, a conflict zone between two energy sources. The first is the internal energy of the planet which cools down and allows the formation of new material, such as volcanic rocks, the degassing of deep carbon dioxide, and the formation of mountains by plate tectonics. The second source of energy is that of the sun, which activates the water cycle by evaporating water from the Earth's surface and the vast oceans that cover 70 percent of the surface of our planet, creating clouds and rainwater, which dissolves carbon dioxide. Even though the amount of energy brought by the sun to the Earth over a surface area of 1 square meter is 500 times greater than that released by internal cooling, both sources of energy have been and are necessary for the dynamics of the Critical Zone and both participate in the evolution of life. In this sense, the notion of the Critical Zone is close to the concept of the biosphere that was coined and introduced by Austrian geologist Eduard Suess in 1875 and elaborated by Russian geochemist Vladimir Vernadsky in the early twentieth century.[2]

The term "Critical Zone" was first used in its current sense in 2001 by the U.S. National Research Council and its study was born historically from the observed mismatch between the

1 See Matthieu Emmanuel Galvez and Jérôme Gaillardet, "Historical constraints on the origins of the carbon cycle concept," *Comptes Rendus Geoscience* 344, no. 11–12 (2012): 549–67.

2 See Vladimir Vernadsky, *The Biosphere* [1926], (New York: Copernicus, 1998). Originally published in Russian as *Biosfera* (Leningrad: Nauchnoe khimiko-technicheskoye izdatel'stvo [Scientific Chemico-Technical Publishing], 1926).

3 See Susan L. Brantley, James D. Kubicki, and Art F. White, eds., *Kinetics of Water-Rock Interaction* (New York: Springer, 2008).

results from experimental physics and chemistry (lab experiments) and field observations.[3] The Critical Zone is such a composite, heterogeneous environment — soil, gas, water, cells, genes, all connected — that it has to be addressed by very different branches of science, ranging from pure physics to geography, geology, hydrology, pedology, geomorphology, geology, ecology, and biology; disciplines that in the history of science have been separate for more than two centuries, not to mention the social and human sciences. As impressive as the progress of knowledge has been over the past two centuries, the study of the Critical Zone as a system has been sidelined. The concept of ecosystem, originally very close to the current concept of the Critical Zone, has gradually focused on organisms by opposing the "biotic" and "abiotic" factors; pedology has focused on the uppermost 30 – 60 cm of the Earth; hydrology concentrates on the complex water system; geomorphology on landforms; and geochemists have developed extremely sophisticated analytical tools to track the behavior of particular chemical elements; however, a multidisciplinary synthesis has not been attempted. The institutions have locked up disciplines in academic fortresses that are oriented on the study of certain compartments of the Critical Zone, while forgetting the "whole." Nowadays, a student who studies ecology will not necessarily take geology classes; a chemist will not study the formation of salt rock deposits; a modeler will not be involved in data acquisition. In France, for example, one state institution is responsible for measuring the discharge of rivers, and another for measuring the water table of aquifers! At the same time, the Critical Zone has become so crucial for societies that it has been hijacked by various disciplines and subdisciplines which address the same questions using different languages and with different approaches. This compartmentalization and multiplicity of Critical Zone representations make predictions difficult because processes playing out at short time periods (such as weather events) are not studied in association with processes that play out at longer timescales (such as the formation of cultivable soils). This also hampers the awareness of humans as to the fragility of the Critical Zone, as a single entity, as an object, which is their habitat (*see fig. 1*).

An Interface of the Earth System

THE WORD "CRITICAL" is important to scientists. The Critical Zone is one of the main and most essential interfaces of the planet whose functioning at different scales makes our planet unique in the solar system. This mobile interface, formed by chemical and physical reactions (weathering) and destroyed by the export of their products (erosion) by rainwater to the oceans — it is often compared to a conveyor belt to express the fact the Critical Zone is a mobile layer under our feet — has many functions for the planet (*see fig. 2*).

On a small scale, by dissolving rock minerals, the reactions occurring in the Critical Zone provide the essential elements that allow life to develop (e.g., phosphorus, whose ultimate provenance can only be rock-forming minerals). The reactions happening in the Critical Zone affect the water quality of groundwater, streams, rivers, and seawater because when passing through the Critical Zone, rainwater is loaded with dissolved and solid materials. The reactions of the Critical Zone also determine the shape of the landforms (geomorphology) that surround us and, therefore, the landscape. Finally, on a global scale, the consumption of carbon dioxide by the reactions of the Critical Zone drives the content of this gas in the atmosphere and thus the Earth's climate, because carbon dioxide is one of the primary greenhouse gases. At the time of its formation, the Earth's original atmosphere contained more than 90 percent carbon dioxide in volume, a level now reduced to 0.03‰ by the neutralization of rock-forming minerals and the accumulation of biological limestone in the oceans. Despite the

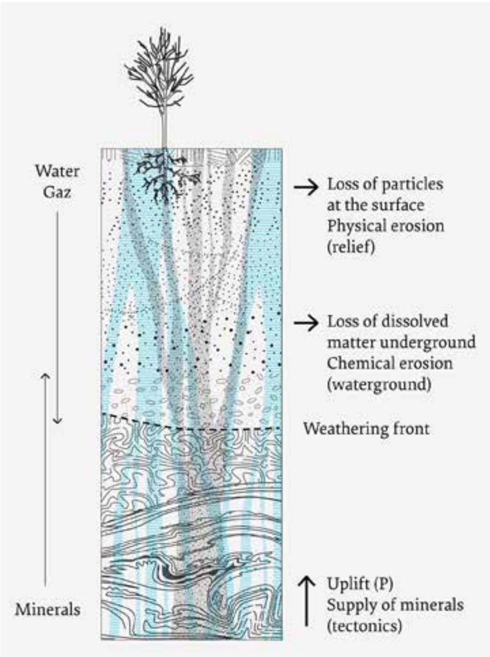


Fig. 2: Alexandra Arènes, Profile showing the dynamics of formation of the Critical Zone from the tree canopy to the deep rocks, 2019. Visualization.

steady increase of sun energy received by the Earth, the Earth has not warmed significantly over the last few billion years because reactions in the Critical Zone regulate atmospheric carbon dioxide content by interacting to a greater or lesser extent with rock-forming minerals. Therefore, it is to the Critical Zone that the Earth owes its habitability and sustainability. The Critical Zone in James Lovelock's theory is an essential ingredient of Gaia (see Lenton and Dutreuil, "What Exactly Is the Role of Gaia?," this volume, xxx–xxx).

A Zone under Threat

THE TERM "CRITICAL" also means that this zone is not a scientific object like any other: it is a fragile, sensitive interface, to be better described and modeled for the sustainability of humanity on the planet. In the Anthropocene, human impact on the environment has become major. The "Great Acceleration"[4] has led to overexploitation of arable land, deterioration of land quality, unprecedented deforestation, loss of biodiversity, and global warming due to the increase in carbon dioxide in the atmosphere, which disrupts the hydrological cycle. Soon, humanity will withdraw 30 percent of the total water flowing through the Critical Zone, waters whose residence times in aquifers, and therefore vulnerabilities, are very variable, ranging from less than a day to a million years; 50 percent of the continental surfaces are exploited by humans, who mobilize a tonnage of various materials (sand, rubble, rocks) approaching 10 times the flux of materials transiting from continents to the oceans.[5] It is not difficult to calculate that in some parts of the world, irrigation will salinize groundwaters that will then become unusable. Since the adoption of agriculture and the first major deforestations, humanity has modified the Critical Zone: its increased degradation over the last few centuries is undoubtedly one of the most obvious markers of our entry into the Anthropocene. At the same time, unlike the atmosphere or the living organisms, the Critical Zone evolves only slowly, giving us a misleading impression of its immutability (*see fig. 3*).

A Scientific Puzzle

SCIENTISTS ARE FAR from understanding the integrated functioning of the Critical Zone, which on a planetary scale is so thin, but so crucial for sustaining life. For example, the transformation rates of rock-forming minerals observed in a laboratory beaker (in the lab) are up to ten thousand times faster than those derived from natural observations (in the field) in the Critical Zone.[6] To understand why this is so, it is necessary to realize that the Critical Zone is a very heterogeneous and porous medium composed of primary and altered minerals (clays and oxides), living organisms and dead organic matter in decomposition, and that these finely divided materials are associated in aggregates whose reactive surfaces are organized in a fractal manner. It is also necessary to realize that the Critical Zone materials are not fixed; they move continuously carried by air, by rivers, or by humans, and that the water with which they interact follows complicated infiltration paths that are often not known and more or less rapid.

The Critical Zone hosts mechanisms with very variable timescales. While it only takes a few seconds for bacteria to reproduce or a couple of days for a tree to pump an excess of soil moisture, it takes tens of thousands of years to transform a mineral into a clay, and a lava flow into cultivable land. Many of the chemical reactions in the Critical Zone, while thermodynamically possible, do not occur for kinetic reasons; they are limited by their slow rates at Earth surface temperature. Dissolving a grain of quartz or zircon in the presence of acidified water by carbon dioxide is possible according to the rules of thermodynamics, but the reactions are very slow and actually do not happen. This is why the river and sand beaches contain so many grains of quartz and zircon: they are largely immutable and survive the rates of formation and destruction of mountains driven by plate tectonics. Most of the other rock-forming minerals dissolve more quickly, but there is still competition in the Critical Zone between the rate of transformation of the minerals and the time that the acidified water resides in contact with them. This competition between the rate of mineral transformation and the residence time of water in the Critical Zone is a major source of complexity when comparing laboratory results to field observations and building predictive mathematical models.

Depending on the location, on geomorphological conditions (slope), on climatic and of course biological settings, the Critical Zone is shaped in forms that can be very different. Life, by using enzymes or secreting aggressive substances, counters the slowness of chemical reactions, accelerates them locally, and is therefore an essential ingredient of the transport–reaction

Fig. 3: After deforestation, the Huay Ma Nai catchment (Thailand) has been submitted to a motorized monoculture of maize resulting in the removal of the fertile top layers and the frequent outcropping of the schistose bedrock.

4 See Will Steffen et al., "The trajectory of the Anthropocene: The Great Acceleration," *The Anthropocene Review* 2, no. 1 (2015): 81–98.

5 See David R. Montgomery, *Dirt: The Erosion of Civilizations* (Berkeley: University of California Press, 2007).

6 See Brantley, Kubicki, and White, *Kinetics of Water-Rock Interaction*.

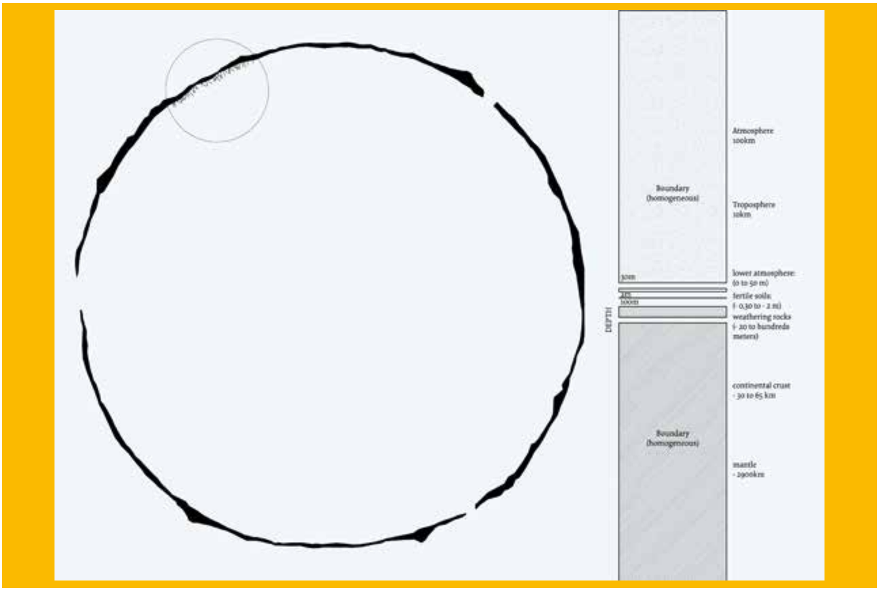


Fig. 4: Alexandra Arènes, The thickness of the Critical Zone at the planetary scale, 2019. Visualization.

pairing that sculpts the Critical Zone. Life plays a role not only by facilitating the transformation of minerals into clays, oxides, and substances dissolved in water, but also because the decomposition of organic matter on the ground produces gaseous carbon dioxide that accumulates in the pores of the soil at levels 10 to 100 times higher than those existing in the atmosphere, and exacerbates the aggressive nature of rainwater percolating towards aquifers and rivers. By developing a dense fabric of roots and fungal filaments, life also protects this soft layer which sustains it. Whether controlled by living organisms or not, the stability of the Critical Zone depends on a subtle balance between the mechanical and chemical processes that produce it and the processes that destroy it. Landslides, the most spectacular manifestations of sudden degradation of the Critical Zone, can wipe out thousands of years of slow transformations in a few seconds. Freeze–thaw alternation and entrainment by runoff water and glaciers are extremely efficient processes that are controlled by Earth's gravity, and that contribute to the formation and destruction of this "living skin" of the Earth (*see figs. 4 and 5*).

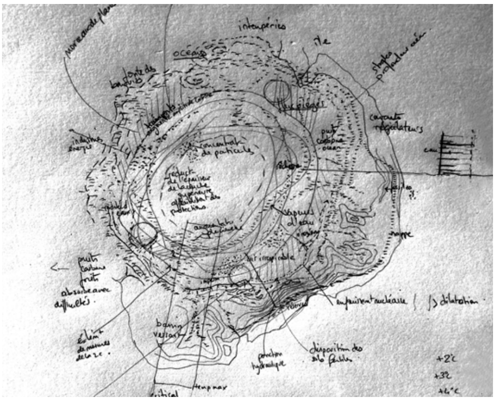
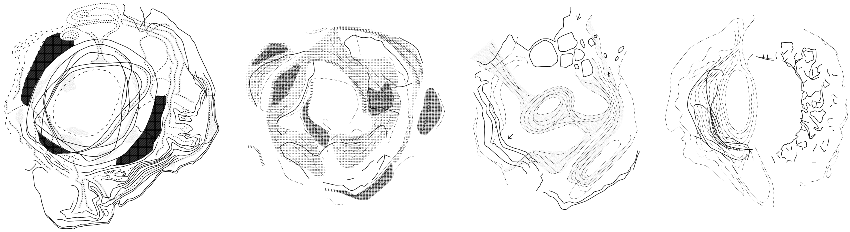


Fig. 5: Alexandra Arènes, Sketch of biogeochemical interactions when the Earth's layers are seen in reverse, 2019. Visualization. The movements of the atmosphere are in the center of the drawing and around them is the transformation of the rocks.



The Terra Incognita under Our Feet

DESPITE THE IMPORTANCE of the Critical Zone for humanity, major questions are still unanswered. First of all, the Critical Zone is a "terra incognita" whose architecture is poorly understood. Beyond the conventional layered textbook representations defining the soil, the regolith,[7] the ecosystem, the water table, the river, and so on, we lack conceptual representations showing the interconnections between these compartments which the different disciplines have erected and frozen as objects of study. Numerical models that tend to reproduce and predict the behavior of the Critical Zone are hampered by this lack of knowledge of its boundaries, and of the spatial and temporal connections of the object that sustains human activities and feeds us.

Very simple questions arise: What is the depth of the Critical Zone? What are its lower (towards the center of the Earth) and higher (towards Earth's upper atmosphere) limits? What are the living organisms that populate it, to what depth do they live, and where do they find their energy? What are the essential interfaces and main water flow paths? How does geologic legacy determine the shape and functioning of the Critical Zone over thousands to millions of years of topographic change, rock fracturing, and controls on the nature of rocks? Conversely, over time, does the Critical Zone "learn" to no longer depend on geologic and climatic initial conditions, but to strike out along trajectories controlled by and for life, as Lovelock suggests? What is the inventory of the processes that animate the Critical Zone? What do we know about the multiplicity of coupling mechanisms in this "functional biogeodiversity" of the Critical Zone which, by connecting the different compartments — soil, water, minerals, air, living organisms — are responsible for the ways in which it responds to perturbations of variable amplitude and temporalities? It is known that trees communicate with each other, so what about all the other agents in the critical soils — water, bacteria, clays, and carbon dioxide? How does a soil destroyed, for example, by the action of too intensive agriculture "remember" how to implement chemical reactions that can restore it? What is the rate of formation of a cultivable soil and what controls it? How long does the rainwater that infiltrates and the pollutants that humans introduce reside in the Critical Zone? These are the questions, both academic and operational, that remain unanswered, but which should condition the way we coexist with this object, which is also our habitat (*see fig. 6*).

Critical Zone Observatories

TO MEET THESE CHALLENGES, scientists are getting organized. Following the initiative of the United States of America, Critical Zone Observatories (CZOs, or networks of Critical Zone Observatories) have been set up in various countries. A global network is being developed. These observatories are well-chosen sites, locations that are heavily instrumented and monitored over sufficiently long periods of time so that processes and fluxes in the Critical Zone can be identified, described, and incorporated into numerical models. Only observation over long time periods makes it possible to capture the different kinetics — temporalities — of the Critical Zone, of extreme events as well as slow trends. CZOs are agrosystems, cultivated or relatively preserved forests, cities, high mountain catchments, instrumented wells, or glaciers. The measurements made in CZOs, either in situ (in the field) or on samples analyzed in the laboratory, are adapted to the processes that are locally best expressed. The instruments are often very sophisticated, whether they are installed directly in the field or in the research laboratories attached to these CZOs. For example, the use of isotopic ratios to track the route of chemical elements in the Critical Zone and the processes in which they are involved (clay precipitation, evaporation, uptake of nutrients by roots, etc.), or the deployment of passive or induced geophysical methods, such as the seismic imaging of gravels transported at the bottom of streams, are widely used by Critical Zone scientists.

Each CZO is a place, a plot, a hillslope, a catchment, characterized by a unique, simply formulated scientific question, which is often of societal interest and for which the place has been chosen as representative. There is *a Critical Zone*, perceived as a new scientific object, but there are *Critical Zone Observatories*,

7 See Clifford S. Riebe, W. Jesse Hahm, and Susan L. Brantley, "Controls on deep critical zone architecture: A historical review and four testable hypotheses," *Earth Surface Processes and Landforms* 42, no. 1 (2017): 128–56.

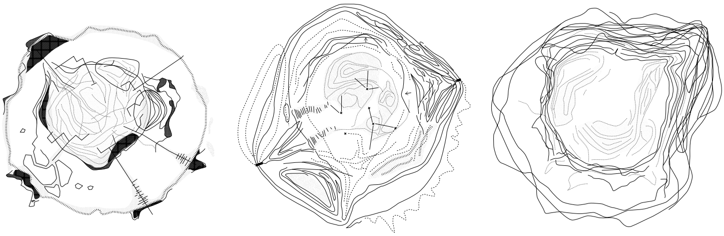


Fig. 6: Alexandra Arènes, Series of terraforming processes: chemical and physical weathering and erosion, solar radiation, melting of ice and sea currents, droughts and floods, carbon extraction and emission, sediment accumulation, plate tectonics and volcanism, 2019. Visualization.

all different in their combination of different parameters: geology, climate, topography, soil, living organisms, human activities, its history, or the conflicts of land use.

