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Special Section:
The Future of Critical Zone Science: Towards Shared Goals, Tools, Approaches and Philosophy

Expanding the Spatial Reach and Human Impacts of Critical Zone Science

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Key Points:

- CZ depth is defined by multiple processes key to human existence, yet is undermeasured and thus poorly understood
- Scientific jargon can make defining and communicating CZ processes difficult to stakeholders and even scientists in other fields
- Legacies in western science, upon which CZ science is based, can be countered to promote progress in the Earth sciences

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Abstract

Two major barriers hinder the holistic understanding of subsurface critical zone (CZ) evolution and its impacts: (a) an inability to measure, define, and share information and (b) a societal structure that inhibits inclusivity and creativity. In contrast to the aboveground portion of the CZ, which is visible and measurable, the bottom boundary is difficult to access and quantify. In the context of these barriers, we aim to expand the spatial reach of the CZ by highlighting existing and effective tools for research as well as the "human reach" of CZ science by expanding who performs such science and who it benefits. We do so by exploring the diversity of vocabularies and techniques used in relevant disciplines, defining terminology, and prioritizing research questions that can be addressed. Specifically, we explore geochemical, geomorphological, geophysical, and ecological measurements and modeling tools to estimate CZ base and thickness. We also outline the importance of and approaches to developing a diverse CZ workforce that looks like and harnesses the creativity of the society it serves, addressing historical legacies of exclusion. Looking forward, we suggest that to grow CZ science, we must broaden the physical spaces studied and their relationships with inhabitants, measure the "deep" CZ and make data accessible, and address the bottlenecks of scaling and data-model integration. What is needed—and what we have tried to outline—are common and fundamental structures that can be applied anywhere and used by the diversity of researchers involved in investigating and recording CZ processes from a myriad of perspectives.

Plain Language Summary

The "critical zone" is the zone of the Earth from treetops to belowground water. It is where crops are grown, water is drawn for drinking and industry, and waste generated by humans ends up. Understanding how deep this section of the Earth is, and how it is changing, is key to being able to determine how impactful changes in land use or climate will be to human systems. That said, it is difficult to get below-ground information, and scientists in different subfields of the Earth sciences define the depth of the critical zone differently. Here, we describe the tools and language we use to make those decisions. We also note that Earth scientists are not a diverse group, which means we miss out on the ideas, solutions, and impacts that those from historically excluded groups might have to address the big problems humans must solve. To advance critical zone science, we need to broaden the physical areas we study, access to these sites, and the inclusion and sense of belonging of people studying them. We also need to measure deep into the Earth where we can, make our data accessible, and tackle scientific obstacles in integrating data and models.

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1. The Challenges and Motivation

Earth-system models predict changes in Earth's climate, land cover, and ecosystem functioning, including challenging environmental conditions for human society even in the current century (e.g., Kawamiya et al., 2020). Key to preparing for these shifts in conditions is understanding the fundamental and interacting geological, hydrological, chemical, and biological processes that shape our world. For more than 20 years, many scientists have engaged in and promoted critical zone (CZ) science in pursuit of this understanding. The CZ is defined as the "heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources" (National Research Council, 2001) and is becoming increasingly important during the Anthropocene (Gaillardet et al., 2018). A predictive comprehension of the CZ is key to adapting to environmental changes as we proceed through the Anthropocene (e.g., Owens, 2020; Wohl, 2013), and CZ science emphasizes a whole-system, cross-disciplinary approach, as suggested 25 years ago by Ashley (1998):

> Topics that push across new frontiers and provide research opportunities and potential for better understanding of the planet upon which we live…It is the home of forests, deserts and agriculture, but potable water and toxic wastes also pass through this zone. A holistic approach is needed to understand the three-dimensional complex linkages involving physical, chemical and biological processes (p.148).

Since the term "critical zone" was first coined, investigators from many spheres of Earth science (lithosphere, hydrosphere, atmosphere, and biosphere) and the social sciences have worked toward a comprehensive and predictive understanding of the CZ's structure and function (Arènes et al., 2018; Lee et al., 2023; Montanarella and Panagos, 2015; NRC, 2001). Two major barriers that hinder the holistic understanding and role of the CZ are (a) an inability to measure, define, and share information on the diverse geologic structure that lies below our feet and (b) a societal structure that inhibits inclusivity and creativity and thus limits our ability to capture the feedbacks between CZ changes and humans. The ability to accurately predict future environmental conditions, processes, and impacts relies on solving both challenges.

We need new approaches to adapt to environmental changes while simultaneously leveraging a tremendous breadth of technical approaches. CZ scientists also must nurture a scientific workforce composed of a diversity of perspectives. Studies demonstrate that doing so helps to maximize creativity and problem-solving (e.g., Hofstra et al., 2020; McLeod et al., 1996; Perdrial et al., 2023). Second, CZ scientists must develop a strategy for exploring the evolution of belowground CZ processes and architecture throughout the Anthropocene. Understanding CZ-architecture evolution is difficult in part because of the diversity of vocabularies and techniques used in relevant disciplines. However, by addressing that issue—by sharing available scientific techniques, defining terminology, and prioritizing research questions that can be addressed by diverse fields about subsurface characteristics—CZ scientists can begin to address many related questions that have basic applications to concerns about contemporary and future environmental changes. It is challenging to integrate the need to diversify science—to have science *look like* and *harness the creativity of* the whole society it serves—with discussion of the technical details of our work. However, we must integrate these ideas in our scientific literature in our efforts to move our science forward. This paper reflects that motivation.

2. Building a Diverse Scientific Workforce From the Community Level

Members of the CZ community have interests spanning the theoretical to applied, as well as environmental justice. This broadly focused scientific community requires integrated education and workforce training to cultivate the human resources to investigate a complex and dynamic CZ. A system-wide effort is needed to integrate technical training with ability to integrate data, models, and communities. However, training skilled scientists is not enough for the CZ discipline to advance. In any endeavor, a narrowly defined set of perspectives will not be as successful as a greater diversity of perspectives (e.g., Perdrial et al., 2023; Phillips, 2014). Additionally, CZ science must be coupled with substantial, durable communications well beyond the academic and western scientific communities. Environmental science is largely framed around academic findings and viewpoints post western-dominated colonization and industrialization, and there is a colonial legacy that some of our CZ observatories worldwide are structured in and benefit from. Partisanship over who is responsible for accelerated environmental impacts and divergent views on equitable commitment policies can leave scientific policies unresolved. Economically developing countries have to be part of the solution, as they are likely to suffer most from a changing climate as a function of geographic location and access to financial and capacity-building resources (Nath and Behera, 2011). Recognition that the social meaning of big environmental challenges—rather than just leaning on scientific "facts"—may help individuals from diverse cultural worldviews focus on viable solutions (Kahan & Braman, 2006). Sustaining the CZ requires an all-hands approach, incorporating international perspectives from social and political sciences, engineering, government and non-government agencies, and local communities, all of whom have insight on why the shallow subsurface matters beyond academic definitions and perceptions. It is also problematic that we may not be keeping our best and brightest in the field; work has shown that scientists from historically excluded groups are less likely to stay in science, despite doing work of equal or better quality to, for instance, white males (Hofstra et al., 2020).

An aim of this paper, aside from advocating for integration and convergence among "diverse" scientific disciplines under the umbrella of CZ science to understand the subsurface, is therefore to contribute to rectifying past legacies of social discrimination in the geosciences, starting with CZ science, and exploring how to improve its future as a diverse scientific community. Past practices of racism, sexism, ableism, classism, and/or religious intolerance, for example, have effectively minimized the presence and participation of many potential scientists (e.g., Bernard & Cooperdock, 2018; Kuchynka et al., 2018). The production of any demographically homogeneous scientific workforce occurs from systematic exclusion of marginalized groups within a public educational system that focuses its resources on groups that reflect those in power.

Consequently, to say that the educational pipeline from student learner to professional in any discipline, field, or occupation has been "leaky" is arguably untrue, specifically in the context of the U. S. natural sciences of which we are most familiar. A leak is often inadvertent and can occur spontaneously. The historic failure to adequately educate anyone not fitting the non-disabled ethnic European (White) male phenotype was not an inadvertent or accidental act (e.g., NASEM, 2021). It is more accurate to say that the pipeline is instead lined with stop gaps along its length that can be opened partly, to allow a controlled volume of access and opportunistic flow, or closed, shutting off access or opportunity to move forward along the pipeline.

Many researchers exacerbate the effects of this system of pipeline valves by denying inequities or justifying inaction (e.g., Dancy & Hodari, 2022), tokenizing or "othering" mentees (Martinez-Cola, 2020), or using unhelpful euphemisms to downplay inequity. For example, Swartz et al. (2019) state their interpretation of the problem in the following way:

> The educational pipeline poses a challenge for underrepresented students who may not have had sufficient educational exposure or support. Many have to overcome significant barriers to access education. Understanding these obstacles should help medical and biomedical graduate schools develop improved recruitment and retention programs and take an active role in promotion and outreach initiatives (p. 34).

It is not the so-called educational pipeline that is the challenge. The real challenge is discrimination based on a perception by those with power. Terms such as "obstacles," "biases," and "significant barriers" are stand-ins. A societal structure based on a false, human-made hierarchy based on imaged differences is guaranteed to remain a problem in the geosciences generally and CZ science specifically if it is never name-checked as racism, sexism, ableism, classism, and the like. The geosciences, more than any other science discipline, have homogenized its ranks such that it is today mostly made up of physically able ethnic European males (e.g., Bernard & Cooperdock, 2018). We note that addressing this problem worldwide is difficult, as the collection of demographic data is not common everywhere, and it remains difficult to find solutions or build targeted, collaborative efforts to implement diversity, equity, and inclusion initiatives when the data describing the magnitude of the problem do not exist.

In the following text, we address gaps in the science to try and integrate CZ processes at Earth's surface through to the depths to which it is connected. We also explore the human factors involved and needed to build human capacity for a more diverse and equitable workforce into the future. We also hope to motivate the community to integrate recognition of the social factors discussed above, for example, discrimination based on race, ethnicity, gender, physical ability, and others, in their research and curriculum. By recognizing discriminatory legacies of the past in STEM, we can begin to integrate the human and scientific infrastructures needed to address the complexities of the science as well as fairness and equity in STEM and society.

3. A Holistic Understanding of the CZ Requires Seeing the Hidden Belowground Structure

To fully understand how the whole CZ evolves over time, we must first define its boundaries. In contrast to the top of the CZ (i.e., the top of the canopy), which is visible and measurable, the bottom boundary typically is difficult to access and thus quantify. Belowground CZ components are defined by the spatial distribution of unweathered bedrock, sediments, and minerals, and their continuous interaction with biotically altered soil gases and porewater occupying the void structures. Investigations related to characteristics and behavior at key interfaces dominate much of the CZ literature (e.g., Brantley et al., 2013; Hahm et al., 2014; Voelkel et al., 2011); however, most of these studies have focused on the top few meters of the subsurface (e.g., Jin & Brantley, 2011; Johnson et al., 2011; Takagi & Lin, 2012) leading to the "deep" CZ below this upper layer to be nicknamed the "unmeasured zone" (Condon et al., 2020; Dietrich, 2010).

Why is mapping the depths of the CZ important, and what are the consequences of failing to properly study it? In short, it is fundamentally important to a variety of CZ processes, including:

- Predicting CZ water storage and dynamics, which controls stream baseflow sensitivity to weather and climate variability as well as water available to plants;
- Understanding the role of saprolite weathering in the carbon budget in a warming climate and as an uptake of atmospheric CO_2;
- Better constraining how the processes at the base of the CZ control the physical structure and rate of formation of saprolite and regolith, as well as the occurrence of landslides;
- Developing a process-based relationship for predicting runoff and hillslope-stream connectivity, including drainage density;
- Developing process-based soil production and erosion equations over time, from anthropogenically affected systems to those evolving over millennia;
- Relating past biogeochemical-climate interactions to present-day relationships to project future CZ functioning; and
- Leveraging solute concentrations in deep soil-water samples to estimate weathering rates, critical minerals, contaminant remediation, and carbon storage and dynamics.

