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Key Points:

- The critical zone is a new and exciting frontier in earth and biological sciences
- Critical zone science is transforming our understanding of linkages among vegetation, soils, bedrock, and the movement of water
- Critical zone science contributes to understanding key social problems: forest health, soil productivity, and effects of natural disasters

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The frontier beneath our feet

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Abstract Following the simple question as to where water goes when it rains leads to one of the most exciting frontiers in earth science: the critical zone—Earth's dynamic skin. The critical zone extends from the top of the vegetation canopy through the soil and down to fresh bedrock and the bottom of the groundwater. Only recently recognized as a distinct zone, it is challenging to study because it is hard to observe directly, and varies widely across biogeoclimatic regions. Yet new ideas, instruments, and observations are revealing surprising and sometimes paradoxical insights, underscoring the value of field campaigns and long-term observatories. These insights bear directly on some of the most pressing societal problems today: maintaining healthy forests, sustaining streamflow during droughts, and restoring productive terrestrial and aquatic ecosystems. The critical zone is critical because it supports all terrestrial life; it is the nexus where water and carbon is cycled, vegetation (hence food) grows, soil develops, landscapes evolve, and we live. No other frontier is so close to home.

Plain Language Summary One of the newest and most exciting frontiers in earth sciences is the critical zone: the thin, dynamic skin of the terrestrial Earth that extends from the top of the vegetation canopy through the soil and down to fresh bedrock and the bottom of groundwater. The critical zone is where water moves, vegetation grows, roots spread, organic matter decomposes, soil develops, and rock weathers. It's also where we, and most life, lives, and is therefore "critical" to our survival. Studying the critical zone has rapidly become an international and interdisciplinary science effort utilizing field studies, long term observatories, and new geophysical measurement techniques. These studies are revealing insights into a broad range of previously unexplored topics: where do trees get their water, how does rock weather, and where does water go when it rains. Understanding the critical zone is vital to addressing key environmental and social problems: maintaining soil productivity in intensively managed landscapes, ensuring that forests don't die during droughts, and improving landscape resilience to wildfires, floods, and hurricanes. Today, the term "critical zone" provides an essential organizing principle for the earth and biological sciences just as "ecosystem" did for ecology half a century ago.

1. New Insights From Ancient Questions

The greatest questions in science are beguilingly simple. How old is the Earth? When did the Grand Canyon form? Was there ever life on Mars? Yet satisfactorily answering even such basic inquiries can be anything but straightforward. In fact, the history of scientific discovery is littered with dramatic conflict, heated contentions, and pointed controversies that developed around competing hypotheses put forward to answer fundamental questions. Many, curious about the inner workings of the Earth, may expect neat, clear explanations to their simple questions; they assume that scientists figured out the answers long ago. As scientists, we know this is not often the case. We are trained to continuously reevaluate even widely accepted conclusions in light of new information. Some of the grandest challenges in science are posed when we continue exploring the simplest questions.

Consider a simple hydrologic question: where do rivers come from? A casual observer watching the seemingly inexhaustible flow of water rise and fall in the channel over time might wonder why there is perhaps only a passing relationship between the amount of water in the river and local rainfall. While it is now well-understood that rivers come from water precipitating out of the sky over wide areas, seeping into the ground, and then emerging at springs that feed creeks, and ultimately flowing into rivers under the

