

## **Report on *Drilling, Sampling, and Imaging the Depths of the Critical Zone*, an NSF Workshop**

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**Executive Summary.** This report summarizes outcomes of an NSF-supported workshop, entitled *Drilling, Sampling, and Imaging the Depths of the Critical Zone*, which was conducted on October 24–26, 2013, in the days preceding the annual meeting of the Geological Society of America, in Denver Colorado. The workshop hosted 49 participants from 35 institutions scattered over 2 continents. Participants represented diverse disciplines, including geophysics, geochemistry, geomorphology, soil science, hydrology, and drilling technologies. Participants were also diverse in career level, ranging from second-year graduate students to directors of national and international facilities and programs. Over the course of two days of presentations, breakout groups, and plenary discussions, the following 10 outcomes, recommendations, and conclusions were reached: (1) There is strong interest and sense of excitement around advancing deep critical zone (CZ) research through a program of drilling, sampling, and geophysical imaging; (2) The CZ research community has now embarked on a long-term effort to unveil the deep critical zone at a scale appropriate to enhanced understanding of processes vital to the evolution of the CZ and to the prediction of CZ response to change in the future; (3) Shallow drilling and geophysical imaging projects do not have a funding source of their own, yet there is a need expressed across the community, including multiple disciplines, to support both drilling and geophysical studies of the deep CZ; (4) Overcoming limitations imposed by disciplinary silos will require new connections between CZ scientists, near-surface geophysicists, and experts in drilling technologies (some promising connections were made at the workshop); (5) Funding mechanisms must accept that proposals to study the CZ could (and often should) have strong geophysics and drilling components; funding of such work could alternatively be structured around a service model (similar to NCALM for LiDAR imaging) over the long-term; (6) Drilling and geophysics need to go hand in hand to capitalize on potentially powerful synergies and to understand the great compositional and spatial variability of the CZO; (7) The observations that are made using drilling and geophysical imaging should be driven from a hypothesis-testing framework; (8) The CZOs have already made many of the measurements needed to simultaneously test and demonstrate the value of geophysics and drilling with abundant existing data to fuel hypotheses; (9) A program of cross-disciplinary education is recommended to grow a new breed of CZ scientists who are educated in deep CZ investigation methods including drilling and geophysics; a good way to start may be to follow the REU model already established at NSF; (10) A panel of experts should be formed to serve in an advisory role for the growing community of scientists interested in deep CZ research using drilling and geophysical imaging.

### **What is the “Critical Zone”?**

The “critical zone” (or just the “CZ”) has been defined as the near-surface environment where water, rock, air, and life meet in a dynamic interplay that generates soils, sustains ecosystems, and shapes landscapes (Brantley et al., 2007; Chorover et al., 2011). Understanding the chemical, physical, and biological processes that influence the CZ and the life it supports is important across a diverse range of problems, from assessing soil sustainability over timescales of human observation, to quantifying feedbacks between climate, weathering, and tectonics over millions of years (Brantley et al., 2006; National Resource Council, 2010). Increasingly, these problems are being tackled in exciting studies that are bridging a broad range of disciplines, from geophysics to geochemistry and from hydrology to soil science.

## **Motivation for a workshop on drilling and imaging the “deep CZ”**

The CZ extends from the outer periphery of vegetation to the lowest limits of freely circulating groundwater (Brantley et al., 2006). Yet, thus far, subsurface CZ research has focused mostly on just the upper 1–2 m or so of weathered rock and soil (Riebe et al.). Although this work has greatly advanced understanding of soil production (Heimsath et al., 1997), erosion (Blanckenburg, 2005), weathering (Anderson et al., 2002), and biogeochemical cycling (Chorover et al., 2007), it is now increasingly recognized that the top 1–2 m, and indeed life as we know it at Earth’s surface, is often profoundly influenced by processes that occur beneath it, in saprolite and fractured rock that collectively extend to depths of 100 m or more in many landscapes (Holbrook et al., 2014; Goodfellow et al., 2013; Rivé et al., 2013; Wald et al., 2013; Anderson et al., 2013; Leopold et al., 2013; Befus et al., 2011; Buss et al., 2013; Buss et al., 2010; Fletcher et al., 2006; Anderson et al., 1995; Graham et al., 2010; West, 2012). This deeper layer, referred to here as the “deep CZ”, lies below the limits of most CZ studies to date. Hence it is an “unmeasured zone”, despite its widely recognized importance in surface-subsurface interactions and the feedbacks that are inherent in the development and maintenance of weathering profiles and the ecosystems that they support.

With the establishment of a diverse network of Critical Zone Observatories (CZOs), both in the United States (Anderson et al., 2008) and elsewhere (Banwart et al., 2011), our understanding of the CZ has deepened markedly. So too has recognition that the community must investigate processes at greater depths within the CZ to understand its evolution to the present, its trajectory into the future, and its influence on the sustainability of vital ecosystem services (Riebe et al.). The deep CZ is crucial theater of processes and interactions relevant to geobiology, geochemistry, geomorphology, and soil science. For example, there are clear indications that the chemistry and hydrologic response of streams at the surface may often depend crucially on CZ processes in complex fractured bedrock systems at depth (Anderson et al., 2002; Onda et al., 2004; Langston et al., 2011; Kuntz et al., 2011; Salve et al., 2012). This implies that characterization of the deep subsurface is crucial to predicting how the CZ will evolve in a changing climate. In addition, it has been shown that the degree of weathering in saprolite may be a key regulator of soil production (Burke et al., 2007; Dixon et al., 2009), making quantitative understanding of the deep CZ crucial to addressing topics ranging from soil sustainability to landscape evolution. Surface processes affect – as well as depend on – deep weathering (Frazier and Graham, 2000; Clarke and Burbank, 2011), raising the prospect of exciting, yet-to-be explored feedbacks among landscape evolution, regolith formation, biogeochemical cycling, and hydrologic processes (Brantley et al., 2011). Hence it’s evident that deep CZ research is a key 21<sup>st</sup> Century frontier for a number of subdisciplines within the broad field of Earth-systems science, including watershed hydrology, geobiology, geomorphology, soil science, and low-temperature geochemistry (National Resource Council, 2010).

One of the great hurdles in understanding and quantifying processes in the deep CZ is depth itself; regolith and subsurface biota, the objects of study, are difficult to characterize *in situ* because they are mostly buried at difficult-to-access depths (Montgomery and Dietrich, 2002; Heilweil et al., 2006; Winter et al., 2008; Sherriff et al., 2009; Befus et al., 2011). Near-surface geophysical techniques can be employed to help image the subsurface over broad scales (Robinson et al., 2008; Samouëlian and Cornu, 2008), but interpretation of such images is problematic in the absence of direct observations of physical and chemical properties of material at depth. Such direct observations are usually possible through drilling and coring, for spot sampling of solid-phase geochemistry, microbiology, pore-water solutions, and other material properties (Begonha and Braga, 2002; Olona et al., 2010). Boreholes from drilling have the added advantage of providing access for pump tests and installation of long-term hydrologic and geochemical monitoring equipment (Day-Lewis et al., 2006). Yet the logistics and technical difficulties of coring make minimally perturbed, representative samples

difficult to obtain, especially from deep boreholes that would be ideal for long-term monitoring installations.

Coring and borehole installations are time-consuming and expensive, placing practical limits on the number of holes that can be drilled in the characterization of the deep CZ. Hence it is crucial to make each drilling effort as effective as possible at addressing key questions about the deep CZ in different landscapes. To achieve this goal, studies of the deep CZ need to be able to optimize locations of boreholes, to provide a high yield of data per unit cost invested in drilling and instrumentation. The traditional approach to identifying prime borehole locations involves geophysical imaging of the subsurface during preliminary site investigations (Kieft et al., 2007). In deep CZ research, geophysical imaging of the subsurface takes on added importance, in the aftermath of coring, as a way to extrapolate the spatial extent of subsurface heterogeneities (Robinson et al., 2008; Befus et al., 2011) observed in individual cores. Such heterogeneities are typically both extensive and often also key targets of study for hydrologists, soil scientists, geobiologists, biogeochemists and geomorphologists alike (Banfield et al., 1999; Hubbard and Rubin, 2000; Massoud et al., 2009; Graham et al., 2010).

In a synergistic development for deep CZ research, the field of near-surface geophysics is in the midst of a renaissance, with its own recently established focus group within the American Geophysical Union and a recently established journal, entitled *Near Surface Geophysics*. This represents tangible evidence of a growing community of geophysicists who are actively studying what we refer to here as the deep CZ. This surge in interest in near-surface geophysics dovetails nicely with the recent surge in interest from Earth scientists who are advancing towards research goals in understanding Earth's deeper records via a renewed commitment to continental scientific drilling in the US. Hence, the time is right for a community-wide consensus on how to best advance CZ science on a vital mutual research frontier for a diverse array of disciplines.

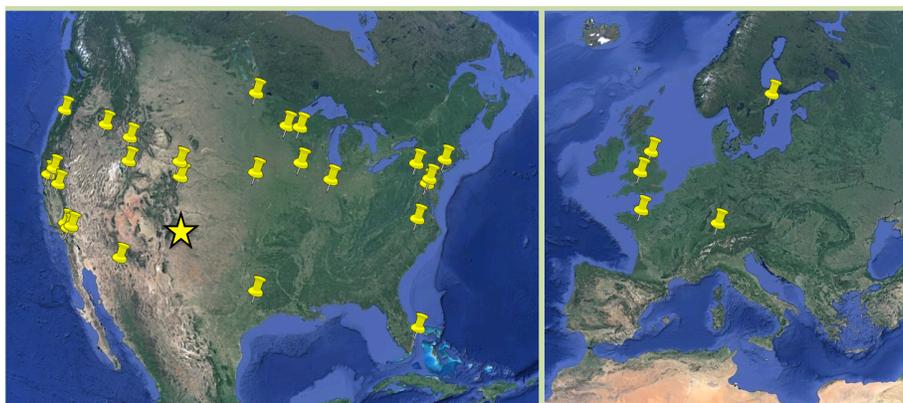
### **Workshop objectives**

The goal of this workshop was to develop a community-wide, cross-disciplinary consensus on how to overcome the traditional difficulties of deep CZ research. The target disciplinary backgrounds of participants included CZ researchers and near-surface geophysicists, as well as engineers with experience in drilling, coring and borehole instrumentation. The workshop was designed to exploit the chance alignment of: (i) an increasing need for advances in deep CZ research, voiced in a recent consensus of CZ scientists from around the world (e.g., see Riebe et al., in review); (ii) recent advances in near-surface geophysics, including improved techniques for imaging the deep CZ and interpreting geophysical properties in terms of CZ architecture; and (iii) recently renewed momentum behind establishing a formal program of continental scientific drilling in the US. It was recognized that the workshop would need to bridge disciplinary gaps and foster productive new collaborations among scientists and engineers from diverse backgrounds, in order to be successful. As indicated next, the expertise and backgrounds of actual participants was indeed very diverse. Moreover, over the course of a series of presentations and breakout meetings during the workshop, there was lively discussion that converged on a series of concise recommendations. We hope these recommendations will serve as a foundation for advancing study of the deep CZ through a coordinated program of targeted drilling and geophysical imaging.

### **Workshop participants**

The workshop was advertised through a number of e-mail list serves, including “gilbertclub”, “GEOMORPH-L”, “CZEN”, and “GEOPHYSICS”. The workshop was also advertised to CZO co-PIs, students, collaborators, and affiliates directly via the lead PIs, who were apprised of the workshop by the workshop PIs. Our advertisements included a clear call for applications from researchers from diverse disciplines at all career levels. An example advertisement is included in Appendix 1. Prospective participants submitted a total of 53 applications using an online application form available

at [http://csdworkshops.geo.arizona.edu/Denver\\_CO.html](http://csdworkshops.geo.arizona.edu/Denver_CO.html). All applications were accepted, but four of the successful applicants (including three from NSF and one from the US Forest Service) were unable to attend due to complications related to the government shutdown. Hence, there were 49 attendees representing 35 different institutions (Table 1) scattered across North America and Europe (Figure 1). On their registration forms, which applicants completed online, participants self-identified themselves as follows (with corresponding numbers of participants in parentheses): “Graduate students” (12); “Professors” (27); “Post-docs” or “Research scientists” (8); and “Other” (2) (see Table 1). Although the official award announcement for the four new CZOs had not yet been made at the time of the workshop, all ten of the current Critical Zone Observatories sent representatives numbering 25 in total. In addition, there were representatives from the US Geological Survey, ANDRILL (the Antarctic Geologic Drilling program), LacCore (the National Lacustrine Core Facility), WyCEHG (the Wyoming Center for Environmental Hydrology and Geophysics), and SoilTrec (the European CZO group) numbering 10 in total. Disciplines represented by participants were diverse, including geophysics, geochemistry, geomorphology, soil science, hydrology, engineering, and drilling technologies. The expertise and interests of participants are captured in this report in a list of self-reported summaries gathered from workshop registration forms (Table 2). In addition to filling out surveys, participants also contributed 10 white papers, collected here in appendices, and 10 posters, which were on display throughout the workshop.



**Fig. 1** – Google Earth images showing distribution (push-pins) of institutions represented by participants at workshop convened in Denver (star).