In short, the full depth of the CZ is integral for life, can be modified by humans, and in turn can modify human decision making at a grand scale.

Defining the bottom boundary of the CZ is challenging (e.g., Riebe et al., 2017). One challenge to determining the lower boundary of the CZ is differences in how the interface is defined by subdisciplines (Figure 1). For example, geochemists often define the bedrock-regolith interface by the infiltration depth of water charged with oxygen (O_2) and carbon dioxide (CO_2), or transition of chemical compositions from unweathered bedrock to regolith (e.g., Bazilevskaya et al., 2013; Brantley & Lebedeva, 2011; Brantley et al., 2013). Soil scientists often define this interface by "depth to refusal" of a hand auger or knocking pole (Gomi et al., 2008; Jarecke et al., 2021; Yoshinaga & Ohnuki, 1995). Geophysicists employ contrasts in seismic velocity and other geophysical properties to estimate the bedrock-regolith contact depth (e.g., Holbrook et al., 2014), and hydrologists assess depth to active flow or the zone that responds to annual recharge and climatic variability (e.g., Condon et al., 2020; Mayo et al., 2003). Geomorphologists consider the regolith-bedrock interface to be best represented by the base of the saprolite, the weathered bedrock that retains its original physical structure but has been chemically eroded (e.g., Dixon & Riebe, 2014; Sklar et al., 2017); however, what distinguishes regolith versus saprolite, and the language used, is confusing within the CZ community. For example, geomorphologists generally refer to material above unweathered bedrock and below the Earth's surface as "regolith" (Figure 1), where regolith is further divided into intact and mobile regions. Intact, immobile regolith is also called "saprolite," which implies weathered and chemically eroded material that can be easily augered but still retains the physical structure of the bedrock (Anderson & Anderson, 2010). Above this intact regolith is mobile regolith, where weathered and chemically eroded rock is moved and mixed. Geomorphologists also call mobile regolith soil, and this definition of soil varies from those in many other Earth science disciplines (Richter et al., 2020). Regolith thickness, soil depth, and total depth from the Earth surface to consolidated bedrock or from the Earth surface to water table are often used interchangeably to describe the thickness of the CZ relevant to catchment and hydrologic processes. All of these delineations result from assessment techniques reflecting states and processes that represent a tremendous diversity of spatial and temporal scales.

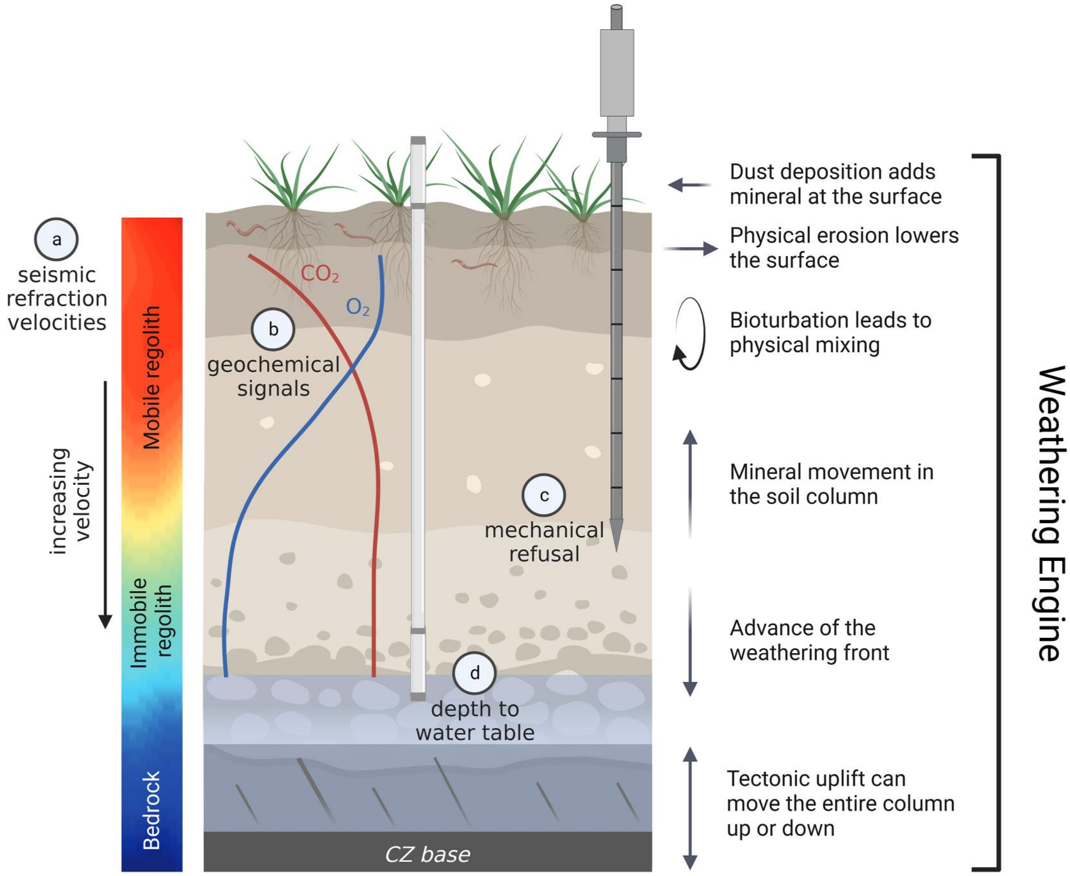

Figure 1. The CZ can be conceptualized as a conveyor belt that moves minerals from fresh bedrock toward the surface as a result of erosion and the downward advance of weathering fronts. Microbial processing of organic carbon and the activities of roots can initiate weathering deep in the system. We define CZ thickness as the distance between the Earth surface and the CZ base. Defining the thickness and base of the critical zone varies by discipline. Different techniques are used to define CZ thickness including (a) seismic refraction velocities, (b) geochemical signals, (c) mechanical refusal, and (d) depth to water table. Geophysical methods, such as seismic surveys, enable the capture of the entire CZ. In contrast, other techniques may be constrained by sampling depth or mechanical refusal along a point in the CZ profile.

Providing an integrated definition of the CZ base and thickness would serve to establish a physical space, architecture, and means for measuring CZ dimensionality in space and time so that its evolution can be studied. Here we define *CZ base* as the elevation of the bottom of the CZ, which coincides with the top of unweathered bedrock, which can be difficult to measure accurately, as we discuss below. We define *CZ thickness* as the distance between the Earth surface and the CZ base. Little is known about linkages and degree of coupling among the surficial and deep processes within the CZ, which limits our mechanistic understanding of how the CZ advances into the continental lithosphere on all scales. Here, we ask two questions that demands a harmonization of approaches and vocabularies leveraged by a diversity of disciplines, as well as creativity—and thus a diversity of humans—to fully address: (a) how does CZ thickness, and thus its base, evolve over time? And (b) what are the impacts of this evolution on and from humans? Lastly, we propose additional research questions to advance and expand CZ science. We posit that by leveraging the below-described approaches, tools, and concepts and developing a scientific workforce that demographically represents the whole of society it serves that we can develop scientifically and socially meaningful ways to predict and adapt to our changing planet.

4. Current Approaches to Constrain the Base and Thickness of the CZ

The breakdown of bedrock is a fundamental process at the base of the CZ. Bedrock composition, tectonic setting, topographic stress, climate, erosion, biology and anthropogenic modification are important factors that regulate the degree of physical and chemical weathering and thus the thickness of the CZ (e.g., Riebe et al., 2017). In particular, the rate at which these weathering processes keep pace with erosion helps to govern the overall thickness of the CZ (e.g., Mudd & Furbish, 2007) and microbial processing of organic carbon and the activities of roots can initiate weathering deep into the system (Drever, 1993; Stolze et al., 2023). One common way to conceptualize the interactions among these factors is the conveyor model (Figure 1), which conceptualizes the CZ as a zone transporting parent rock (at times referred to as unweathered bedrock or protolith) up toward Earth's surface, where physical, chemical, and biological weathering converts that rock into regolith and soil (e.g., Brantley et al., 2017; Dixon and Riebe, 2014; Riebe et al., 2017). Fresh bedrock moving into the conveyor can also be altered physically through faulting and fracturing (e.g., DiBiase et al., 2018; Molnar et al., 2007), generating porosity and pathways for fluid flow. The degree of rock damage created by tectonic and topographic stress is in part governed by rock properties (e.g., hardness, brittleness). Once water can circulate through rock, chemical weathering processes can enable the further transformation of rock into regolith. Here, we describe a series of approaches—from geochemistry, geomorphology, geophysics, and ecology—for determining the CZ base and thickness as derived from these processes.

4.1. Geochemical Approaches for Mapping the CZ Base and Thickness

If the CZ base and thickness can be defined by the geochemical alterations of the parent rock, we can rely on direct measurements of soil, rock, and ground- or stream-water chemistry (perhaps coupled with numerical and mass-balance models, described below) to quantify chemical weathering processes (i.e., kinetic and thermodynamic reactions) over space and time. Where humans drive changes from aquifer dewatering, subsidence, mining, agriculture, or urban development, chemical-weathering processes and thus the base and thickness and the evolution rates of the CZ are also impacted.

Overall, chemical-weathering processes at the base of the CZ are controlled by intrinsic rock properties of the CZ (i.e., bedrock type, mineralogical composition, particle size distribution, specific surface areas, tectonic stress, and geological structures) and extrinsic climate conditions (i.e., temperature, precipitation). To a first approximation, infiltration of dilute, oxygenated and carbonated water through soil and saprolite to unweathered rock drives geochemical weathering (e.g., Bazilevskaya et al., 2013; Brantley et al., 2017), which defines the depth of geochemical reactions in the CZ. This influx of fresh water with reactive gases (CO_2 and O_2) can drive geochemical reactions or activate microbial communities, causing "hot spots" and "hot moments" of work at the regolith-bedrock interface (e.g., Li et al., 2017). Dissolved CO_2 is neutralized through silicate and carbonate mineral dissolution, while dissolved oxygen is an electron acceptor for oxidation of metals, such as iron, contained in minerals (Heidari et al., 2017). Mineral dissolution increases porosity and therefore the depth of infiltration (e.g., Bazilevskaya et al., 2013; Jin, Rother, et al., 2011b; Navarre-Sitchler et al., 2009), which feedbacks to additional chemical weathering processes. Water movement is enhanced through development of preferential flow paths in regolith due to this chemical weathering or also growth and decay of roots (e.g., Buss et al., 2008; Fletcher et al., 2006; Navarre-Sitchler et al., 2009; Sullivan, Price, et al., 2016; Sullivan, Stops, et al., 2019; Figure 2). Water infiltration can also be impeded by the development of low-permeability zones due to clay precipitation, formation of carbonates, or illuviation in soils (e.g., Lawrence et al., 2014).

The weathering of primary bedrock and secondary mineral formation ultimately change the thickness of the CZ (Figure 2). A valuable way to conceptualize this process is by picturing a series of nested reaction fronts moving through the subsurface where the most soluble minerals are dissolved down to the greatest depths, which often coincides with the permanent or regional groundwater table (Brantley et al., 2013; Sullivan, Hynek, et al., 2016). The weathering front is defined as the location in the subsurface where the transition occurs. Its depth is quantified as the depth between weathered rock (with near-zero mineral fractions) and unweathered bedrock (the mineral fractions of the bedrock) (Brantley & Lebedeva, 2011; Brantley et al., 2007; Lebedeva et al., 2007; White and Brantley, 1995). Here, rock permeability governs the dominant processes that transport solutes across the reaction front, with diffusion often dominating in less-permeable rock and advection dominating in more-permeable rock (Brantley et al., 2017; Wen & Li, 2017). The mode of transport has notable consequences for the timing of developing weathering fronts. Reaction fronts may be distinct, with clear boundaries over which the primary mineral has been removed (Buss et al., 2008; Jin et al., 2010; Jin, Andrews, et al., 2011; Jin, Rother, et al., 2011), or they may be patchy, with combinations of primary, secondary, or even tertiary minerals present in layered or highly fractured systems (Moravec et al., 2020; Olshansky et al., 2018; Wen et al., 2016; Zapata-Rios et al., 2015, 2016).