For example, a CZO can be designated to understand the response of the Critical Zone to the increasing (or decreasing) acidity of rain, the generation of destructive flood events, the response time of an agrosystem to changes in agricultural practices, the retreat of a glacier, or the role of climate change in Amazon floods. The main characteristic of a CZO is that it is site-specific; that is, determined by local conditions, and chosen to exemplify a particular type of mechanism to be understood at a particular scale. Elementary processes are discernible at the scale of a small river basin. At the scale of a region, such as the drainage area of the entire Amazon River, other processes emerge that require observations and modelling tools different from those required at the scale of a small river or a parcel of land.

In CZOs or networks of CZOs, ideally scientists from different backgrounds and speaking different languages work together to understand the object in an integrated way. They do it by sharing instruments, data, and numerical models. The beauty of this integration has allowed some CZOs to attract scientists from the human and social sciences, while some are working more and more with local stakeholders, users, and citizens. One of the hopes of the global network of CZOs is to develop a set of common metrics that can be applied everywhere according to the scale of observation to build standardized and interoperable common databases informed by common metadata. These data will describe characteristic processes at each scale, and will inform numerical models that will improve our ability to predict the evolution of the Critical Zone in response to climatic, anthropogenic, or geologic forcing.

Thus to study the Critical Zone, scientists study critical places, as Alexander von Humboldt had already understood when he wrote in his famous book *Cosmos* (1845–62) that "every where, in every separate portion of the earth, nature is indeed only a reflex of the whole."[8] Every corner of the globe, every CZO, is an instrumented natural laboratory, in which the processes and pulsations that characterize the Critical Zone are identified.

The conceptual view that describes CZOs not as static objects structured into different subentities, but as animated by biogeochemical cycles is particularly new and relevant: CZOs manifest the water cycle, the carbon cycle, the phosphorus cycle, or the cycle of rare earth elements, and are offering a new perspective on habitats. In the same way that the CZOs provide information to paint the picture of the Critical Zone, each chemical element or molecule provides its own systemic image of the Critical Zone without caring about the divisions between subcompartments. In this biogeochemical approach, the biological nature of the organism is less central than the chemical or physical reactions that they render possible. There is a significant difference here between the concepts of a Critical Zone introduced by Earth scientists and that of ecosystem, introduced by ecologists — at least in the historical meaning of the term "ecosystem." Living organisms participate in the formation and evolution of a biogeochemical system that we must learn to name and represent better. Their biodiversity is important because it conditions the physical, chemical, and biological reactions in the Critical Zone (*see figs. 7 and 8*).

Our Territories Are "Critical Zones"

THE CONCEPT of a Critical Zone does not set up an opposition between humans and nature or between living and nonliving states. It refers to a system, which we still have difficulty naming and representing that is anchored locally, and orchestrated by biogeochemical cycles in which living organisms including humans are agents, among others. The sun's energy animates these cycles, but they would not exist without the action

8 Alexander von Humboldt, *Cosmos: A Sketch of a Physical Description of the World*, vol. 2, trans. Elise C. Otté (New York: Harper & Brothers, 1866), 95. Originally published in German as *Kosmos: Entwurf einer physischen Weltbeschreibung*, vol. 2 (Stuttgart: J. Cotta, 1847).

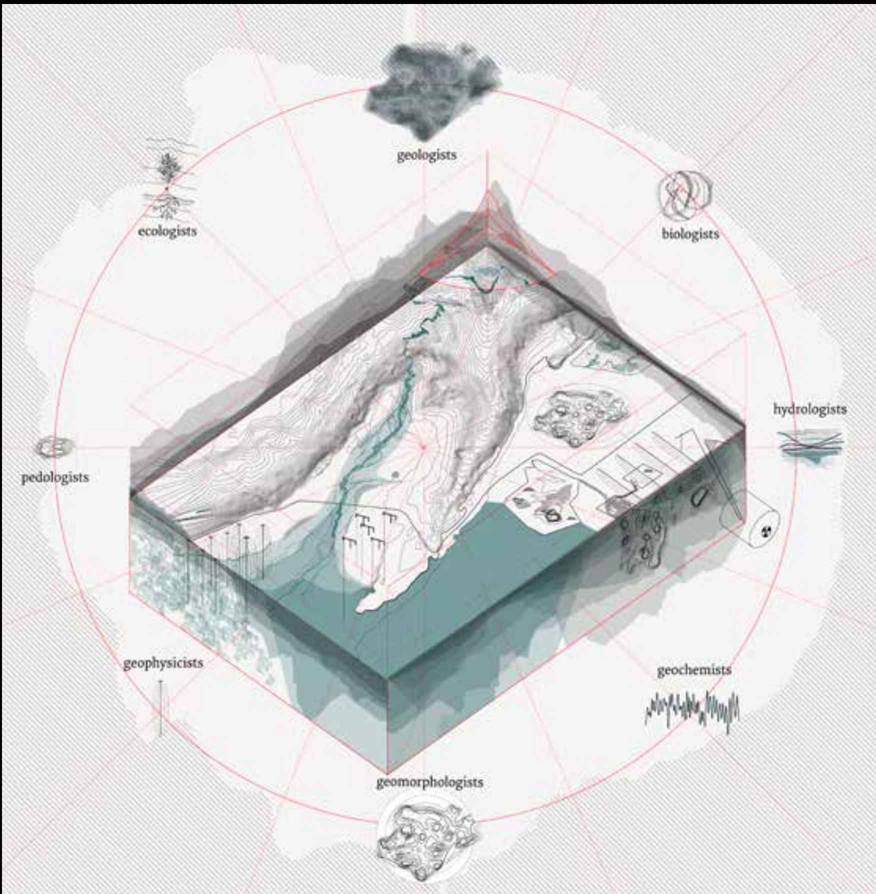


Fig. 7: Alexandra Arènes, Functional diagram of a generic watershed
equipped with instruments from each discipline studying the Critical Zone, 2019. Visualization.

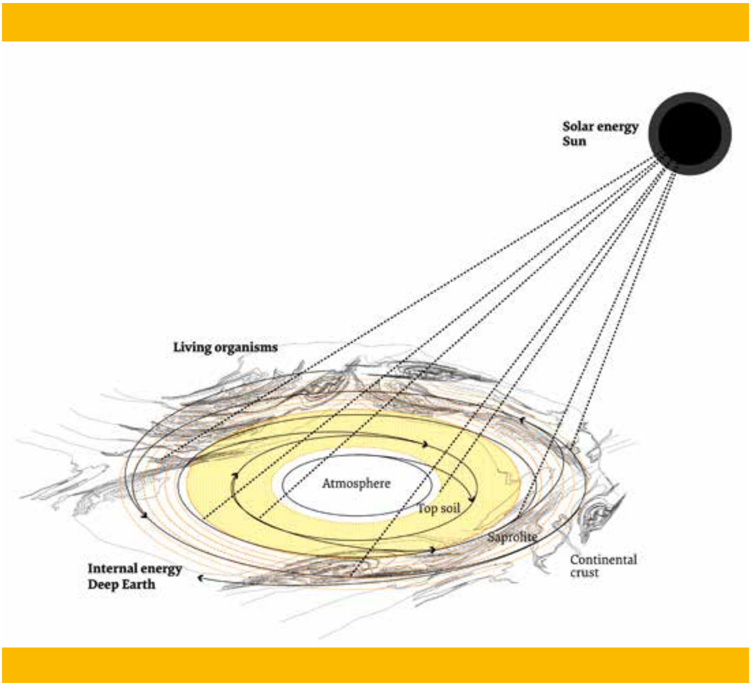
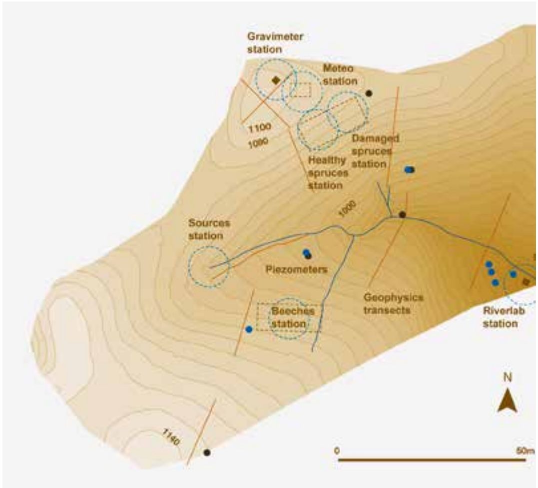


Fig. 8: Alexandra Arènes, Axonometric view showing the role of the sun in a dynamic hydrological and geochemical perspective, 2019. Visualization. Matter and elements are activated by a cosmo-tectonic circulation denoted here as the "energetic maelstrom." The Critical Zone is both geocentric and heliocentric.

of plate tectonics, ultimately a result of the secular cooling of our planet. The concept of a Critical Zone is restoring importance to local heterogeneity and deep time (as opposed to global and short times, described by Earth System Models aimed at predicting the next century). It inaugurates, with modern tools of scientific investigation, a new way of understanding human territories and their relationship to nature. These territories are ultimately "Critical Zones" for human activity. By giving geology a central place in what conditions our existence on the planet, the critical concept reintroduces slow- and long-term evolution, ultimately manifested in the vertical dimension of depth beyond the cultivable soil or canopy, and encourages a certain humility in humanity by confronting it with the temporal and spatial scales that shape its habitat. The Critical Zone is fragile, endangered by often brutal and senseless human actions, and requires more than ever before to be understood through observation over long periods of time utilizing sophisticated and systematic instrumentation. Our fragile but fertile Earth's skin is sick, and it must be better understood. Research institutions and funding agencies prefer to encourage competition between scientists rather than collaboration, but for our future on the planet, it is collaboration and powerful infrastructures that scientists need. There is no longer any doubt that it is in understanding biogeochemical cycles at the territorial scale (so nicely illustrated by the term "territorial metabolism") that the solution to the sustainability issue of our species on the planet rests.

A

B



Traveling through the Critical Zone

1 The village of Aubure lies at an altitude between 800 and 900 meters.
2 The scientists call this "a budget."

Alexandra Arènes

INTRODUCTION: WATERSHEDS. Foxgloves, bark beetles, acid rain. The forest is toxic and yet very quiet. During the walk, there are troubling patches: clumps of foxgloves — lethal flowers — in the clearings, a tree stripped bare here, a whole stretch of dead forest, dry and earth-colored there (*see fig. A*). It's very hot on this July day. The 30°C bar was crossed last week. Yet, the village of Aubure, near the monitored forest with its instrumentation, is one of the highest villages in France,[1] nestling in the Ballons des Vosges, a dense forest, "black" like its German counterpart a few miles away; a forest of shade with harsh winters.

Two days before, Marie-Claire (see Pierret, this volume, *xxx–xxx*) took us with her on her tour of the site, which consists in gathering the measurements made at each of the stations — that is to say, the places with instrumentation — in the catchment basin. The first station is the meteorological one. A Critical Zone Observatory (CZO) is first and foremost about calculating the quantity (of water and elements) which enters, minus what exits from the system, and hence everything that happens in between.[2] The meteorological station is the entry point of the system, the high point from which to deduce the other measurements, the registration of all the parameters that heat, cool, feed, ventilate, humidify, and recharge the catchment basin and which, in the case of the Strengbach CZO, enable the scientists to follow the evolution of the impact of acid rain.

A catchment basin is a geographical unit that receives a quantity of water and runs it off from its hillsides or slopes into a common outlet. Drainage divides mark the limits between catchment basins. A catchment basin isn't a legal entity or an administrative territory, but a geological entity in which water circulates, sometimes at depth, in a particular way. Their size, morphological characteristics, and occupancy of land may be variable, but a catchment basin is recognizable as such because it is a sort of receptacle for water, and is, therefore, in that sense, the living ground of the beings it irrigates. A watershed becomes a CZO when it is equipped with — often discreet — machines that register the pulsations and dynamics of the Critical Zone.

Thus, a CZO is never obvious as such; it is always a host of distributed instruments that enable us to recognize it (*see fig. B*). As we shall see, these tools provide a new understanding of nature. There is no river, there are levels of wetness, clouds, molecules, and chemistry. There is no ground, there is water around grains of sand. What is this new understanding of nature that substitutes the Critical Zone for the classical notion of landscape? What are the tools, methods, techniques, and practices required to produce the sciences of the Critical Zone? In what way does this enable us to better understand the Earth and our way of inhabiting it?

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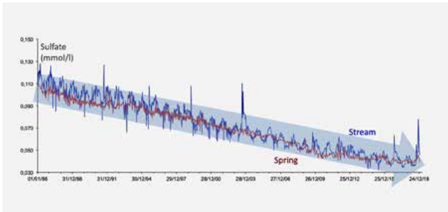
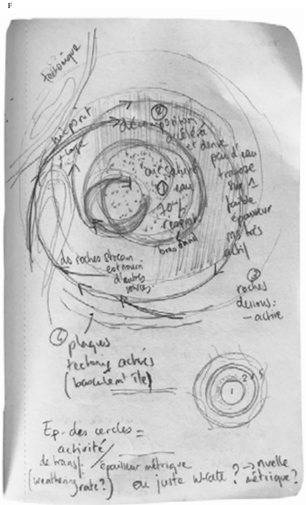


FIGS.: A — **The Strengbach forest, 2019.** B — **Alexandra Arènes, Map of the Strengbach CZO, 2019. Visualization.** C — **Soheil Hajmirbaba, The meteorological station at the Strengbach CZO, 2019. Drawing.** D — **The station of damaged spruces, 2019.** E — **Sulfur chronicles. Variations/decrease of sulfate (SO_4^{2-}) concentrations since 1986 in the stream at the outlet and in spring (drinking water) at the Strengbach catchment.**

Story 1: Trees

MARIE-CLAIRE records the temperature variations printed by an automatic arm on the graph paper. It has been unusually hot for a moderate-altitude mountainous environment. She adds that this doesn't mean the winters are less harsh: it is just as cold, but there is more rain, at the expense of snow cover. Yet, groundwater tables are recharged thanks to snow cover here. Marie-Claire is worried about the drinking water supply for the village — and for the thousands of other villages in France and towns worldwide. This is one of the research issues here, as local as it is global. Marie-Claire goes round the various instruments in the enclosure, which is protected from animals and humans (*see* fig. C). She picks up the water bags, but there are just a few drops in them; it isn't worth noting the quantity. We carry on with her round. A few meters from there, there's the spruce station. Large horizontal metal trays perched on slender legs are set up among the trees. Marie-Claire explains that these big steel rays, perched on their precarious vertical legs, harvest the rainwater that has fallen on the branches and needles of the pine trees (the "throughfall" (*see* fig. D)). In the lab, her team compares the chemical composition of the rainwater that has escaped contact with the trees with the water that has run off the leaves. The aim is to understand how the water is transformed on contact with the trees: Do the trees effect a reduction of the acidity of the rain that results from industry releasing sulfuric acid into the atmosphere? Do they manage to produce more nutrients than they lose? Scientists, answer these questions and make some disturbing findings: on the one hand, the anthropic emissions of sulfur from Asia that cause acid rain are transported to the site in twenty days under certain climatic conditions; on the other hand, thanks to other "good" wind conditions, the nutrients feeding the Vosges forest are brought in with the sand from the great deserts (for example, the Sahara). I notice something strange at the station and exclaim: "You measure the rainwater beneath the canopy, but the trees around the gutters are dead!" Marie-Claire explains that these gutters have been there for some ten years or so, but that an epidemic of bark beetles — Scolytinae — a common parasite in our latitudes, but one whose life cycle has speeded up with global warming, is developing, and virulently attacking the trees. Particularly as these trees are already fragile due to the acidity of the soils and the increasingly long and frequent drought episodes. The soil acidity is not only a product of acid rain, which has in fact decreased since the 1980s although its effects are still felt (*see* fig. E), it is also due to the very nature of the spruce trees whose acidic needles carpet the soil with a cover that promotes acidity. The spruce trees are trapped in this mortuary bed, a dramatic situation maintained by the industrial forestry activity that continues to plant spruce in order to fell and sell them. The gutters await in the void, perched on their sloping ground facing the mountain, as if suspended in the sky. A mist hangs over the watershed this morning and heightens our feeling of vertigo.

F



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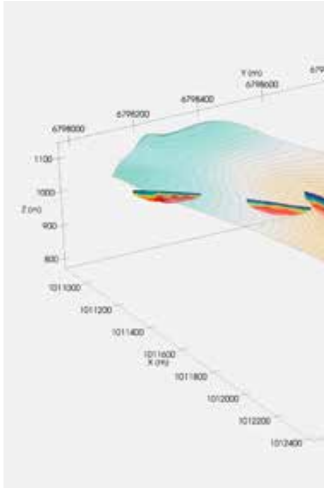


3 Field book entry by Alexandra Arènes. Translated from the French.
4 Webster's: a place in a stream bed where a nick occurs due to a change of tectonic level.

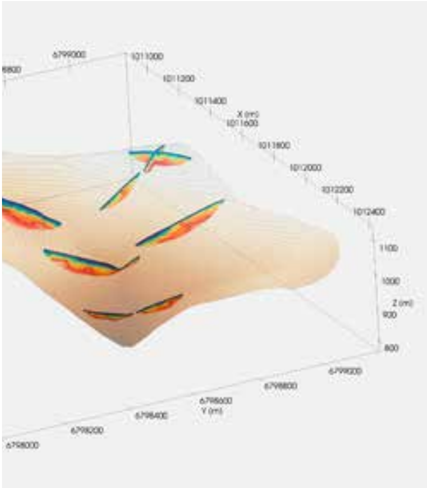
Story 2: Water

WE MOVE TO another instrumented spot. Marie-Claire measures the flow and temperature of the four springs of the watershed. In summer, the temperature difference between the springs is significant, since some flow out at the surface and hence are heated by the sun, whereas others are protected in the depths of the Critical Zone. In the spring there is almost no temperature gap. I learn from several other interviews that water has different ages. Some waters are termed "fossil" because they remain stuck deep in the rocks for hundreds of years. On average, a drop of water remains in the Strengbach catchment for 30 months before coming out again, but this varies from one observatory and one part of the world to another. In Guadeloupe, scientists suspect that infiltrated water stays much longer. So researchers are creating models to understand the water pathways. To do so, they need to know the precise composition of the Critical Zone and therefore to travel directly to the field.