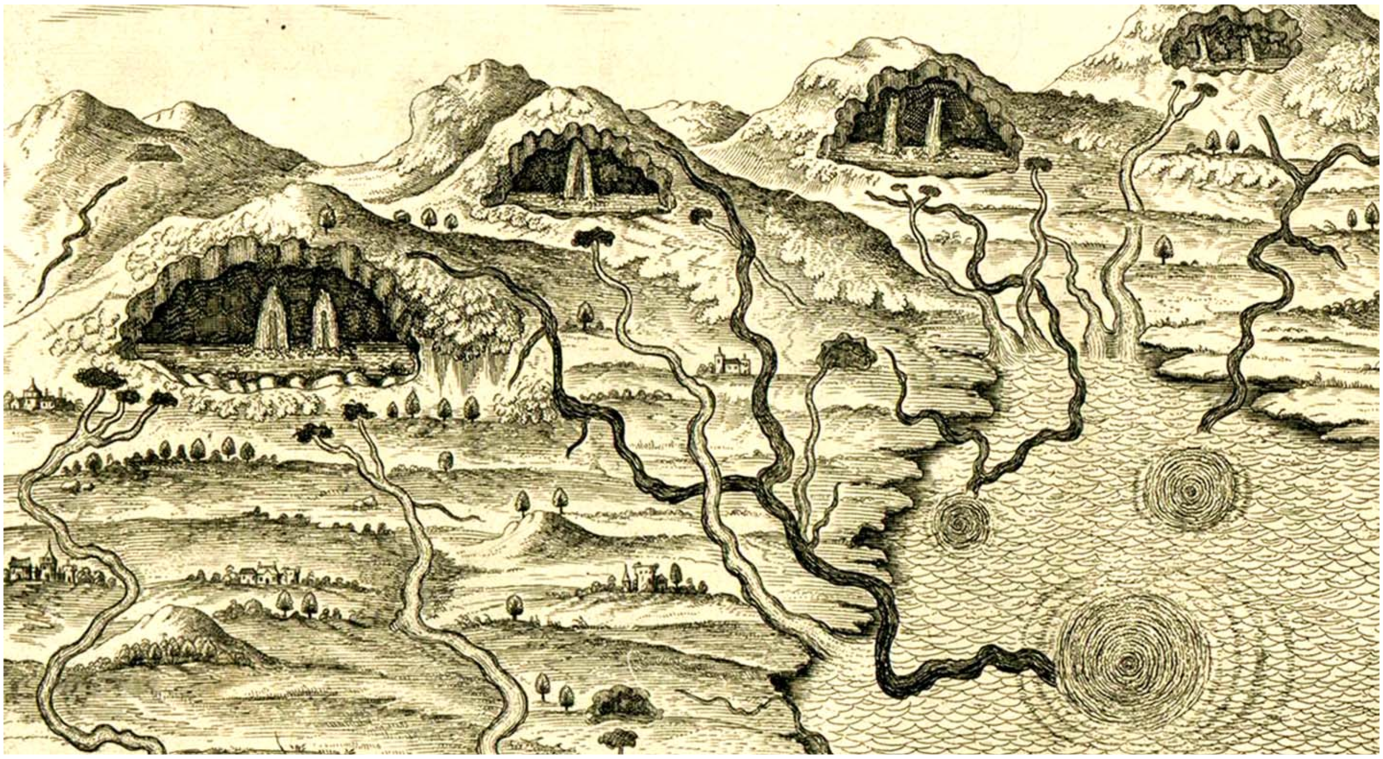

Figure 1. A medieval conception of how the ocean serves as the source of water for springs. Giant whirlpools suck water into subterranean passages that travel underground through hydrophylacia to feed mountain springs; in the process, low porosity rocks and/or heating and condensation from fires deep in the earth filter out the salt. From *Kircher* [1665], *Mundus Subterraneus*.

influence of gravity, this was anything but clear to those living in the 16th and 17th centuries. At that time, there was widespread conjecture that the direct source of the water that emerged at springs was the ocean, as illustrated by *Kircher* [1665] (Figure 1). The pressure of whirlpools in the ocean pushed water uphill through complex subterranean passages termed hydrophylacia [*Tuan*, 1968; *Karterakis et al*., 2007]. Bernard Palissy (circa 1510 to circa 1589), a French hydraulics engineer and potter, was the first to elucidate a hydrological cycle connecting the ocean, atmosphere, precipitation, and river systems [*Karterakis et al*., 2007]. Today, the concept of the hydrologic cycle is widely taught and most might therefore consider the matter closed scientifically.