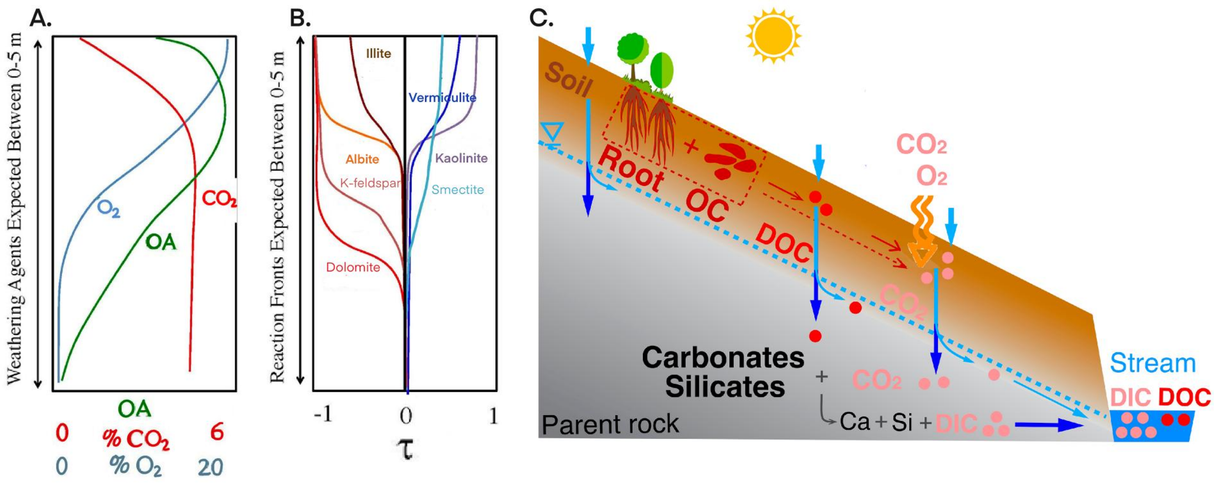

Figure 2. Conceptual depth profiles of (a) weathering agents (i.e., oxygen, organic acids, carbon dioxide) and (b) reaction fronts depicted by "tau" profiles for primary and secondary minerals in the CZ (adapted from Wen et al. (2022)), and (c) a hillslope cross-section view of soil and rock zones. Soils are more enriched with reactive agents like organic matter, roots, and dissolved organic carbon, and the rock below receives reactants from the soils that enhances weathering processes. Positive tau values indicate mineral accumulation compared to the parent rock (unweathered bedrock), negative values indicate the loss of parent mineral. As reactive agents propagate over depth (a), chemical weathering occurs by removing primary minerals (negative tau values, e.g., dolomite, K-feldspar, etc.) in parent rocks (tau = 0) and forming secondary minerals (mostly clays like smectite) (b). Stream chemistry reflects the chemistries of source waters and can be used to infer CZ reactions and base.

Our understanding of the base of the CZ—its thickness, architecture, and overall functioning—is impeded by a lack in understanding of what controls the spatial variability in the formation of secondary minerals, particularly clays. Clays play an important role in limiting flow, but also controlling biogeochemical processes, as they create surface area for chemical reactions and hold charge for ion exchange. Small additions of clay (e.g., <10% by mass) can lead to vastly different solute concentrations and weathering dynamics because of the change in the reactive surface area. At the physical level, factors such as water flow, climate, and bioturbation (e.g., root growth) influence the downward translocation of clay minerals and clay-sized particles (Honeycutt et al., 1990; Lawrence et al., 2021). This variability poses a challenge in discerning the spatial distribution of these constituents in the subsurface. Subtle and difficult-to-measure distinctions in pore-fluid chemistry govern the likelihood of secondary mineral formation. For instance, biogenic cycling of elements by vegetation can result in mineral formation preferences. Specifically, when potassium is translocated from depth to the surface, it can lead to the formation of 2:1 clays (e.g., illite; Austin et al., 2018), while silica translocation can induce the formation of 1:1 clays (e.g., kaolinite, Lucas, 2001). Much of our understanding regarding the formation of secondary clays is derived from studies conducted on pure minerals under laboratory conditions; consequently, there exists a gap in our comprehension of the rate and types of secondary mineral formation in natural systems (Maher et al., 2009).

4.1.1. Direct Sampling and Measurements

Physical sampling techniques such as digging pits for visual inspection and measurement can be used to identify the contact between mobile soil/regolith and immobile saprolite or bedrock (weathered or unweathered), although pits are not often used for spatially distributed measurements of deep CZ architecture (e.g., Patton et al., 2018). Instead, deep physical investigations within bedrock often use drilling, the recovery of drill fines or cores, the use of borehole geophysical measurements (described below), and/or the installation of wells to measure the variability in chemistry and deduce if groundwater is chemically equilibrated with the surrounding minerals. Drilling and coring require specialized instruments and experience and are physically and time intensive, although portable drills can be used to install bedrock monitoring wells (Gabrielli & McDonnell, 2012; Harmon et al., 2020). Coring depths are dependent on drilling, which may allow samples to 100s of m and deeper. Many shallow probes of CZ thickness exist, such as handheld cone penetrometers, also known as knocking poles (Gomi et al., 2008; Jarecke et al., 2021; Yoshinaga & Ohnuki, 1995); the resistance of the rod penetration along a depth profile can be used to distinguish subsurface horizons (Ziegler et al., 2006) and subsurface hydraulic characteristics (Shanley et al., 2003). Augering is a way to capture soil or, sometimes, weathered rock samples. These shallow physical methods can be useful when bedrock is relatively near surface (<3 m). Road cuts may be another way to collect data on the CZ. Other options for defining the CZ base are geophysical methods, described in Section 4.3 below.

Geochemical signatures over depth, collected via sampling, can elucidate the position of reaction fronts and depth to chemically unweathered bedrock (e.g., Sullivan, Hynek, et al., 2016). Fluid samples of gas (CO_2, O_2) and solutes provide insights into modern processes governing weathering, while soil and rock material provide insights into weathering over geologic time (Brantley et al., 2011). When we analyze the composition of groundwater across a catchment it can divulge a variability in residence times and the minerals upon which the water interacted (e.g., Warix et al., 2023, 2024; Wen et al., 2022). Within a catchment, groundwater residence time can vary greatly. While most groundwater ages are generally less than 3 months old (Jasechko et al., 2016), it is not uncommon to find groundwater water is also on the scales of decades (Rademacher et al., 2001, 2005; Sullivan, Goddéris, et al., 2019) and centuries (e.g., Sprenger et al., 2019). This groundwater provides a rich history in its dissolved load that indicates what minerals it has interacted with along its flowpaths (Toth, 1999).

Conversely, the elemental composition of rock and regolith samples tell us about the long history of weathering processes in a given environment. Such depth profiles can be quantified by collecting samples from road cuts and coring and then measuring their geochemical properties. Rocks can also be analyzed using non-invasive, but low accuracy, X-ray fluorescence analyzers. Alternatively, samples can be digested and then run on elemental analyzers such as inductively coupled plasma optical emission spectrometer (ICP-OES) or mass spectrometry (ICP-MS) to quantify element concentrations. To understand the degree of weathering, the elemental concentration of mobile elements (e.g., Na or Ca) and immobile elements (e.g., Zr or Ti) of the regolith are often compared to that of the parent material and is termed *tau* (Brantley et al., 2007; Brimhall & Dietrich, 1987; Riebe et al., 2001). Other normalized indices to quantify the degree of weathering include the chemical index of alteration, chemical index of weathering, and weathering index of Parker (e.g., Brantley et al., 2008). Rock and regolith samples can also be analyzed by X-ray diffraction to obtain semi-quantitative mineral abundances. When paired with elemental analysis, X-ray diffraction can be used to determine the "average" mineral composition (Jin et al., 2010). Finally, minerals can be visually assessed to understand the degree and type of chemical weathering in rock and regolith samples using scanning electron microscopes (SEM). High-resolution chemistry of specific mineral grains can additionally be obtained from synchrotron-based analysis. More recently, mobility behavior of U-series isotopes (e.g., ^{238}U, ^{234}U, ^{230Th}, and ^{232}Th) during low-temperature water-rock interactions at weathering interfaces, soil profiles, or watersheds have been studied extensively (e.g., Chabaux et al., 2003; Dosseto et al., 2008), enabling the use of U-series isotopes in weathering clasts as a geochronometer (Engel et al., 2016; Guo, Ma, et al., 2020; Guo, Mount, et al., 2020; Ma et al., 2012; Pelt et al., 2008). While geochemical measurements offer one means of identifying the thickness of the CZ, they are often expensive and best suited for areas where regolith represents residuum, meaning it was derived from the local parent rock beneath it, where the parent rock composition is relatively homogeneous (e.g., lacks interbedding), and where parent rock is accessible.

4.1.2. Inferring Weathering Rates and Depths of Reaction Fronts Using River Chemistry

Direct measurement of subsurface geochemical properties is typically intrusive, expensive, and labor-intensive, such that deep CZ data have remained sparse. The base and thickness of the CZ can potentially be estimated using more readily available measurements from streams and rivers. Recent data and model comparisons have shown that relations between riverine solute concentrations (C) and discharge (Q) often reflect the depth profiles of solutes in subsurface (Stewart, Shanley, et al., 2022; Figure 2c). For example, concentrations of weathering-derived geogenic solutes (e.g., Ca and Mg) are often higher under low-flow, dry conditions when deeper groundwater dominates the river discharge, and are lower under high-flow, wet conditions when shallow waters from more weathered soils dominates river discharge (Shand et al., 2005; Shanley et al., 2004). This riverine C-Q pattern reflects increasing concentrations with depth in the CZ (Brantley et al., 2013; Jin, Andrews, et al., 2011; Maher, 2011; Torres & Baronas, 2021). In contrast, solutes that are abundant in shallow soils or linked with human activities (e.g., NO_3 and DOC) often have lower concentrations at low flow, reflecting their low abundance in deeper CZ; they also have higher concentrations at high flow, mirroring their abundance in the shallow CZ (Barnes et al., 2018; Jobbágy & Jackson, 2001; Pinay et al., 2015). The mirroring of these riverine concentrations to their respective source-water chemistry at different depths can potentially be used to quantify and constrain weathering rates and approximate the depth of the reaction fronts and CZ base, especially at locations near streams and rivers (Li et al., 2022; Stewart, Zhi, et al., 2022; Zhi & Li, 2020; Figure 2c). Interestingly, numerical simulations are converging on the idea that at the hillslope scale, reaction fronts are continually adjusting to stream incision as propagation of weathering fronts and the removal of weathering products appear to keep pace (Brantley et al., 2017; Harman & Cosans, 2019; Rempe & Dietrich, 2014).