Extract from the field visit, Guadeloupe CZO, Bras-David river (*see fig*. F):

> Rainforest: indeed, it is pouring rain. The space here is water particles: the water is not only in the flow of the stream we climb, where we slide and end up being totally wet, but also in the pores of the ground, the water is also in the heavy air, as the trees breathe loudly around us. Jérôme reminds me of the explorer Humboldt; he moves rapidly through the jungle. He and his team make rough drawings out in the field, note the location of a place of interest. This is a kind of exploration, but not *in extension*, to discover new lands (since there is no longer a square meter of Earth's surface that is unknown), but an exploration to discover the intensity of the changes, reaction, and movement of the Earth. It is all about registering small intensities occurring on the surface (an eroded rock, water with a high ion content) that are "echoes" of major (biogeochemical or hydrological) cycles. The scientists are therefore not mapping places but points of transformation.[3]

Water flow paths are among the most challenging features of the Critical Zone to observe, model, and understand. Yet this is crucial for the management of our water supplies. Water paths follow currents, as in the ocean, depending on the porosity of the Critical Zone: the surface layer of the Critical Zone (commonly called the soil and containing organic matter) is averagely porous, that is to say, it allows a middling amount of water to pass; the trees are very porous, the air even more so, while rock has low porosity, but can be fractured — that is to say, split from the inside by a continuous flow of a stream of water that alters the chemistry of the rock and reduces its density. Water can also be captured in pockets or come out suddenly through "macropores," which are a kind of tube,



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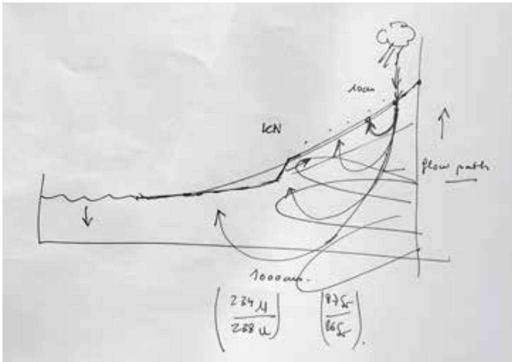


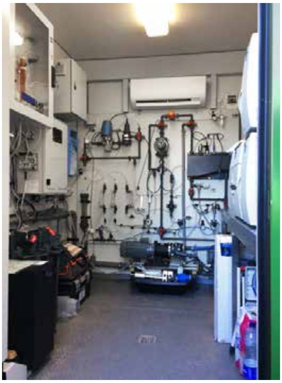
F — **Alexandra Arènes, Sketch of the cycles in the CZO Bras-David, Guadeloupe, 2019.** G — **Geophysics campaign, Seismic characterization of the Strengbach catchment, August 2019.** H — **Sylvain Pasquet, Seismic velocity profiles in the Strengbach catchment, 2019. Visualization.** I — **Jérôme Gaillardet, Sketch of the water paths and knickpoint in the CZO Bras-David, Guadeloupe, 2019. Drawing.**

opened up by mammalian activity or the decomposition of a root.

We are, however, blind to these depths unless geophysics and geochemistry afford us a glimpse of what is going on beneath our feet. Geophysics allows us to visualize the location of the porous regions (*see* fig. G), while geochemistry provides hypotheses on these trajectories by studying the chemical composition of the spring water or the water collated at depth by the piezometers. If the water pathways are so important to discover, this is because the water carries chemical elements. Driven by solar energy, the water activates the cycles of the biogeochemical elements that end up transforming landscapes. The surface is easier to understand. At depth, however, the Critical Zone is much more complicated; in this case, the images are simplified and are forced, in a way, to synthetize the features; such as these colorful transects that Sylvain showed me at the IPGP which render the porosity of the soil (*see* fig. H). By contrast, geochemistry is an exercise in acupuncture. Essentially, the idea is to multiply several measurement points (the more differences there are, the better the data), as I learned by exploring the rivers with the team that measured conductivity upstream and downstream, in order to choose the river to study that offers the most contrasting measurements (before/after knickpoint[4] (*see* fig. I)). The differences and heterogeneity enable them to see better what is happening beyond the reach of sight. They register the variations, the alteration, the erosion. It is these processes that actually give the Earth its heterogeneity by constantly modifying the chemical composition of the planet.

Instruments enable the scientists to plot the variability of the natural elements. By taking small extractions from what they call the different "compartments," they isolate micro-events that generate changes. By extracting a leaf or taking a sample of water, they can isolate a molecule and trace the sulfur cycle; by generating a wave in the ground, they can observe a vibration and reconstitute the depths of the Critical Zone. By noting and tracing these small events, they deconstruct a monolithic vision of the landscape. The landscape is not a space to be filled, nor inert matter that can be shaped at will, but a volume of phenomena, entities, movements, and reactions: with cycles that animate it. The sciences of the Critical Zone shift the anthropocentric view of nature as a background to human actions, and restore the complexity of what constitutes a territory, of the entities that compose it, element by element. The landscape has quite another "shape," composition, granulometry, and dynamic. The instruments, sensors, and tools recompose "nature," pixel by pixel, across the cycles and the connections between agents. By cross-checking data, ordering micro-events, the scientists see all the disturbances, sometimes even micro-changes, that would not be perceptible on a human time scale or with the naked eye, but which nevertheless generate a virulent reaction within the system.

J



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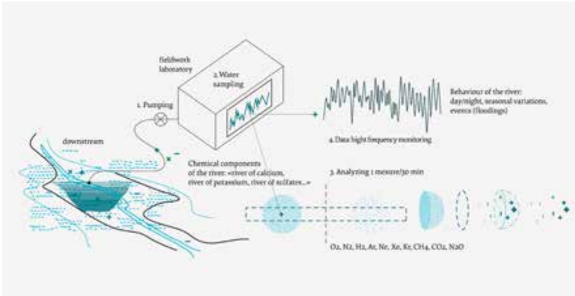

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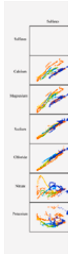

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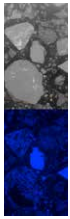


5 See the contributions by the Critical Zone scientists in this volume; Pierret, *xxx–xxx*; and Gaillardet, *xxx–xxx*.

6 Nils Ole Bubandt and Anna Tsing, “An Ethnoecology for the Anthropocene: How A Former Brown-coal Mine in Denmark Shows Us the Feral Dynamics of Post-industrial Ruin,” *Journal of Ethnobiology* 38, no. 1 (2018): 1–13, here 8.

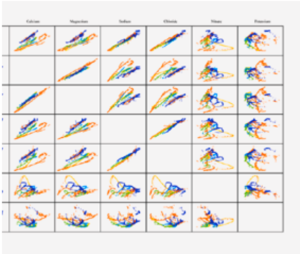
7 Cosmogram, in the sense developed by John Tresch, “Cosmogram,” in *Cosmogram*, ed. Melik Ohanian and Jean-Christophe Royoux (New York: Lukas and Sternberg, 2005), 67–76.

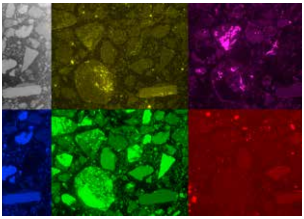
8 This visualization has been described in Alexandra Arènes, Bruno Latour, and Jérôme Gaillardet, “Giving depth to the surface: An exercise in the Gaia-graphy of critical zones,” *The Anthropocene Review* 5, no. 2 (2018): 120–35.

Story 3: Cosmograms

HOWEVER, why should we be interested in such unremarkable sites? It isn’t here that the glaciers are melting, the forests burning, or emblematic species of wild fauna going extinct. No, these aren’t hotspots of the global crisis. The CZOs are, above all, places of life, a nearby territory that is dying slowly and discreetly. We also need those scientists who look carefully at the environments closest to us. For Solenn, the challenge is to amplify the site — that is to say, to collect different measurements, since everything interacts and moves without regard to boundaries. The CZOs are special because they are inhabited — and have been for many years — and because issues have emerged from concerns that relate to both human and nonhuman assemblages, bonds that maintain the ecology of a site.[5] The CZOs enable us “to notice the complicity at stake in the political ecology of humans and nonhumans,”[6] as Tsing and Bubandt say. This is what can be described as cosmopolitical, those unheralded actions that nevertheless constitute the most mundane and ordinary territories all over the world.

WE GO A BIT FURTHER down the Strengbach and come to the Riverlab. The Riverlab is a prototype in situ laboratory, sheltered inside a container and located on the river bank (*see fig. J*). It measures various river parameters continuously: its chemistry, physical properties, and sediments (*see fig. K*). These continuous measurements have uncovered significant and irregular chemical oscillations between day and night, particularly during heat waves, to the point that researchers call these phenomena a “nychthemeral concert” (*see fig. L*). In the Strengbach, we find a different tune. The river is very heavy with sediment, particles of matter that obstruct the instruments that have been placed in the river to take measurements and send water into the Riverlab. The river doesn’t make itself easy to monitor. We go into the Riverlab. The researchers set the machine going. It spits, groans, and begins to work. The pressure is too high and it chokes. After renewed attempts and by letting the coughing water tap run for several minutes, the measuring screen at last turns green. The noise and agitation are astonishing and contrast sharply with the other spots where we took measurements manually, calmly, and in silence. Bringing a fully equipped laboratory onto the site was not without its problems, both human and technical. However, when Jérôme and Paul explain to me how Riverlab works, I can glimpse the potential that is there. It is a kind of temporal chemical microscope that enables us to see all the variations of the river: seasonal variations, diurnal and nocturnal variations, one-off variations (floods). All these have different physical and chemical characteristics. To see them in real time is a major advance. These are the minute-by-minute rhythms, the pulsations of the water that runs through the heart of the Critical Zone and transforms it. Inside the Riverlab, however, the water is never visible as such. It is what there is inside it — its particles, its molecules — that appears on the





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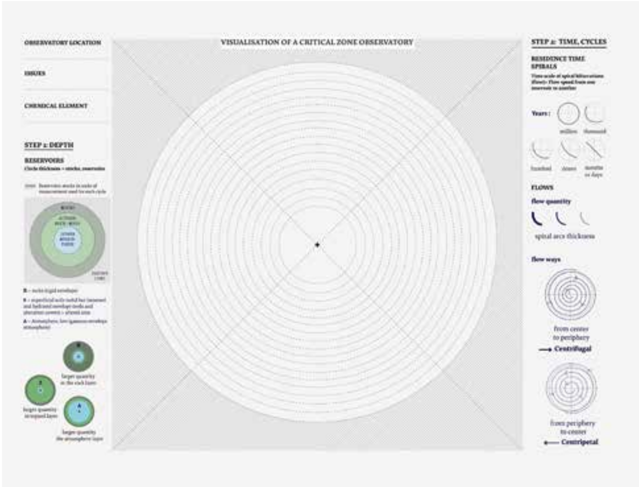


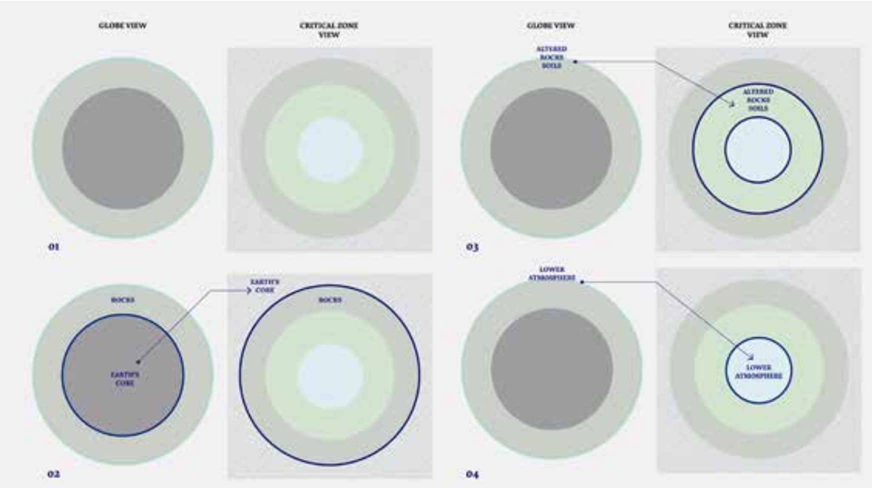
J — Interior of the Riverlab, CZO Strengbach, 2019. K — Alexandra Arènes, Scheme of the Riverlab data acquisition, 2019. Visualization. L — The geochemical matrix or the orchestra of the elements in the river of the Orgeval CZO. Each color represents a flooding event. M — Scanning Electron Microscopy (SEM) images of a soil sample from a spruce plot in the Strengbach watershed. The different colors correspond to the areas of concentration of different elements (yellow: titanium, violet: iron, blue: potassium, green: silica, red: sodium) N — Alexandra Arènes, template for the visualization of the Critical Zone, 2019.

graphs in the form of waves which the scientists know how to interpret. To me, it is pipes, valves, taps, test-tubes, and a computer. Yet I can see that the Riverlab is a true cosmogram[7] that takes us right into the Critical Zone.

On the last day, I have a meeting at the laboratory of the Hydro-Geochemical Observatory of the Environment (Observatoire Hydro-Géochimique de l'Environnement, OHGE) in Strasbourg. Extracts and samples from the observatory fill the basement of the building: these are the biological and geological archives, including the rock cores drilled to a depth of 120 meters during the installation of the piezometers. The tubular rock cores, extracted by boring, are laid out in large cabinets and labeled with their depth of extraction. This is a dive into the depths, but horizontally this time! We pass through the ages and the strata, we follow the faults — those fractures where water circulates in the granite, although that rock isn't porous to water — which complexify the understanding of the Critical Zone at depth. Naturally, at these depths, we must not think of clear, free-running water: as Jérôme reminded us, water is wet grains. Other cabinets contain surface rocks, bags of branches and bags of leaves, a fridge full of water samples, and shelves loaded with soil samples. There are also microscopic images of sediments, showing traces of organic and mineral material. The Strengbach CZO is there, too, its natural history is there, but it is not preserved as in a museum; it is consulted and archived here only because the aim is not to freeze the site in time, but to understand how it changes.

We climb the floors of the building. All trace of naturalistic materiality has disappeared here. The flasks of soil, organic matter, water, and rock are digitized, then converted into light rays (*see fig.* M). The Strengbach takes on quite another form. The geophysics maps are drawn up from the propagation of seismic waves or electromagnetic signals. There is the animated map of the recharging of the spring, the map of the surface water runoff, the map of electrical resistivity, and the map of porosities across the whole of the watershed. The raw digital data do not give an image. The world is made up in this way of contrasts that one may choose to ignore or accentuate. The combination of these measurements is represented figuratively, particularly because geophysics is linked to the spatialization of data. This is not quite the case with geochemistry, which follows changes through trajectories, that is to say, the trace of an element surveyed in the Critical Zone. However, on my excursions into the Critical Zone, I have never seen a suitable solution for mapping the biogeochemical cycles. Therefore, we have begun to develop a visualization tool to map the processes of the Critical Zone (*see fig.* N).[8]

A



The Strengbach Catchment Environmental Observatory: A Needful Key for a Global Investigation of the Critical Zone

Marie-Claire Pierret

LONG-TERM OBSERVATIONS remain the only way to quantify and characterize the perturbations of the Earth induced by human activities, and to accept that humanity has now entered a new geological epoch: the Anthropocene.

THE HYDRO-GEOCHEMICAL Observatory of the Environment (Observatoire Hydro-Géochimique de l'Environnement, OHGE) of the School and Observatory of Earth Sciences (EOST) in Strasbourg documents the anthropogenic effects on the Critical Zone through long-term observations, abundant interdisciplinary research, and strong involvement in training and communication activities.

The OHGE's site is located in the small-scale water catchment (80 ha) of the Strengbach river in the Vosges Mountains (880–1150 m elevation) in Eastern France where multidisciplinary projects and research have been conducted since 1985, exploring all the compartments of the Critical Zone, from the scale of atoms to the scale of satellite observations, from the scale of instantaneous mechanisms to several thousand processes. This "open sky laboratory" and monitoring site is situated in the commune of Aubure, a small village where the economic activity is mainly agriculture, forest management, and tourism. The village inhabitants are particularly dependent on environment conservation as all their drinking water is supplied by mountain springs, some of which are located in the studied site.

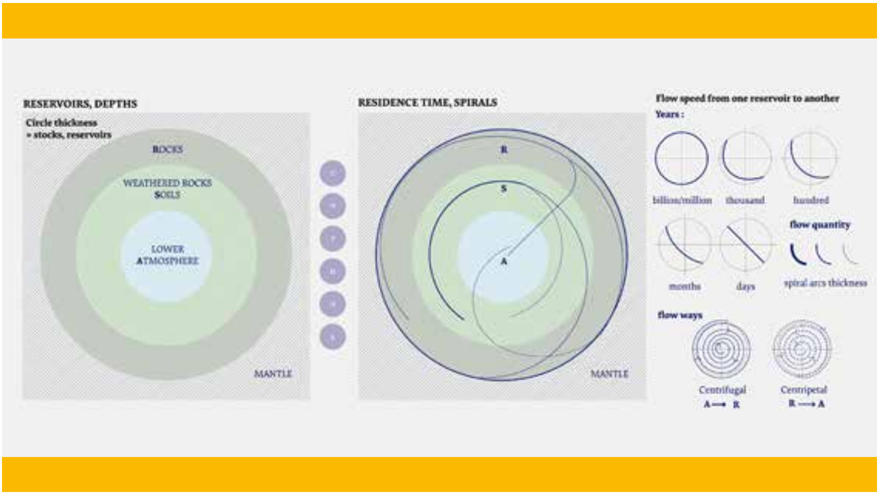
Long-term observations allow the detection of modifications of biological, physical, and chemical variables such as precipitation, temperature, river flow rate, concentration of chemicals in soil water and river water, air contaminants, or vegetation growth.

The changes in these variables are the consequences of several perturbations occurring concurrently with different intensities, which generate answering processes with different characteristic times (from seconds for flooding to several hundred thousand years for erosion). These mechanisms have to be described and understood in order to develop mathematical models capable of reproducing the observations, of predicting the evolution of the system in the near and distant future, and then attempting to conserve, protect, and preserve the water and soil resources.

Therefore, the OHGE is the meeting point of many scientific disciplines involved in the geosciences (hydrology, geochemistry, geophysics), life sciences (microbiology, plant biology, plant physiology), informatics and mathematics (database management, mathematical and numerical modelling), and social sciences (history, sociology, education). The mixing and collaboration between wide varieties of scientific disciplines is the only way to investigate globally the (past, present, and future) Critical Zone.