### **A brief account of what happened at the workshop**

The workshop was held in conference rooms at the Hilton Garden Inn in downtown Denver, Colorado from October 24–26, 2013. A copy of the schedule for the workshop is included in Appendix 2. Some modifications were made as the workshop progressed in response to feedback from participants. This section provides highlights of what actually happened during the workshop.

#### ***Plenary keynote presentations***

On Thursday, October 24<sup>th</sup>, participants gathered for an icebreaker dinner at the Hilton Garden Inn in downtown Denver. (Many of the participants stayed in this hotel during the workshop and thus capitalized on the low lodging rates secured as part of a block deal by the conveners.) Following the dinner, there were two excellent keynote talks about needs and prospects in deep CZ research. The first was given by Professor Bill Dietrich (UC Berkeley and lead PI on the new, Eel R. CZO) and the second was given by Professor Sue Brantley (Penn State and lead PI on the Shale Hills CZO). These talks provided motivation and context for the workshop activities that followed.

Topics that Dietrich stressed included: (i) the fundamental importance of understanding the topography of unweathered bedrock at depth (in particular it is a crucial boundary condition for all processes in the critical zone); (ii) the merits of studying “characteristic” hillslopes at each site that

might reflect, in a general way, how the surface and subsurface interact during deep weathering; (iii) the general observation that regolith thickness increases from the channel bottom to the drainage divide; (iv) the need to focus some effort on the ridge, where weathering can be conceptualized as a 1 D process; (v) the hypothesis that the position of the water table is a regulator of bedrock weathering in some landscapes (i.e., if bedrock can't be drained, it can't be weathered); and (vi) the need for multiple theories about bedrock weathering to motivate the drilling campaign.

**Table 1. List of Attendees and Affiliations**

<b>First name</b>	<b>Last name</b>	<b>Affiliation</b>	<b>Title</b>
Suzanne	Anderson	University of Colorado, Boulder	Professor
Allan	Bacon	Duke University	Graduate Student
Steve	Banwart	The University of Sheffield	Professor
Art	Bettis	University of Iowa	Professor
Olivier	Bour	Geosciences Rennes	Professor
Sue	Brantley	Penn State University	Professor
Heather	Buss	University of Bristol	Professor
Aniela	Chamorro	Texas A&M University	Graduate Student
Jon	Chorover	University of Arizona	Professor
Brian	Clarke	Penn State University	Research Scientist
Xavier	Comas	Florida Atlantic University	Professor
Martha	Conklin	University of California, Merced	Professor
Bill	Dietrich	University of California, Berkeley	Professor
Ty	Ferre	University of Arizona	Professor
Brady	Flinchum	University of Wyoming	Graduate Student
Sarah	Godsey	Idaho State University	Professor
Marty	Goldhaber	US Geological Survey	Research Scientist
Brad	Goodfellow	Stockholm University	Post doc
Bob	Graham	University of California, Riverside	Professor
Jesse	Hahm	University of Wyoming	Graduate Student
Scott	Harris	College of Charleston	Professor
Pete	Hartsough	University of California, Davis	Research Scientist
Jorden	Hayes	University of Wyoming	Graduate Student
Steve	Holbrook	University of Wyoming	Professor
Scott	Hynek	Penn State University	Post doc
Harry	Jol	University of Wisconsin-Eau Claire	Professor
Anne	Kelly	University of California, Irvine	Graduate Student
Jim	Kirchner	ETH Zurich	Professor
Xiao-Ming	Liu	Carnegie Institute of Washington	Post doc
Risa	Madoff	University of North Dakota	Graduate Student
Jill	Marshall	University of Oregon	Graduate Student
Brian	McGlynn	Duke University	Professor
Burke	Minsley	US Geological Survey	Research Scientist
Dennis	Nielson	DOSECC Exploration Services	Other (DOSECC)
Anders	Noren	LacCore/Limnological Research Center	Research Scientist
Toby	O'Geen	University of California, Davis	Professor
Joe	Orlando	Penn State University	Graduate Student
Joshua	Peschel	U. Illinois, Urbana-Champaign	Professor
Shane	Putnam	Johns Hopkins University	Graduate Student
Frank	Rack	University of Nebraska-Lincoln	Professor
Craig	Rasmussen	University of Arizona	Professor
Daniella	Rempe	University of California, Berkeley	Graduate Student
Daniel	Richter	Duke University	Professor
Cliff	Riebe	University of Wyoming	Professor
Kamini	Singha	Colorado School of Mines	Professor
Lee	Slater	Rutgers University	Professor
Beth	Wenell	University of Minnesota	Graduate Student
Josh	West	University of Southern California	Professor
Dave	Zur	dZur Consultants	Other (Consultant)

**Table 2. Self-reported interests of workshop participants**

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My main interest lies in physical and geochemical development of the weathering profile in fine-grained, glaciogenic materials
I am a groundwater hydrologist who is mainly interested in the characterization of groundwater systems, especially in heterogeneous crystalline rocks. My main research activities focus on the understanding of groundwater systems at watershed scales and on the development of new methods for characterizing and imaging the flow and transport properties of deep heterogeneous critical zones.
PI of Susquehanna Shale Hills CZO
I am interested in understanding the coupled mechanisms that create the critical zone and develop its characteristics including its resilience. In particular, I study the relationships between chemical, physical and biological weathering of rocks in the deep critical zone.
I am applying Ground Penetrating Radar and Electromagnetic Induction to study the variability of soil depth across Providence watershed in CZO Southern Sierra.
The Jemez-Catalina CZO seeks to understand the role of deep subsurface flow paths in biogeochemical weathering reactions and surface water dynamics.
developing methods of imaging, exploring, and sampling the deep CZO and quantifying material properties - understanding how the deep CZO influences geomorphic, hydrologic, weathering processes
Coming to the workshop as representative of the Luquillo CZO
My interest is the depth of the regolith and its role in groundwater movement in catchments. Specifically, I am interested estimates of regolith volume, temporal scales for water movement in the regolith and its connection to montane stream and meadow systems.
I am interested in developing methods to identify crucial information before drilling in order to make drilling as efficient as possible. I am also interested in combining direct sampling and geophysical methods.
I am interested in the process of granitic weathering and using geophysics to help answer hydrological and botanical questions.
Collaborator in the proposed Reynolds Creek CZO; interested in linkages between plant water use, groundwater, and stream networks
Ecological processes in our research area in the Prairie Potholes Region of the northern Great Plains is controlled by deep critical zone processes that have occurred over the last 10K years. We seek to characterize these processes over large areas using core and geophysical data.
Geomorphology/chemical weathering - Processes that control critical zone thicknesses and the spatial distribution of chemical weathering
The formation, distribution, and role of weathered bedrock in landscapes, ecosystems, and hydrology.
Interested in how lithologic (and hence geochemical/mineralogical) differences affect rates of weathering and the distribution and thickness of the weathered zone. Also interested in feedbacks between regolith and plants.
The primary interest focuses on remotely sensing and sampling the CZ, not only from a geological and landscape evolution focus, but also with respect to hydrogeologic and geochemical standpoint. Coming from a strong background in near-surface coastal plain studies, I want to better serve additional purposes with colleagues and students in my department who focus on geochemical and hydrological issues and to strengthen undergraduate and graduate training and research in CZ science.
I am working on the Southern Sierra CZO trying to coordinate Geoprobe sampling of deep regolith and pairing that with Geophysics. I am very interested in cross-CZO and experiments to investigate water holding capacity of the deeper regolith and the potentially buffering capacity of this water reservoir.
My interest is to use geophysics, particularly seismology, to help inform deep Critical Zone science. I am more specifically interested in quantifying the spatial distribution and frequency of heterogeneity at the scale of seismic resolution.
I have been working on near-surface geophysical characterizations of the deep (10's of m) critical zone for the past couple of years, including several field surveys at the Southern Sierra CZO. I am also Co-Director of the new Wyoming Center for Environmental Hydrology and Geophysics, which aims to promote cross-disciplinary work in the CZ, with an emphasis on hydrogeophysics.
I am interested in chemical weathering and solute export (chemical erosion), particularly in subsurface environments. Recent work includes grain discrete geochemical microanalysis of minerals, and the elemental and isotopic chemistry of surface and subsurface waters to constrain weathering reactions. Currently, I am focused on using transient atmospheric tracers to constrain residence times of groundwater and estimate groundwater weathering and subsurface solute export rates.
Use of geophysical (in particular ground penetrating radar) and associated subsurface drilling tools (vibracoring, geoprobe, diamond drilling) to map the subsurface in 2D and 3D perspectives.
I am interested in soil development feedbacks between vegetation and bedrock and wish to better understand methods for measuring the deep critical zone.

**Table 2. Self-reported interests of workshop participants**

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Together with Riebe and others, I developed the method of inferring long-term weathering rates from cosmogenic nuclides and geochemical mass balance. To do this right, one needs to know the unweathered bedrock composition, and thus one needs to sample well below the nominal "bedrock boundary". I have also championed the importance of deep "residual" storage in catchment hydrology, which also requires understanding the deep CZ.

I am interested in using non-traditional stable isotopes to trace processes in deep Critical Zone. In addition, I am interested in drilling and sampling the DCZ.

To better understand the subsurface dimension affecting surface processes and degradation that I have been investigating with terrestrial LiDAR on hillslope surfaces and to gain insight into regional differences, such as temperate and polar climates. I am interested in knowing about the techniques that will be developed for studying the deep critical zone and whether it will be a field of research I would want and be able to pursue further through collaborations when I complete my PhD.

1. The legacy of sub-surface frost cracking in temperate non-glaciated soil-mantled landscapes on critical zone architecture and present-day processes 2. Feedbacks between surface topography (curvature) and deep Critical Zone topographically generated fractures .

New Calhoun CZO and general interest in watershed hydrology and interactions of deep and shallow flow systems. Development of tools and techniques to effectively drill and sample the CZ.

Understanding linkages between surface and deep subsurface. Scaling approaches from point measurements to landscape. Pedogenic transformations in weathered bedrock.

I am interested in drilling into the critical zone with a focus on water and rock chemistry.

Sensors and Measurements

Currently, I am a PhD student in the Department of Geography and Environmental Engineering at Johns Hopkins. My research broadly falls within the category of landscape hydrology though I am most interested in understanding flow and transport processes in the thick saprolite of the eastern Piedmont. I am eager to discuss methods of mapping, conceptualizing, and generally understanding the processes which are at work within the deep Critical Zone, especially those that may affect flow mechanisms.

I've submitted a proposal to NSF for the Continental Scientific Drilling (CSD) Coordination Office and we are currently waiting to hear their decision about this matter. I would like to participate in the CZO Workshop to better understand the needs of the CZO community with respect to continental drilling and also take the opportunity to meet the people involved in CZ science.

Coupling geophysical techniques and deep CZ imaging with digital soil mapping techniques.

controls on the spatial pattern of fresh bedrock topography under ridge and valley topography; near-surface geophysics; fractured rock hydrology.

Lower boundary issues in pedology and CZ science

I've been a PI on the Shale Hills CZO, and am now actively working at the Boulder Creek CZO. I'm interested primarily in groundwater flow at both.

advancement of geophysical characterization and monitoring technologies for provided spatiotemporal information that can better constrain understanding of deep critical zone processes.

The deep Critical Zone science is the topic of my research on chemical weathering and the generation of mineral surface area.

I am interested in deep critical zone science from the point of view of understanding weathering processes at the scale of watersheds, and how they regulate long-term global climate and supply of nutrients to ecosystems. I published a paper in 2012 that used a global inversion to consider the problem of where weathering takes place and identified deep weathering as being particularly important in upland settings, which complements prior and ongoing work on hydrochemical perspectives.

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Topics that Brantley stressed included: (i) the control of weathering at depth by acid-base reactions and redox titrations; (ii) the weathering front is an undulating surface where O<sub>2</sub> and CO<sub>2</sub> in circulating waters are depleted (i.e., electron rich rock has neutralized the water as it moved down through the subsurface); (iii) case study: oxidation of biotite in granite drives fracturing and produces a thick (10 m) profile of regolith, whereas regolith on diabase, which is iron-rich, is thinner (2 m), due to downward propagation of CO<sub>2</sub> front before O<sub>2</sub>, (iv) when weathered minerals are observed at the surface in landscapes, it implies that erosion is fast compared to weathering (or, rather that residence time is too short to completely deplete soil of mineral); and (v) saprolite may be thickest at ridges because fluctuations are largest there.

***Plenary talks on drilling and sampling the deep CZ***

On Friday, October 25<sup>th</sup>, the workshop reconvened at 7 am over breakfast, which was followed by the first session of talks on drilling and sampling of the deep CZ. The first speaker was Dennis

Nielson (DOSECC) on the basics of drilling in the CZ. There were several important messages conveyed in this talk: (i) there are challenges to drilling at remote, off-road sites in steep country that might be preferred by CZ scientists; (ii) there are technical challenges to recovering core from incoherent weathered material, which may often be desirable sample material in a deep CZ drilling project; and (iii) DOSECC is available to help with these technical challenges. Some of the possibly useful technologies discussed included freeze coring to extract unconsolidated materials, and a number of in-situ tests (blow counts, standard penetration tests, cone penetration tests) to quantify properties of subsurface in zones that yield limited core materials for laboratory tests.