4.1.3. CZ Thickness Assessed by Modeling of Chemical Weathering

In addition to direct measurements, reactive transport modeling (RTM) has been used with constraints from field data (weathering profiles and stream and groundwater chemistry) to simulate chemical weathering and the generation of weathering fronts that directly link to the thickness and depth of the CZ. Modeling of chemical weathering has thus far focused primarily on one-dimensional (1-D) systems at time scales typical of soil development and bedrock weathering (e.g., 10,000 years), although hillslope models have also been developed in recent years (Wen et al., 2022; Xiao et al., 2021). RTMs emphasize complex reaction networks among primary and secondary minerals, aqueous complexes, and adsorbed species. They have illustrated key controls of Earth's surface evolution, namely fluid transport and reaction thermodynamics and kinetics, in regulating both the advance rate and thickness of weathering fronts or the CZ (Li et al., 2017). Modeling studies have probed the effects of time and climate on weathering rates using chronosequences and climosequences (i.e., soils of different age or soils of similar age in different climate regimes, respectively) (Goddéris et al., 2010, 2013; Heidari et al., 2017; Lawrence et al., 2014; Maher et al., 2009; Moore et al., 2012). The advance rate of the weathering front may be limited by the accumulation of weathering products (Maher et al., 2009; Moore et al., 2012) and by the drainage rate of groundwater from the fresh bedrock (Li et al., 2022; Rempe and Dietrich, 2014). Conversely, the advance of weathering fronts can be accelerated by the recharge of reactive solutes such as dissolved CO_2 into the deeper subsurface (Brantley et al., 2013; Heidari et al., 2017; Wen et al., 2021). RTMs and weathering-profile data have helped place constraints on conversion of rocks to regolith at the weathering front, including basalt clasts and carbonates (Brantley et al., 2013; Hausrath et al., 2008; Hausrath & Olsen, 2013; Navarre-Sitchler et al., 2009, 2011).

RTMs calibrated with weathering profiles have also been used to test hypotheses about CZ thickness and evaluate the competition between reactants such as reactive gases (e.g., soil O_2 to CO_2) and water availability under conditions beyond measurements. It has been hypothesized that soil O_2 to CO_2 ratios in different landscape positions (ridgetops vs. valleys) are key measures of reactivity and can directly link to the depths of weathering fronts and CZ (Brantley et al., 2013; Li et al., 2017); this has indeed been shown to be the case using RTM (Heidari et al., 2017). Geochemical modeling capabilities have been recently expanded to include root processes to test hypotheses regarding how plants affect weathering and CZ thickness (Sullivan, Goddéris, et al., 2019; Wen et al., 2021) as well as to better incorporate fracturing and fracture networks, a major component of the deep CZ (Andrews et al., 2023). A major limitation of current RTMs is the assumption of constant, stable, physical upper boundary at the ground surface without integrating dynamic processes such as soil erosion, dust deposition, and sediment transport. These processes may be important to capture CZ thickness at millennial time scales and beyond. Integrated RTMs to understand detailed processes in individual sites demand extensive, co-located data, including reactive gases and water chemistry at depth (Hasenmueller et al., 2015; Li, 2019) to mineral and hydrologic properties, including surface area, porosity, permeability, and rates of soil erosion; these data are often arduous to measure but critical to constrain RTMs (Jin et al., 2010; Navarre-Sitchler et al., 2009; Takagi & Lin, 2011). For cross-site comparisons, parsimonious RTMs have been developed to capture salient, essential characteristics of individual sites to understand, quantify, and interpret the dynamics of weathering and river chemistry (Li et al., 2022; Maher, 2011).

4.2. Geomorphologic Perspective on the Evolution of the CZ Base and Thickness

Understanding the geomorphological evolution of landscapes over hundreds to thousands of years and longer can shed light on the factors governing the base and thickness of the CZ in ways different from those derived from geochemistry. Conceptual and empirical relationships have been developed to describe the conversion of saprolite to mobile regolith. In the parlance of geomorphology, this is called the soil production rate. The current pervasiveness of soil across terrestrial Earth suggests that, at least until recently, rates of soil production and erosion have, on average, matched. If the erosion rate outpaced the soil production rate, soil would eventually be stripped from the landscape. In contrast, if soil production rates outpaced erosion rates, soil would deepen unchecked. In both cases, this alteration to soil thickness alters the thickness of the CZ. To keep a balance in soil thickness, geomorphologists as far back as G.K. Gilbert (1877) have assumed that the soil production rate scales inversely with soil thickness. With this conceptual model, a period of increased erosion would lead to shallower soils and faster soil production, stabilizing the soil and CZ thickness. Similarly, decreased erosion would lead to deeper soils and slower soil production, again stabilizing the soil and CZ thickness. These ideas have been explored extensively (e.g., Anderson & Anderson, 2010; Carson & Kirkby, 1972; Crozier, 1986; Dietrich et al., 1995; Heimsath et al., 1997; Perron, 2017) and form the framework for how many geomorphologists view long-term dynamics of the CZ.

4.2.1. Direct Measurements

The first study to observe an inverse relationship between soil thickness and production rate used cosmogenic radionuclides (Heimsath et al., 1997). At a steady soil thickness, the concentration of cosmogenic radionuclides at the soil-saprolite boundary is predicted to be a function of the soil thickness, erosion rate, and the nuclide production rate in soil (assuming steady bulk density of soil; Figure 1). Over the last few decades, cosmogenic radionuclides have been used to explore the nature of the soil-production function in landscapes across the globe under the assumption of a steady-state soil thickness (e.g., Byun et al., 2015; Heimsath et al., 2012; Riggins et al., 2011; Wilkinson et al., 2005). These data allow for an empirical relationship between soil thickness and production rate at a given site. These data have not resulted in empirical relationships for how climate, rock type, and other parameters impact soil production.

Another measurement of soil production relies on uranium. Uranium is ubiquitously present as a trace element at ppm levels in most common rock-forming silicate minerals in regolith. Some common U-bearing phases with high U concentrations in regolith include apatite, zircon, gypsum, pedogenic carbonate, secondary clay minerals, and amorphous Fe oxides and hydroxides. The creation of U-series disequilibrium in the weathered residuals that starts when the major U-bearing phases are exposed to non-equilibrated waters (e.g., at mineral-water interfacial area) and the degree of disequilibrium in regolith is time dependent. We thus can infer duration of chemical weathering in the regolith zone from the disequilibrium signature, and rates of regolith or soil formation from modeling efforts (e.g., Chabaux et al., 2003, 2008; Dosseto et al., 2008; Ma et al., 2010, 2013).

As more and more data were collected, it emerged that some locations showed no relation between soil thickness and production rate (see compilations in Dixon & Riebe (2014) and Harrison et al. (2021)). Much of our understanding of landscape and soil evolution and landform variability is derived from constructs that assume an inverse relation between soil thickness and production rate (e.g., Ferrier & Kirchner, 2008; Roering, 2008; Sklar et al., 2017). Despite leaning on this relation, the physical and chemical processes that might lead to a relation between soil thickness and production rate have never been fully explained. This issue has led some to question whether such a relation exists or if it arises due to invalidated assumptions (Harrison et al., 2021). Regardless of the answer, without a mechanistic, quantitative relation for how variables such as climate and rock type impact soil production over decades to millennia, an important piece of the landscape evolution puzzle is missing, and thus limits our ability to understand how the base and thickness of the CZ has evolved over hundreds of years and longer.

4.2.2. Modeling Landscape Evolution

Application of mechanistic frameworks, that is, mathematical landscape-evolution modeling, can test a range of parameters against empirical observations within long-term soil production rates operating on timescales longer than RTMs. For example, Barnhart et al. (2020) model an area of 4.65 km^2 over 13,000 years with a spatial resolution of 7.3 m and a temporal resolution of 10 years. This is a relatively high resolution and short time scale for a landscape evolution study. The spatial scales of RTMs vary tremendously, from individual pores (sub microns to microns) (Molins et al., 2012) to watersheds spanning tens of kilometers (Li, 2019). Most RTM work that examines the development of CZ thickness and weathering fronts, however, have been 1-D, spanning a few centimeters to meters (e.g., Heidari et al., 2017; Maher et al., 2009; Moore et al., 2012; Navarre-Sitchler et al., 2009), or 2-D hillslopes at tens of meters (e.g., Harman & Cosans, 2019; Lebedeva & Brantley, 2013; Xiao et al., 2021) over the time scale of 10,000 years. Nevertheless, landscape evolution models benefit from a CZ perspective, in which knowledge from the RTM community is scaled up to inform landscape-evolution questions. By focusing on modeling soil-production rates, the landscape-evolution community offers the opportunity to move beyond the empirical models currently in use and develop new process-based models for soil production that apply over longer time scales than explored with RTMs.

Several soil-production models have been developed to explicitly incorporate climate, erosion rates, and rock properties. For example, Poulos et al. (2012) found that hillslope asymmetry, or whether pole-facing or equator facing hillslopes were steeper, varied with latitude. In a global, continental-scale study evaluating soil-thickness controls for both northern and southern hemispheres, Pelletier et al. (2018) linked hillslope steepness with soil thickness. They proposed opposing conceptual models of regolith thickness depending on the degree to which a system is water or temperature limited. Specifically, in water-limited systems, pole-facing hillslopes have thicker soils and the depth to unweathered bedrock is deeper, in comparison with equatorial-facing hillslopes. In temperature-limited systems, the pattern changes and equatorial-facing hillslopes have deeper soils in comparison with pole-facing hillslopes. Interestingly, the degree to which these processes materialize on the land surface is controlled, to some degree, by the anisotropy of the rock fabric (i.e., permeability variations in foliated rock; Eppinger et al., 2021). Testing such models numerically remains an important area of research.

Developing and calibrating conceptual and mathematical models of soil production that apply over timescales of decades and millennia is critical for informing how the CZ will evolve in the coming centuries. The models must parameterize erosion rate, climate, and rock properties in measurable ways. There is no debate that the subsurface extent of the CZ is linked to surface processes and land-surface change. However, the lack of a validated model for how the Earth surface and CZ base co-evolve remains a large knowledge gap moving forward into a time of rapid climate and land-surface change. We suggest that soil-production models operating over long time scales and large spatial scales should be informed by the hydrological, geochemical, and geophysical models that are operating at smaller spatial and temporal scales. A creative simplification and scaling up could lead to important insights on the long-term sustainability of the CZ. Quantifying how CZ processes affect volumetric changes in different lithologies and climates can address rates of material weathered, eroded, and transported, including groundwater solutes, soil stability, and sediment and regolith mobility. Such parameters are needed for predictive assessments of how climate change will affect the CZ and, hence, its impact on humans.

4.3. Geophysical Measurements to Identify the CZ Base, Thickness, and Function

Yet another complementary approach to measuring the thickness and base of the CZ is geophysics. Geophysical data are uniquely able to render spatially explicit the large-scale variability in subsurface properties and thus can be used to provide a view of the deep CZ that is otherwise unobtainable (e.g., Parsekian et al., 2015). For example, changes in physical rock properties such as porosity can be measured to define the base and thickness of the CZ. Geophysical tools rely on either active or passive sources of energy that pass through rock; the response of this energy as it moves through the subsurface can then be interpreted based on our knowledge of rocks and fluids. It is important to note two issues that arise around interpreting geophysical inversion data for CZ properties of interest: (a) the non-uniqueness of inversion images (e.g., Day-Lewis et al., 2005) and (b) the application and applicability of rock physics models used (e.g., Grana et al., 2022). Below, we describe some geophysical tools that may be uniquely capable of detecting the base and thickness of the CZ.