Training of MA and PhD students and communicating research findings to a large audience are important activities of the OHGE since it addresses in a very timely fashion societal challenges such as (I) water resource availability and sustainability in mountainous environments in the context of climate and precipitation regime changes and (II) forest health and future evolution of

B



FIGS.: A–D — **Series of diagrams showing the steps in the construction of the alternative visualization of the Critical Zone by Alexandra Arènes.**

A 01–04 — **Giving depth to the Critical Zone, from a global view to a Critical Zone view. These diagrams present an alternative visualization of the Earth by reversing its layers like a glove turned inside out. The core is now at the edges and the Critical Zone is now at the center: the weathered layers, where the rocks are transformed into soft soil, with the atmosphere in the middle.** B — **Cartographic system of the Critical Zone view: to describe a place through its reservoirs and depths, and to locate a space through the movement of the cycles that shape this place, made visible by a series of spirals.**

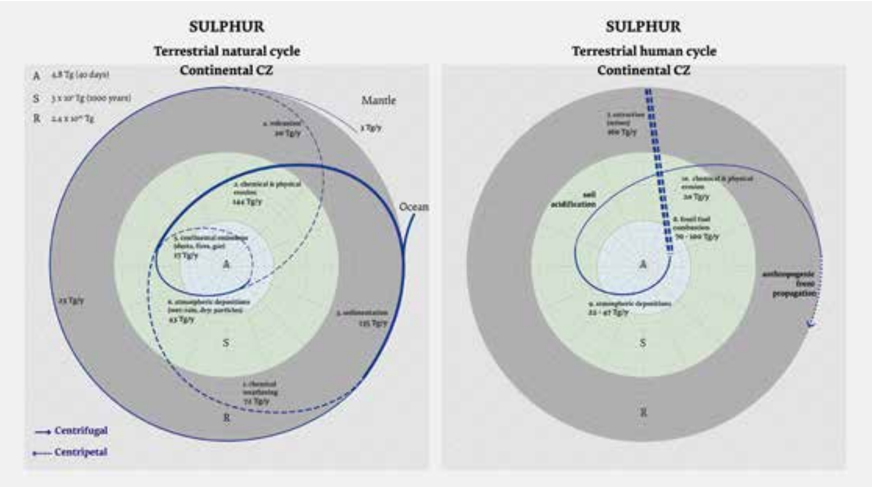
soil fertility in an era when economic pressure on wood production and supply is growing.

The site location was studied and selected on account of different parameters such as the geomorphology, the geology, the presence of a large proportion of forest and a small river, as well as a positive and supportive local commune. This was the situation in Aubure in 1985 with a Green mayor involved and concerned by forest dieback, who offered his support to the observatory project. Since then, scientific and technical OHGE teams visit the site on average once a week, sometimes with field campaigns lasting five or even ten days, and they are also actively linked to village associations and institutions by holding regular events. In this way links have developed between the observatory's team and the inhabitants of the village. The OHGE scientists have also developed ties with the municipal council and local people because they share the same questions and issues — all wish for a better understanding of the possible evolution of the ecosystem. The future of the forest and the available water is a crucial question for the development and sustainability of the village. Actually, this is a two-way connection: the inhabitants of Aubure have special knowledge about traditional land use and its resources and about past extreme events (e.g., mud flow, severe storms, exceptional climatic perturbations), which can affect the present-day parameters, and the OHGE teams are potentially a source of knowledge, expertise, and cultural or social vitality, as well as being an attractive advertisement for the village. For example, events concerning the OHGE are regularly reported in the local media. The OHGE also organized a science festival in Aubure for children and the general public, with several workshops and a scientific tour of the different stations of the observatory and also offered public presentations of the results achieved. Further, the OHGE teams are part of events organized by the local festivities committee such as the "Gourmet Walk." When new large-scale equipment is installed on the site, the OHGE usually proposes an official opening with local institutions and organizations to explain and describe the devices.

In addition, the OHGE interacts with the National Forests Office (Office national des forêts, ONF) concerning the health and future of the various tree plots and the scientists meet regularly in the field. They also participate together in the International Day of the Forest by organizing hikes through the site for the public, describing the forest plots, the forestry management, the equipment, and the scientific problems we are working on, or by planting trees or listening to poetry. Common projects to preserve the fertility of soils and the health of the forest are planned for the future.

In addition, the field campaign is scheduled to respect the hunting season and the squall of the deer. During field work the OHGE scientists stay in village accommodation and support the social bonding in rural areas by buying food at the local grocery store. This makes the OHGE team feel they belong to the village of Aubure and are involved in its development.

c



THE SUCCESS and the longevity of the observation of this site are due to the combination of several factors, mainly: (I) the ability to develop connections and relations between researchers, policy makers, and associations; (II) the motivation and investment of the successive researchers responsible for the site to form an alliance with and welcome international scientists; and (III) the continuous funding and support from the Institut national des sciences de l'Univers (INSU) [National Institute of the Sciences of the Universe] and the French National Center for Scientific Research (Centre national de la recherche scientifique, CNRS).

The Strengbach catchment site was chosen because it was affected by severe forest decline, like many places around the world in the 1970s. Hydrologic, meteorological, and geochemical parameters, as for instance precipitation under and outside the canopy, air temperatures, river discharge, concentrations of minerals and chemicals in springs and in the river, have been continuously recorded since 1985. It is therefore one of the oldest sites on granitic basement in the world to be monitored continuously.

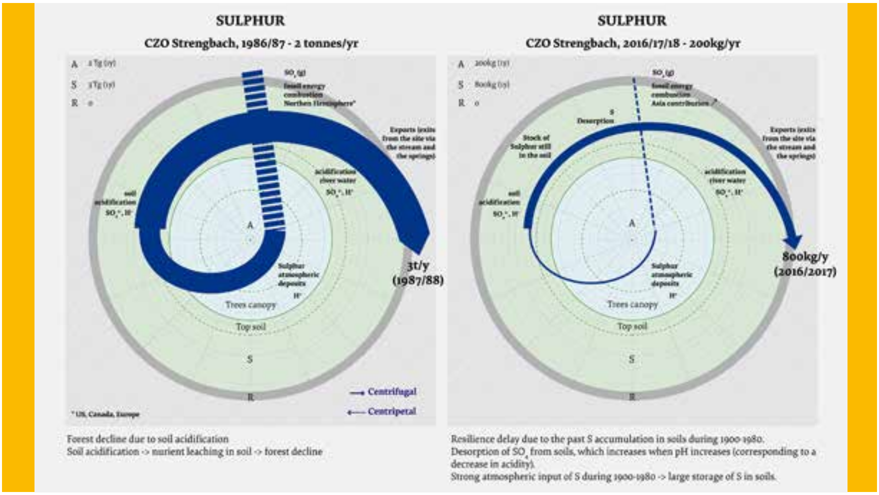
During the past 35 years, several anthropogenic perturbations have been identified and studied. One emblematic example is the evolution of acid rain due to sulfur dioxide and nitrogen oxides gaseous emissions during fossil energy combustion. Some political decisions and clean air acts were enacted in 1980s in North America and Europe, implying a significant decrease of emission. At the scale of the Strengbach catchment, far away from the direct sources of pollutants, the sulfur atmospheric deposits decreased from 2t/yr to less than 200kg/yr currently, followed by a significant decrease in the river water concentrations, which highlights the potential recovery or resilience of this natural system.

Another representative result is the impact of tree species on the biogeochemical cycle of nutrients at the soil scale. Higher acidification and leaching under spruces were observed, which result in higher impacts on and threats to soil fertility, and has implications for the sustainability of the spruce plantations, which represent 80 percent of the managed forest.

Climate changes in temperature and pluviometry have also been observed, with a global warming of about 1°C in 30 years, and a global increase of average precipitation. However, the distribution differs with the season, with a higher increase of temperature in spring and a higher increase of precipitation in fall and winter.

Very importantly, we learned that interdisciplinary research is mandatory to enrich one's own discipline, but it needs time to cultivate colleagues from other disciplines, that is, to understand their vocabulary and to build trust. Time is needed to develop humility and trust in the partners' words. Humility, because we need to recognize that our own discipline is not "better" than that of others, that we need the support of other disciplines or, even "worse," that our discipline is not the most appropriate to improve our knowledge about the issue at hand. Time has to be dedicated to numerous discussions and exchanges between partners and, of

D



C — **Alternative visualization of the terrestrial cycle of sulfur, without human influence (natural cycle) and with human influence (human cycle). The Critical Zone view shows how human activity perturbs a cycle. Drawn with the help of Jérôme Gaillardet.**

D — **Alternative visualization of the terrestrial cycle of sulfur at the scale of the Strengbach CZO, for the year 1986/87 and then 2016–18, showing the impact of the sulfur cycle on a local observatory. Drawn with the help of Marie-Claire Pierret.**

course, depends on the type of relationship between the partners. One of the main difficulties in promoting interdisciplinarity is the evaluation of the scientific work. In science, evaluation is mainly performed by counting the number of papers published in high-ranking international journals. Publishing extensively means that the scientist must dedicate a lot of time to writing and, therefore, is likely to devote less time to discussions with colleagues from other disciplines. Peer-reviewed international journals very often specialize in a single discipline. Most of the interdisciplinary journals are, unfortunately, less prestigious. Therefore, young scientists not involved in interdisciplinary research face a contradiction: their research will benefit from interdisciplinary work but not their career.

However, interdisciplinarity is made easier when researchers work on the same object, with questions they share. The study of the Critical Zone is, of course, a good candidate for this. This is why the multidisciplinary research on the observatories of the OHGE has developed quite naturally for decades. Moreover, its long and unusual data series, its many already existing facilities, and the broad knowledge already acquired makes it particularly attractive scientifically.

We have also learned that regular contacts with a wide audience are a real source of personal and scientific enrichment. These good relationships, sometimes even friendships, that we developed with the local population, are also essential for different reasons: (I) scientists are "only" the guests and the visitors of the site; (II) the different visitors of the forest (e.g., hikers, hunters, loggers, inhabitants, scientists) have to develop their own activities in peace, freedom, and respect; (III) we have so much to learn from each other and so much to exchange; and (IV) the protection of the Earth, our most precious common possession, is easier to understand and to be involved in, via local challenges, with territorial issues.

THE IMPLICATIONS of the water storage dynamic, hydric stress, and forest health are significant, with, for instance, concerns about the sustainability of springs, the development of wood parasites leading to tree mortality, and modification of forest management for non-adapted tree species. Ongoing research at the OHGE is based on the interlinked geophysical, hydrological, biological, and geochemical investigations to better understand and model the past, present, and future functioning of the watershed with regard to water resources, forest health, and soil fertility.

The development of such Critical Zone Observatories around the world in a variety of geological, climatic, and anthropic contexts is one of the key responses to evaluate, calculate, model, imagine, and protect the future evolution of the Earth during the Anthropocene, and then the future way to inhabit the Earth.

The Critical Zone Paradigm – A Personal View

Susan L. Brantley

In many countries, if a doctor doesn't focus on problems of a specific body part such as the heart, or a specific patient type such as children, or doesn't learn techniques of surgery or some other specialty, we call them a general practitioner (GP). These GPs observe the entire patient and consult on health issues holistically. In Earth surface science before 2004, we didn't have many GPs. That's why many of us pushed to create a new type of scientific GP. We created Critical Zone Science to focus on studying the Earth's surface — from air to trees to water to rocks to humans.

I am a geochemist and I was heavily involved with the birth of Critical Zone Science, but I am not sure exactly why it happened. Some of it was that geochemists were tired of studying smaller and smaller pieces of a system and watching opportunities go to other geoscientists.

But my own trajectory toward Critical Zone Science actually began in my graduate work in geology. I began measuring the rates of reactions between water and rocks. But I became unsatisfied because I could not use the measured rates to predict what was happening in natural hillslopes and watersheds. When we estimated rates of reactions in nature, we discovered they were always slower, sometimes almost a million times slower, than our measured lab rates. Many people puzzled over this. We considered everything from biological effects (do trees slow down reactions between water and rock?) to the effect of time (does a rock react slower and slower over geological time?) to the effect of humans (had we perturbed natural systems?).

All of these aspects of the natural system affect the rates that rocks interact with water. Eventually scientists discovered that where the reactions occur together simultaneously in nature, one reaction can slow another down. When we measured isolated minerals separate from others in the laboratory in my experiments, we simply missed what happens in nature where multiple minerals react together.

One scientist at the U.S. Geological Survey who was way ahead of me in his thinking, Arthur F. White, was deciphering the rates of mineral-water reactions in field systems. He taught me how to read the rates of reactions in soil layers. We started learning from others how to use computers to simulate the reactions. These computer models helped us realize that we needed to cease studying one isolated mineral reaction at a time, but instead to study each field site in its entirety. This, of course, was difficult, and meant we had to engage a lot of researchers who could help us study the trees at the same time that we needed others to study the bacteria, and others to study the water flow ... and the atmospheric deposition ... and the worms ... all the things we didn't know much about because of our own training histories.

At that time, however, scientists from the different environmental disciplines competed harshly against one another for funding, sometimes denigrating each other's science to push forward their own field. Clearly, we needed to put the whole scientific target back in focus to fight together. We called this new idea something slightly funny in retrospect — "weathering system science." We didn't get anywhere because only we thought that sounded interesting. Then once again we realized we needed to emphasize the "thing" we wanted to study rather than one isolated process. We grabbed a term that a prescient sedimentologist, Gail Ashley, had coined a few years earlier: the Critical Zone. We finally realized that what we had to do was put the Critical Zone back together and study it as one integral entity: how it works, how the different pieces interrelate, as well as how it evolves over time.

We didn't fully grasp until later how the idea of the Critical Zone would captivate students and researchers around the world. It was a deeply popular idea that engaged not only scientists but also nonscientists. We had discovered a hunger to stop reducing systems to small pieces of the puzzle and instead to put the puzzle pieces back together into one integrated picture. Soon we had educated students who could work across all the subdisciplines much better than we could. We laughed and tried to figure out what to call them — C-zologists?

C-zologists defined the Critical Zone to range from the top of vegetation to the bottom of groundwater. Instead of fighting to fund work separately as geochemists or ecologists or soil scientists or hydrologists or geophysicists, we worked collaboratively side by side. And slowly the Critical Zone started to reveal itself to us. Geologists learned how trees shared nutrients underground with fungi, while soil scientists learned how the layers in rocks influence the thickness of a soil. By looking at the Critical Zone over short and long timescales, we began building models that we now find useful in projecting — "earthcasting" — these systems into the future.

The attractiveness of the holistic nature of Critical Zone Science led to the growth of Critical Zone Observatories (CZOs) in country after country. But, just as general practitioners don't always command the respect of a specialist in surgery, C-zologists found themselves under attack. I suppose this was inevitable. In the USA the pushback was stubbornly fierce. Predictably, the pendulum swung, and the USA decided to stop funding CZOs. The biggest scientific agency that had funded Critical Zone Science from its inception began to encourage their scientists to again focus only on a few isolated aspects of the Critical Zone.

But, we still need to understand the whole system, not just the isolated parts, and Europe and China and other parts of the world are growing observatories to continue to train C-zologists to integrate measurements and models to cross the interface between rocks and life — including humans. Like any vibrant area of research, we don't know what will happen next in C-zology. But the students are now working around the globe. They are hungry to understand the Critical Zone in ways we could not even imagine just a few years ago. The USA may have started Critical Zone Science but, luckily, the whole world is now moving it forward.

A

Ansichten der Calzone: Views of the Calhoun Critical Zone Observatory

Daniel D. Richter, Sharon A. Billings

1 See Alexander von Humboldt, *Ansichten der Natur mit wissenschaftlichen Erläuterungen* (Tübingen: Cotta, 1808). The book is most recently published in English as *Views of Nature*, ed. Stephen T. Jackson, Laura D. Walls, trans. Mark W. Person (Chicago, IL: University of Chicago Press, 2014).
2 See Scott Huler, *A Delicious Country: Rediscovering the Carolinas along the Route of John Lawson's 1700 Expedition* (Chapel Hill, NC: University of North Carolina Press, 2019).
3 See http://www.city-data.com/city/Cross-Keys-South-Carolina.html.
4 See Paul S. Sutter, *Let Us Now Praise Famous Gullies: Providence Canyon and the Soils of the South* (Athens, GA: University of Georgia Press, 2015).

The German title of our piece follows Alexander von Humboldt, to honor his 250th birthday in 2019. Humboldt's Ansichten der Natur[1] *was first published in 1804 after his five-year expedition to the Americas.* Ansichten *was a small book that fused geology and biology, nature and culture. We assert here that Humboldt's integrative approach is congruent with the twenty-first-century's Critical Zone science.*

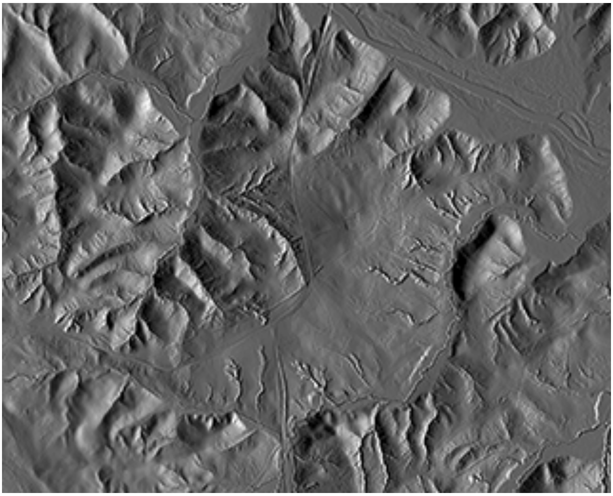
On a sunny morning in April 2014, historian of geosciences Dr. Enriqueta Barrera of the US National Science Foundation (NSF) opened a meeting of several dozen Earth scientists from across the United States. The group was gathered at Padgett's Creek Baptist Church in rural South Carolina, in preparation for a field trip to one of the NSF's newest Critical Zone Observatories (CZO). The Earth scientists were surrounded by flowering dogwoods and gentle mild breeze of early spring in the Piedmont, a region known in colonial times as the "Flower of Carolina."[2] The rural community around the church has about 1,200 inhabitants, many of whom are descendants of multigenerational families. Their average age is about forty, 60% are white and 40% black, and about 25% of those working-age are employed by textile-related industries.[3] The landscape and its people have a rich interactive history that is appreciated and explored by contemporary Critical Zone studies that seek to achieve what can be called Humboldtian goals — a merging of scholarly disciplines with rigor and beauty.

The US South is well known for its writers such as William Faulkner, Charles Chesnutt, Eudora Welty, Zora Hurston, Richard Wright, and James Agee. Much less appreciated is that the South is made famous by scientists. Even during the first decades of cotton farming in the early 1800s, the region's soil erosion and declining soil fertility attracted the attention of geologist Charles Lyell, landscape architect Frederick Olmsted, and agricultural scientist and pro-slavery firebrand Edmund Ruffin.

On this bright April 2014 morning, a new generation of scientists meet at Padgett's Creek Church, excited to learn about the remarkable geology and agricultural legacies of the Southern Piedmont (*see figs.* A *and* B).

The well-respected hydrologist and geomorphologist Gordon Grant opened with a general introduction, pointing with outstretched arm to the hay field in front of the church. Grant suggested that beneath the Piedmont's gently rolling hills were secrets yet to be told, dynamic forces, and past events that were fundamental to the structure and function of the landscape that only a fully integrative Calhoun CZO could discover. In particular, the Piedmont's declension story of how humans have transformed the land is scientifically, historically, and philosophically

B



5 See Terry A. Ferguson et al., "Re-investigation of a colluvially filled valley containing deeply buried organic-rich sediments of Pleistocene age, Pauline, *South Carolina," Southeastern Geological Society of America* 51, no. 3 (2019). doi: 10.1130/abs/2019SE-327726.