The next two talks included results and discussion about recent successful applications of drilling to CZ science. Brian Clarke was first with a presentation about drilling at the Shale Hills CZO; his topic was geologic preconditioning (i.e., lithology and fracture distribution) and its influence on deep-CZ processes. As the title suggests, Clarke's talk focused on the role of lithology in influencing subsurface properties, including fractures. He showed how borehole geophysics can help in measuring fracture spacing and orientation in wells. This was followed by a talk by Heather Buss, who highlighted results from drilling at both the Luquillo CZO, and a CZO in the Czech Republic. Buss's talk highlighted results from each site, including the finding of repeated zones of highly weathered and fresh rock, which made core recovery difficult at the Luquillo CZO. She ended with a sobering warning about not underestimating the difficulty of sampling the deep CZ by drilling. In particular she stressed the reality that most of the local drilling companies that CZ scientists might use will not know how to drill/core through unconsolidated materials, particularly when they are very variable in coherence as a function of depth.

This was followed by an introduction to the posters, which were on display in an adjoining room throughout the workshop; these introductions consisted of brief two-minute "pop-up" talks with one or two slides featuring overview images and graphs of poster content. Many of the graduate students and some of the other participants presented introductions to their posters during this time. Topics spanned a diverse range, from isotope fractionation during basalt weathering to the use of geophysics to quantify the depth to bedrock along an elevation transect. One of the pop-ups was delivered by Anders Noren, who highlighted core research facilities available at LacCore. This session was followed by a brief coffee break and a period of time where people could gather and talk about the posters in the next room.

Next, participants gathered in the plenary room for talks by Olivier Bour (Geosciences Rennes), Bob Graham (UC Riverside), and Suzanne Anderson (University of Colorado, Boulder). Like the first set of morning talks, this set was topical, featuring specific examples of deep CZ research, with an emphasis on aspects of sampling. Bour discussed tracer studies to image flow pathways and fracture geometry with GPR and time lapse imagery; an important take-home message was that in-situ experiments (a form of sampling) can be used to determine properties of the subsurface empirically, and thus have an important place at the table along with geophysical imaging and coring. Next, Graham gave an overview talk of the deep CZ from the perspective of a soil scientist, with an emphasis on the nomenclature and properties of "saprock" and "saprolite". Graham also stressed the importance of biological processes that generate these layers (e.g., penetration of mycorrhizal hyphae to depths much greater than roots, and the role of roots themselves in the breakdown of rock at depth). Then Anderson discussed drilling work at the Boulder Creek CZO and the Coos Bay site of her PhD dissertation, showing how drillholes could be used to map subsurface 3-D structure. Anderson also discussed response of wells to the fall 2013 storm that pummeled the Front Range, where the Boulder Creek CZO is situated.

### ***Breakout session 1***

After a break for lunch, which was provided by the workshop, participants returned for breakout group discussions. There were three breakout groups. This culminated in a plenary synthesis,

wherein each breakout group presented outcomes. This was followed by group discussion. Summaries provided by breakout group leaders are provided next.

Group 1 discussed the first order questions that remain unresolved: *Where is the bottom of the CZ and how does one define it? How does the base of the CZ relate to the surface? In particular, what factors control the thickness of the CZ, and the variability of CZ thickness?* Group members recognized that, to address these questions, the community will need to determine subsurface architecture (spatial distribution of material properties) within a broad tectonic and geologic framework. It may be possible to accomplish this using geophysics to extend 1D view from cores to 3 dimensions (across slopes). The point was raised that describing fractures in boreholes will not be a panacea for hydrologic modeling of subsurface flow. In addition it was stressed that most hydrologic models are based on physical observations and not on geochemistry, which reflects fluid flow. Roadcuts may work well for calibrating geophysical techniques (shallow seismic refraction and GPR).

Group 2 discussed an overarching strategy to tackle deep CZ unknowns in a community wide project. Step 1 is to establish context: topography, surficial geology, soil maps, and geophysics, including a synthesis of existing site data. This is a good time to look at proxy locations (roadcuts, quarries, etc.). Step 2 would be to formulate multiple hypotheses, based on current theory. At this stage one could target observations and measurements at sites where competing hypotheses disagree, based on simulations and back-of-envelope estimates that put bounds on what one should expect to see according to different models. Step 3 would be to “saw” or trench the ridge as deeply as possible. This would provide horizontal context, at least near the surface (as far down as you could get with the trenching). It would, in particular, allow 2-D observations and measurements of soil, saprolite, and the near-surface bedrock zone. Step 4 would be to drill the ridge with multiple holes for multiple purposes. It will be crucial at this stage to understand tradeoffs of how many holes to drill. The idea came up to make a matrix of which types of samples needed from each hole are compatible with others and which are not, and why. It was stressed that in context, the drilling will be relatively cheap, compared to the personnel costs of sampling, analysis, and interpretation, which will always be the bulk of the budget.

Group 3 discussed competing model-driven hypotheses that leverage existing well instrumented sites and informative datasets, such as those from the CZOs. They discussed the idea of beginning the testing with inexpensive observations including push tests and small (Winkie-type) drills, ground-based geophysics, and geoprobing. This would inform future drilling of more expensive boreholes. One recommendation was to develop a proposal vetted by community for drilling plan for a more expensive drilling program with core extraction. They discussed post-drilling infrastructure development. They also discussed the need for expertise to help inform and execute drilling, reflecting on themes introduced earlier by Buss and Neilson.

### ***Plenary synthesis***

In the plenary synthesis of Day 1, implementation strategies were a continuing theme. It was argued that one might drill a specific lithology across topographic and climatic gradients to develop a theory to explain observations. One possibly testable hypothesis that was suggested was that the depth of the weathering zone is controlled by tectonics, erosion, climate and climatic history. A series of theoretical models, developed from competing conceptual frameworks, would provide specific predictions of measureable CZ properties across the sites.

It was suggested that the community might coordinate the drilling activities and science questions so that they could be integrated and explored at all 10 CZO locations. This would bring the CZOs together as a network, as originally envisioned by NSF. An unresolved question that came up (especially from coPIs of the Intensively Managed Landscapes CZO) was what fresh bedrock is, and where its boundary might be when the landscape is underlain by 1000s of m of unconsolidated materials.

It was argued that the community should drill outside the present CZO network as well as across it. For example, it was proposed that the community might drill “between” current CZO sites based on gradients in climate, tectonics, disturbance, and lithology. It was also suggested that the study might be designed to vary multiple factors at the same time, and thus look across a range of sites and seek an envelope of conditions that the models could accommodate. It might then be possible to use one or more of the theoretical models to predict change when any one parameter is varied. By looking across multiple sites outside the CZOs, researchers could expand the network through new “mini” networks. A discussion arose about the need for cross-borehole geophysics, and thus it was stressed that multiple holes would be needed at each site to identify CZ architecture, regolith thickness, height of the water table, and to decide what the specific questions are about subsurface processes.

Specific outcomes of the workshop were discussed. It was recognized that the workshop would need to culminate in a set of specific recommendations. A debate arose over whether the community should focus on a very specific research question or a series of general questions that might be addressed through combinations of subsurface techniques. It was noted for example, that the community might suggest a program in which its researchers developed the skill sets, methodologies, and technologies on the way to the initiation of a program that explores variations across controlling factors of the deep CZ. The framework for such a program was discussed and it was recognized that such an effort would need to have both theoretical and pragmatic aspects. It was recommended that the community might suggest a three-year study proposal to illustrate how the field work might be implemented, with the goal of bringing together the technical skills and to articulate the problems.

#### ***Plenary talks on geophysical imaging of the near surface***

On Saturday, October 26<sup>th</sup>, participants reconvened after breakfast (provided by the workshop) for a session on geophysical imaging that started with a talk by Lee Slater (Rutgers) and ended with a talk by Steve Holbrook (WyCEHG). These talks were somewhat longer and involved than the talks of the previous day, and Slater and Holbrook used the time to give broad overviews of what can be done in the near surface with geophysics, including case studies for illustration.

Slater has been particularly interested in methane release from peat lands, and he featured that work in his talk. He also featured work on groundwater-surface water interactions at sites on the Columbia River in Washington. Slater highlighted several tools: fiber-optic distributed temperature sensors; resistivity; and ground penetrating radar. Slater focused on the challenges of geophysical imaging of the deep critical zone. The limited resolution of the imaging was discussed, and it was stressed that a parameter of interest must be identified. Slater also stressed the power of joint inversions of multiple types of geophysical data and or investigations that include measurements of both geophysics and hydrologic data).

Slater discussed at length some of key aspects of resistivity. In particular he stressed that resistivity is a complex function of many things CZ scientists care about, including moisture content, surface area, porosity, temperature, and groundwater composition. In general, petrophysical relationships are used to interpret results. Induced polarization is a type of resistivity measurement. It reflects how energy is stored and is affected by surface area. Slater also discussed the use of towed arrays and cross-borehole resistivity to do tomography. Resistivity can also be measured over time, both from continuous monitoring and using tracers.

Slater clarified that GPR does not work in conductive materials. Hence it is crucial to know the conductivity of the material. GPR is sharper than resistivity. It can be used to measure moisture content using a petrophysical model. Measurements can be made down boreholes. Permittivity of soil, water, and air may need to be known. Slater stressed the challenge of imaging fractures, which are planar features; geophysics is better at resolving change across a continuum.

Slater stressed the importance of driving the geophysics with hypothesis-based science. He likened geophysical imaging to “eye-candy” if it is not accompanied by a physical framework for interpreting it. However, it was recognized that it should be easy to find the depth to bedrock and how

it varies, thus solving a major 1<sup>st</sup> order challenge of deep CZ research. Ground-truthing, via drilling, is needed to interpret layering observed in geophysical images.

Steve Holbrook followed Slater with a talk in which he suggested that geophysical interrogations of the CZ might start with airborne geophysical surveys, for a broad overview, and progress to ground-based investigations at sites identified in part from the airborne data. He motivated the talk by saying that geophysics can help researchers test CZ hypothesis and that it can both add value to and benefit from drilling. Holbrook focused for some time on seismic refraction as a tool for identifying the bottom of saprolite and for quantifying porosity. Porosity is of course important in hydrology but also in understanding weathering in the deep CZ. It may also be possible to measure the subsurface structure with high resolution (10 m scale) using full waveform inversion techniques applied to seismic refraction.

EM induction and electrical resistivity were also discussed. Holbrook indicated that 4 to 5 people could get 1 km/day of resistivity data. He also highlighted the possible usefulness of time-lapse resistivity to show differences in conductivity over time, with particular reference to tracer studies. Holbrook discussed Ground Penetrating Radar next, indicating that it may be useful in imaging fractures and other reflectors in weathered granite. He stressed the need for direct observations to confirm patterns inferred from the GPR. Holbrook then talked about a series of tools including magnetics, sub-bottom profilers, complex resistivity, and magnetic resonance sounding. He finished his discussion of techniques on airborne geophysics, highlighting the possible benefits of making measurements quickly over broad scales.

Next Holbrook shifted to a discussion of how geophysics could be used to answer questions about the deep CZ. Examples included: quantifying aspect-related differences in weathering profiles; climatic and topographic effects on weathering; and the thickness of regolith. Some of the key challenges to making advances are: overcoming current limits on horizontal and vertical resolution to quantify heterogeneity; parameterizing petrophysical relationships, so that geophysics can be used to measure flow and water holding capacity; using passive source (ambient-field) seismic approaches to maximize use of information and thus resolve more detail in the subsurface. He stressed the importance of not overly relying on a single technique (i.e., GPR, or seismic, or resistivity) but rather should always seek to use the strengths of each method to overcome the weaknesses of the others. Holbrook stressed that geophysics should insofar as possible always be accompanied drilling and that drilling should be informed by geophysics. Downhole geophysical logging is something to consider at any significant deep CZ drilling effort.

Finally, Holbrook set the group up for the breakout session by asking whether the community can come to a consensus on “baseline” geophysical data that should be acquired at CZ sites. He also suggested that the CZOs would be well served by acquiring airborne geophysical data as a baseline subsurface dataset (akin to LiDAR for the surface).

### ***Breakout session 2***

The morning talks were followed by a coffee break, provided by the workshop, and then a set of morning breakout group discussions about geophysical imaging. Summaries discussed in a plenary synthesis are given below:

Group 1 raised the compelling concept of calibrating geophysical images using direct observations from a site where it is easy to collect data. This could lead to measurements in areas that are more difficult. They identified several questions that could be answered with geophysics, including: *What is the total amount of stored water in porous rock? What are the lower and upper boundaries of porosity?* They also noted the importance of quantifying petrophysical parameters; it was suggested that the CZOs could become an initial database of geophysical parameters. There was recognition that airborne geophysics would be a great tool. It was argued that we should construct a matrix of geophysical methods and what they can do, what they cannot do, and the limitations of each.

There was discussion of distributed temperature sensing, EMI, and both surface-based and down-hole ERT, downhole temperature monitoring, and downhole Nuclear Magnetic Resonance (NMR). The value of airborne geophysics for at least some of the CZOs was discussed.