4.3.1. Indirect Measurements

One geophysical tool that can provide high lateral- and verticalresolution images of CZ heterogeneity are seismic surveys, which measure seismic-wave velocity in the subsurface. These data can be used to map the velocity variations between unconsolidated and consolidated materials and the presence of fractures and fluids in the subsurface, which can be used to characterize CZ thickness. For example, air- and water-filled pore space, which is produced during weathering, has lower seismic P-wave velocity (Vp) than consolidated bedrock (Figure 3). P-wave velocities therefore decrease when parent minerals weather to clays (e.g., Olona et al., 2010) or regolith (e.g., Holbrook et al., 2014). Seismic P-wave velocity models are inverted from refraction data using traveltime tomography. At various CZ sites, velocities are generally observed to go from low to high, indicating unconsolidated soil, weathered rock, and unweathered rock (e.g., Befus et al., 2011; Flinchum et al., 2018; Gu et al., 2020; Ma et al., 2021; St Clair et al., 2015; Wang et al., 2021). Vp is sometimes transformed to porosity through rock physics modeling, making a number of assumptions (Gu et al., 2020; Hayes et al., 2019; Holbrook et al., 2014; Mavko et al., 2009; Parsekian et al., 2015), and we note that these assumptions and relations may be hard to extrapolate from one site to another. Shear wave velocity (Vs) provides a useful complement to Vp, as it responds differently to fluid saturation and fracture geometry (Mavko et al., 2009); recent studies have reprocessed seismic refraction to distinguish the water- and/or gas-filling zones in the CZ by building the Vs model from surface waves/converted waves and/or sonic logs and then deriving Vp/Vs (Casto et al., 2009; Gu et al., 2020; Liu

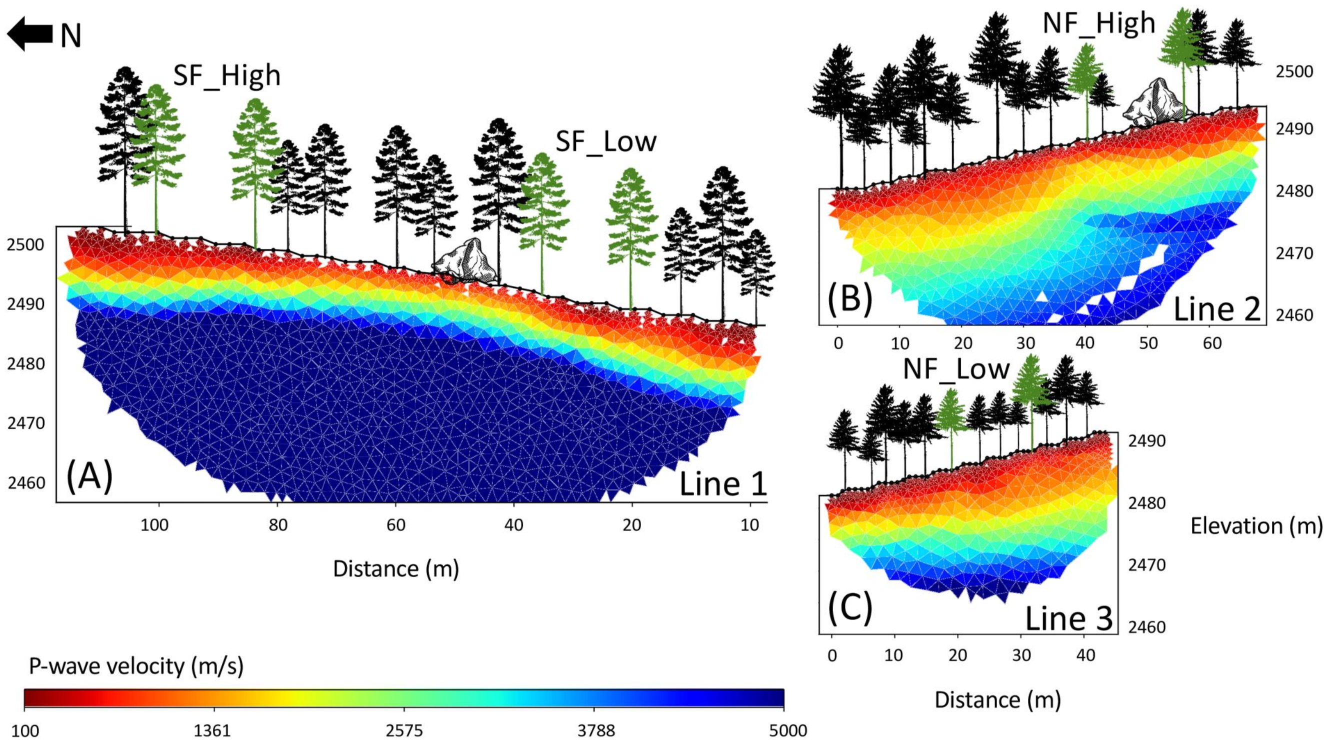

Figure 3. P-wave velocities for the three seismic lines on a (a) south-facing slope and (b-c) two north-facing slopes inside the Boulder Creek Critical Zone Observatory in Colorado, USA. CZ thicknesses, as interpreted by seismic, appear to be different on the two slopes, which in turn has feedbacks to tree species present on site (figure from Hicks, 2023).

et al., 2022; Pasquet et al., 2022). In addition, advanced data processing of seismic refraction data, for example, elastic full-waveform inversion, can improve the spatial resolution of Vp and Vs models that enable us to constrain CZ physical processes with more detail (Eppinger et al., 2024; Liu et al., 2022).

Electromagnetic (EM) methods are also a potential tool for mapping the CZ base in some systems, and are sensitive to the subsurface electrical conductivity and dielectric permittivity. One commonly used EM instrument is ground-penetrating radar (GPR), which is a high-frequency (usually 50–200 MHz in most CZ systems) method used for mapping the CZ base in shallow (usually <10 m) systems (e.g., Guo, Ma, et al., 2020; Guo, Mount, et al., 2020; Orlando et al., 2016). A deeper option is controlled-source electromagnetics (CSEM), which can map low-resistivity anomalies 100s of m into the subsurface (Ashadi, 2022), and has produced high-resolution images of subsurface fluid movement (Neal & Krohn, 2012). The high-resolution capacity of CSEM can be taken to greater depths by using focused-source electromagnetics (FSEM), which focuses the EM field vertically and eliminates horizontal electric current density (Davydycheva & Rykhlinski, 2011). Such ground-based EM measurements are often limited in the spatial scale that can be covered; however, airborne electromagnetic (AEM) is tool that can be considered to map the base of the CZ in some settings at much larger scales (100–1000s of km^2). For example, Smith et al. (2010) and Abraham et al. (2012) mapped the geometry of surficial aquifer systems around the North Platte River in western Nebraska. Most importantly, AEM was able to map the base of the aquifers, allowing for notably improved groundwater models that matched field data, which could not be done from boreholes alone. In a more CZ context, Wainwright et al. (2022) used a variety of airborne methods (AEM with LiDAR and hyperspectral data) to cluster hillslopes within a large watershed system to predict sensitivity to issues such as drought or nitrogen export.

Lastly, muography (muon tomography) is another subsurface detection method worth consideration in CZ thickness investigations (Roche et al., 2022), although it is not commonly used in CZ systems to date. Muons are unstable subatomic particles born from cosmic rays colliding with air molecules. The mass of a muon particle is 207 times greater than that of an electron and it does not lose significant energy in transit. For this reason, muons have the capacity to penetrate materials deeper than other forms of radiation, so can be used to reveal the processes of density change over long periods of time. Denser materials inhibit the quantity of muons that can potentially pass through. Muon graphic density maps depict the volume of interest located between the detectors and the open sky, so muon detectors must be installed behind or underneath the volume of interest (Kaiser, 2019). Logistically, cliffs, gorges, hillsides, mountain facades, valleys, caves, river terraces, boreholes and tunnels are the best sites for applying muon tomography. Holma et al. (2022) demonstrated the effectiveness of muography in visualizing groundwater tables, detecting concealed fractures, and uncovering zones of high soil and rock mass porosity. These successful outcomes of muon subsurface detecting and imaging suggest than muography could be useful agents in identifying CZ thickness and its change over time (e.g., Jourde et al., 2016).

4.3.2. Integration of LiDAR With Subsurface Geophysical Data

LiDAR (light detection and ranging) is a remote-sensing technique that uses lasers to measure distances to targets on the Earth surface. The reflected light is detected by the receiver and the travel time is used to create a map of the objects captured. LiDAR data can be collected from spaceborne, airborne, and ground-based platforms, with potential maximum data resolutions on the order of meters, decimeters, and millimeters, respectively (e.g., Harpold et al., 2015). Depending on the data resolution, LiDAR has the potential to map the top of the canopy, vegetation structure below the canopy, and the Earth surface all with one device. This makes LiDAR a powerful tool for the Earth science community in general and the CZ community in particular (see overviews in Harpold et al., 2015; Passalacqua et al., 2015; Eitel et al., 2016; Okyay et al., 2019). One-time and repeat mapping have been used for applications relevant to the CZ community; for example, topographic maps made from LiDAR have been useful for precise river channel mapping (e.g., McKean et al., 2009; Passalacqua et al., 2010) and mapping landslide scars (e.g., Booth et al., 2009). Estimates of above-ground biomass can be made with LiDAR data (e.g., da Costa et al., 2021), and repeat collection allows for difference mapping, with numerous applications such as mapping snowpack (Harpold et al., 2014), land-surface (e.g., DeLong et al., 2018) and ecological change (e.g., McCarley et al., 2017). Because the same LiDAR data set can be analyzed in different ways to estimate ecologic, hydrologic, and geomorphic variables, its application to aboveground CZ science is vast. Further, the ability to compare temporal data sets makes LiDAR useful for quantifying human impacts on the CZ.

Although some types of LiDAR can be used to collect sub-aqueous data (e.g., Islam et al., 2022), LiDAR technology does not possess the capacity for subsurface data collection because of its inherent dependency on reflective light. It may however be leveraged with other geophysical and remote-sensing techniques for obtaining information on the subsurface. LiDAR has been shown to be highly effective for correlating key surface features that, in some environments (e.g., permafrost), are critically connected to their subsurface geophysical features in temperature, hydrology, and structure. Correlation and integration between surface techniques, such as LiDAR, with subsurface techniques shows promise (e.g., Hubbard et al., 2013; Voytek et al., 2016). Similarly, we note the promise of Interferometric Synthetic Aperture Radar (InSAR) for CZ studies, perhaps coupling deformation to other systems of interest, like landslides and rainfall or groundwater dynamics at large scales (Fustos et al., 2017; Handwerger et al., 2022) and the role on humans.

4.4. Ecohydrology and Biological Data to Infer CZ Base

Surface vegetation patterns cannot tell us the thickness of the CZ. However, vegetation carbon balance is proportional to subsurface water storage and root-zone availability (Fan et al., 2017). As a result, ecosystem carbon balance can be indicative of the relative CZ thickness and is used locally and regionally to identify areas with deep versus shallow CZ development (e.g., Fan, 2015). While the importance of soil properties in controlling plant-available water is well known, recent work has highlighted the importance of terrain and subsurface geophysical structure in managing plant water availability (e.g., Rempe and Dietrich, 2018). At the hillslope scale, forest transpiration and growth rates appear to be more strongly related to subsurface storage than to local precipitation supply (McDonnell, 2003; Pelletier et al., 2013; Swetnam et al., 2017; Thompson, Harman, Konings, et al., 2011; Thompson, Harman, Troch, et al., 2011; Tromp-van Meerveld & McDonnell, 2006). Additionally, forest-stand density and sapwood area may be correlated to the amount of available storage in the plant's local root zone (Klos et al., 2018; Pawlik et al., 2016). Numerous studies have documented that forests take advantage of moisture in weathered bedrock tens of meters beneath the surface to sustain transpiration and gross primary production during seasonal drought (Carriere et al., 2020; Goulden & Bales, 2019; Hahm et al., 2020; Rempe & Dietrich, 2018). (We note that "rock moisture" implies water held in unsaturated systems, as opposed to groundwater in fully saturated systems). Consequently, plants can be physically and chemically coupled to the bottom boundary of the CZ. Where regolith is thin (<10s of m), roots penetrate down into bedrock, physically fracturing weathered rock

10.1029/2023EF003971

(Brantley et al., 2017; Hasenmueller et al., 2017; Roering et al., 2010). The fraction of deep water used by plants increases under drought conditions, but at the continental scale woody plants also appear to access water stored in weathered and fractured bedrock routinely (McCormick et al., 2021). Consequently, the depth to the CZ controls plant productivity.