6 Alexander von Humboldt and Aimé Bonpland, *Personal Narrative of Travels to the Equinoctial Regions of the New Continent*, vol. 3, trans. Helen Maria Williams (London: Longman, Hurst, Rees, Orme, and Brown, 1818), 321. Originally published in French as *Voyage aux regions équinoxiales du nouveau continent*, vol. 3 (Paris: J. Smith et Gide Fils, 1825).

7 Robert H. Montgomery, *The Cooperative Pattern in Cotton* (New York: Macmillan, 1929), 251.

FIGS.: A — **In the midst of the Calhoun CZO sits Rose Hill Plantation, which is today restored to its appearance in antebellum years. The plantation is of interest to natural scientists, environmental anthropologists, historians, and the public.** B — **In the high resolution LiDAR image (~10km²), the square in the middle of the image is the Rose Hill house with the rose garden the small rectangle to the north of the house. Severe and deep gullies in the old cotton fields encroach on the house from all directions. All the accelerated erosion, gullies, terraces, and legacy sediments occurred from a century of farming, from about 1820 to 1920.**

stunning. The erosion of soils wrought by Europeans and enslaved African Americans since the late 1700s is nearly unbelievable (*see figs.* C 1, 2). Farming for cotton, tobacco, and food crops, most intense from 1810 to 1930, eroded a staggering twenty centimeters of soil across more than ten million hectares.[4] Today, that eroded soil has buried nearly all bottomlands and floodplains under a meter or more of this legacy sediment. Of course, in America, "the land of the free," farming with African slaves eroded more than the soil, a view joined by Alexander von Humboldt, who saw slavery as a critical failure in the young American democracy.

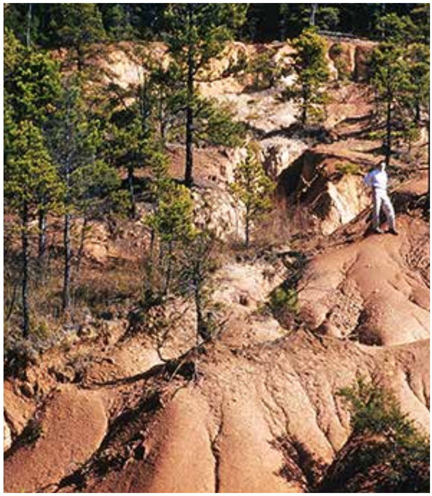
The severity of agricultural erosion across a century of agriculture has long astonished scientists, but equally astonishing are the data being assembled by contemporary scientists. They have quadrupled the estimated age of Piedmont soils to a minimum of two to three million years. Over that time, Piedmont s oils have developed deeply. Soil under the church may extend 40 meters over the granite bedrock. The scientists' work also points to massive instabilities and erosion events throughout geological time.[5] These new data challenge the long-standing paradigm that the Piedmont is one of the most geologically stable regions in America. This new perspective of the Piedmont's inherent instability is reminiscent of Humboldt's comment made after experiencing an earthquake: "We feel that we have been deceived by the apparent calm of nature; … we mistrust for the first time a soil, on which we had so long placed our feet with confidence."[6]

By the early 1900s, the region became one of the most severely eroded and gullied in America. At that time, it was also home to many of the nation's most impoverished people. In 1929 Robert Montgomery, cotton economist at the University of Texas, wrote that farming had turned the South into "a miserable panorama of unpainted shacks, rain-gullied fields, straggling fences, rattletrap Fords, dirt, poverty, disease, drudgery, and monotony that stretches for a thousand miles across the cotton belt."[7]

The impoverishment of land and people attracted a wave of scientists in the 1930s, many of whom worked in and around Padgett's Creek Church. Within kilometers of the church, river sediments were studied by Hans Albert Einstein, who had a lively correspondence about Piedmont erosion with his father, Albert Einstein, then at Princeton. The accomplished geographer Carl Sauer organized Piedmont erosion research from his home in Berkeley, California. Hugh Bennett, the world's leading champion for soil-erosion control, actively publicized erosion research across the Piedmont. Sociologist Howard Odum wrote prolifically about the human-soil Piedmont problem, and Duke

C1

C2



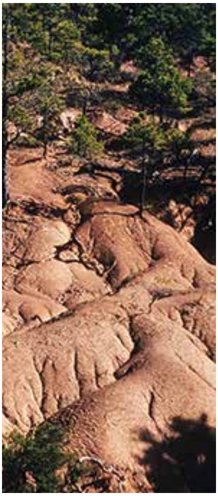
8 See Stanley W. Trimble, *Man-Induced Soil Erosion on the Southern Piedmont*, 1700–1970 (Ankeny, IA: Soil Conservation Society of America, 1974).
9 Louis J. Metz, *The Calhoun Experimental Forest* (Asheville, NC: USDA Forest Service Southeastern Forest Experiment Station, 1958).
10 See Daniel D. Richter et al., "Evolution of Soil, Ecosystem, and Critical Zone Research at the USDA FS Calhoun Experimental Forest," in *USDA Forest Service Experimental Forests and Ranges: Research for the Long Term*, ed. Deborah C. Hayes et al. (New York: Springer, 2014), 405–33.
11 See Daniel D. Richter and Sharon A. Billings, "'One physical system': Tansley's ecosystem as Earth's critical zone," *New Phytologist* 206, no. 3 (2015): 900–12.
12 See Henry J. Oosting, "An Ecological Analysis of the Plant Communities of Piedmont, North Carolina," *American Midland Naturalist* 28, no. 1 (1942): 1–126.

University ecologist Henry Oosting promoted the concept of plant succession that described how Piedmont fields were transforming into secondary forests. Finally, UCLA's Stanley Trimble authored the definitive geographic history of agricultural erosion in the Piedmont, a book still in print today.[8]

By the mid 1930s, the United States Forest Service (USFS) purchased many of the worst-eroded farms in and around Padgett's Creek Church and launched the nearly 1,500 square kilometers Sumter National Forest. The USFS recognized quickly that they were ill-equipped to manage such degraded lands, and in 1947 opened the Calhoun Experimental Forest, which they claimed represented "poorest Piedmont conditions,"[9] given the severity of its land use history, gullying, sedimentation of streams and rivers, and the socio-economic plight of its people. While we can find no documentation explaining why the experimental forest was named after John C. Calhoun, the antebellum senator, vice president, and ardent advocate of slavery, we acknowledge the irony the name brings to this special landscape. After all, the forest was named by the same USFS personnel who selected this landscape for research because it represented "poorest Piedmont conditions."

The Calhoun Experimental Forest had new laboratories and motivated scientists, including Marvin Hoover, Carol Wells, Jim Douglass, and Lou Metz. They brought instrumentation like neutron probes to measure water deep within soils, and delineated experimental watersheds to measure streamflow response to rainfall on deeply gullied and eroded lands. They were particularly interested in how flooding would be attenuated during forest regrowth. Though these Calhoun scientists prolifically published their results, USFS administrators lost interest in the work, and in 1962 curtailed research at the Calhoun Experimental Forest.[10] Fortunately for science, the scientists meticulously archived their treasure trove of samples, data, and photographs.

The 2014 scientists gathered at Padgett's Creek Church are a new wave of investigators to retake the pulse of this severely damaged land (*see fig.* D). They were excited not only to study the Calhoun landscape but to bring their Critical Zone science to pursue and integrate their individual sciences in the same landscape. The Critical Zone after all is defined by a slogan, "From tree top to bedrock," by fluids "from atmosphere to the deepest circulating groundwater," and by its diverse timescales "across human, ecosystem, and geologic time." On the landscape surrounding Padgett's Creek Church, the new Calhoun CZO would engage geophysics, geochemistry, geomorphology, soil science, ecology, hydrology, environmental history,



D

C1, C2 — **Nearly 1000 photographs were taken and archived from the 1930s to the 1950s by the United States Forest Service scientists at the Calhoun Experimental Forest. The Forest Service opened the Calhoun Experimental Forest in 1947 to learn more about managing such fragile and eroded landscapes.** D — **In 2014 nearly 100 scholars and land managers interrogated the Earth's Critical Zone on a trip led by Critical Zone scientists across the Calhoun CZO.**

anthropology, and even geopoetry, to gain a Humboldtian understanding of the land. The prospects must have impressed NSF program manager Barrera, for the Calhoun had recently become one of nine CZOs nationwide and one of dozens worldwide, each testing site-specific hypotheses using tools and ideas from a similarly wide diversity of disciplines. Critical Zone science had been championed by Barrera for years, and by 2014 it was vigorously circulating in the Earth and ecological sciences.[11]

Another idea of Critical Zone science is that data are to be shared as common stock, with first-author and student rights of use respected. Scientific papers interweave individual sciences to forge a deeper understanding of the Earth. Critical Zone science provides advanced education to students and veteran scientists alike, as it accelerates interdisciplinary and disciplinary sciences.

One question that scientists regularly ask at the Calhoun CZO concerns the landscape's regeneration following accelerated agricultural erosion and gullying. Because the Piedmont's erosion has diminished greatly during the region's reforestation since the 1930s, today's impressive green blanket of trees prompts many to suggest that the seriously degraded fields have undergone significant recovery and even restoration in a matter of decades. Some reference Henry J. Oosting's old-field succession to describe the process.[12] Calhoun Critical Zone scientists, however, bring a more critical perspective to landscape restoration and recovery, and thus to soil, ecosystem, and Critical Zone evolution. Although the Calhoun scientists are impressed that Montgomery's "miserable rain-gullied fields" have regrown into an impressive forest in less than one hundred years, the same scientists have repeatedly demonstrated that this reforestation is more mask than recovery; they argue that the fundamental alteration of the Critical Zone by agriculture — including the hydrology, geomorphology, soils, biology, biogeochemistry, hillslopes, and floodplains — will be attenuated only over many centuries and millennia. A most important lesson from the Calhoun CZO may be that landscape restoration simply does not apply to how landscapes and ecosystems evolve through time.

The great intellectual fascination with Earth's Critical Zone will always derive from the extreme diversity among local Critical Zones, as much as from the interweaving of those diverse Critical Zones into the larger Earth system. There is little doubt that this most Humboldtian approach will carry generations of Earth scientists into the future of environmental science — a future in which both place-based and cross-site Critical Zone research will thrive.

The Critical Zone Revelation: I Am in the Skin

William E. Dietrich

One of my favorite activities as a child was to climb to the top of the grass-covered hills behind my parent's house near San Francisco (California) and then slide down the hill on a sturdy piece of cardboard. This often ended in a crash of some sort, leaving me rolling on the grass and partly covered in soil. I found that the Earth has a wonderful smell and feel. This experience must have seeded my interest in nature.

When I went to college I sought out geology, something rarely taught in high school in the USA. I wanted to read the Earth text. But I was not drawn to the jagged mountains of bedrock that pierce the sky, but rather to the rolling hills, mantled by soil and often organized into regularly spaced ridges and valleys. Some great set of processes must be at work to create such landscapes. How is it that hard bedrock can be shaped into the smooth rounded (fun to slide down) hilltops? Those valleys bordering the ridges are lined with channels that join downstream, forming a network of progressively larger channels, which convey away water and sediment — and cut into the bedrock itself. Rivers cut down into bedrock; hillslopes emerge between the channels; regular spacing of ridges happens: a self-organized system. No genetic code to guide it. Wow.

One rainy day in the mid 1970s, early in my graduate studies at the University of Washington, I sat in my International Harvester four-wheel drive vehicle in the Cascade Mountains and drew in my field book a boxes and arrows flow diagram of how I thought soil-mantled landscapes worked and produced the sediment found in streams. Bedrock must be converted to soil, the soil must move downslope, and the soil must enter the stream. Locally, on steep slopes, the soil mass can collectively fail, producing a landslide, which may carry on down the receiving canyon, scouring it of sediment and delivering it to downstream channels. All this happening over tens to hundreds of thousands of years and, but for the landslides, invisible to the eye.

I had spent months walking river channels in the Oregon Coast Range and surveying freshly made logging road cuts to get a glimpse of the soil and the underlying bedrock. The road cuts showed that the bedrock beneath the soil was greatly altered due to chemical and physical changes as infiltrating rain water passed through it. This weathering was the first step that turned hard bedrock into the mobile material that became the soil that entered streams. The road cuts showed deep tree root penetration and infilled burrows of animals that had dug into the weathered bedrock, suggesting that life was the primary agent breaking up the weathered bedrock and turning it into soil.

Looking back now I see that the box and arrows plot I made up became a road map for my scientific research. In my graduate studies, and then through my scientific research career of some forty years, I have sought to identify and to quantify the mechanisms that shape the Earth's surface. Life was a player in this, but I didn't really see the whole stage in which it played, and I didn't recognize this dynamic skin in which we live. It was only recently have I realized that I had mapped the skeleton of a section of the Critical Zone, but I had not yet seen it as a thing, but rather as a series of interactions that I needed to sort out.

About a decade ago, the entirety of the Critical Zone — from forest canopy top down to fresh bedrock — came as a revelation as I leaned against a 60 m tall tree in the Northern California Coast Range. It was a cool afternoon at the end of summer. No rain had fallen for nearly five months, yet the needles of this tree were bright green. The soil it grew in was less than 50 cm thick and, to the touch, very dry. How can such a thin soil provide moisture for a huge tree throughout the dry summer (and to the surrounding dense forest of tall trees)? A quick simple calculation said it couldn't.

I had recently learned that each day hundreds of little mouths (stomata) on individual needles would open to draw in atmospheric carbon, but at a price of losing water. This is how the trees "eat" and "transpire." That released water elevates the local moisture in the air, cooling it. That moisture is swept away by winds and can gather with other moisture to form clouds: somewhere to the east, moisture from this tree's mini mouths were raining out and returning to the ground. I had never looked up before: geologists look at the ground.

The tree had to be getting its moisture from a deeper source than the soil. It must be the underlying weathered bedrock. OK, then the depth and porosity of the weathered bedrock must determine how much moisture can be stored there. And what determines that porosity? What converts impermeable bedrock, that we use to make kitchen counters, into the equivalent of a kitchen sponge — holding winter rain that is tapped by tree roots, which then send that water out to the stomata and to the atmosphere? How might the Critical Zone depth influence what vegetation can grow and how vegetation communities will respond to extended drought?

Suddenly, I saw that the slow workings of geologic processes, that shape hills and weather to a porous stone the underlying bedrock and produce a mobile soil, were driven by biotic processes that enhanced the storage of water (and nutrients) to life itself: a co-evolving system connected from canopy top down to fresh bedrock.

Now I wish I could put on some kind of underground diving gear and swim through the soil and weathered bedrock and see how the deep Critical Zone works and how it varies across different landscapes. Imagine swimming through the root zone and peering close up at the complex root system in which trees share nutrients and disturbance warnings. I would want to dive deep to the fresh bedrock boundary of the Critical Zone and follow that boundary across hillslopes, taking notes on how the boundary varies and what might control that. I would need special magnification on my face mask to see the abundant microbial life there, and I would need to bring my own oxygen, as the microbes will have caused the CO_2 to rise to greater than two hundred times our current atmospheric levels.

We know that in general the Critical Zone mediates the currencies of watersheds: including water, sediment, biota, and nutrients. Water that saturates the pores in the weathered bedrock forms groundwater that runs off and becomes stream flow. In seasonally dry environments, all the water in streams is drainage from the Critical Zone. Fish habitat and water supply to wildlife and to people in the dry season depends on how much groundwater is stored during the wet season in the Critical Zone and then slowly released to streams. We must learn how this dynamic, self-organized, co-evolving skin of the Earth works in order to anticipate how water supplies, ecosystems, and climate will change in our warming Earth.

Scientists are sometimes criticized for being most excited about what we don't know. But isn't that why as children we poke things and taste things, and why we build ships to go to uncharted waters of the Earth or to the strange worlds beyond this planet? The Critical Zone is where we live and, surprisingly, it is also a frontier area of research.

Let's go back to the hillslope behind the house. Let's explore down to the fresh bedrock and discovery how this dynamic skin varies across that hill, across watersheds, and across continents. There is so much to read in this earthly text, and we need to do it now.

Fig. 1: Black Diamond Mines Regional Preserve, Northern California, USA, October 2019.

Students descending a grass-covered convex-shaped hillslope

Fig. 2: Eel River CZO, Northern California, USA, July 2015.

When a large tree fell downslope, the roots that had penetrated deeply into the underlying weathered bedrock of the Critical Zone pulled up intact weathered bedrock. The broken blocks slowly are released and then tumble downslope as the roots decay.This process of "tree throw" both produces soil from bedrock and causes downslope transport of soil.

Fig. 3: Black Diamond Mines Regional Preserve, October 2019.

Here, dense marine shale is weathered and broken into a clay rich soil which when wetted in the winter swells and moves downslope. Measurements show the transport rate is proportional to steepness of the slope. The steepens downslope (making the convexity) to accommodate the increasing soil transport.

Fig. 4: Eel River CZO, August 2017.

Students collecting water samples from the Vadose Zone Monitoring System by using a slight vacuum to displace water at depth to the surface. The open panel shows each of the control devices to bring water to the surface. There are two holes with ten sample ports each.

Fig. 5: Eel River CZO, July 2015.

On this hillslope, over 500 sensors send data every five minutes to data loggers housed in the wooden structure. Sap flow in trees, moisture in the soil and underlying bedrock, groundwater levels, air humidity and temperature, solar radiation, wind, and rainfall are all tracked across the hillslope.

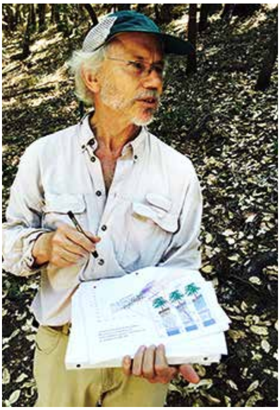


Fig. 6: Eel River CZO, July 2015.

William E. Dietrich is shown discussing the pattern of moisture availability (documented by Daniella Rempe) and pattern of isotopes in water in the Critical Zone (documented by Jasper Oshun). It is through such measurements that vital processes of the Critical Zone are revealed.

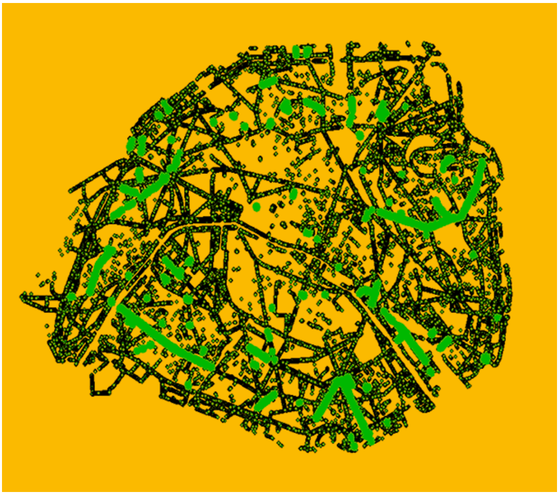
Fig. 7: Eel River CZO, July 2015.