In fact, the slightly broader question—where does the water go when it rains—remains an open and exciting topic in hydrology. Again the answer (water collects and runs off the surface or goes into the ground) appears obvious at first; but then where? What pathways does it follow, and how long does it take to journey from the ground to the river? Can it go somewhere else? How much of it never reaches a river because it is returned to the atmosphere by evapotranspiration? When did the water in the river today fall from the sky? How does the passage of water transform its own chemistry and the media through which it travels? In pursuing the answers, even leaving aside the underground mysteries of urban plumbing, we rapidly encounter a multiplying set of complexities and unknowns that take us to the very frontiers of earth science, and highlight the ongoing need for basic—boots on the ground, hands in the dirt—field studies.

2. The Critical Zone: An Emerging Frontier

One new frontier in hydrologic science is the *critical zone* (Figure 2). The critical zone is the thin (10s to 100s of meters thick) dynamic, skin of the terrestrial Earth, extending from the top of the vegetation canopy through the soil and down to fresh bedrock and the bottom of groundwater. In landscapes underlain by bedrock, typical of most hilly and mountainous regions, the bottom of the critical zone is associated with the transition to fresh bedrock. In effect, the slow weathering of bedrock creates increased porosity and conductivity that draws water deeper into hillslopes. More broadly the critical zone is where water moves, vegetation grows, roots spread, organic matter decomposes, soil develops, and rock weathers. It is also where we, and most life, lives, and is therefore "critical" to our survival.

While efforts to understand the relationship between the surface and subsurface are not new (one can view Figure 1 as a medievalist view of the critical zone), what makes the critical zone a scientific frontier is several fold. First, it has not been previously identified, labeled, and understood as a unit of study in and of itself. The critical zone is as much about dynamic interactions and processes as it is about a static structure. Within the critical zone, water is the master currency. Water moves through the profile, depleting some subsurface soil layers of cations while enriching others. Vegetation communicates with the weathered bedrock as roots take up water and nutrients and release acids that attack the rock. Microorganisms, including fungi, bacteria, and viruses, that have not even been identified much less described, set up housekeeping on roots, soil particles, and rock fracture zones where they mediate water uptake, chemical exchanges, and ecosystem functions. Over time, subsurface weathering fronts advance in response to this suite of processes, even as the elevation of the surface itself changes in response to water-driven cycles of erosion and deposition. Hence, the critical zone defines a discrete, bounded, describable, mappable, and researchable layer of the Earth's terrestrial surface.

Second, the critical zone below the soil is hard to observe. The conductive weathered bedrock region that lies between the base of the soil and the fresh bedrock is virtually unexplored. Stimulated by support from the National Science Foundation, recent deep drilling campaigns and explorations with near-surface geophysics are beginning to open the window into the architecture, structure, and moisture dynamics below ground [e.g., *Holbrook et al*., 2014; *Parsekian et al*., 2015]. Although the subsurface is hard to see, fortunately, the zone above the ground can be scanned and documented with airborne laser mapping of ever increasing resolution. But matching surface topography to what lies beneath remains a challenge.