Additionally, vegetation feeds back to the development of the CZ. Plants physically govern water fluxes by influencing the structure of soil and the overall abundance of macropores that facilitate the recharge of non-equilibrated water to depth (e.g., Sullivan et al., 2022). Recharge rates, and the ability of water to move down to the depth of the unweathered bedrock interface is dependent in part on transpiration; the greater the demand, the less water available to infiltrate to depth. Where plants source their water is in part dependent on relatively long-time-scale processes that generate porosity in the subsurface and enhance available water storage. These long-time-scale processes are dependent on the variations in energy and water limitations (Geroy et al., 2011; Pelletier et al., 2018; Tesfa et al., 2009). It is both the abundance of incoming solar radiation that is harnessed for photosynthesis and meteoric precipitation that allow a given species to meet its transpirative demands. This trade-off between losing water through transpiration to capture carbon through photosynthesis dictates processes such as the depth distribution of roots, hydrologic partitioning of precipitation into recharge waters, root activities that promote microbial activities in the soil, and the injection of acids and carbon dioxide that accompany respiration and exudation of both roots and microbes that also help facilitate chemical weathering reactions (White & Blum, 1995). Reactive transport models of temperate forests in the northeastern U.S. have shown aspect-driven differences in temperature that led to different chemical weathering rates (Sullivan, Goddéris, et al., 2019; Sullivan et al., 2020); however, the impact of biotic nutrient cycling by plants on weathering outpaced temperature.

4.5. Human Impacts and Feedbacks on CZ Base and Thickness and Sustainability of Its Natural Resources

The base of the CZ and its thickness has thus far in this manuscript been defined by its geochemical, geomorphological, geophysical and ecohydrologic properties; however, humans can impact all of these properties. Much of CZ science has focused on minimally impacted sites, leading to notable unknowns about CZ base and thickness in human-impacted agricultural or urban sites. Human disturbance to the base and thickness of the CZ does not have homogeneous impacts but instead is an emergent property based on human behavior and CZ resilience. Disturbances such as mass wasting events, floods, and contamination have cascading effects on human infrastructures that support access to transportation, energy, food, and potable water. Below, several examples of regional disturbance are briefly explained to demonstrate the effects of human influence on the base and/or thickness of the CZ and their feedbacks on the human experience, including agriculture, land use, and climate.

Agricultural practices generally accelerate erosion, which is directly linked to CZ thickness. Agriculturally accelerated erosion is implicated in the loss of vast amounts of topsoil worldwide (Amundson et al., 2015; Hooke & Martin-Duque, 2012; Montgomery, 2007). For example, in the U.S. Midwest, soils have been eroded from land that was formerly tallgrass prairie or savanna at a rate of $\sim$2 mm yr^{-1} (Thaler et al., 2022). This fact has led to a median reduction in soil thickness by 0.04–0.69 m since the time of first cultivation. Overall, erosion thins the CZ from the top, though methods such as no-till farming and soil-regenerative practices have been shown to reduce erosion (Seitz et al., 2020). However, there continues to be social and economic barriers to widespread adoption of these practices (Di Bene et al., 2022; Sánchez et al., 2016). Simultaneously with erosion, the imposition of modern crops across landscapes is responsible for the removal of what otherwise would be perennial vegetation. Averaged globally, roots have shallowed since the imposition of agriculture on our planet; indeed, of the $\sim$48% of Earth's land surface that has experienced root shallowing, 2.3×10^7 km^2 have experienced root shallowing due to agricultural expansion (Hauser et al., 2022). Because roots and the microbes that thrive in the rhizosphere serve as biotic weathering agents, root shallowing could conceivably reduce deep soil-weathering rates. Roots generally increase surface-water infiltration rates (e.g., Bartens et al., 2008; Lange et al., 2009; Wu et al., 2016), and less subsurface water would decrease weathering rates. If robust across space and time, we might posit that globally shallowing roots may result in a thinning of the CZ from the bottom.

Farming practices may also influence the thickness of the CZ through irrigation and the application for fertilizers, particularly at industrial scales. Excessive irrigation can deplete groundwater and lower the water table, leading to land subsidence, and subsidence is associated with conditions that accelerate erosion on the land surface to thereby influence the base and thickness of the CZ. Mismanagement and overuse of fertilizers is also a major culprit which renders CZ natural resources less usable because of soil and groundwater contamination (Srivastav, 2020; Zhang et al., 1996) but the application of nitrogen-based fertilizers may also impact CZ thickness. Where nitrate infiltrates to the ground it can be removed in situ through denitrification, where pyrite and organic carbon are the most common electron donors (e.g., Jessen et al., 2017). At depth, organic carbon becomes scarce and denitrification proceeds with the oxidative dissolution of pyrite (when present), which in turn creates sulfuric acid and eventually sulfate. This process generates acidity, which prompts further weathering of bedrock and the generation of porosity. Over long timescales such processes can impact the base and thickness of the CZ.

Finally, there are well-recognized changes at the surface resulting from changes in climate. Warmer temperatures are leading to early melt and reduced snowpack (e.g., Beniston, 2012; Notarnicola, 2020). Drought and fire are leading to greater particulate matter being deposited on snow, further increasing melt-rate dynamics and changing the timing and degree of infiltration (e.g., Skiles et al., 2015). Changes in groundwater levels due to reduced snowpack will have long-term consequences for the base and thickness of the CZ, which have yet to be quantified.

In short, human modifications of the landscape at large-enough scales will impact the CZ. Landscape change coupled with climate change will likely increase the frequency of catastrophic hazards in many places. In montane or steep landscapes, for example, disturbance to the CZ base and thickness may result from landslides (Handwerger et al., 2022; Riebe et al., 2017) that can be triggered by oversteepening of hillslopes from road cuts (Pradhan et al., 2022; Sidle et al., 2014), and slope destabilization due to clear cutting (Saito et al., 2017; Swansen & Dyrness, 1975). Wildfire alters infiltration rates and removes anchoring roots, leading to debris flows and landslides (Culler et al., 2023; McGuire & Youberg, 2019; Rengers et al., 2020). Human activities play an increasing role in such cascading events. Modeling landscape change in recent times, including humans, compared to what might have been expected through long-term forecasting, is therefore increasingly critical as a tool in land management, urban development, and sustainability of natural resources.

5. Looking Forward

Our capability to develop reliable conceptual and numerical models of CZ depth and associated processes is constrained by the scarcity of subsurface data, inadequate modeling tools, and insufficient communication among disciplinary scientists. Additionally, the lack of input from diverse stakeholders further limits our ability to predict the response of the CZ to disturbances and its impact on humans. Here, we outline measurement and modeling needs for mapping and constraining CZ base and thickness, ways of optimizing those measurements and models, and where and who need to be involved for developing transferable frameworks.

5.1. Approaches to Diversifying CZ Science I: Broadening the Physical Spaces Studied and Their Impacts and Relationships With Inhabitants and Vulnerable Communities

The CZ needs to be defined structurally and in a way that allows the broadest possible application anywhere on Earth. Currently, there is a strong bias in our data collection toward minimally impacted, pristine sites, often in the northern hemisphere, often in temperate climates. Human-impacted systems such as urban and agricultural systems are underrepresented in CZ studies but are obviously essential to understand (e.g., Blair et al., 2022; Kumar et al., 2018). We also note that many CZ sites within the international network are established on colonial vestiges, particularly in North and South America and Africa. With broad agreement on what defines CZ thickness, we could laterally extend and connect our understanding of different physical locations and their interactions beyond current systems. Such expansion requires linkages across boundaries of climate, soil type, geology, hydrology, and topography.

Cold regions are areas not commonly explored within a CZ context, despite these northern high latitudes and alpine environments being home to human communities, agriculture and infrastructure. The Arctic and associated cold regions have soils and have been considered part of the CZ, especially where agricultural intersections are considered (Pi et al., 2021). Soils in Antarctica have been classified and mapped (Bockheim, 2015) although the CZ has not been attributed to the continent; however, ecohydrological research exists there as well. Cold regions are responding at different rates to a changing climate and in different ways than temperate systems, depending on vegetation and subsurface hydrogeology, directly impacting thermal and hydrological feedbacks with thawing permafrost (Pi et al., 2021). While increased monitoring and observational data are needed, a single observatory would not be enough to understand and predict evolution across high-latitude regions and how such extreme environments will respond to climate change. Continued and greater engagement of the CZ community with programs like Next-Generation Ecosystems Experiments Arctic, funded by the U.S. Department of Energy, is one way to leverage existing platforms.

Another understudied area with respect to CZ architecture is drylands. Drylands are one of the largest biomes on Earth, covering ∼45% of Earth's terrestrial surface, and one of the most sensitive to climate variability, land-use change, and other human activities (Bestelmeyer et al., 2015; Feng and Fu, 2013; Seager & Vecchi, 2010). Hydrological processes limit biogeochemical evolution and fluxes in these systems (e.g., Budyko, 1974; D'Odorico and Porporato, 2006). Current dryland hydrology research has focused on understanding the impacts of extreme weather events and climate variability on the complex interactions of land surface-atmosphere-vegetation-soil systems. Most of these studies are focused within the upper 10 m of the thick vadose zone (>100 m), while the hydrological processes of the deeper dryland CZ remain enigmatic (e.g., Stuckless, 2012). The hydrological connectivity between shallow and deep CZ become even more important in wet parts of drylands, including playas and irrigated agriculture in converted drylands. Infiltration is important for the fate and transport of water, salts and carbonates, nutrients, and potential contaminants in the deep dryland CZ (Walvoord et al., 2003). The connectivity between the shallow and deep CZ relies on the evolution of CZ architecture and more critically the accumulation of pedogenic carbonates that control unsaturated-zone water fluxes and availability (Duniway et al., 2010, 2018; Rossi et al., 2018).

Lastly, coastal environments, which connect fluvial, hillslope, and inland environments with oceans, are important to an understanding of how the effects of climate change, such as sea-level rise, affect surface and subsurface hydrology, vegetation, and geochemistry (e.g., Michael et al., 2017; Sawyer et al., 2016). Including the work of coastal researchers who have knowledge of both ocean interactions with terrestrial environments and coastal processes is essential for advancing science of changing boundaries across lateral space (Liu et al., 2021). Human impacts on coastal regions affect all the systems that have been included in the CZ: subsurface hydrology, biogeochemistry, vegetation, bedrock weathering, and erosion. Defined by architecture, that is, base and thickness, rather than a particular region, may allow scientists to apply a common template to both explore and communicate with other scientists studying the same structures with the same motivations of human impacts and effects on human infrastructures.

5.2. Approaches to Diversifying CZ Science II: Meaningful Engagement of Historically Excluded Scientists

As a relatively young geoscience subfield, CZ science started with foundations motivated by interdisciplinary integration and cooperation. However, historical legacies such as colonialism, at the roots of western science, upon which CZ science is firmly based, continue to create barriers to social progress in the Earth sciences generally. As systems theory dictates, this dynamic of domination against specific groups within society in general is also mirrored within that society's scientific community as well (Blakemore, 2023). Because only a handful of countries in the entire world escaped colonialism's expansive reach, western science's historical ethos of dominance rather than one of collaboration has proliferated. Perhaps, then, it is no surprise that the United States and western Europe dominate in ownership of the most influential academic journals, while simultaneously serving as gatekeepers for who gets published in them and who does not (Deb Roy, 2018). Most scientists are comfortable exchanging scientific dialog, but less comfortable discussing the impacts of colonialism or the struggles of historically marginalized groups (e.g., Morris and Washington, 2018). Although the conversations specific to CZ science may have only begun in the last 25 years, the devastation that racism, sexism, classism, and ableism—among other explicit or implicit discriminatory behavior —have continued to impact public knowledge and scientific achievement for far longer. Given that dialogs on these topics are important to moving forward as a community (e.g., Dutt, 2020), we ask: how can the CZ research community serve as a beacon for social change?