By digging with a geologic hammer, William E. Dietrich is showing that the weathered bedrock is highly fractured and loose. Weathering of the bedrock creates porosity in an otherwise dense and nearly impermeable bedrock. On average 300 mm of the annual winter rainfall of 2,000 mm is stored in the weathered bedrock and used by trees during the long hot summers.

Fig. 8: Eel River CZO, October 2015.

Installation of the Vadose Zone Monitoring System. The blue sleeve is being slid down a hole which was drilled at 55 degrees to the horizontal. On the sleeve's walls are devices for extracting water and gas and measuring temperature and moisture content every 1.5 m below the surface to about 16 m depth. Monitoring every two weeks was initiated in 2015. This enables tracking of moisture and the chemistry of the water and gasses as they evolve through the unsaturated part of the Critical Zone above the water table.

A



B

C

D

Exploring Trees, Soils, and Microbes in the Streets of Paris

Aleksandar Rankovic

URBAN TREES, LAWNS, and shrubs surround us, the majority of humans today, every day, in parks or along sidewalks. Fast-paced greening initiatives are multiplying in many cities worldwide, as has recently been best illustrated by New York City's program MillionTreesNYC and its goal to plant one million new trees across the city in a decade. Such programs usually aim for embellishing cities but also, increasingly, to adapt cities to climate change and make them more livable altogether. Harnessing the healing power of plants to better the lives of urbanites subjected to the harshness of their cities' climate has long been present in modern thought. Noah Webster, for instance, the lexicographer who compiled the first American English dictionary, worried about the excess heat of cities and its effect on health, writing in 1800 that "wide streets, bordered with rows of trees, would be infinitely preferable to all the artificial shades that can be invented. Trees are the coolers given us by nature."[1] Coolers, yes, or even mere ornaments. In typical modern fashion, we also have a long history of neglecting the agency of trees and other plants, even of those in front of our houses, office buildings, or universities. Now that we expect even more from them, with the threat of climate change, it might finally be time to turn toward them and kindly ask what they have been up to.

Their answer, of course, cannot be straightforward, and it will take a lot of patience and scientific mediation to understand even some of the most basic features of their existence. This, in itself, can be true for any organism on Earth. But urban regions are also the most complex, and least well known, parts of the Critical Zone. They are often characterized by high spatial heterogeneity, reduced connectivity, anthropogenic soils, surface sealing, high near-ground atmospheric CO_2 concentration, high levels of atmospheric nitrogen (N) deposition, increased surface temperatures and heat island effects, high levels of pollutant contamination, hydrologic changes, increased presence of non-native organisms, highly diverse materials and artifacts, intense management practices, and so on.[2] Understanding trees in a forest is already a daunting task, but in an urban jungle, it is exponentially more difficult.

THE CITY OF PARIS manages close to 200,000 trees, with about 100,000 in its streets alone (*see fig. A*). Planting a tree in Paris has rested on similar principles since the nineteenth century and the Haussmannian works that established street tree plantations as part of the Parisian landscape (*see fig. B*).[3] When planting a new sapling (of age seven to nine years), a pit about 1.3 meters deep and 3 meters wide is opened in the sidewalk and filled with newly imported peri-urban agricultural soil

1 Noah Webster, *A Brief History of Epidemic and Pestilential Diseases*, vol. 2 (London: G. G. and J. Robinson, 1800), 376. See William B. Meyer, "Urban Heat Island and Urban Health: Early American Perspectives," *The Professional Geographer* 43, no. 1 (1991): 38–48; Aleksandar Rankovic, Chantal Pacteau, and Luc Abbadie, "Services écosystémiques et adaptation urbaine interscalaire au changement climatique: un essai d'articulation," *VertigO*, special edition 12 (May 2012), http://journals.openedition.org/vertigo/11851.

2 See Mark J. McDonnell and Stewart T. A. Pickett, "Ecosystem Structure and Function along Urban-Rural Gradients: An Unexploited Opportunity for Ecology," *Ecology* 71, no. 4 (1990): 1232–7; Lisa G. Chambers et al., "Developing the scientific framework for urban geochemistry," *Applied Geochemistry* 67 (April 2016): 1–20.

E

3 See Patricia Pellegrini, "Pieds d'arbre, trottoirs et piétons: Vers une combinaison durable?," *Développement durable et territoires* 3, no. 2 (July 2012), http://developpement-durable.revues.org/9329.

4 See Carlo Calfapietra, Josep Peñuelas, and Ülo Niinemets, "Urban Plant Physiology: Adaptation-Mitigation Strategies under Permanent Stress," *Trends in Plant Science* 20, no. 2 (2015): 72–5.

5 See Aleksandar Rankovic, "Living the street life: Long-term carbon and nitrogen dynamics in Parisian soil-tree systems" (PhD diss., Université Pierre et Marie Curie, 2016).

FIGS.: A — **GIS layer produced by the City of Paris, each dot represent a street tree. Highlighted are the locations of silver lindens.** B — **The Parisian culture of trees, the grid surrounding trees. Then a cart (and its operator) used to move and plant trees, and a sideview of a young tree, with the grid not resting directly on the soil, to avoid its compaction. Georges Lefebvre, *Plantations d'alignement; promenades, parcs et jardins publics* (Paris: Vicq-Dunod, 1897), figs. 97, 114, and 15.** C — **Measuring the circumference of a silver linden "at breast height".** D — **The rewarding sight of a 50 cm soil core.** E — **Sampling the leaves of an old Parisian silver linden.**

from the surrounding region. If soil is already in place from a previous tree, it is entirely excavated, disposed of, and replaced. This process occurs because it is assumed that trees "exhaust" soils during their lifespan, and that a "new" soil, full of nutrients, is necessary for the next tree. This "soil exhaustion" hypothesis has never been tested empirically, however. Once a tree and its soil are placed in a sidewalk, surrounded by a landscape of stone and concrete, it is now up to them to find their own resources: no fertilizers are applied by city managers, nor is irrigation provided. To make things worse, the aboveground leaf litter is almost completely removed every year: no recycling is possible, no rich humus development in sight. No wonder people think that trees will exhaust soil resources to the last drop.

But the complex interactions of trees and their soils should not be underestimated. And trees, like all plants, are far from passive organisms: although urban plant ecophysiology is still a nascent discipline, it already shows that plant response to urban environments can be full of surprises.[4] But how to explore these responses? How to reveal the agency of street trees and soils, and the strategies they put in place for subsisting? I hypothesized that trying to reconstruct the long-term history of street soils and trees could help us catch glimpses of their mode of existence,[5] and this essay is the story of this work.

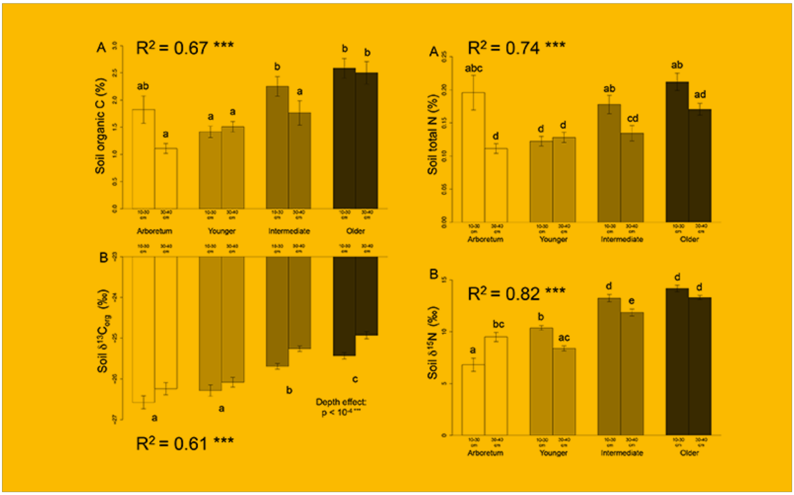
How can one study the history of trees, soils, and their interactions? One way is to use the research apparatus that we ecologists like to call a chronosequence. A chronosequence is an approach, widely used in ecology and soil sciences, based on the assumption that similar systems of different ages, when put into a series of data, can depict a theoretical temporal trajectory for the studied systems.

How could we apply this approach to Parisian trees and soils? Remember that in Paris, tree age provides a good proxy of soil-tree system age, e.g., the time that a tree and soil have spent interacting in street conditions. Comparing soils and trees that have just been placed together in Paris to soils and trees that have already spent decades in the city's street conditions could help us reconstruct an urban ecological history.

The first step, here, was to select the tree species to study and then select the precise trees to be studied. This was easier said than done! Put yourself in the shoes of the urban ecologist walking the streets and hoping to find some statistical regularity in the behavior of trees on which virtually no such data is available, and which live in a milieu that is already giving the researcher a headache.

By order of elimination, the choice was set on the beautiful silver linden (*Tilia tomentosa*),

F



G

6 See Markus Ammann et al., "Estimating the Uptake of Traffic-Derived NO_2 from ^{15}N Abundance in Norway Spruce Needles," *Oecologia* 118, no. 2 (1999): 124–31.
7 See Margaret M. Carreiro and Christopher E. Tripler, "Forest Remnants Along Urban-Rural Gradients: Examining Their Potential for Global Change Research," *Ecosystems* 8, no. 5 (2005): 568–82; Nancy B. Grimm et al., "Global Change and the Ecology of Cities," *Science* 319, no. 5864 (2008): 756–60; Marina Alberti, "Eco-Evolutionary Dynamics in an Urbanizing Planet," *Trends in Ecology & Evolution* 30, no. 2 (2015): 114–26.

a species from Central Europe, considered well suited for street plantations because of its aesthetics and resistance to street conditions, and which has been used in Paris since at least the nineteenth century. From my understanding, there were about 11,000 of them in the streets of Paris. I first tried to select "my" trees remotely: I explored the databases of the city, and especially the Geographic Information System (GIS) layers that are publically available and which contain, for each tree planted in Paris, the information on its species and its diameter — which I used as a first proxy for tree age. I aimed for the smallest trees (the youngest) and the largest trees (the oldest), and also chose medium-sized trees (of supposed intermediary age). The selection eventually had to be done by foot and by hand, by exploring streets where I knew the silver linden could be found, and measuring and selecting trees that could compose my chronosequence (*see fig.* C — yes, it was market day).

This led to the design of a 75-year chronosequence of street plantations, comprising 78 sites spread across Paris.

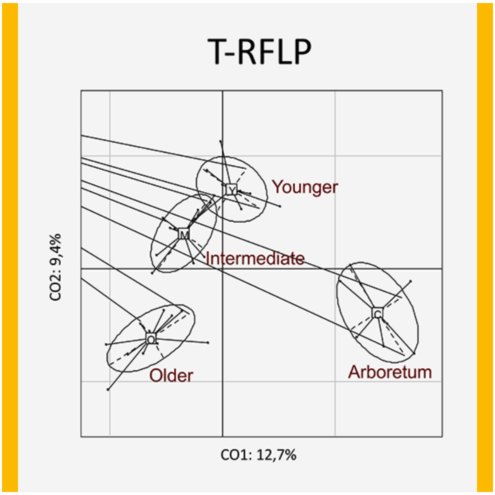
But now, what to measure, and what to compare? There are hundreds of variables that could have been assessed, but one has to start somewhere.

Street trees and soils face quite a puzzling situation. Intuitively, the removal of leaf litter could indeed suggest a gradual loss of organic matter and nutrients from soils. But plants also bring a massive amount of organic matter to soils through their roots, both through exudates and the death and regeneration of fine roots. Very little is known about street trees' root ecology, or how they explore the confined space of their pit. The soil in pits is also likely to receive a series of contaminants, to be compacted, and to be regularly disturbed… What life could we find in these soils (*see figs.* D *and* E)?

Furthermore, the urban environment contains more nitrogen sources than other settings. At first, you would probably, maybe amusingly, think this is mostly due to "animal droppings"; it is in fact a much more complex situation. Because of numerous combustion processes (such as car engines and domestic heating), the urban atmosphere is full of nitrogen that can be assimilated by soils and plants, either after it has been deposited on soils or even directly through leaves. A study of pine trees along a highway in Switzerland estimated that no less than 25% of the nitrogen in their needles originated from car exhausts.[6] Trees could thus find benefits in pollution, and become partly independent from their soil … partly landless!

In Paris, contrary to what had been assumed,

H



F — On the left, data on soil organic carbon content and stable isotope ratios. On the right, data on soil nitrogen content and stable isotope ratios. A strong age-related effect is visible for each variable. G — Preparing soils for incubation, to analyze different microbial activities in the lab. H — Soil DNA was extracted, and molecular analyses show that soil microbial communities tend to differ between soil groups (here showing data for soil bacteria).

older soils were found to be richer in carbon and nitrogen than younger soils, and contained at least as much carbon and nitrogen as soils from a peri-urban arboretum: they don't seem to get exhausted with time (*see* fig. F). Why is this? Street trees seem to develop a higher fine-root density (intermediate and older street trees showed three times more fine roots in the topsoil than younger trees and trees from the arboretum of a similar age), maybe because there is not much space to explore in their pit and they try to maximize the resources they can get from the surface: nutrients, but also water.

The accumulation of nitrogen in soils, with a specific isotopic signature, suggests strong inputs to soils from the atmosphere — probably coming from cars. Isotopic data on nitrogen also showed a very strong difference between roots and leaves, maybe the highest difference ever reported in the literature: trees seem to get a substantial amount of their nitrogen from outside of the topsoil. As they grow, and as their need for nitrogen grows as well, street trees seem to develop strategies to acquire nitrogen either from deeper in the pit or outside of their pits, by exploring under the sidewalks (tree roots usually do not respect the boundaries given to them; they can, for example, be found down in the sewers, to get water) or by directly absorbing nitrogen from car exhausts through their leaves — like the trees along the Swiss highway (*see* fig. G).

Some authors have suggested that urban ecosystems could be seen as "sentinels of change," foreshadowing what ecosystem responses to global changes, such as global warming and human inputs of nitrogen into the biosphere, could look like in the decades to come.[7] What is the broader message that trees are telling us? Their soils are getting richer with time, but they seem to be getting hungrier and thirstier still. The main reason for this is that the territory we allocate them, these cubes of soil in sidewalks, are too small to sustain them in the long run. Oh, trees are not as docile as we might think; their roots can move and crack the hardest rocks and macadam. But still, living in the street is hard and stressful for them too. What they tell us is that they need us to expand their territory on our sidewalks, they simply need more space in the highly anthropized world they live in. When you think of it, this message actually makes them eloquent representatives for the rest of biodiversity, and true sentinels of the Anthropocene (*see* fig. H).

Beware of Precursors: How Not to Trace the History of the Critical Zone

Simon Schaffer

THE RECENT CONSTRUCTION of the Critical Zone as an object of collectively coordinated surveillance depended on the institution of an innovative and extensive observatory network. This observatory system is defined by the integration of the characteristic sites the stations occupy and, simultaneously, by coordination of the broad scope of what gets done there. Connections within the Earth's thin surface layer rely on and sustain links in the systems of observatory practice.[1] There is an obvious precedent for this Critical Zone network in the innovative earlier nineteenth-century projects to set up observatory networks to scrutinize meteorology and natural history, geomagnetism, and atmospheric physics in regions just below and above the planet's surface. The protagonists of these observatory networks, scientific servicemen and protagonists of a physics of the globe, conjectured that the phenomena they studied were of worldwide dimensions. Then they used this claim to recruit massive public resources to work at that global scale. Finally, they exploited these resources to seek to make their original conjecture stick. These programs depended on the expansive aims of militant European and North American states. They proclaimed the advantages of resident observers backed with reliable equipment in comparison with the allegedly superficial gaze of the passing traveler. Importantly, they welded new-fangled systems of combined scientific labor to the zone connecting mines and mountains, oceans, and rivers.

In his 1836 manifesto for what he defined as global "data," the great Prussian naturalist Alexander von Humboldt declared that "certainty and importance" could be secured only through "establishments which shall remain permanent for a great number of years, of Physical Observatories."[2] Humboldt's Creole collaborators and informants in South America sometimes denounced the speed and superficiality of his own rapid travels there.[3] For Humboldt, the vertical program that would address the "grand problem of subterranean meteorology"[4] and the physiognomy of life just beneath and just above the surface of the planet was the central endeavor of these new sciences. The aim was to "depict entire countries as a mine is represented."[5] In 1831, Humboldt's ally the astronomer John Herschel spelled out how the observatory enterprise would work: "All the information that can possibly be procured, and reported, by the most enlightened and active travelers, must fall infinitely short of what is to be obtained by individuals actually resident upon the spot."[6] The aim was somehow to combine the expertise of residence with the authority of the observatory to win "that complete acquaintance with our globe as a whole, which is beginning to be understood by the extensive designation of physical geography."

There is thus a long-term history to be explored connecting the very definition of the Critical Zone and models of scientific development with enlightenment and civilization. Sources for the model of the planet showing a laminar zone of biogeological significance have been located in the decades around 1800. Alongside the Humboldtian provenance, the Earth theories and historicist philosophies of the later eighteenth century are especially favored as candidates for the ancestry of this account of the Earth which links its physiology, geology, and surveillance. The Scottish milieu of the gentleman farmer and natural philosopher James Hutton (1726–97) has been singled out as a key moment in the inauguration of the program. Immediate interactions between steam technologies, labor transformation, and new enterprises in political economy and civic polity put this Scottish culture at the center of the transformation that has attracted some of the most intense debate about the advent of the Anthropocene epoch.[7] In his important 2002 note on the "geology of mankind," Paul Crutzen notoriously identified the coincidence between what he chose to call "the design of the steam engine"[8] by James Watt in 1784 and the start of the growth of carbon dioxide and methane in polar ice concentrations.The collective civic and industrial network occupied by Watt and his colleagues, including Hutton, Joseph Black, David Hume, and Adam Smith, lay at a fateful fulcrum of social and physical transformations.

The network including James Hutton as well as Adam Smith, of whom Hutton was the literary executor, insisted that

1 See Susan Brantley et al., "Designing a network of critical zone observatories to explore the living skin of the terrestrial earth," *Earth Surface Dynamics* 5 (2017): 841–60; Cheryl Lyn Dybas, *Discoveries in the Critical Zone: Where Life Meets Rock* (Alexandria, VA: National Science Foundation, 2013).

2 Alexander von Humboldt, "Letter on the Advancement of Knowledge of Terrestrial Magnetism," *London and Edinburgh Philosophical Magazine and Journal of Science* 9 (July–December 1836): 42–53, here 50.

3 See José Cañizares-Esguerra, *Nature, Empire, and Nation* (Stanford, CA: Stanford University Press, 2006), 114f.

4 Alexander von Humboldt and Aimé Bonpland, *Personal Narrative of Travels to the Equinoctial Regions of the New Continent*, vol. 1 (London: Bohn, 1851), 270. Originally published in French as *Voyage aux Régions équinoxiales du nouveau continent*, vol. 1 (Paris: F. Schoell, 1807).