Group 2 discussed the importance of measuring depth to bedrock, depth to clay-rich illuvial horizons, depth to original soil surface, the location and size of corestones and fractures, and spatially distributed hydraulic conductivity. They introduced the term “depth to critical interfaces” to refer to these measurements. There was also discussion of the spatial distribution of properties both on the surface and at depth. They wondered how these properties vary across the CZOs. They recognized the importance of multiple methods at each site and wondered if it was suggested that the full dataset of properties would help geophysicists develop petrophysical models. They also asked whether gravity, not discussed at length in the morning talks, could yield information about weathering at depth.

Group 3 discussed the importance of bringing geophysicists together with hydrologists, geomorphologists, and geochemists. They recognized the tradeoffs between high resolution borehole data and lower resolution surface surveys. The idea that airborne surveys may be the best way to integrate this data was discussed. The strength of looking at surfaces, interfaces, and changes in time using geophysics was discussed. It was recognized that quantifying surface area as a function of depth is a different way of quantifying depth to bedrock. Questions came up about how to identify the depth of weathered bedrock using geophysical imaging. The group made a list of questions and issues that might be addressed with geophysics: (i) quantifying spatial variations in subsurface properties in a way that we cannot be done via direct measurements from a single borehole; (ii) drilling probably should never be done without geophysics; (iii) geophysics might be trained using hydrology, including pump tests and tracers; and (iv) use wells to extrapolate data and ground truth geophysics. As a way forward, the group suggested that the community should request support for cross-site work between CZO sites. The goal would be to solve a common problem across the CZO sites using geophysics.

### ***Grand synthesis***

After lunch, provided by the workshop, there was a plenary grand synthesis of what was learned during the workshop, culminating in a discussion of study design and recommendations for future actions. Participants started by restating the importance of deep CZ research. It was recognized that the evolution of the deep critical zone changes how earth’s surface interacts with everything, affecting land-atmosphere-biota interactions, influencing its own evolution, and governing the conveyance of water, energy, and Earth materials across the surface as well as at depth. Understanding precisely how is essential to an integrated understanding of the critical zone.

The base of the critical zone is a critical boundary condition for a vast array of surface processes. Saturated hydraulic conductivity, determined in part by fracturing and weathering in the subsurface, is a crucial property that determines the pace of water exfiltration from the subsurface. One thing that all learned during the workshop is that the deep CZ may be invisible but is nonetheless accessible using geophysics. It was recognized again that the CZOs offer an environment where lots of measurements have already been made and where geophysics can be tested. However, the great compositional and spatial variability of the CZOs demand both geophysics and drilling. No single measurement can give researchers what they need, though it was recognized that previous studies have yielded valuable information when guiding drilling locations using hypothesis based questions (without geophysics). Nevertheless, a clear consensus emerged that drilling needs to be informed by geophysics and geophysics in turn must be informed by drilling.

It was recognized that some of the site-specific questions of the different CZO’s will require different tools. In addition, there was an unresolved issue of what the deep CZ is or rather what the question to be answered is in upland and lowland regions. Despite the site-specific nature of the questions, some common measurements may be needed. A common staged-approach to site investigation was also suggested. However, there was debate over this among the participants. It was argued, for example, that the most important and interesting questions are likely to be different from

site to site. Moreover, geophysics does not work everywhere, and coring does not work everywhere either.

There were vocal proponents of the idea that airborne EM surveys could change the way we look at subsurface processes. However, pilot studies to validate results are needed in topographically complex terrain where several CZOs are situated. (Most previous work has been over flat terrain.) One hope is that airborne geophysics could allow researchers to scale observations from hillslopes to watersheds. This could greatly improve understanding of deep CZ processes.

It was acknowledged that the measurement program should be driven by hypotheses, but that observations are needed to drive hypotheses. The tension inherent in these needs is further enhanced by the fact that hypotheses are needed for the foundation of viable proposals to fund the work.

A consensus was reached to build on the CZOs, at least at first, and then populate study sites along state-factor gradients (i.e., sites spanning gradients in lithology, climate, and tectonics). This would bring in a much wider community with new types of expertise that add to the whole. It was deemed wise to start by making measurements in CZOs that are already well developed. The concept of establishing a panel of experts, to help guide the effort, was raised. It was recognized that this would help build a community of scientists to enable cross-site comparisons and leverage a quickly evolving knowledge base on methodology and data interpretations.

### **Outcomes, Recommendations, and Conclusions**

The *Drilling, Sampling, and Imaging the Depths of the Critical Zone* workshop brought together 49 scientists from diverse disciplines for two days of community-building discussion on how to overcome outstanding challenges of deep CZ research. Specifically, the focus was on the part of the CZ concealed at depths that are difficult to directly access without major excavations or intensive drilling campaigns. Based on discussions that arose after 10 oral presentations, around 10 posters, in two breakout sessions (consisting of three breakout groups each), and during three plenary discussion sessions, we offer the following summary of outcomes, recommendations, and conclusions:

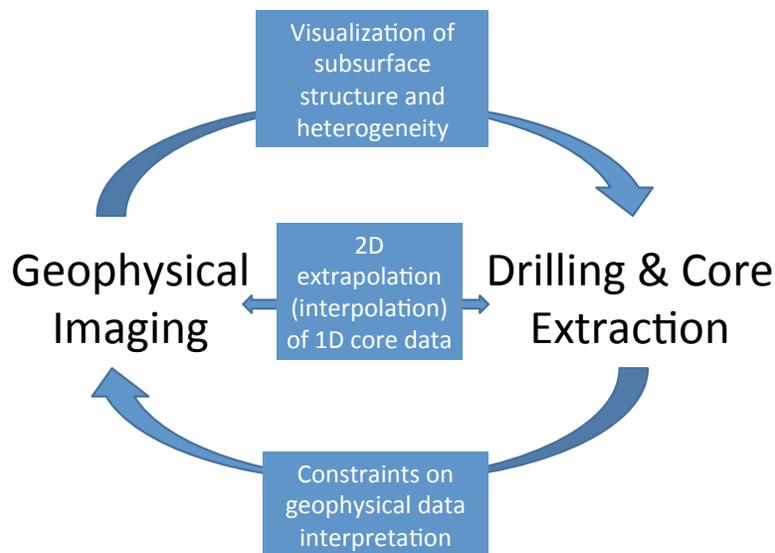
1. There is strong interest in advancing deep CZ research through a program of drilling, sampling, and geophysical imaging. This is a consensus that represents opinions from a broad community of geochemists, geophysicists, geomorphologists, soil scientists, and drilling engineers. The strong attendance at the workshop, with representation from each of these disciplines underscores the excitement that people have been expressing recently around this research objective.
2. Workshop participants agreed that the community is at the beginning of a long-term effort to unveil for the first time the deep critical zone at a scale that is appropriate to understanding of processes that are vital to the evolution of the Earth's terrestrial surface to its current state and to understanding the sustainability of critical zone services into the future.
- 3A. Shallow drilling projects do not have a funding source of their own, separate from disciplinary programs at NSF and other agencies. In addition, drilling projects are not currently part of the funded CZ proposals to the extent that the workshop participants feel drilling should be, given the importance of the deep CZ in the coupled biological, chemical, and physical processes that shape Earth's surface, modify its soils, and drive its biogeochemical cycles.
- 3B. Shallow geophysics does not have a funding source of its own, separate from disciplinary programs at NSF and other agencies. In addition, shallow geophysics projects are not currently part of the funded CZ proposals to the extent that the workshop participants feel that it should be.

3C. All agreed that the time is right to support wide campaigns of coordinated drilling and geophysical studies of the deep critical zone.

4. A key challenge will be to overcome limitations imposed by disciplinary silos. Near-surface geophysicists will need to understand the significance of their trade with respect to advancing critical zone science. This will require new thinking and new studies involving geophysical sensors, instrumentation, and petrophysical interpretation. Leadership by programs like WyCEHG at the University of Wyoming may be key to overcoming these challenges, but the entire community needs to get behind the effort in support. Meanwhile, CZ scientists need to be made aware of the great advances geophysical imaging might help bring to understanding CZ evolution and processes.

5. We suggest that proposals to study the CZ could (and often should) have strong geophysics and drilling components. Funding of this work could be structured around a service model (similar to NCALM for LiDAR imaging) over the long-term. LacCore, which has already claimed a role as a facilitator for continental scientific drilling (though this was not known at the time of the workshop), could aid in making petrophysics (measurements on core material) accessible to the geophysicists for calibrations.

6. There was a consensus that drilling and geophysics go hand in hand. One can be (and has been) done without the other, but this overlooks potentially powerful synergies (Figure 2). Moreover, it can be argued that the great compositional and spatial variability of the CZO demand use of both techniques together. The corollary is that there is no single method that will solve all problems in the CZ. Some sites and questions will require different tools.



**Fig. 2** – Schematic illustrating connections between drilling and geophysical imaging. Drilling generates boreholes for direct observations of deep CZ architecture (e.g., fracture spacing and orientation in the subsurface) and for sampling of circulating fluids at depth. Meanwhile, core extraction during drilling provides materials for measurements of critical zone properties (e.g., porosity, bulk geochemistry, and microbial makeup of regolith). Geophysical imaging can provide visualization of the subsurface structure and heterogeneity of CZ properties; this can be used to interpolate between multiple borehole and extrapolate beyond them to characterize the subsurface over broad spatial scales.

7. The observation that we make using drilling and geophysical imaging should be driven from a hypothesis-testing framework.

8. The CZOs have already made many of the measurements needed to simultaneously test and demonstrate the value of geophysics and drilling. Here “test” refers to validation of techniques. Value comes from proving that the drilling and geophysics can help us overcome gaps in understanding of CZ processes and evolution. A consensus was reached that the community could overcome the limitation inherent in the need to calibrate and demonstrate the value of geophysics by building an initial program around the CZOs. It is important to stress, however, that it would be crucial to follow up initial work by expanding along state-factor gradients. This would bring in a much wider community of people who know their study locations and have new types of value-added expertise.

9. A program of cross-disciplinary education is recommended to grow a new breed of CZ scientists who are educated in deep CZ methods including drilling and geophysics. For example, there could be an REU in near-surface geophysics. Another way to foster education would be through field camps (for both graduate and undergraduate students) at institutions with strong programs in near-surface geophysics.

10. A panel of experts should be formed to serve in an advisory role for the growing community of scientists interested in deep CZ research using drilling and geophysical imaging.

### **List of White Papers in Appendices**

Appendix 1: Dear Colleague Workshop Advertisement.

Appendix 2: Workshop Schedule.

Appendix 3: Drilling and Sampling the Critical Zone.

Appendix 4: Beyond the Regolith: A Deep Critical Zone Drilling Perspective on Weathering Profiles, by Heather L. Buss and Oliver W. Moore.

Appendix 5: Resolving the structure and composition of water flow paths in the deep critical zone, by Jon Chorover.

Appendix 6: Selecting Sites for Technical Exploration of the Deep Critical Zone, by Brad Goodfellow.

Appendix 7: Planning an International CZO Programme, by Steve Banwart, Jerome Gaillardet, Marty Goldhaber, Don Sparks, and Sue Trumbore.

Appendix 8: Topographic Stress and Rock Fracture: Probing the Effects of Landforms on Bedrock Structure in The Shallow Subsurface, by J. Taylor Perron.

Appendix 9: Weathering Profiles in the Intensively-Managed Landscape Critical Zone Observatory, Illinois and Iowa, by Andrew Stumpf, E. Arthur Bettis III, and Scott Elrick

Appendix 10: Dating Alteration and Exhumation in the Deep Critical Zone, by A. Joshua West and Pete Reiners.

Appendix 11: The Deep Critical Zone (DCZ) Need Not Go “Unmeasured”: Advancing Process-Based Geophysical Characterization and Monitoring, by Lee Slater

Appendix 12: Exploring Weathered Bedrock Characteristics: A Pedologic Approach, by Toby O’Geen, Craig Rasmussen, Bob Graham, and Peter Hartsough.

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# **Appendix 1: Dear Colleague Workshop Advertisement.**

Dear Colleagues:

Mark your calendars for the upcoming NSF Workshop “Drilling, Sampling, and Imaging the Depths of the Critical Zone”.

Timing: 24-26, October, 2013, immediately before the annual Geological Society of America meeting.

Location: Downtown Denver, Colorado (details to be determined).

Our goal in hosting this workshop is to build a community-wide consensus on strategies for investigating critical zone processes below the depths that are easily accessed with a shovel and hand auger. Our workshop will be highly informative, involving presentations by experts in drilling, sampling, and geophysical imaging of near-surface Earth materials. We also expect it to be highly productive, leading to research proposal development and a written commentary to be published in AGU Eos or similar outlet.

We expect attendance by scientists at all career levels, from students through senior professors. We also expect representation from diverse disciplines, including engineering, near-surface geophysics, geochemistry, geobiology, geomorphology, soil science, and hydrology.

A tentative schedule:

Thursday, 24 October 2013

Participants arrive in afternoon and early evening and attend icebreaker dinner and introductory presentation at workshop venue (to be determined).

Friday, 25 October 2013

All day workshop, with presentations by invited speakers and breakout groups

Saturday, 26 October 2013

More presentations by invited speakers and breakout groups, concluding mid to late afternoon.