According to the latest *Status of Recent Geoscience Graduates* report (AGI, 2022), the demographics of those responding to their survey reflects the continuing lack of visible diversity within the geosciences. We focus here on U.S. institutions, where demographic data were easily accessible to us. Geoscience professionals and organizational membership in the U.S. remain overwhelmingly ethnic European and male (Table 1). Other "racial" identities were reported at effectively negligible percentages. Women make up only 35% of people employed in STEM occupations (NCSES, 2023). Only 11% of STEM majors have declared or documented disabilities (Atchison and Libarkin, 2016); in the Earth sciences, numbers are likely low because of the perception that fieldwork is a necessary requirement (Stokes et al., 2019) and the exact numbers of students marginalized by

Table 1
Demographics of Two U.S. Geoscience Organization's Memberships: The Geological Society of America (GSA) as of 2021, and the American Geophysical Union (AGU) as of 2020

	Ethnicity					Gender		Age		
	European	African	Hispanic	Asian	Native American	Male	Female	Between 30-59	Between 30-40	40+
AGU	54%	1%	4%	6%	0.3%	60%	28%	18%	50%	18%
								Under 30	*Between 30-59*	*Between 60-75+*
GSA	67.1%	1.4%	4.1%	5.4	0.4%	53%	48%	–	–	–
All Geosciences	82.5%	1.2%	6.6%	7.6%	0.2%	76%	24%	10%	30%	60%

ableism is unknown in the U.S. due to limited data given restrictions associated with Family Educational Rights and Privacy Act (FERPA) and Health Insurance Portability and Accountability Act (HIPAA), which protect education and medical records (Carabajal and Atchison, 2020). Until the geosciences broadly and CZ science specifically take seriously this lack of diversity and inability to even acknowledge racism, sexism, and ableism by name, progress toward equity and inclusion will not be achieved. For example, historical legacies of discrimination in the U.S. of ethnic Africans—two centuries of slavery, a century of Jim Crow laws, and subsequent decades of social discrimination in general—are reflected in STEM graduate and workforce percentages that do not represent their relative proportions in society at large.

While changes in diversity and inclusion at system-wide levels that would require governmental and institutional initiations, such as scientific funding agencies, have proven to be slow, actions taken at the individual and local level and motivated by cultural change can sometimes be more effective at changing behaviors and communities. Such changes work their way to the system level by providing new norms of social interaction leading to new leadership and new expectations. For example, Chamorro-Premuzic (2017) highlighted multiple important factors surrounding diversity and creative outcomes. The following four ideas are selected from that list and expanded on here for adaptation to CZ science:

5.2.1. There's a Difference Between Generating Ideas and Implementing Ideas

Does diversity and inclusion increase creativity? Research is mixed on a definitive answer to that question, but some findings are consistent. While diverse team composition does help when it comes to generating a wider range of original and useful ideas, studies have suggested that such benefits disappear once the team is tasked with deciding which ideas to select and implement, presumably because diversity hinders consensus given less social integration (e.g., Chamorro-Premuzic, 2017; Mannix and Neale, 2005). It is one thing to generate creative ideas, but another to put those ideas into motion. This is consistent with psychological competencies associated with the creative process: divergent thinking, openness to experience, and brainstorming are needed to produce many original ideas, but unless they are followed by *convergent thinking*, *expertise*, and *effective project management*, those ideas will never come to fruition.

5.2.2. Good Leadership Helps

Disagreements and conflicts arising from diversity can be mitigated if teams are effectively led. It is the psychological process that enables individuals to set aside their individual agendas to cooperate with others for the common benefit of the team, articulating the natural tension between our desire to get ahead of others and our need to get along with others. This is especially true when teams are diverse, *for it will be harder for team members to see things from other members' perspectives*, empathize with them, and suppress their own conscious and unconscious biases. Of course, the definition of "leadership" can be difficult (e.g., Winston and Patterson, 2006), especially across cultures globally that may have different perspectives (Peterson and Hunt, 1997).

5.2.3. Deep-Level Diversity Is Key

Most discussions about diversity focus on superficial demographic variables like "race," gender, age, sex, etc., but *deep-level diversity* discussions, focusing on personality, attitudes, and values (e.g., Harrison et al., 2002), for example, can be more productive. Whereas demographic discussions only perpetuate stereotypical and prejudiced characterizations, deep-level diversity focuses on the individual and interpersonal skills, providing a more detailed understanding of human diversity. Finally, regardless of if the focus is on personality, motives, and values, or simply creativity, group differences are insignificant when compared with differences between individuals, even when the individuals are part of the same group.

5.2.4. Knowledge Sharing Is Important

No matter how diverse the workforce is, and regardless of what type of diversity we examine, diversity will not enhance creativity unless there is a culture of sharing knowledge. Studies have found higher levels of creativity in groups that are more interconnected, particularly when creative and intrapreneurial individuals are a central node in those networks. In other words, making CZ science important and relatable to those other than "scientists" themselves will require those "scientists" to make their work accessible to, inclusive of, and involving individuals in discussions who are not "scientists." An additional, often-overlooked fact is that in generating even a single creative product, group members must also build on and combine one another's ideas, which require some convergence, agreement or coming together (Harvey, 2013).

Within CZ science specifically, other possibilities for broadening participation include open science software and hardware, which may reduce inequalities in research (Arancio, 2023). Developing codes and hardware and sharing those broadly opens up doors for knowledge production in CZ science to be truly global. Also, social media networks are open platforms for knowledge sharing that help research grow and thrive. Though concerns with social media such as the proliferation of uncited scientific information and biased opinions exist (Ghermandi et al., 2023), social media are a way to find collaborators and telegraph the impacts of scientific research on an equitable platform, which can promote the democratization of science (e.g., Hunter, 2020). Beyond information sharing, social media is a critical networking tool, notably for scientists from historically excluded groups. Social media enables connections among scientists with shared backgrounds and identities. For example, the GeoLatinas is an international group whose members organize around activities that embrace, empower, and inspire Latinas to pursue and thrive in careers in Earth and Planetary Sciences. The power of social media has connected over 1,000 scientists in over 50 countries through GeoLatinas. Similarly, the #BlackInGeoscience movement has showcased the accomplishments of Black Geoscientists and allowed for connections that would not otherwise be possible without social media.

In short, there are many places where change is needed. Many works have outlined roadmaps to tackle racism and discrimination (Ali et al., 2021; Chaudhary and Berhe, 2020; NASEM, 2021). We also offer the following places where one might start, which is certainly not exhaustive:

- Taking action and leadership in role modeling by talking about actions and approaches used to normalize relating research to effects—positive and negative—on humans, such as during research presentations;
- Recognizing that there are academic haves and have-nots: there is a bias toward particular, usually wealthy, institutions and those attending them, which propagate throughout many facets of science (e.g., Wapman et al., 2022), and expanding one's network beyond those schools;
- Relatedly, collaborating with and including students and researchers from international institutions, community colleges, or universities supporting students from historically excluded groups to expand one's reach and impact;
- Intentional mentoring of scientists from historically excluded groups that does not tokenize mentees or put the needs of the mentor first (Martinez-Cola, 2020);
- Developing field opportunities where disabled researchers can meaningfully contribute (e.g., Stokes et al., 2019);
- Co-production of knowledge with inhabitants of the lands researched (e.g., Matson et al., 2021);
- Convergence of research goals to improve circumstances of historically excluded and vulnerable groups;
- Development of open software and hardware tools for the community;
- Creating awards and recognition structures to elevate activities involving not merely "service" but application of diversity, equity, and inclusion principles in research; and
- Striving for self-awareness of one's own place in hierarchies of power, hearing and seeing the impacts of legacies in the circumstances aiding or hampering career access and advancement in the cases of self as well as others.

Lastly, CZ scientists must be cognizant of the social and economic influences of their work, including ethical, political, and philosophical issues (Das and Paital, 2021). The current funding structure for research worldwide often requires that training of undergraduate and graduate students come through focused research projects, typically individual investigator grants. One suggested strategy for encouraging more broad-based training is for funding agencies to establish a program of research training grants, either on their own or with other science divisions, to provide undergraduates and graduate students with access to alternative research environments.

5.3. Measuring the "Deep" CZ FAIRly and With CARE

Sampling and sensing methods are needed to capture CZ architecture and material processes at different spatial scales. These methods will help determine processes responsible for the chemical and physical breakdown of bedrock and regolith. These processes will dictate where boundary changes occur in bedrock and above and how those boundaries connect with each other and to changes on the surface. One place where additional emphasis can be placed is on "deep" biological sampling. Much of the research on biological processes in the CZ have sampled within and just below the majority of the rooting zone to assess plant uptake and have focused on determining terrestrial ecosystem fates of carbon and nutrients (e.g., nitrogen and phosphorus) (e.g., Hobbie, 1992), microbial competition for nutrients (e.g., Kaye & Hart, 1997; Van Der Heijden et al., 2008; Zak et al., 1990), and leaching losses (e.g., Hinckley & Matson, 2011; Lohse & Matson, 2005; Rao et al., 2014). In many studies, only the top 10–30 cm of the soil profile has been sampled and analyzed because it captures the greatest biomass of fine roots and most abundant microbial communities. Yet important biogeochemical transformations and transfers occur deeper within the CZ where they influence bedrock-weathering processes. Roots can penetrate several meters in some systems (e.g., Canadell et al., 1996) and have a role in releasing and/or transporting rock-derived nutrients, such as calcium (Perakis & Pett-Ridge (2019)) and others essential for growth (Jobbágy & Jackson, 2001). Preferential flowpaths can transport carbon and nutrients well below most of the rooting zone to depths where they fuel microbially mediated geochemical transformations. A few recent studies have pointed to the presence of active microbial communities at depths to 1 m or more (Eilers et al., 2012; Minyard et al., 2012; Will et al., 2010). There may be a whole under-explored realm where biology does chemical work. While geochemical data are often limited in the CZ to the top 30 cm (Richter & Billings, 2015) it's rare to have data looking deeper than a few meters (e.g., Parsekian et al., 2015).

New technology will undoubtedly push our understanding of deep processes. Geophysical techniques provide one of the most promising ways to see deep into the CZ, and new methods may help us quantify properties at depth that we haven't be able to measure yet. Most seismic refraction surveys at the catchment scale use conventional vertical-component geophones that only provide vertical motion data and P-wave tomographic models. As attention has been drawn to deeper CZ physical and chemical processes objectives, these single component seismic data are limited, and seismic attenuation and S-waves, and their temporal changes, provide promising ways of deciphering additional processes (Liu et al., 2022; Xing, 2023). Generating and recording different components of the seismic wave field in the Earth will complement P-wave measurements to map the CZ that could not be extracted previously. Li and Pyrak-Nolte (1998) showed that seismic attenuation can be used to monitor the ion exchange between pore fluids and sediment in situ. S-waves are increasingly being used in CZ settings given their sensitivity to fluid saturation (e.g., Liu et al., 2022; Pasquet et al., 2015, 2022). Moreover, geophones are difficult to maintain over months to years, especially in suburban and rural environments like many CZ sites, so continuous seismic monitoring data has rarely been collected in the CZ. A rapidly developing sensing technology, distributed acoustic sensing (DAS), provides a promising alternative to geophones. DAS systems utilize a single optoelectronic interrogator unit that can sample tens of kilometers of optical fiber at sub-meter sensor spacing. The advantage of a DAS array is it is easy to maintain for time-lapse seismic recordings over large distances and over long-time spans, which has been experimented in urban environments (Zhu et al., 2021) and the Shale Hills Critical Zone Observatory (Zhu, 2022). DAS should enable field measurement of 4-D seismic-hydrologic signals over time periods of years with unprecedented spatial resolution.