5 Hanno Beck, "Alexander von Humboldts 'Essay de Pasigraphie' (Mexiko 1803/04)," *Forschungen und Fortschritte* 32, no. 2 (1958): 33–9, here 37.

6 Here, and in the following, references are to John Herschel, *Preliminary Discourse on the Study of Natural Philosophy* (London: Longman, Rees, Orme, Brown, and Green, 1831), 349f.; see also Christopher Carter, *Magnetic Fever: Global Imperialism and Empiricism in the Nineteenth Century* (Philadelphia, PA: American Philosophical Society, 2009), 32–5.

7 See Fredrik Albritton Jonsson, *Enlightenment's Frontier: The Scottish Highlands and the Origins of Environmentalism* (New Haven, CT: Yale University Press, 2013).

8 Paul Crutzen, "Geology of mankind," *Nature* 415, no. 6867 (2002): 23.

the system of the Earth be understood as a complex machine. The key object that bound these two models together was the steam engine. The Earth understood as steam engine generated the notion of a coordinated zone of earthly activity. Perhaps it was therefore unsurprising that when seeking a genealogy for his own account of the Earth system, James Lovelock would find it in the late Enlightenment world of Smith, and especially of Hutton. In 1972, recalling his proposal for the very term "Gaia" and its derivation from the Greek personification of Earth as mother, Lovelock remarked that "the concept of Gaia has been intuitively familiar throughout history and perhaps only recently has it been distorted by anthropocentric rationalizations."[9] Pressed to locate this concept in a better lineage, Lovelock claimed that Hutton had lectured at the Royal Society of Edinburgh in the 1790s on the Earth as a "superorganism" to be studied through physiology; the subsequent view of Earth from space allegedly confirmed Hutton's notion of Earth as superorganism; and in Hutton's honor, Lovelock named his own science "geophysiology."[10]

The provenance of these keywords in the vocabulary of Gaia is telling. James Hutton never spoke of a superorganism nor of any physiology of the Earth. Furthermore, his model was ruthlessly teleological: this was a machine subject to a purpose.[11] The word "superorganism" was coined in the mid-1890s to express one version of the organic metaphor of the state: large-scale social communities were to be understood as structured like biological systems, often with a white supremacist sense of evolutionary ascendancy and interracial struggle.[12] The term "geophysiology" was introduced into Earth sciences at exactly the same moment by the pre-eminent Oxford geographer Halford Mackinder to encompass the disciplinarily geographic study of climates and of organic life.[13] It somehow seemed useful for Lovelock, however, instead to locate such idioms of an animate planet not in the Gilded Age racial science and geopolitics that spawned them, but in the Edinburgh Enlightenment. Lovelock's source for this version of Hutton was a pair of lectures, one given in 1948 on the 150th anniversary of Hutton's death at Edinburgh by the geologist Sergei Tomkeieff, the other delivered by one of Tomkeieff's students, Donald McIntyre, to the American Geological Society in 1962. According to Tomkeieff, the Edinburgh natural philosopher made no distinction between organic and inorganic materials and accepted the notion of the Earth "as a sort of superorganism."[14] In this, so Tomkeieff claimed, Hutton strikingly anticipated both Alfred North Whitehead's version of organicism and Vladimir Vernadsky's concept of the biosphere.[15] Speaking at a similarly celebratory and disciplinary occasion, McIntyre echoed the claim: "the secret of Hutton is that he thought of the world as a sort of superorganism. His was not the mind of a narrow specialist. For him the biological sciences were completely integrated with the physical."[16]

The sanctification of James Hutton — and, by implication, the specific traditions on which he drew in geotheory and the precedents he found in classical and early modern doctrines of purposive design and the system of the world — has played a significant role in subsequent formulations of the disciplinary site for studies of ecosystems and geobiology. In the inaugural pages of a new journal on the health of marine ecosystems in 1992, it was argued bluntly that "the concept of ecosystem health was probably first applied by James Hutton, a Scottish physician and geologist, who in 1788 delivered a paper to the Royal Society of Edinburgh on a theory of the Earth as a superorganism capable of self-maintenance."[17] Similarly, in the very first article published in a new journal on geobiology in 2003, the Harvard biologist Andrew Knoll cited Lovelock's judgment that "the founding document of geobiological thought is none other than the foundational text of modern geology, James Hutton's (1788) *Theory of the Earth*" and that "Hutton's arguments strike the 21st century reader as surprisingly modern, but then our sense of modernity in geological thought derives in no small measure from Hutton himself."[18] Knoll did note that Hutton made no outright acknowledgment that life was any important part of geologically significant process. More boldly, the Princeton ecologist Simon Levin a couple of years later simply restated Lovelock's attribution to Hutton of the lapidary claim that "I consider the Earth to be a superorganism and ... its proper study should be by physiology."[19]

This form of creative historical invention is not of itself immensely significant. More indicative, however, is the relation it implies between the active surveillance of the Critical Zone and the other kinds of disciplinary practices pursued within geophysiology. Hutton's schemes provided none of the materials attributed to them by twenty-first-century practitioners of geophysiology, but nevertheless reordered and focused traditions within modernity's notions of the animate planet and its quality as a complex system. Hutton was intimately involved in the early stage of the massive reorganization of agricultural production and the political economy of agrarian labor and its effects. He thus applied Scottish experimental chemistry

9 James Lovelock, "Gaia as seen through the atmosphere," *Atmospheric Environment* 6, no. 8 (1972): 579f., here 580.

10 See James Lovelock, "The Earth as a Living Organism," in *Biodiversity*, ed. E. O. Wilson (Washington, DC: National Academies Press, 1988), 486–9; James Lovelock, "Geophysiology," *Transactions of the Royal Society of Edinburgh* 80, no. 3–4 (1989): 169–75, see especially 169.

11 See Cándido Manuel García Cruz, "De la 'Teoria de la Tierra' de James Hutton a la 'Hipótesis Gaia' de James Lovelock," *Asclepio* 59, no. 1 (2007): 65–100, see especially 96.

12 See Daniel Brinton, *The Basis of Social Relations: A Study in Ethnic Psychology* (New York: Putnam's Sons, 1902), 39.

13 See Halford Mackinder, "Modern Geography, German and English," *Geographical Journal* 6, no. 4 (1895): 367–79, see especially 375.

14 Sergei I. Tomkeieff, "James Hutton and the philosophy of geology," *Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences* 63, no. 4 (1949): 387–400, here 398–400.

15 See ibid., see especially 398–400.

16 Donald B. McIntyre, "James Hutton and the Philosophy of Geology," in *The Fabric of Geology*, ed. Claude C. Albritton (Reading, MA: Addison Wesley, 1963), 1–11, here 7.

17 Peter Calow, "Can ecosystems be healthy? Critical consideration of concepts," *Journal of Aquatic Ecosystem Health* 1 (1992): 1–5, here 1.

18 Andrew Knoll, "The geological consequences of evolution," *Geobiology* 1, no. 1 (2003): 3–14, here 3.

19 Simon Levin, "Self-Organization and the Emergence of Complexity in Ecological Systems," *BioScience* 55, no. 12 (2005): 1075–9, here 1075.

and thermal measures to the puzzles of Earth history in a setting dominated by the principles of the division of labor and exploitation described by his friend Smith, whose writings he edited as executor. In writings now anachronistically read as the founding texts of modern geology, Hutton explained the course of Earth's history as guided by an invisible hand so that the amount and quality of cultivable land was preserved and the security of landowning agrarians secured. There was a precise equivalence between Hutton's Earth history and Smith's political economy: in both systems, apparently errant individual behavior in the natural economy (such as volcanic eruptions and gaseous uplift) or the moral economy (such as individual self-interest) were in fact means of maximizing the welfare of the whole of nature (through processes such as preservation of fertile soil) or society (through the increase in common wealth).[20]

The enlightened agronomist became surveyor of the entire planet (*see fig.* 1), with agricultural production as the goal of the invisible hand's wise governance. Hutton compared the limited view of mere shepherds and farmhands who saw no change in mountain or valley with the perspective of the informed philosopher who could divine a system of change and wisdom: "It is thus that a system may be perceived in that which, to common observation, seems to be nothing but the disorderly accident of things; a system in which wisdom and benevolence conduct the endless order of a changing world."[21] Finding Hutton as an ancestor thus matched Lovelock's attitude to the Smithian invisible hand. He has compared the dilemma of self-interest that Smith's principle of the invisible hand was supposed to resolve with that of "selfish genes" and natural selection which nevertheless permit the emergence of a common good. Gaia theory holds that "as our planet evolves, it keeps its climate and its chemistry always fit for life. The invisible hand that regulates the earth system operates through feedbacks, negative and positive, between its living and nonliving parts."[22] The political message was unmistakable: "in politics, it took a long time before we recognized that feedback from market forces could not be ignored; I suspect that we face a similar slow learning process about our relationship with the Earth. Meanwhile we are still trying to shape it to our needs and we ignore, even disable, its own powerful guiding hand."

It is plausible to conjecture that this kind of market politics played its role in the widespread decision to choose Hutton as the ancestor of contemporary geophysiology. Hutton was clear that the planet must be seen as a machine, a system of circulation that evidenced processes of repair, circulation, and reproduction: "We are thus led to see a circulation in the matter of this globe, and a system of beautiful œconomy in the works of nature. This earth, like the body of an animal, is wasted at the same time that it is repaired."[23] This was a machine in the form of what he called "an organised body"[24] that was capable, like a highly idealized Watt engine, of self-repair and maintenance. Crucially, life was understood not as the principal part of the machine's function, but rather as its ultimate goal: "the circulation of the blood is the efficient cause of life; but, life is the final cause, not only for the circulation of the blood, but for the revolution of the globe."[25] The potent claims that humanity played a decisive role in Earth history as "efficient cause," and that the planet itself was to be seen as animate, were absorbed and then effaced in Huttonian geotheory.

Hutton's avid interpreter Humboldt never used such notions as "superorganism" or "geophysiology." Yet, he much more clearly debated the active agency of organisms in the scenography and physiognomy of the planet's history. His admiration for Hutton was clear, and he used the Edinburgh theorist to reassess the data he'd collected in his surveys of the so-called New World after 1800: "Hutton was without doubt on the path to a large number of things which we now know or believe," Humboldt wrote. "I regard it is as a great misfortune not to have read Hutton before my departure for the Americas. The *sciences of combination* are not created all of a sudden."[26] Combination would turn out to be decisive in the reformation of the animate world. The fascinating relationship between Humboldt and the traditions of human agency and of a living planet embodied and debated in early modernity and the Enlightenment help show how, in the enterprises in which Humboldt and his collaborators engaged, models of the system of the Earth were gradually reconstructed as accounts of an Earth system. Humboldt's great survey of this system was entitled *Cosmos: A Sketch of a Physical Description of the Universe*, a work he started writing in 1819.[27] He long pondered its proper title. In the end (and in German), he chose *Kosmos* because it explicitly and unavoidably linked heavens and Earth in a single whole, precisely because it was "quite opposed to '*Gaea*,'"[28] a term then associated with the physical survey published by the Berlin teacher August Zeune, a solid and orthodox account of the geography of the Earth.

20 See R. Grant, "Hutton's theory of the earth," in *Images of the Earth: Essays in the History of Environmental Sciences*, ed. Ludmilla Jordanova and Roy Porter (Chalfont St Giles: British Society for the History of Science, 1997), 37–51; Charles W. J. Withers, "On Georgics and Geology: James Hutton's 'Elements of Agriculture' and Agricultural Science in Eighteenth-Century Scotland," *Agricultural History Review* 42, no. 1 (1994): 38–48.

21 James Hutton, *An Investigation of the Principles of Knowledge*, vol. 2 (Edinburgh: A. Strahan, and T. Cadell, 1794), 239; see also Martin J. S. Rudwick, *Bursting the Limits of Time: The Reconstruction of Geohistory in the Age of Revolution* (Chicago: University of Chicago Press, 2005), 160f.

22 Here and in the following James Lovelock, "Selfish Greens," *Prospect*, June 20, 2004, http://www.prospectmagazine.co.uk/magazine/selfishgreens.

23 James Hutton, *Theory of the Earth, with Proofs and Illustrations*, vol. 2 (London: Cadell, Junior, and Davies; Edinburgh: William Creech, 1795), 562.

24 James Hutton, "Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe," *Transactions of the Royal Society of Edinburgh* 1 (1788): 209–307, here 216.

25 Hutton, *Theory of the Earth*, vol. 2, 546.

26 Letter from Alexander von Humboldt to François Arago, 19 February 1840, in *Correspondance d'Alexandre d'Humboldt avec François Arago*, ed. Théodore Jules Ernest Hamy (Paris: Guilmoto, 1909), 185. Translated from the French, emphasis added.

27 Alexander von Humboldt, *Cosmos: A Sketch of a Physical Description of the Universe*, 5 vols., trans. Elise C. Otté (New York: Harper & Brothers, 1866). Originally published in German as *Kosmos: Entwurf einer physischen Weltbeschreibung*, 5 vols. (Stuttgart: J. G. Cotta, 1845–62), 22.

28 Letter from Humboldt to Karl August Varnhagen von Ense, 24 October 1834, in *Letters of Alexander von Humboldt to Varnhagen von Ense from 1827–1858*, trans. Friedrich Kapp (New York: Rudd & Carleton, 1860), 38. Originally published in German as *Briefe von Alexander von Humboldt an Varnhagen von Ense* (Leipzig: F. A. Brockhaus, 1860); see also Aaron Sachs, *The Humboldt Current: A European Explorer and His American Disciples* (Oxford: Oxford University Press, 2007), 87.

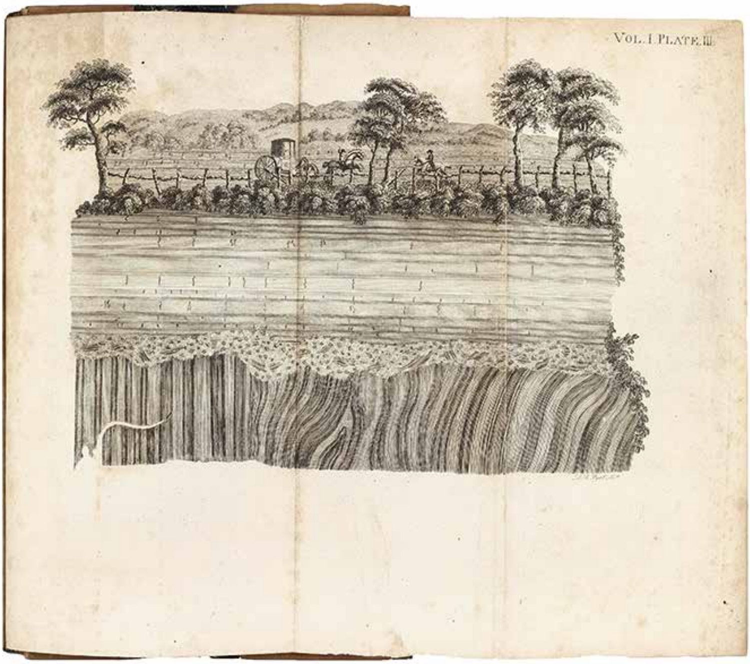


Fig. 1: James Hutton, *Theory of the Earth, with Proofs and Illustrations*, vol. 1 (London: Cadell, Junior, and Davies; Edinburgh: William Creech, 1795), plate 3. James Hutton's representation of an unconformity at Jedburgh in the Scottish borders, where sandstone overlays shale, engraved from a drawing by Hutton's collaborator John Clerk. The orderly society of agriculture and civilization is sustained by the succession of layers deposited in Earth history.

Humboldt and his allies aimed to innovate and systematize the survey sciences and the biogeography and cosmology they inherited and accumulated. They assembled resources to suggest how living beings could play a fundamental role in the transformation of the planet, exactly the notion absent from Hutton's writings. It was in the cartographic and survey programs of Humboldt and his interlocutors in Europe and the Americas that the lineaments of a theory of the Critical Zone were constructed. Their insight — that the thin biofilm beneath and above the planet's surface is where atmosphere and geology have been modified by life — draws much of its plausibility from the data systems inaugurated at that earlier nineteenth-century moment of the imperial meridian and the aggressive scrutiny of the planet that accompanied it. Crucial here, no doubt, was the enterprise of the survey: the centralized accumulation of immense series of data extracted and extorted from geological, paleontological, meteorological, and natural historical traces, juxtaposed and compared in a *science of combination*.[29] In choosing Hutton as ancestor, versions of climate science and geophysiology have selected a machinist and a teleological model of the system much indebted to the carbon transformation of the world economy. This is a provenance that undermines the enterprise whose ancestry is at stake. By reflecting instead on the preconditions of the systems of representation, information, and combination that made possible the modeling of and inquiry into the biogeography of the Earth's surface and crust, a better history of the Critical Zone as concept and aim would emerge.

29 See Michael Dettelbach, "The Face of Nature: Precise Measurement, Mapping, and Sensibility in the Work of Alexander von Humboldt," *Studies in History and Philosophy of Science, Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* 30, no. 4 (1999): 473–504; Patrick Anthony, "Mining as the Working World of Alexander von Humboldt's Plant Geography and Vertical Cartography," *Isis* 109, no. 1 (2018): 28–55.

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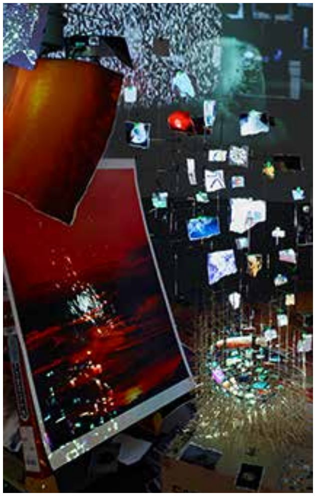

Sarah Sze as the Sculptor of Critical Zones

1 See Philip Morrison, Phylis Morrison, and the Office of Charles and Ray Eames, *Powers of Ten: A Book about the Relative Size of Things in the Universe and the Effect of Adding another Zero* (San Francisco: W. H. Freeman and Company, 1982).
2 See Bruno Latour and Timothy M. Lenton, "Extending the Domain of Freedom, or Why Gaia Is So Hard to Understand," *Critical Inquiry* 45, no. 3 (2019): 659–80.

Bruno Latour

IF I WAS AWESTRUCK by this version of *Timekeeper*, it is because Sarah Sze managed to bring about a model perfectly attuned to the actual state of our material conditions, *seen from within*. It took a sculptor to curb our obsession with the globe, as if the fine arts could also yield discoveries able to give object lessons to scientists and their findings.

Viewers experience first an arresting effect of *multiplicity* when they encounter the *Timekeeper* series for the first time, or when they close in on its shimmer. It's pullulating. And this is indeed why astronomical space is so distinct from the Critical Zone: the latter is *heterogeneous*. When you consider a terrain, a forest, a city, or a body, each and every centimeter is different. Each and every detail matters. The space is not isotropic, and cannot be unified quickly. What must be conveyed first are profusion and superposition. Sarah Sze manages to do this not by scattering nature's component parts, but by multiplying the elements we must learn to *compose* with, frame by frame, piece by piece, pixel by pixel.