Additional announcements about funding for travel and lodging are forthcoming. For now, mark your calendars and contact us if you are interested in attending.

Best Regards,

Cliff Riebe ([criebe@uwyo.edu](mailto:criebe@uwyo.edu))

Jon Chorover ([chorover@cals.arizona.edu](mailto:chorover@cals.arizona.edu))

## **Appendix 2: Workshop Schedule.**

# NSF Workshop: Drilling, Sampling, and Imaging the Depths of the Critical Zone

## Schedule

### Thursday, October 24th

- 6:00 PM Icebreaker dinner (provided by workshop)
- 7:00 PM Bill Dietrich; 25 min + 5 min discussion
- 7:30 PM Sue Brantley; 25 min + 5 min discussion

### Friday, October 25th

#### *Session 1 – Drilling and sampling*

- 7:00 AM Breakfast provided by workshop
- 8:00 AM Introduction by session conveners
- 8:15 AM Dennis Nielson – Drilling 101 (50 min + 10 min discussion)
- 9:15 AM Brian Clarke; 15 min + 5 min discussion
- 9:35 AM Heather Buss; 15 min + 5 min discussion
- 9:55 AM Poster introductions; brief 2-min, 1 slide overviews of poster content; 10 posters = 20 min
- 10:15 AM Coffee break followed by poster session
- 10:50 AM Oliver Bour; 15 min + 5 min discussion
- 11:10 AM Bob Graham; 15 min + 5 min discussion
- 11:30 AM Suzanne Anderson; 15 min + 5 min discussion
- 11:50 AM Plenary discussion leading to breakout groups
- 12:15 PM Break for lunch (provided by workshop)
- 1:00 PM – 3:00 PM Breakout Group Discussions
  - (a) Drilling technology: core recovery in weathered rock
  - (b) Drilling technology: core recovery for robust geobiology
  - (c) Designing a timely, insightful drilling study (site selection & experimental design)
- 3:00 PM Coffee break (posters are still up)
- 3:30 PM Plenary synthesis. (Each Breakout group presents outcomes, followed by group discussion.)
- 5:00 PM Break for dinner (on your own)

### Saturday, October 26th

#### *Session 2 – Geophysical imaging*

- 7:00 AM Breakfast provided by workshop
- 8:00 AM Introduction by session convener
- 8:05 AM Lee Slater – Geophysics 101: 50 min + 10 min discussion
- 9:05 AM Steve Holbrook; 30 min + 10 min discussion
- 9:45 AM Coffee break (Posters are still up.)
- 10:00 AM Someone leads plenary discussion leading to breakout groups
- 10:15 – 12 PM Breakout Group Discussions
  - (a) Seismic refraction and waveform tomography
  - (b) Drilling and measurements to inform geophysics
  - (c) Resistivity, EM methods, NMR
- 12:15 PM Break for lunch (provided by workshop)
- 1:30 – 3:00 PM Session Syntheses Breakout Groups
  - (a) Drilling
  - (b) Sampling
  - (c) Imaging
- 3:00 – 4:30 PM Grand Synthesis: What have we learned? Discussion of study design. What next? Proposal. AGU Eos.

## **Appendix 3: Drilling and Sampling the Critical Zone.**

## **DRILLING and SAMPLING the CRITICAL ZONE**

Dennis L. Nielson  
DOSECC Exploration Services  
Salt Lake City, UT

The Critical Zone represents a unique environment that is not difficult to drill, but has challenges in terms of sample quality. For this discussion, we will consider maximum drilling depths of about 100 m. There are a number of drilling techniques that can be used to this depth including: rotary, sonic, augering and coring. The size of the drill rig is generally dependent on the depth objective, sampling system and the resulting weight of the drilling assembly. Of the above techniques, coring collects the highest quality lithologic sample and is preferred for most scientific drilling projects. The other techniques are often less expensive and may be used for the installation of ground water monitoring wells, but their sample quality is generally poor.

There are several coring methods that can be used depending on the sampling requirements and soil or rock character. Soft sediment and soils require methods that collect the core in liners. DES uses this methodology in our sampling of modern and ancient lake sediments. Our suite of soft sediment sampling tools collect core that is consistent with dimensions from ocean drilling and are therefore easily handled by research laboratories (66.3 mm diameter). The tool suite is wireline-deployable includes the following.

- Hydraulic Piston Corer (HPC). A beveled shoe is fired into unconsolidated, saturated sediment. Depth capability ~100 m in modern lake sediments.
- Extended Nose (EXN). A non-rotating shoe is pushed into unconsolidated sediments aided by a rotating outer bit.
- Alien (ALN). A rotating bit cuts semi- to consolidated sediments.
- Non-sampling Assembly (NSA). Used to advance the hole to a specified sampling interval.

Consolidated rocks are most effectively sampled using diamond coring, a technique commonly used in the mining industry. A diamond bit cuts a core from the rock and the sample is collected in a lined or unlined core barrel. Diamond core bits are available in established sizes (PQ, HQ, NQ). Alternatives that utilize liners are designated HQ3 or HQTT (Triple Tube). Custom core catcher assemblies are effective in adapting these systems to collect core from unconsolidated rocks.

DES is currently working with Columbia University to adapt its soft sediment suite to sample unconsolidated aquifer sands using a freeze shoe technique. This freezes the bottom of the core sample and will allow the collection of aquifer sands in contact with pore water. The purpose of the system is an evaluation of high arsenic ground water in SE Asia. An ICDP project to test the technique in Illinois has been funded for 2014.

Drilling often requires the circulation of a drilling fluid, generically referred to as "mud". This may consist of anything from water to complex combinations of clays, polymers and chemical additives. Mud has several purposes: lubricate and cool the bit, remove cuttings from the hole and condition and stabilize the hole. Although the success of a drilling program may depend on the efficiency of the mud program, it also serves as a source of contamination of the core and fluid samples. The references below include papers that discuss contamination and strategies for mitigation.

Scientific drilling projects range from shallow and simple ( $\$10^4$ ) to deep and complex ( $\$10^7$ ), and their development often takes time and a considerable amount of persistence (Cohen and Nielson, 2003). It is important to formulate drilling, sampling and logging objectives and then formulate a drilling plan to achieve those objectives. Costs can be predicted on the basis of the plan, and they often are in the range of \$300/m to \$400/m for shallow scientific holes. Local contractors can be used to do the work, but monitoring is generally required to achieve the desired results.

## References

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**Appendix 4: Beyond the Regolith: A Deep  
Critical Zone Drilling Perspective on  
Weathering Profiles, by Heather L. Buss and  
Oliver W. Moore.**

## Beyond the Regolith: A Deep Critical Zone Drilling Perspective on Weathering Profiles

Heather L. Buss\* and Oliver W. Moore

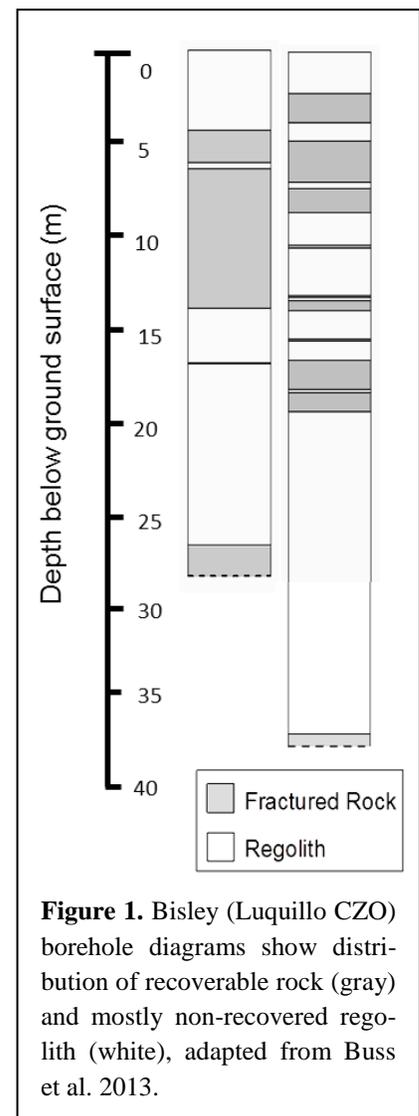
School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK (\* [h.buss@bristol.ac.uk](mailto:h.buss@bristol.ac.uk))

Geochemical changes with depth through a weathered or weathering material are known as weathering profiles and are commonly used in critical zone (CZ) studies. Regolith (here including mobile and *in situ* weathered material) weathering profiles record CZ processes over the timescale of regolith development. Weathering profiles are frequently represented in terms of the mass transfer coefficient, commonly known as tau (Brimhall and Dietrich, 1987; Anderson et al. 2002), which describes the amount of a specific component (element, isotope, mineral) mobilized during weathering by comparison to a parent material (e.g., bedrock) and have proven particularly useful in identifying weathering mechanisms and mineral-specific weathering rates (e.g., White and Buss, 2013).

A typical regolith weathering profile consists of component concentrations in either solute (pore water) or solid (<2 mm sieved regolith) fractions with depth. However, the entire belowground CZ also includes fractured bedrock and rock fragments and corestones of various sizes and stages of weathering (Fig. 1). The rock (>2 mm) components of the CZ are integral to the narrative of CZ development; they record geologic history and provide clues to the physical and chemical feedbacks in CZ formation. Therefore, as deep CZ drilling pushes our weathering profiles beyond the regolith and into the parent material, some adaptation of the regolith-centric model of weathering profiles is required.

Deriving meaningful information from tau profiles of CZ rocks as a function of depth in drilled boreholes is problematic: unless samples are highly weathered (e.g., saprock), it is likely that lithological variations will swamp out incipient weathering signals in many locations. For example, in the volcanoclastic Bisley watershed at the Luquillo Critical Zone Observatory (LCZO), mineral abundances in unweathered rock can vary by 30 wt% in a single borehole. However, borehole weathering profiles need not be defined on the m or cm scale as done for regolith. CZ boreholes containing corestones or fractured bedrock may contain multiple weathering fronts in the guise of mm's thick rinds along fractures and corestone surfaces (Buss et al. 2013). Micro-scale weathering profiles extending from visibly un-weathered rock into an attached rind record incipient weathering and regolith formation processes.

Micro-scale analysis of weathering profiles across rinds have documented dramatic mass losses and mineralogical transformations across core-rind boundaries in basaltic, andesitic volcanoclastic and granitic rocks (e.g., Navarre-Sitchler et al. 2011; Sak et al. 2010; Buss et al. 2008, 2013). Although weathering rinds make up a much smaller volume % of a watershed than regolith, they likely record the vast majority of mass transfer in most CZs. For example, in the Bisley watershed, ca. 40% of protolith Mg is lost over ca. 3 mm of weathering rind, reflecting significantly more and faster weathering than the final 20% of protolith Mg, which is lost over 8 m of regolith. Micro-profiles may also reflect differ-



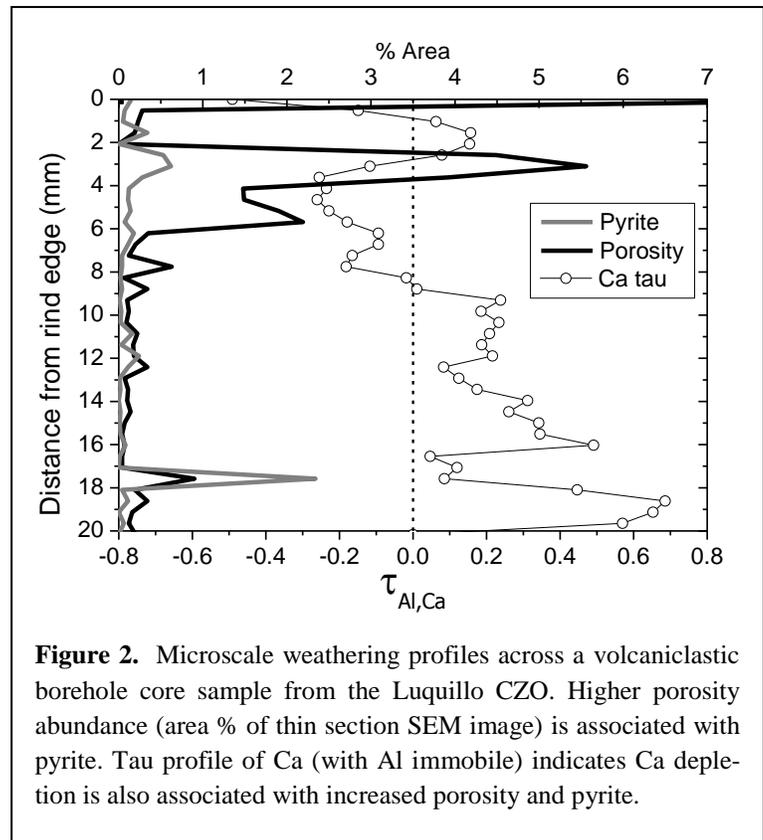
ent weathering mechanisms as well as different weathering rates in that highly reactive phases will be present in weathering bedrock that are no longer present (or are inaccessible, e.g., shielded by oxides) in regolith. In Bisley borehole rocks, we find pyrite and other sulfide and sulfate phases associated with early weathering of silicate minerals, suggesting a weathering mechanism involving sulfuric acid, whereas regolith weathering is dominated by carbonic acid and, in surficial layers, organic acids (Fig. 2).