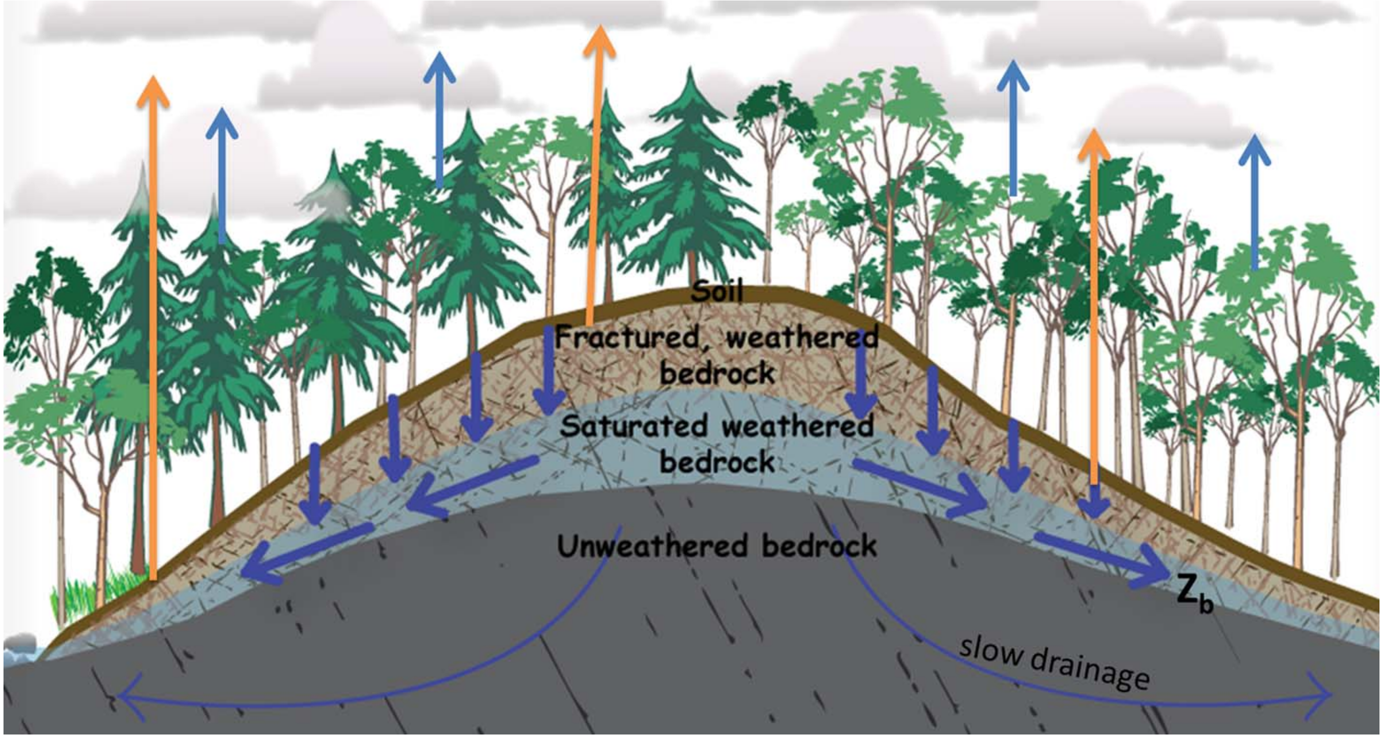

Figure 2. In upland landscapes underlain by bedrock, the critical zone extends from the canopy top to the transition to fresh bedrock. In this example, the critical zone thickens toward the hillslope divide, developing a thick weathered bedrock zone. The thick blue arrows show the vertical path of water through the unsaturated (vadose) zone. Reduction in saturated conductivity at the transition to fresh bedrock can lead to perching of groundwater, which then drains laterally to adjacent streams. Water is returned to the atmosphere from soil moisture and rock moisture (in the weathered bedrock) via transpiration (upward directed blue arrows) and evaporation (orange arrows and mostly from the soil). In this case, slow drainage and drying of the saturated fresh bedrock leads to weathering, and permits the introduction of atmospheric and biotically controlled acids and oxidants, and progressive advance of the weathering front (modified from *White et al*. [2015]).

Third, the critical zone is not uniform across the landscape. It is evolving in response to the properties of the underlying bedrock, type, and density of vegetation, temperature, and hydrologic regimes driven by climate, human land use, and geological history and differs widely in its fundamental architecture over varying spatial scales. Understanding how these fundamental controls dictate critical zone structure requires targeted field campaigns and detailed long-term measurement programs in a range of biogeoclimatic settings [*Tetzlaff et al.*, 2017]. These campaigns and programs become the windows through which we observe the cryptic critical zone and explore hypotheses as to its formation and function.

3. An Interdisciplinary and International Initiative

Studying the critical zone is inherently an interdisciplinary science effort, requiring the perspectives and methods of hydrologists, geomorphologists, biogeochemists, ecologists, and climatologists. This combined approach allows scientists to better explore the exciting and scientifically rich questions that must be woven together to answer the simple ones. What controls the spatial pattern of the critical zone across different landscapes? Does the vegetation know what kind of bedrock lies beneath the root zone, and does the bedrock know what is growing on top of it? How will a climatically changed atmosphere and a land surface modified by human activities affect the deeper critical zone and vice versa? These fundamental inquiries lead directly to more applied questions. Can landscape degradation be reversed? Can intensively managed soils retain carbon, nutrients, and the capacity to grow food? Can the critical zone be managed to improve water quality?