Second, there is the issue of *scale*. No one has ever managed to assess the scale of Sarah Sze's artworks. Nobody knows whether they represent the infinitely large or the infinitely small, whether they champion atoms or viruses. In the case of astronomical view, everything is neatly arranged by size, as perfectly as in *Powers of Ten*, the remarkable short film produced by Charles and Ray Eames.[1] Although we are well aware of its trickery, of the fabricated nature of its seamless traveling shot, we are irresistibly engrossed in the montage, believing it, in the same way we feel we are floating through space when using *Google Earth* — while in reality the computer merely switches between databases. The same protocol will not apply to Sarah Sze's work: the closer you get, the less you can hold on to concepts like traveling shots or nesting dolls.

Yet her goal is not to make you feel discombobulated. On the contrary, she is simply being a realist. Like her art, the world she aims to depict does not follow *Google Earth*'s logic. A drop of milk, a puma roaming the wild, the fragment of a door, a cell, a galaxy, a hair, a truck... each and every thing surveys all others according to its own metrics, in its own way. Indeed, doesn't the very definition of Gaia hold that the smallest parts (bacteria) eventually form the largest ensembles (the atmosphere)?[2] It is impossible to hierarchize in a single definite order of precedence all the elements contributing to the animation of the Critical Zone. Of all things, the measure is each thing.

This extraordinary vision does not stop here. How do you address the issue of the viewer's position? How do you solve the problems brought by any type of global vision? In front of a globe, everybody feels like Atlas, as powerful as a god. Global vision prompts hegemonic abuse, facilitating unchecked maneuvers towards power or knowledge. The globe makes the megalomaniac. How can we watch the world without seeing it as — at best — a mere spectacle to enjoy, or — at worst — a territory to seize by force?

Sarah Sze does give a successful answer: viewers must be *surrounded* by the artwork as they

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FIGS.: A – C — **Sarah Sze, *Flash Point* (*Timekeeper*), 2018. Mixed media, dimensions variable. Installation views Gagosian, 2018/19.**

tiptoe towards it. Layer upon layer, veil upon veil, reflection upon reflection — this is how viewers can escape the dichotomy between seeing inside-out or outside-in, as if they were caught in a vortex, or pushed onto a carousel. They become "composers of space" in their own right, explicitly so when their T-shirts briefly stand as some of the many screens on which the projections appear, hosting this or that thing visitors will have to compose with. For the Critical Zone cannot be escaped, cannot be judged from a distance — and this is one of the most exact characteristics of the verifiable image of the world.

What's more, the artist has undone another limitation tied to an astronomical view: the continuous and homogeneous representation of all successive layers harboring life on Earth — as if the Critical Zone looked like a *mille-feuille* or a pile of mattresses — stacking geospheres, hydrospheres, biospheres, atmospheres, and so on. On the contrary, Sarah Sze's assemblages are never structured through continuous, self-contained envelopes that would stand apart one from another. Each one is permeable, and every one is constantly interrupted. What matters is the intermeshing of the components rather than their similarity. Water, CO_2, ozone, migratory birds, pollutants, bacterial plasmids, financial flows, iterations of memes: they each follow a different cycle that intersects all others but do not form a spherical structure. Besides, in front of *Timekeeper*, the clicks and gasps of the sonic landscape invented by the sculptor prevent you from imagining yourself sitting in front of a spectacle simply meant to be enjoyed from afar. Once again, the lack of tidiness is striking, not because it would answer the need for an artificial injection of disorder, but conversely because it strives to replicate realistically the *heterarchy* that characterizes life on Earth. Sarah Sze sculpts the anti-sphere as well as the anti-globe.

This *modus operandi* is precisely what confers most of their realism on the images of the world Sarah Sze manages to animate. After all, the living beings of the Critical Zone also have limited means to elaborate their great schemes: they would use the most ordinary objects readily available and hastily throw them together, patch up whatever might last longer or better the best they could, relying solely on fleeting opportunities. This explains the eerie familiarity viewers experience when they come into contact with Sarah Sze's work: everything is structured, balanced, composed with care, yet everything is eminently fragile. Indeed, scientists have dubbed as "critical" the zone they are trying to define in contrast to nature or the cosmos, for the very reason that it is extremely fragile and obstinately resilient. Earth — the Earth we actually live on — is not monumental at all. Consequently, its sculpted representation must also avoid monumentality by all means.

Excerpt from Bruno Latour, "*La vérifiable image du monde*," *published in the upcoming catalogue of the exhibition* Sarah Sze, *Fondation Cartier pour l'art contemporain*, *Paris*, 2021.

Translated from the French.

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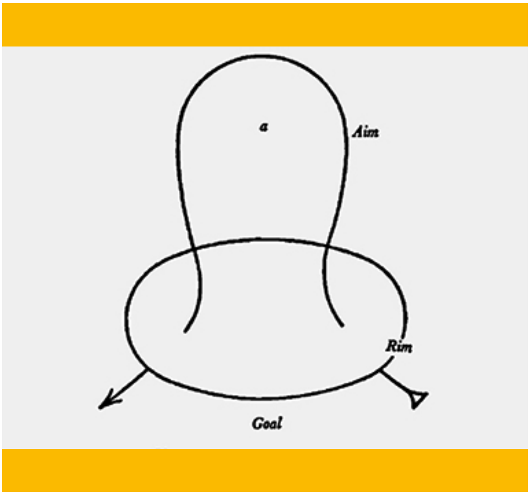

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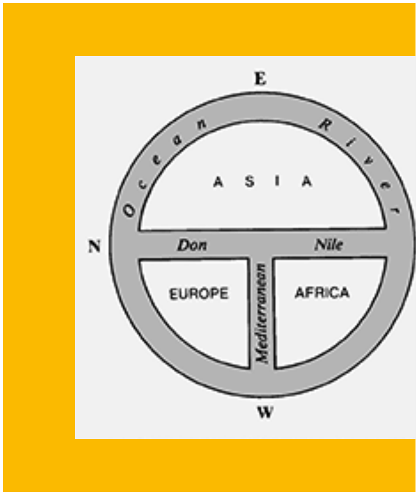


This Planet Which Is Not One: On the Notion of Zone

Jeanne Etelain

THE EARTH HAS long been conceptualized via the figure of the globe. The confrontation between an ahistorical, disinterested eye and an external, inert world seen only from afar seems rather too clearly required by a predatory culture. For the Earth is conceived as a uniform and unified totalizing whole that can be appropriated, divided, and exploited at the risk of endangering life. In these terms, the planet never amounts to anything more than an abstract ball structured with vertical lines, horizontal parallels, and right angles: a homogeneous, continuous, universal space.

Yet "where are you residing when you say that you have a 'global view' of the universe?," asks Bruno Latour.[1] In the age of human-induced environmental disaster, it is no longer possible to pretend to see the Earth from outside; we cannot deny that we are *on* it and that it responds to us. Isabelle Stengers speaks of the intrusion of Gaia. This Goddess, however, is nothing like Mother Nature, the generous one who continuously provides for us despite how we treat her. Gaia is a set of interconnected entities that function in their own way, with their own goals, yet together create the ideal physicochemical conditions of their existence. Her geography is far more diversified, more multiple in its differences, more complex, and more subtle than is commonly imagined — in an imaginary rather too narrowly focused on oneness. And, above all, Gaia is ticklish.

Thus, a group of scientists are working to rework the concept of Earth with that of the Critical Zones. The term refers to the heterogeneous portions of the planet's surface, which stretch from the top of the tree canopy to deep underground, encompassing all of the processes that make life possible. Put another way, Critical Zones form the skin of Gaia. But why opt for the term "zone"? Perhaps "land" is too embedded within the nature-talk, "territory" sounds too political, and "area" reads as overly geometrical. Perhaps, too, the term better connotes the sense of the unknown, reminiscent of a mysterious place such as the one visited by the characters in Andrei Tarkovsky's science fiction movie *Stalker* (1979). In any case, "zone" emphasizes a different topography, one that challenges and resists established notions of space.

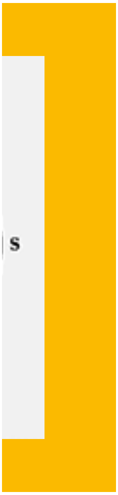
"Zone" comes from the Greek *zônê*, derived from the verb *zonnunai*, "to gird," which itself is derived from the Sanskrit *junāmi*, "to join, to link." Although it designates a girdle or belt in Homer, it was mainly a scientific term used in premodern cosmology. Zones appear in an ancient speculative theory and cartographic representations of the world, which became outdated through fifteenth and sixteenth century sea expeditions. Greek astronomers inferred from the sphericity of the Earth and its inclination

1 Here Bruno Latour paraphrases Peter Sloterdijk in *Facing Gaia: Eight Lectures on the New Climatic Regime,* trans. Catherine Porter (Cambridge: Polity Press, 2017), 123. Originally published in French as *Face à Gaïa: Huit conférences sur le nouveau régime climatique* (Paris: La Découverte, 2015).

2 There has been some confusion between zone and climate. Although both express the inclination of the Earth in relation to the Sun, climate (from the Greek "to slant") translates the length of the days while zone translates the length of the shadow. See Jean-Marc Besse, *Les grandeurs de la Terre* (Lyon: ENS Éditions, 2003), 50–3.

3 Ibid.

4 See Jeanne Etelain, "Qu'appelle-t-on zone? A la recherche d'un concept manqué," *Les Temps modernes*, no. 692 (2017): 113–35.



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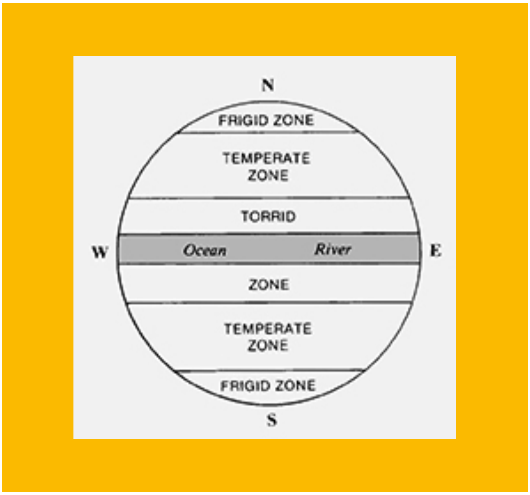

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5 Luce Irigaray, *This Sex Which Is Not One,* trans. Catherine Porter and Carolyn Burke (New York: Cornell University Press, 1985). Originally published in French as *Ce sexe qui n'en est pas un* (Paris: Éditions de Minuit, 1977).

6 Sigmund Freud, "Three Essays on the Theory of Sexuality," [1905] in *The Standard Edition of the Complete Psychological Works of Sigmund Freud*, vol. 7, ed. James Strachey (London: The Hogarth Press, 1975), 123–243. Originally published in German as *Drei Abhandlungen zur Sexualtheorie* (Leipzig: Franz Deuticke, 1905).

FIGS.: A — **Figure from Jacques Lacan, *Le Séminaire: Livre XI. Les quatre concepts fondamentaux de la psychanalyse* [1964] (Paris: Éditions du Seuil, 1973), 163.** B — **David Woodward, the tripartite type of *mappamundi*, 1987. A T-O map is a type of European medieval world map that represents the three known continents (Asia, Europe, and Africa) divided by the "T" formed by the Mediterranean Sea and the Nile River, and encircled by the "O" of the Ocean beyond which the Earth ends.** C — **David Woodward, the zonal type of *mappamundi*, 1987.** D — **The five zones of the Earth. In Macrobius Ambrosius Theodosius, *Commentarii in Somnium Scipionis*, manuscript on parchment (ca. 1150), f. 34r.**

relative to the Sun the division of the planet's surface into five latitudinal areas (one torrid, two frigid, and two temperate) according to the length of the shadow cast on a gnomon.[2] Put literally, terrestrial zones were conceived of as the belts of the Earth.

But the theory goes further. It led to certain beliefs about the habitability of the planet and the perfect conditions under which life could flourish. Since exposure to the Sun was considered either too long or too short in the torrid and frigid zones, these were considered inhospitable. As for the temperate zone located in the southern hemisphere, the Antipodes, it was regarded as habitable yet unknowable because inaccessible due to the deadly heat of the torrid zone that isolates it. That is why, according to historian Jean-Marc Besse, early modern Portuguese austral navigations — which demonstrated to Europeans that the torrid zone could be crossed and even inhabited — invalidated the doctrine of zones and prompted the formation of a new concept of the Earth.[3]

Maps derived from this ancient doctrine stand out from T-O maps and other medieval varieties that depict only the ecumene: the known and inhabited world. On the contrary, zonal maps offer an entire view of the planet showing little interest in topography such as relief, hydrography, or settlement. However, they have nothing to do with the imaginary of the globe, which drives the concept of a universal Earth wherein the ecumene fully coincides with the terrestrial orb considered in its totality. If only one part of the world is habitable, then the doctrine of zones entails that space is heterogeneous from the point of view of physics, discontinuous from the point of view of mathematics, and regional from the point of view of human existence.

Locating the ecumene in relation to the rest of the Earth, zonal maps decenter human beings and relativize the size of their world with respect to the extent of the planet. Moreover, the doctrine emerges from a reflection on the relation of the Earth to the Sun within the cosmos. For both these reasons, zone appears as a relational concept while pertaining to a consideration of the whole and its parts. Unlike the globe, which imposes its oneness, zones always express a relation between at least two terms (e.g., the Earth/the Sun, or the ecumene/the planet). This is perhaps why the various uses of the word suggest that it connects as much as it divides.[4] Zones, always at least double, come inevitably in the plural.

The differential ontology that underpins zones has not escaped the attention of feminist psychoanalyst Luce Irigaray. In *This Sex Which Is Not One* she rejects the monist Freudian theory of sexuality, one which undermines (sexual) difference in favor of the primacy of the male sexual organ in the constitution of the human psyche.[5] Instead, E

7 See Gilles Deleuze and Félix Guattari, *Anti-Oedipus: Capitalism and Schizophrenia*, trans. Robert Hurley (New York: Viking Press, 1977), especially 43–60, for an extensive analysis. Originally published in French as *L'Anti-Œdipe: Capitalisme et schizophrénie* (Paris: Éditions de Minuit, 1972).

8 Sigmund Freud, "Three essays on the Theory of Sexuality," 169.

9 This principle of differentiation is also found in land-use planning: zoning consists in dividing a city or a territory according to specific purposes alongside permitted uses and exceptional regulations. See Etelain, "Qu'appelle-t-on zone?"

10 First developed in Gayatri Chakravorty Spivak, *Imperative zur Neuerfindung des Planeten. Imperatives to Re-Imagine the Planet* (Wien: Passagen Verlag, 1999); then reworked in Chapter 3: Planetarity in *Death of a Discipline* (New York: Columbia University Press, 2003), 71–102.

11 See Jeanne Etelain, "La caresse philosophe," *La Deleuziana*, no. 6 (2017): 40–9.

she explores a pluralist theory of sexuality using as an alternative paradigm the female genitals, conceived not as being composed of one, but of at least two organs: the vulva's touching lips. She progressively pluralizes sexuality further by referring to the very multiplicity of women's — but arguably of all humans' — erogenous zones, ranging from the tips of the nipples to the core of the clitoral hood.

The concept of erogenous zone was first coined by Sigmund Freud. It is precisely the observation that "certain regions of the body" (*Körperstellen*), other than the genitals, are experienced as pleasurable that leads him to elaborate a non-reproductive theory of sexuality.[6] It is telling that Freud substitutes the word "zone" for *Stelle*, meaning "place" or "position," but also "point" or "digit." Whereas *Stelle* designates pregiven units that can be gathered into a whole, such as a straight line or a set of numbers, zones are always partial, to use Mélanie Klein's words, meaning untotalizable.[7] Thus, the erogenous body differs equally from the organism — the organized functional body found in biology — and the phenomenal body — an unequivocal lived, occupied place. Although one zone always calls for another — the mouth sucks, the hand caresses, and the arms embrace — connecting zones together will never yield a well-rounded body.

We should be careful therefore not to allow the theory of erogenous zones to become too easily associated with the psychosexual stages. Freud paved the way when he imagined a progressive integration of the erogenous zones into a harmonious whole. Each stage — the oral, the anal, the phallic, the latent, and the genital — is matched to a different erogenous zone as the primary source of pleasure. Ordered in a temporal sequence, transitioning from early childhood to adulthood, and intertwined with complex psychic mechanisms, zones become instrumental in the libidinal organization of the body unified under the rule of the phallus. This teleological development is exactly what Irigaray rejects, for it reduces difference to oneness. In her text, she revives instead the anarchic multiplicity found at the core of erogenous zones.

Using the notion of "drive," psychoanalysis resorts to a conceptual framework borrowed from modern physics and sees the body as an energetic field rather than an extended surface (*res extensa*). In this understanding, subdivisions of space that we normally envision as static and unchanged locations imply the idea of mobile areas activated by a stream of energy. Accordingly, space would be indeterminate in terms of its divisions as well as fundamentally dynamic in character, moving us well beyond conceptions of space as some kind of empty, homogeneous

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D — **Kamal Zharif Kamaludin, Lujiazui Finance and Trade Zone, Pudong, Shanghai, China, 2010. Photograph.** F — **Andrei Tarkovsky, *Stalker*, 1979. Film, 161 min.**

container. The sense of swarming indetermination is further supported when Freud argues that the skin, and by extension the whole surface of the body, is the erogenous zone "*par excellence*."[8]

Is it stretching it too far to bring the planet together with the erogenous body? Despite the almost two millennia separating psychoanalysis from ancient cosmology, it seems clear that both notions of zone depart from an imaginary centered around oneness. Both envision another kind of totality, one that is neither atomist nor holist, since the part is always richer than the whole and the whole is nothing but partial. That is why talking about the zones of Gaia might change our conception of her, imagining her less like a superorganism. Furthermore, the zone paradigm invokes in both theories a surface — be it the Earth or the body — that is heterogeneous, relational, multiple, indeterminate, and dynamic. Thus, zones would correspond to differentiated spaces — hence the need to qualify them with the use of adjectives such as "temperate" or "torrid."[9]

Thinking of the Earth as we think of a lover might not be such an odd idea. Ecosexual activists lead by performance artists Annie Sprinkle and Elizabeth Stephens consider, for example, that the lover archetype is more ethical insofar as a lover must care for their romantic partner or they will likely lose them. Gayatri Chakravorty Spivak advocates a similar analogy when she imagines the planet as the "home" of all living beings, a generative source akin to the female womb, which is as uncanny (*unheimlich*).[10] Her argument acquires a special resonance in the Anthropocene: as landscapes, seasons, and species undergo radical changes, our surroundings become increasingly unfamiliar, even threatening. And many are aware of an ambient feeling, reflected in apocalyptic discourses, that we may no longer be welcome at home. To conclude, I would simply add that if Stengers is right to describe Gaia as ticklish, then the Critical Zone might be especially so. Perhaps our task, as Earthbounds, is to caress them.[11]