Micro-scale weathering profiles may prove to be more significant in terms of CZ development and weathering fluxes than regolith weathering profiles; recent work has suggested that most of a watershed's weathering solute flux is sourced from bedrock fracture zones (Kurtz et al. 2011; Schopka and Derry, 2012). Furthermore, fracture spacing combined with mineral dissolution may largely control watershed topography in many watersheds (Fletcher and Brantley, 2010; Buss et al. 2013).

Deep CZ drilling provides unparalleled opportunities to study CZ formation processes *in situ*, however, these processes may operate in discrete zones such that micro-scale weathering profiles may be more appropriate and more informative than whole-borehole weathering profiles.

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**Figure 2.** Microscale weathering profiles across a volcanoclastic borehole core sample from the Luquillo CZO. Higher porosity abundance (area % of thin section SEM image) is associated with pyrite. Tau profile of Ca (with Al immobile) indicates Ca depletion is also associated with increased porosity and pyrite.

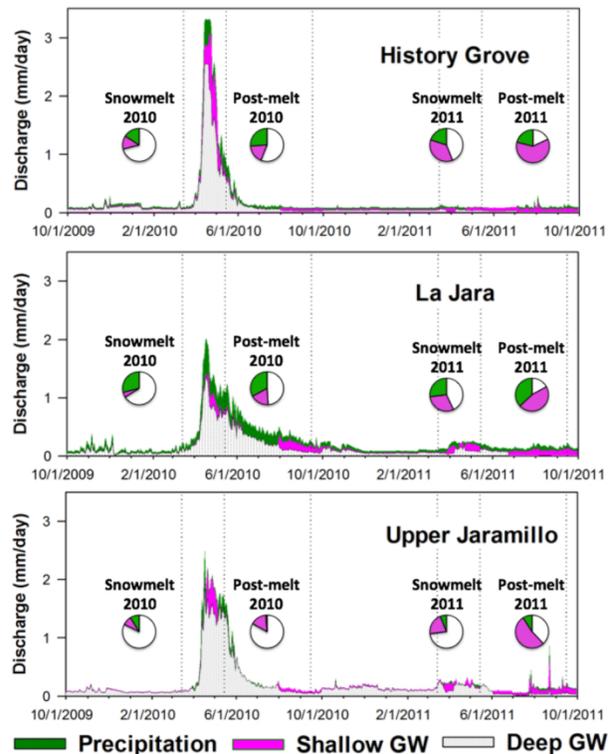
**Appendix 5: Resolving the structure and composition of water flow paths in the deep critical zone, by Jon Chorover.**

## Resolving the structure and composition of water flow paths in the deep critical zone

Jon Chorover, Department of Soil, Water and Environmental Science, University of Arizona

Our CZO team has the goal of resolving the relation between the evolution of water biogeochemical composition during flow through the CZ subsurface and structure evolution of the CZ matrix itself. Results of our CZ research to date suggest an important role for deep (below soil, in fractured bedrock) CZ flow paths affecting water delivery to streams even in upland forested catchments, particularly in rhyolitic terrain of the Jemez River Basin Critical Zone Observatory (JRB-CZO). Aqueous geochemical data for stream discharges, analyzed using an end member mixing model analysis (EMMA), suggest that a large fraction of water discharged from these small forested catchments during the spring snowmelt pulse derives from deep groundwater reservoirs that are apparently displaced during pressure wave propagation through the subsurface (Figure 1). These waters have tritium ages of ca. 4-12 years. Meanwhile, geophysical (seismic) surveys indicate regolith depth extending meters deeper than the soils that we have excavated to date and wherein our sensor and sampler array is installed.

We have yet to conduct any deep drilling exercises in our CZO. Hence, although data indicate a strong influence of deep subsurface flow paths on stream water dynamics and, therefore, a deep subsurface rock weathering regime, we have not yet been able to observe this portion of the CZ directly. Drilling even a single borehole and effectively extracting the core for analysis is an expensive undertaking that must be done with careful planning. Given our strong interest in the coupled biological, physical and geochemical processes controlling CZ evolution, we need to employ geophysical imaging methods that can help to inform on where such drilling may provide the most useful information on deep GW flowpaths. Further, we seek methods that will enable us to best preserve intact cores for geochemical and microbial analysis while introducing the fewest artifacts. Finally, since our goal is to instrument the excavated boreholes with an appropriate sensor/sampler array that will enable follow-on time series measurements of fluid (both liquid and gas) composition and dynamics at depth, a key question pertains to the spatial distribution of boreholes when drilling only a few is possible, and how we can make the most beneficial and synergistic use of multiple borehole installations.



**Figure 1.** End member mixing analysis (EMMA) of stream water discharges based on geochemical parameters for three streams draining different aspects of Redondo Mountain in the Jemez River Basin CZO. All streams show the largest contribution from deep groundwater (GW) deriving from a portion of the CZO that has yet to be elucidated. (From Harpold et al., in revision).

**Appendix 6: Selecting Sites for Technical  
Exploration of the Deep Critical Zone, by  
Brad Goodfellow.**

This will be a learning experience for me with respect to how these workshops operate but more specifically to the types of techniques that are being used in probing the deep critical zone. One of my primary interests is controls and processes of regolith production (from a geomorphologist's perspective) from the macro-scale (climate, tectonics) down to the granular-scale (weathering reactions, formation of connected porosity, etc). My experience of working in the deep critical zone has been through using road cuts and natural exposures excavated by streams and visible in wave-cut sea-cliffs. I have also used GPR (with some success) to measure depth to bedrock in *in situ*-produced periglacial regoliths in Arctic Scandinavia.

Given this background, my most useful contribution may be in highlighting some factors that could be considered when selecting sites for technical exploration of the deep critical zone (within and beyond the existing network of critical zone observatories). My perspective is that weathering does not generally follow a neat top-down decrease in intensity below the soil but rather displays a complex 3-D spatial pattern that reflects where water is accessing rock (according to joints, faults, fabric, hydrothermal alteration, etc). Clearly then, this 3-dimensionality of the deep critical zone poses both a technical challenge and a research opportunity. An additional technical challenge is posed by the extreme depths to which weathering can occur (10s to 100s of meters). Neither of these issues will likely surprise anyone at this workshop but I can perhaps offer some insight on how, or where, to constrain these depending on the research question at hand.

Key constraints on critical zone thickness include tectonic uplift rate (through its control on surface erosion rate) and climate (specifically long-term water balance). Assuming, firstly, a zero erosion rate to unravel the role of climate: Observations across steep rainfall gradients on 'uneroded' surfaces on Hawaii indicate that where the water balance is negative over regolith forming timescales (i.e. mean annual precipitation < potential evapotranspiration): (i) the critical zone is thin (<~2 m); (ii) its base is perched above local base (stream incision) level, and; (iii) weathering is confined to water flow paths through the critical zone, leaving a high proportion of unweathered rock and a complex 3-D spatial distribution of weathering (see Scenario A in the figure). Conversely, where water balance is positive over regolith forming timescales (i.e. mean annual precipitation > potential evapotranspiration): (i) the critical zone is thick (many 10s of meters); its base corresponds with local base (stream incision) level, and (iii) much more of the rock is comprehensively weathered, which reduces the spatial variation of weathering intensity (see Scenario C in the figure). In transitional zones (where mean annual precipitation ~ potential evapotranspiration) the base of the critical zone correlates with local base level but the intensity of weathering is intermediate between positive and negative water balance sites (see scenario B in the figure).

This simple pattern is, however, disrupted where tectonic uplift and surface erosion occur. As rates of these processes increase, it is predicted that the critical zone will thin, become perched above local base (stream incision) level, and the intensity of weathering will decrease because less time for weathering has been available (see the Figure below). Qualitative observations, for example in the Santa Cruz Mountains, support this (speculative) conceptual model. Where uplift and erosion rates are high near Loma Prieta, a summit located on a lateral restraining bend in the San Andreas Fault, the critical zone appears in general to be relatively thin (~ 8 m deep) and is perched above local base level. However, further north past the focus of uplift at the restraining bend, erosion rates have decreased by about a factor of 6, the critical zone is 10s of meters thick and its base appears to correlate with local base level.

So what might all this mean for site selection? If we want to capture what governs the spatial distribution of weathering in the deep critical zone, or investigate incipient weathering processes, then select sites that experience a negative water balance and/or which are undergoing active tectonic uplift. Conversely, if we wish to investigate what ultimately constrains the thickness of the critical zone, then select sites in positive water balance locations. Of course, sites that have been subjected to a relatively consistent climate over regolith forming timescales are difficult to locate. In this regard, tropical sites might offer the best possibilities (less variation over Quaternary glacial-interglacial cycles). Because of the steep and persistent rainfall gradients, Hawaii is excellent, but the leaky basalts pose a hydrological headache. Qualitative observations indicate that the western flank of the Sierra Nevada, California, offers some promise perhaps because, while temperatures and precipitation magnitudes have varied over time, the relative drying with declining altitude has persisted!? The region also has the advantage of containing lots of granite.

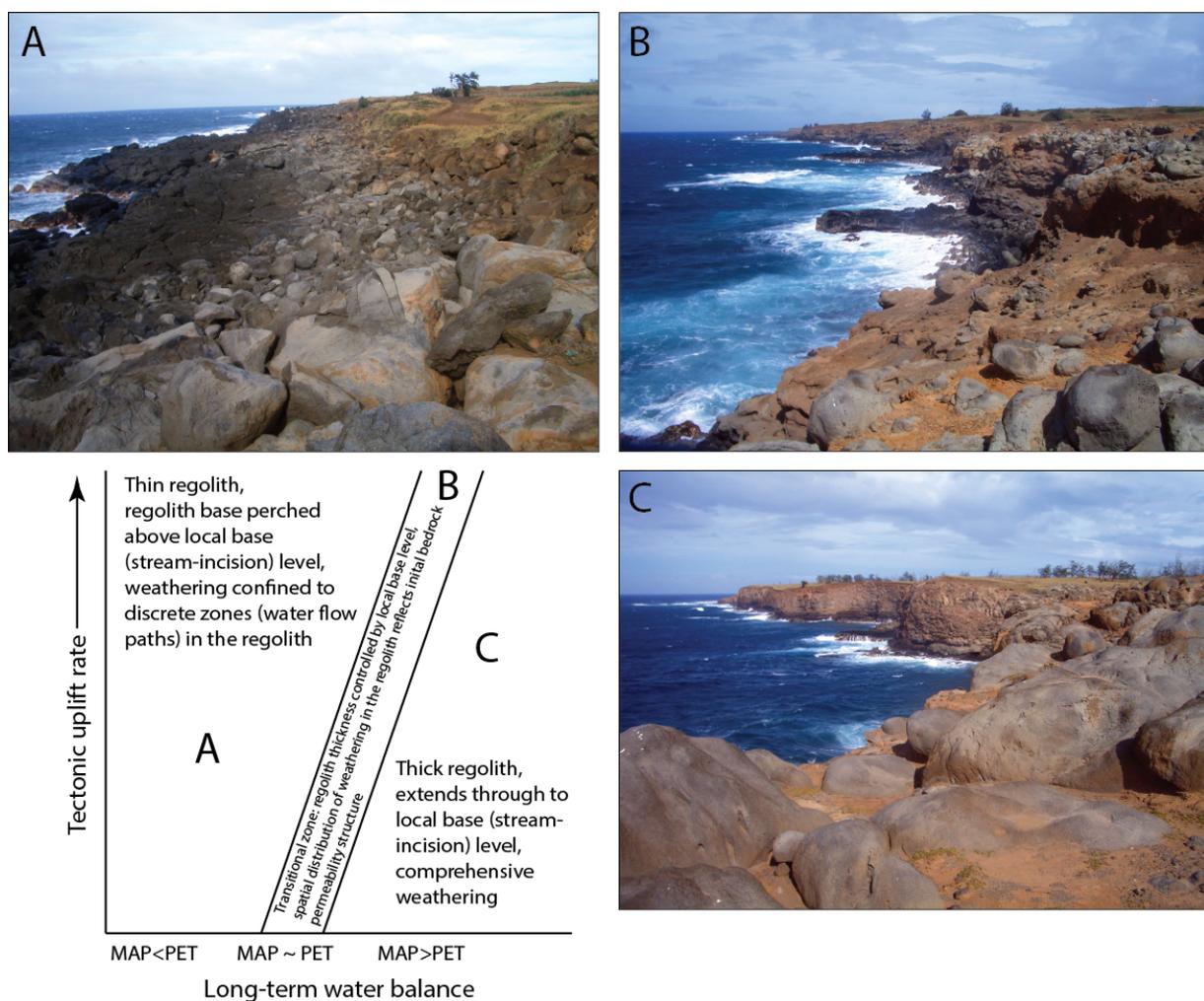


Figure: Conceptual model of water balance and tectonic uplift controls on the thickness of the critical zone and intensity and spatial distribution of weathering within it. The model is based primarily on observations of Kohala Peninsula, Hawaii, which has been subject to a steep rainfall gradient and minimal erosion of interfluves. Rainfall rate declines from NE to SW and this directionality has persisted through glacial and interglacial periods. The 'A', 'B', and 'C' labels indicate the parts of the figure that illustrate some key features of critical zones developed where the long-term water balance is negative, transitional, and positive, respectively. MAP = mean annual precipitation, PET = potential evapotranspiration.