Answering these questions is an international endeavor. Critical zone science has emerged as one of the fastest growing arenas in the earth sciences with organized efforts underway in the United Kingdom, France, Germany, China, Greece, and many other countries (see http://www.czen.org/site_seeker). Within the United States, the primary flagship of critical zone science is the National Science Foundation supported Critical Zone Observatory program (http://criticalzone.org/national/). In nine locations ranging from the tropical mountains of Puerto Rico to the alpine and subalpine mountains of Colorado and California to the cornfields of Illinois, the critical zone is intensively studied to expand our understanding of this fascinating frontier and answer the challenge posed by the simple questions.

4. Lessons From the Critical Zone

What are we—the collective science community—learning from all this work? Much of what has been discovered about the critical zone is counterintuitive. We are learning, for example, that the deepest critical zones in montane settings tend to be on the ridges and not the valleys [e.g., *St. Clair et al.*, 2015]. In the time-honored tradition of the scientific method, multiple hypotheses have been put forward to explain this finding [*Riebe et al.*, 2017], including topography interacting with regional tectonic stresses to cause bedrock fractures [*St. Clair et al.*, 2015], an advancing chemical weathering front [*Lebedeva and Brantley*, 2013], and drainage of saturated fresh bedrock induced by incising streams [*Rempe and Dietrich*, 2014]. Discerning among these and other competing hypotheses is vital to understanding how water storage and release in the critical zone sustains terrestrial and riverine ecosystems.

Beyond the inherent curiosity and wonder embedded in such questions, there is good reason to continue to search for answers: it is all about water and life. We are learning, for example, that we do not understand trees very well: why they grow where they do, why they experience water stress and die, what strategies they have for obtaining and redistributing water to optimize their growth, and how these strategies vary by species, setting, and climate. Isotope studies have revealed that different tree species growing right next to each other use different water [*Moreno-Gutierrez et al.*, 2012], perhaps relating to species-specific survival strategies, and the use of deep rock moisture may provide resilience to drought if the storage is not exhausted. Recent studies suggest, for example, that in the weathered bedrock of the critical zone over 30% of the annual precipitation may go into rock moisture storage and then be used by trees, a process missing in climate models [*Rempe*, 2016]. Understanding these dynamics are crucial if we want to predict water stress on vegetation and continue to have productive forests across the landscape in the face of massive droughts and widespread forest mortality [*Grant et al.*, 2013]. Furthermore, all summer stream flow in the western United States derives from slow drainage of the critical zone. Hence, identifying critical zone structure and processes should help in guiding vegetation management and water use needed to sustain ecologically significant base flows.

5. What Makes the Critical Zone So Critical?

Today, the term "critical zone" provides an essential organizing principle for the earth and biological sciences just as "ecosystem" did for ecology half a century ago. This emerging understanding of the critical zone speaks directly to critical societal challenges around the globe. Beyond the issues discussed above, insights from critical zone science are broadening our perspective on provisioning ecosystem services [*Field et al*., 2015]. The science is helping farmers maintain soil productivity, conserve water, and sustain crop yields in intensively managed agricultural landscapes. It is helping resource managers understand the consequences of wildfires, floods, and hurricanes on hillslopes and rivers in diverse mountain landscapes. It is painting a comprehensive picture of how water, carbon, and nutrients move through landscapes and control water quality of streams. The critical zone is critical because it is not only where we live, but affects most of what we depend on to live.

These are exciting times for field studies and development of critical zone science. Testable theories are being proposed that can guide field observations. Improved geophysical surveying capabilities (including lidar) and monitoring instruments are enabling us to delineate the structure of and processes in the critical zone. The commitment to support long-term field observatories has led to discoveries about fundamental mechanisms that could not be inferred or revealed by any other means. Finally, a new generation of graduate students are training in core disciplines but identifying as critical zone scientists. They are uniquely poised to embrace the entirety of the critical zone, ask new questions, work interdisciplinarily, and thereby see new connections in an invisible, and until recently, inaccessible and unknown world that lies beneath our feet.

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