Other options for new CZ geophysical techniques may come from space. The Radar Imager for Mars' subsurFAce eXploration (RIMFAX; developed by NASA) has been used to noninvasively collect data at 10 m depth across Mars to assess the likelihood of ancient habitability (Hamran, 2020). RIMFAX has advanced the use of GPR technology by including frequency-modulated continuous-wave radar that offers more accuracy than its pulse-radar predecessors. Frequency-modulated continuous-wave radar emits a continuous signal and uses the frequency difference between the emitted and reflected signals to determine the distance of a target. RIMFAX operates at 150–1200 MHz (Hawk Measurement Systems, 2022). Similar technology and methodology could be used to identify Anthropocene effects at depth over time and better characterize CZ thickness, especially when used in tandem with other geophysical measurements.

Lastly, beyond recognizing the need for new data, data sharing is an essential part of open science. Open CZ data will require scientists to follow protocols for storage and recovery. CZ-related data are often collected and saved by individual researchers, perhaps published as supplementary material or uploaded online. The CZNet Coordinating Hub was designed to help researchers from diverse disciplines share their data according to FAIR (Findable, Accessible, Interoperable, and Reusable) principles (e.g., Wilkinson et al., 2016). It recommends appropriate CZ repositories for investigators' research, and formats and conventions for creating complete metadata. Ideally, CZ researchers would be aware of this repository before data collection, preferably at the proposal writing stage. Another tenet for expanding the research limits of the CZ is to encourage researchers whose work falls into Earth system processes share their work with the community in FAIR ways, as is being encouraged by many journals and granting agencies (e.g., see Table 1 in Erickson, Elliott, et al., 2021; Erickson, Burnett, et al., 2021). In addition, to enhance FAIR data coverage for CZ sites across gradients of climate, vegetation, geology, and land-use conditions, coordinated efforts across the globe are often necessary. Yet international collaboration is often rare due to the sparsity of international funding support for global collaboration as well as diverse operation and rules that regulate data availability and accessibility across different countries (Arora et al., 2023). Further still, although less discussed, are CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles, which address data sharing from Indigenous contributors to the knowledge base and their data sovereignty (e.g., Carroll et al., 2020; Garba et al., 2023).

Beyond data are the computational tools needed to use and analyze data and/or the models that created data (collectively referred to as software). Open-science principles require that both data and software are accessible. Yet there are few guidelines on how to make software FAIR (Barton et al., 2022). Despite many journals requiring software to be accessible, a study of articles published using agent-based and individual models found that in 2018, just 11% of these articles used code that was accessible (Janssen et al., 2020). Part of accessibility includes practices such as version control, the use of computer environments for application of software, and access to advanced computing resources (Erickson, Burnett, et al., 2021; Erickson, Elliott, et al., 2021). To support these practices, groups such as CSDMS (Community Surface Dynamics Modeling System; Tucker et al., 2022) and CoMSES.net (Network for Computational Modeling in Social and Ecological Sciences, Janssen et al., 2008) provide FAIR-aligned repositories for models of geophysical systems and social and ecological systems, respectively. FAIR data and software will not only push forward CZ science, but they will also aid in making the CZ community open to more scientists worldwide.

5.4. Leveraging Machine Learning and Artificial Intelligence (AI)

An emerging trend to address the subsurface-data scarcity problem is the use of machine-learning approaches. Such approaches have been used to infer subsurface structure, properties, and functioning, including stream water quality, groundwater chemistry and permeability that can potentially be used to infer CZ thickness (Erickson, Burnett, et al., 2021; Erickson, Elliott, et al., 2021; Ouedraogo et al., 2019; Podgorski et al., 2020, 2022; Wen et al., 2021). Traditional methods such as random forest or generalized boosted regression models are being used (Bergen et al., 2019; Hare et al., 2021; Li et al., 2021) as well as deep-learning models with multiple layers of neural networks that automate pattern extraction (Zhi et al., 2021; Zhi, Ouyang, et al., 2023; Zhi, Klingler, et al., 2023). For example, Convolutional Neural Networks (CNN), a particular type of deep neural network, have been used to extract spatial patterns of subsurface characteristics from surface data; Sun (2018) used a deep CNN-based model with 2-D land-surface data, including digital elevation maps and remote sensing images, to construct 3-D subsurface structures. Their model revealed complex relationships between surface and subsurface features and offered an automated, low-cost method to generate 3-D subsurface images that inherits the probability structure from 2-D surface images. Machine-learning methods have been shown to outperform traditional calibration approaches in estimating subsurface parameters because they can directly infer parameters from observations and better capture the highly nonlinear relationships with fewer realizations (Cromwell et al., 2021; Jiang et al., 2021). Another deep neural network model used widely available time series of streamflow data to estimate subsurface permeability, which can be further used to estimate flow paths and weathering fronts (Jiang et al., 2022; Tartakovsky et al., 2020). By incorporating the governing equations of Darcy's Law and Richards equation into its loss function, the model enhanced accuracy with limited data availability. These examples highlight the potential of emerging machine-learning models in estimating subsurface properties, including CZ thickness.

Despite of the advances in machine-learning techniques, a potential concern is that AI could threaten to extenuate inequalities in the geosciences. Bias is encoded into our machine-learning algorithms given that they are built by humans such that the use of AI and its machine-learning algorithms may reinforce and exacerbate the racism and "racial" bias humans have embedded into U.S. and western European societies' structures and institutions (Intahchomphoo & Gundersen, 2020). In addition, AI models are trained by data that are collected unequally in time, geography, and population representation (Ntoutsi et al., 2020). Such data biases add bias on top of algorithm and code bias. It remains an open question about what impacts bias might have as these methods become increasingly used (e.g., Howard & Borenstein, 2018). McGovern et al. (2022) suggested that in the environmental sciences specifically, bias in AI can lead to non-representative training data (e.g., lack of geographic diversity that could be impactful to environmental justice issues) in environmental data sets, faulty training labels or algorithm strategies, or lack of consent or input on training data that lead to poor consequences in economically developing areas or countries, for example. It is also likely that AI could exacerbate inequalities internationally, with countries with better access to money, technology, and training, better able to access the benefits of AI (Fatima et al., 2021).

5.5. Addressing the Bottlenecks of Scaling and Model Integration

Approaches that can combine and integrate techniques that measure the CZ base with total CZ thickness are needed for quantifying the response of the CZ to forcing factors and understanding the response of the near surface in different regions. For example, region-wide topographic variation acquired with DEMs correlated with subsurface geophysical models would be useful to supplement with data informing bedrock-to-regolith transitions. Topographic modeling of highlands and lowlands using DEMs (Pelletier et al., 2016), based on thicknesses of soils, regolith, and sediment, could be compared with subsurface data on bedrock depth to adjust land-surface models where conventionally uniform thickness are used in modeling. Geophysical, mapping, and DEM applications with stratigraphic modeling of deposition through time, such as site-descriptive modeling (Nyman et al., 2008), may improve accuracy and understanding of subsurface spatial variability in porosity, water storage, and fluxes (Sohlenius et al., 2013) and estimates in thicknesses and volumes. Such site-descriptive stratigraphy may be a way to link bedrock with soils and the CZ.

Geophysical mapping for CZ thickness on a continental-wide scale (similar to the soil suitability map of Doolittle et al., 2007) could likewise be supplemented by local-scale data of soil composition, for example, clay abundance by integrating infrared spectroscopy to identify and measure abundances of clays in soils (Viscarra Rossel, 2011; Wilfred et al., 2016), which can then be used to associate with parent material and bedrock sources and the scale of their occurrences in the landscape. Such an integrated geophysical and geochemical approach would provide a first-order quantitative approach to answer what spatial scales geochemical processes at depth are occurring, what factors affect their rate changes, and at what lateral spatial scales surface ecohydrological processes respond to them. Methods already exist that permit continental-scale estimates of a bottom boundary (Pelletier et al., 2016; Willfred et al., 2016), but their resolution is not at the scale at which most CZ processes are measured.

In general, a major data gap exists between local data sources and remotely sensed data. While soils have been mapped globally using climate zones, from deserts to tropics (e.g., products such as SoilGrids, Hengl et al., 2014, 2017), a critical gap is in measurements of soil temperature and soil moisture at the model pixel scale (Rutten et al., 2010). The coupling needed to bring the different data sets into a land-surface-atmosphere model needs to address computational demands for variability in scales across space and time. For example, land-atmosphere-energy exchanges are crucial for hydrological, biological, and shallow subsurface processes in the CZ, yet occur on short temporal scales compared to geologic uplift. Methods for connecting rates of processes at different scales are needed for improving land-surface models. At least two areas can facilitate such integration: (1) a framework that recognizes variation across space and time given unification of basic processes, mechanisms, architectures, and methods for measuring and mapping within them and (2) means of managing the data that is accessible to all scientists working in the CZ realm. Feedbacks to humans and human systems should also be incorporated into these coupled models, such as in agent-based and risk-based modeling (e.g., Sun et al., 2016).

6. Conclusions: Can we develop a framework that enables the necessary creativity and diversity to holistically understand how CZ thickness evolves and responds human pressures?

Our review of geochemical, geomorphological, geophysical and ecohydrologic and processes and techniques is intended to expand the spatial reach of CZ science and to expand the "human reach," or the communities impacted by the CZ and the practitioners who study it, by setting a common vocabulary. The goal of this paper is to help CZ practitioners—new and old—develop questions and methodologies to define CZ depth and how it is changing, and what that means for humans in the Anthropocene. Numerous processes are at the heart of defining thickness and the base of the CZ, and specific sub-field nomenclatures may limit the application of data and scientific results to a particular region. If thickness and CZ base are used abstractly, such as in model construction, how should additional related factors, such as climate, vegetation, or life factor in? We hope that by sharing available scientific techniques and defining terminology from subfields in the geosciences that we can make our communication to one another, as well as stakeholders, more transparent. Language can bring people together just like it separates us. By outlining research questions that can be addressed by diverse fields about subsurface characteristics, we hope that a new generation of CZ scientists see research gaps that we yet haven't. We also challenge ourselves, and the CZ community more broadly, to think about how our words can be powerful tools for including others when we talk about science, no matter who is in the room when we speak. In so doing we serve as models for holistically inclusive science.

Investigation into key factors defining CZ architecture mapped across space at various spatial scales are needed, as are field investigations with the stated purpose of contributing to local characteristics for the purpose of comparing broader regions within and external to the watershed scale. Perhaps a unifying research goal in CZ science should be to reformulate and capture the natural-system framework of the CZ with the role human beings play in it, broadly defined.

But this opens questions: should the CZ be reduced to a physical 3-D space or is it intended to necessarily include human space? Does this restrict the CZ space to only those habitable areas of life in general or just humans or both? Do such restrictions also restrict a time frame in which the CZ can be considered?

What is needed to address these questions—and what we have tried to outline—are common and fundamental structures that can be applied anywhere and used by the diversity of researchers involved in investigating and recording CZ processes from a myriad of perspectives. Doing this also sets the potential for expanding what has conventionally been viewed as the CZ so that its "critical" human relevance can be recognized in all near-surface processes on Earth. We also provide suggestions to make sure that we build a sense of belonging in CZ science such that the next generation of scientists is part of both problem setting and problem solving. Formulating a framework to have inter- and trans- disciplinary Earth scientists relate their research across systems worldwide and compare their data and models through the full depth of the CZ across all landscapes—as well as advancing improved techniques—geochemical, geophysical, ecohydrological—through all four dimensions, and needed to account for and reconcile changes in rates with changes in spatial scale. We hope that this integrated exploration adds to the existing approach of CZ science and highlights where it could go, and what questions need to be addressed for CZ to have a more integrated and expanded reach across the Earth's surface.

Data Availability Statement

Data were not used, nor created for this research.

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