**Appendix 7: Planning an International CZO  
Programme, by Steve Banwart, Jerome  
Gaillardet, Marty Goldhaber, Don Sparks,  
and Sue Trumbore.**

# Planning an International CZO Programme

Steve Banwart, Jerome Gaillardet, Marty Goldhaber, Don Sparks, Sue Trumbore

## Introduction

Recent advances in national programmes and funding for critical zone observatory (CZO) science provide a platform to establish a global network of advanced field research sites. This network will enable scientists around the world to work together – to achieve transformative basic science advances in knowledge of Earth's surface and to create interdisciplinary solutions to the global challenges of adapting to rapid environmental change and food and water supply security.

## International Call to Action

Earth's Critical Zone (CZ), the thin planetary veneer extending from the top of vegetation to the bottom of aquifers that supports almost all human activity [1,2], is under intensive pressure from growth in human population and wealth. Critical Zone Observatories (CZOs), established during the past 5 years, intensively study the complex interactions of rock, soil, water, air and organisms that regulate CZ properties and their ability to provide life-sustaining resources.

CZOs are providing transformative advances in basic natural sciences with far greater, holistic understanding of how geophysical, geochemical, and biological processes integrate from the vegetation canopy, across the land surface through soil, to aquifers and the deeper biosphere [3,4]. CZOs have established scientific focal points that define major research questions, raise awareness of critical zone vulnerability, and interface with environmental policy. They have fostered the interdisciplinary research necessary to rapidly deliver solutions to the major societal challenges of land degradation, climate change, food security, biofuel production and a clean and plentiful water supply. International networks of CZOs offer enormous potential to globally integrate basic science with innovation in human adaptation to rapid and intensive environmental change [5].

Achieving this vision requires a transformation in the ambition and integration of CZO science agendas worldwide. Our goal in forming an International CZO Programme is to facilitate the integration and broad communication of knowledge gained from new and existing CZOs, with an aim towards understanding of the resilience and vulnerabilities of the Earth's CZ and its inhabitants and to formulate interdisciplinary solutions to sustaining Earth's CZ for future generations.

## Programme Plan

An international workshop was convened 9<sup>th</sup>-11<sup>th</sup> November, 2011 at U. Delaware, USA to develop an international Critical Zone science agenda for the next 10 years [6]. Eighty-nine scientists from 25 countries representing around 60 CZOs and associated field sites around the world attended the meeting.

The workshop participants debated and refined six key science questions and developed these into research hypotheses and framework experimental designs, in order to drive this 10-year agenda forward. The science areas spanned basic science enquiry and challenge-driven research that delivers solutions. The six science questions were divided into time scales of environmental change. Long-term geo-biological evolution of Earth's near-surface environment and short-term, rapid change driven by human activity.

### Long-Term Processes and Impacts

1. How has the geological evolution and paleobiology of the CZ established ecosystem functions and the foundations for CZ sustainability?
2. How do molecular-scale interactions between CZ processes dictate the linkages in flows and transformations of energy, material and genetic information across the vertical extent of above ground vegetation, soils, aquatic systems and regolith - and influence the development of watersheds and aquifers as integrated ecological-geophysical units?
3. How can theory and data be combined from molecular- to global- scales in order to interpret past transformations of Earth's surface and forecast CZ evolution and its planetary impact?

## Short-Term Processes and Impacts

4. What controls the resilience, response and recovery of the CZ and its integrated geophysical-geochemical-ecological functions to perturbations such as climate and land use changes, and how can this be quantified by observations and predicted by mathematical modelling of the interconnected physical, chemical and biological processes and their interactions?
5. How can sensing technology, e-infrastructure and modelling be integrated for simulation and forecasting of essential terrestrial variables for water supplies, food production, biodiversity and other major benefits?
6. How can theory, data and mathematical models from the natural- and social- sciences, engineering, and technology, be integrated to simulate, value, and manage Critical Zone goods and services and their benefits to people?

A common feature of the experimental designs is the establishment of networks of CZOs located along planetary-scale gradients of environmental change, e.g. gradients of climate and intensity of land use.

The workshop prepared a 3-year plan to establish a coordinated international CZO programme. The report proposed to review progress and agree next steps 10 months later, during the CZO Geobiology conference, convened 5<sup>th</sup>-8<sup>th</sup> September, 2012 at the China University of Geosciences in Wuhan. An outcome of discussions with the participating scientists and national funders at the Wuhan meeting was the concept to develop an international steering committee, whose members are the authors of this white paper, in order to further develop and drive forward this project plan. The committee members are committed to the hard work and the necessary consultation and preparatory work with partners around the world, to enable this vision to be realised.

## Initial Steps

To advance this global project requires a series of steps through 2013 and continuing into 2014:

1. Establishment of an international forum of CZO leaders to integrate with additional observatory networks, to broaden the disciplinary mix, and to debate, test and strengthen the programme of research,
2. Creation of a Critical Zone Science Joint Working Group of The International Union of Soil Science (IUSS), American Geophysical Union (AGU), and the Ecological Society of America (ESA);
3. Preparation and presentation of a proposal to develop and implement this CZ Science agenda within the interdisciplinary activities of the International Council for Science (ICSU);
4. Preparation of a bid with national funders for multilateral international funding with the Belmont Forum;
5. Coordinated advocacy and strategy development with national funders and research foundations; and
6. Continued development and implementation of this plan for a coordinated international programme of CZO research.

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**Appendix 8: Topographic Stress and Rock Fracture: Probing the Effects of Landforms on Bedrock Structure in The Shallow Subsurface, by J. Taylor Perron.**

# Topographic stress and rock fracture: Probing the effects of landforms on bedrock structure in the shallow subsurface

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## Summary

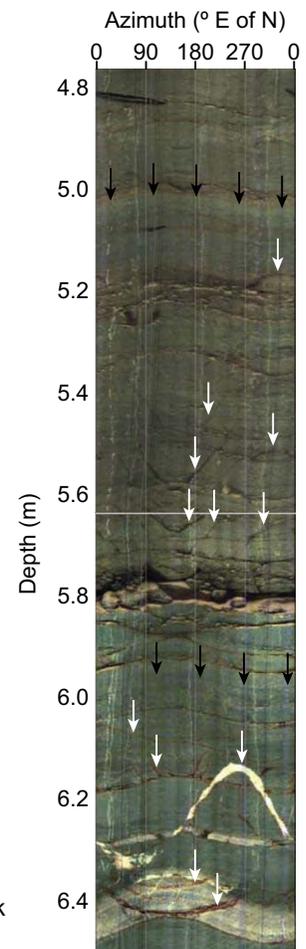
The development of landforms influences numerous processes on Earth's surface, ranging from the routing of water and sediment to the distribution of species. Theory predicts that landforms should also perturb the state of stress in the underlying rock, potentially altering rock fracture patterns in the shallow subsurface and leading to long-term feedbacks between erosion and rock fracture. However, the extent of these effects is unknown, because there have been few attempts to compare calculated stresses with observed fracture patterns in specific landscapes. There is currently an opportunity to make rapid progress on this basic problem by adapting existing stress models and obtaining field data on subsurface rock structure. A field-tested model for predicting topographically induced rock fracture patterns would have applications in geomorphology, hydrology, seismology, and the design of near-surface infrastructure.

## The Challenge

Theoretical calculations indicate that topographic stresses – gravitational stresses associated with the presence of landforms at Earth's surface – can be large enough to fracture rocks [1-6]. These calculations typically have involved idealized, hypothetical topographic profiles [1-6], with few direct comparisons between predicted topographic stresses and observed fractures at specific field sites [7,8]. Images of shallow boreholes (Figure 1) reveal populations of fractures that are distinct from bedding planes and that vary spatially in abundance, but it is not clear whether these fracture patterns are correlated with topographic stresses. Thus, despite several decades of theoretical studies, it is unknown whether Earth's surface topography significantly influences the distribution of bedrock fractures.

## Significance

Fractures in the shallow subsurface affect bulk rock strength and permeability, which should in turn affect rock erodibility, slope stability, infiltration capacity, and groundwater flow [4,7,9]. These effects have implications for short-term land use as well as long-term landscape evolution. Over human timescales, an understanding of topographic effects on the distribution of bedrock fractures could help predict the location and frequency of landslides, patterns of runoff and streamflow, and the suitability of potential building sites for above- or below-ground infrastructure.



**Figure 1.** Borehole image log from a Pennsylvania shale. Planar features that intersect the borehole have sinusoidal traces in this unwrapped view of the borehole walls. Black arrows mark examples of bedding planes. White arrows mark examples of fractures.

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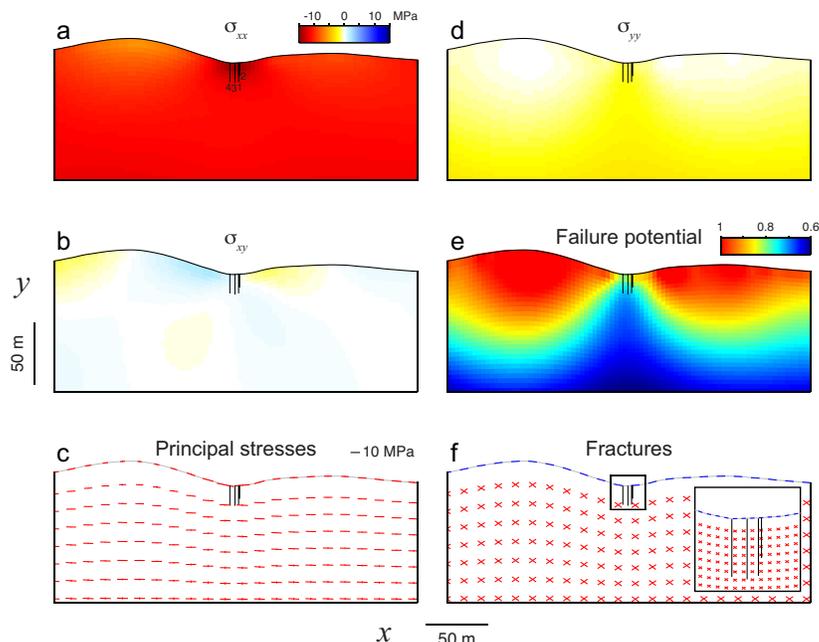
Over longer timescales, topographically induced fracturing could lead to feedbacks between landscape evolution and rock fracture patterns. For example, several investigators have suggested that the incision of river valleys may induce topographic stresses that promote rock fracture beneath valley floors, which could in turn accelerate valley incision [1,4,6]. Fracturing is also an essential part of soil formation, a key mechanism in the development of the interface between the atmosphere and the lithosphere [10]. The factors controlling the population of fractures that arrives in the shallow subsurface as rock is exhumed by erosion are major uncertainties in the study of Earth's surface.

## Opportunities

Determining the extent to which these effects actually occur will require a detailed understanding of the mechanisms that generate stresses and fractures beneath real-world topography as well as an evaluation of field evidence for topographic fracture, including comparisons of observed rock fracture patterns with predicted topographic stresses. The basic theoretical groundwork for such comparisons has been laid over the past few decades. The elastic stresses induced by surface topography in a uniform two-dimensional half-space can be calculated analytically for certain idealized ridge and valley cross-sectional profiles that are amenable to analytical solutions [2,3]. These stress solutions have been compared with rock fracture criteria to predict spatial patterns of fracture mode and occurrence [4,6].

The main obstacle preventing a direct test of these predictions is that the analytical solutions for idealized topographic profiles across isolated ridges and valleys are too simple to be applied to field sites with irregular, asymmetric, three-dimensional topography that includes many adjacent ridges and valleys. Thus, the next steps toward assessing the effects of topographic stress on bedrock structure are to create models that can calculate stresses beneath complex topography and to compare the predicted fracture patterns with field measurements of shallow fracture patterns.

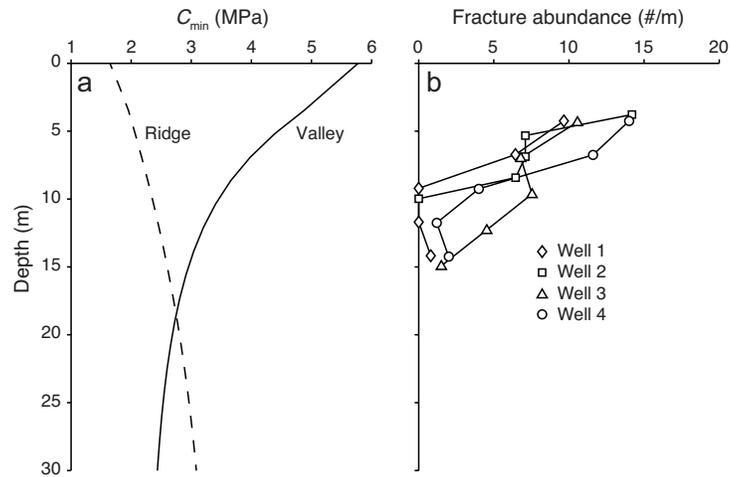
Four recent developments have made these steps possible, creating a new opportunity to test long-standing ideas about topographically induced fracturing. First, numerical methods for calculating stresses near geometrically irregular free boundaries have been adapted to Earth's surface [5,11], making it possible to calculate stresses induced by arbitrary topographic profiles. Second, new technologies such as airborne laser altimetry have been used to acquire high-resolution digital maps of bare-earth topography, which are necessary inputs to the stress models. Third, new methods for mapping shallow bedrock structure have been developed and tested, including active-



**Figure 2.** Boundary element model solution for stresses (a-d), failure potential (e), and predicted fracture modes and orientations (f) beneath a laser altimetry profile across a valley in the Shavers Creek watershed in central Pennsylvania. The calculation uses a compressive ambient horizontal surface stress of -10 MPa. Locations of four shallow boreholes are indicated. In (f), blue lines indicate opening mode fractures in compression at the land surface, and red lines indicate shear fractures. Inset shows a solution in the vicinity of the boreholes with higher spatial resolution. Color scale in (a) applies to (a), (b), and (d).

source seismic surveys [12] and digital image logs of boreholes [13]. Fourth, advances in landscape evolution modeling [14] have provided a framework for exploring potential feedbacks between topography, erosion, and rock fracture. These recent developments have created a timely opportunity to compare theoretical predictions of topographic stresses with rock fracture patterns observed in the field.

Figures 2 and 3 illustrate the potential for such comparisons. In Figure 2, a boundary element model [15] has been adapted [5,11] to calculate the stresses induced by a topographic profile across a valley in the Shavers Creek watershed in central Pennsylvania, an experimental site maintained by Pennsylvania State University. In addition to the horizontal, vertical, and shear stresses (Fig. 2a,b,d), it is straightforward to calculate the orientations and magnitudes of the principal stresses (Fig. 2c), a widely used proxy for normalized differential stress (Fig. 2e), and the predicted modes and orientations of fractures for typical mechanical properties of shale (Fig. 2f). Four existing wells in the valley floor have been logged with an optical borehole imager (OBI), making it possible to compare trends of fracture abundance as a function of depth (Fig. 3b) with modeled proxies for shear failure (Figure 3a). Fig. 3 shows that fracture abundance and the modeled failure proxy decline similarly with depth beneath the valley floor, whereas a very different trend is predicted beneath ridgetops. This preliminary comparison suggests that fractures beneath the valley floor may have been influenced by topographic stresses, and illustrates the potential for a more thorough test through comparisons of modeled stresses with fractures in ridgetop boreholes.



**Figure 3.** Comparison of measured fracture abundance with model-based proxies for shear fracture. (a) Depth profiles of the minimum cohesion required to prevent shear failure,  $C_{min}$ , beneath the valley floor and higher ridgetop in Fig. 2. (b) Depth profiles of fracture abundance based on fracture counts in borehole image logs like the one in Fig. 1. Well numbers are labeled in Fig. 2a. The gap in fracture abundance near the surface occurs because the wells are cased from the surface to 3 m depth.

## Research Needs

An expanded effort to explore topographic effects on rock fracture would include several components:

1. Creation of models capable of calculating topographic stresses and fracture patterns beneath arbitrary topographic surfaces. Although the basic components of such models are in place [5,11,15; Fig. 2], additional refinements and extensions are necessary for a rigorous examination of topographic stresses in a wide range of landscapes. These include improving procedures for calculating induced stresses on and near boundaries; extending two-dimensional models of stresses beneath arbitrary profiles to three-dimensional models of stresses beneath arbitrary surfaces [16]; and incorporating recent theoretical and experimental insights into transitions between different modes of fracture [17].
2. Better estimates of regional near-surface tectonic stresses. The extent, mode, and orientation of fractures should be sensitive to the sign and magnitude of the regional tectonic stress. Regional estimates of tectonic stresses have been compiled from a variety of sources [18], but local measurements from hydrofracture or borehole deformation in the

vicinity of study sites would complement these regional estimates and provide an additional constraint on stress models.

3. Field measurements of subsurface fracture distributions. Few measurements of fracture patterns in the shallow subsurface, where topographic effects are most pronounced, are currently available, because most efforts to characterize subsurface structure (for oil or gas exploration, for example) focus on depths deeper than a few tens of meters. Surveys of fracture mode, orientation and abundance in a variety of lithologic, topographic and tectonic settings will be critical for evaluating the extent to which topographic stresses control bedrock fracturing. Surveys of field sites could be conducted with complementary techniques such as optical imaging of shallow boreholes [13] and low-cost, active-source seismic surveys [12].
4. Application of stress models to sites where high-resolution surface topography and subsurface fracture measurements are available. This will provide a test of the hypothesis that topographically induced stresses can significantly influence subsurface fracturing, as well as a calibration of the relationship between modeled stresses and observed fractures that could potentially be applied to other landscapes where observations of subsurface fractures are not available. These efforts would leverage the growing availability of high-resolution laser altimetry.
5. Exploration of feedbacks between rock fracture, erosion, and landscape evolution. Comparisons of static stress models with present-day fracture patterns will provide a snapshot of two dynamic processes – landform evolution and bedrock deformation – that may be coupled if spatially variable fracture patterns influence spatial patterns of erosion. Incorporating topographic stresses and spatially variable rock fracture into models of landscape evolution will provide a framework for exploring the coevolution of topography and bedrock structure as erosion exhumes rock and shapes the land surface.

## Summary and Recommendations

The influence of topography on bedrock fracture patterns is predicted by theory, but these predictions remain largely untested due to the generic nature of analytical stress models and the scarcity of fracture measurements in the shallow subsurface. If topographic stresses do indeed control bedrock fracture patterns, the implications and applications are numerous, and could include assessments of rock strength effects on infrastructure, predictions of reservoir characteristics, slope stability modeling, and characterization of near-surface seismic response. An improved understanding of topographic effects on rock fracture would also benefit basic research into Earth surface processes by revealing the influence of topographic stresses on soil development and landscape evolution.

Two steps that will make rapid progress on this topic are (1) producing models for calculating the three-dimensional topographic stresses generated by arbitrary topographic surfaces, and (2) collecting field measurements of fracture patterns in the shallow subsurface at field sites with varied topography and tectonic context. Recent technological advances have made both of these steps possible, creating an opportunity to shed light on decades-old questions. However, the lack of existing field data on topographically mediated rock fracture could lead some funding agencies to label new efforts to investigate this topic as “high-risk”. Given the ARO’s directive to support research that carries some risk but potentially yields large returns, an effort to generate new tools and datasets for investigating the largely untested hypothesis that Earth’s surface topography shapes bedrock fracture patterns would be consistent with the objectives of the ARO Geomorphology Program.

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**Appendix 9: Weathering Profiles in the  
Intensively-Managed Landscape Critical  
Zone Observatory, Illinois and Iowa, by  
Andrew Stumpf, E. Arthur Bettis III, and  
Scott Elrick**

## **Weathering profiles in the Intensively-Managed Landscape Critical Zone Observatory, Illinois and Iowa**

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The critical zone's geologic materials in Illinois and Iowa house a 2 million year old legacy of deposition and erosion controlled primarily by the actions of glaciers, flowing water, and wind. Sixty to 130 meters of glacial, fluvial, lacustrine, and eolian sediments overly an eroded surface cut in Paleozoic bedrock. Within this thick package of unlithified sediments resides multiple weathering profiles formed as the landscape evolved between glacial episodes (Bettis, 1998). Weathering profiles in these deposits are recognized by pedologic features and structures, color and mottling patterns, fractures, and geochemical alterations such as leaching of primary carbonate minerals and/or accumulation of secondary minerals (Bettis, 2007).

The uppermost weathering profile in the area includes the postglacial or modern soil, a prairie soil (mollisol), or forest soil (alfisol). This weathering profile is most often formed in loess (Peoria Silt) or overconsolidated loamy glacial till, but along river valleys it may be formed in alluvium and glacial outwash (e.g., Figs. 1 and 2). The Peoria Silt includes variably thick deposits of windblown material deposited by dust storms that were common during the last glacial period (Bettis et al., 2003). Regionally across the IML-CZO, the thickness of loess varies from 7 m in Clear Creek Basin (CCB) to about 0.75 m in parts of the Upper Sangamon Basin (USRB). Loess typically thins downslope as a result of postglacial erosion, and the upper weathering profile is often developed through the thin loess and extends into underlying glacial till. In the CCB, the Peoria Silt buries Pre-Illinois Episode till (>500 ka) while in the USRB the Peoria Silt buries Wisconsin Episode till (c.a. 21 ka). Oxidation from the modern surface extends to a depth of at least 4 m and in some places beyond 8 m.

A second prominent weathering profile occurs beneath the thick loess in CCB (Fig. 2) and between deposits of the Wisconsin and Illinois Episodes at depths between 15 and 50 m below the present land surface in USRB (Fig. 1). This profile formed from a land surface that developed during the last interglacial period (c.a. 130-30 ka) in USB and between about 500 and 30 ka in CCB. The Sangamon Geosol formed during an extended period of climate warming (Follmer, 1979) that lasted from ~130,000–60,000 years ago (Curry et al., 2011) and forms the upper, pedogenically altered part of this weathering profile. The paleosol in the USRB is developed in a variety of materials including glacial diamicton, sand and gravel, and silt and fine sand of the Illinois Episode Glasford Formation, while in the CCB the geosol is in loamy glacial till of the pre-Illinois Episode Wolf Creek Formation (Figs. 1 and 2). The Sangamon Geosol often has well-developed Bt horizons with notable eluvial clay accumulations in the sand and gravel. Typically, only part of the Sangamon Geosol solum remains; the A and E horizons were truncated either by glacial erosion in USRB or by periglacial processes in CCB. Below the paleosol the weathering profile is recognized by either olive green (reduced) to dark brown (oxidized) fine-grained sediment and matrix-supported diamicton or yellowish brown- to reddish brown sand and gravel. The fine-grained sediments were deposited in flat areas or depressions that were poorly drained, the sand and gravel form elevated plains or fill paleovalleys and are well drained, and the diamicton is glacial till on slopes and elevated parts of uplands (cf. Jacobs, 1998). Typically, these sediments are leached of primary carbonate minerals, usually to a depth of 1.5–3 m below the paleo-land surface. Oxidation and mottling commonly extend much more deeply. The weathering profile extends along subvertical fractures into unaltered (unoxidized and unleached) dense glacial till.

Another weathering profile is buried beneath till of the Illinois Episode Vandalia Member in USB. Well- to moderately-drained facies of the Yarmouth Geosol occupy the upper part of this profile. In USRB this weathering profile is developed in pre-Illinois Episode tills that cover bedrock highlands or in valley fills in tributaries of the Mahomet Bedrock Valley (Fig. 1). Less frequently, the geosol is associated with a poorly expressed weathering profile. These profiles are only encountered in the Mahomet Bedrock Valley where pre-Illinois till was deposited on erosional hills on the valley bottom that are formed of bedrock or glacial sediment. To preserve these profiles in the till, the surfaces of these hills must have been above the maximum level of scour by glacial meltwater during the Illinois Episode glaciation. The weathering profile associated with well-drained facies of the Yarmouth Geosol is thicker and more oxidized than that associated with poorly drained facies of the geosol. Pedogenic alteration may extend 3–5 m into the till. In southern Illinois, mineralogical and magnetic measurements from these oxidized weathering profiles suggest that Yarmouth Geosol alteration and soil development was about triple the intensity as compared to alteration associated with the Sangamon Geosol (Grimley et al., 2003). Glacial erosion has truncated the upper soil horizons of this weathering profile in USRB.

Illinois Episode glaciation did not extend as far west as CCB where landscape evolution and weathering profile development continued uninterrupted through the Illinois Episode and into the Wisconsin Episode. Thus, the profile beneath the Peoria Silt in CCB represents weathering over the period encompassing development of the Yarmouth and Sangamon geosols in USRB. Almost without exception this thick weathering profile (usually 10-15 meters) is formed in loamy glacial diamicton of the upper Wolf Creek Formation and often extends into older, partially truncated weathering profiles formed in older Wolf Creek Formation glacial sediments (Fig. 2).

Other buried weathering profiles are present in the sequence of glacial sediments in CCB and USRB. These weathering profiles range from thin to thick and are associated with soils formed in deposits of sand, silt, clay, diamicton, or gravel that in some places contain organic matter. In the buried Mahomet Bedrock Valley (in USRB), a weathering profile extends into the underlying glacial outwash (Mahomet Sand Member of the Banner Formation) (Fig. 1) that was deposited during the first ice advance into Illinois (Stumpf and Dey, 2013). This glacial outwash comprises part of an aquifer (Mahomet aquifer) that is an important source of groundwater in the USRB. On the adjacent uplands, the weathering profile extends into the underlying till that Stumpf and Dey (2013) assigned to the West Lebanon Member. In west-central Indiana, this till is believed to have been deposited prior to the Matuyama-Brunhes magnetic reversal (Bleuer, 1976), which occurred  $773.1 \pm 0.8$  ka (Channell et al., 2010). A similar-age buried bedrock valley with a prominent weathering profile developed into its alluvial fill is present in the lower reaches of CCB near its junction with the Iowa River Valley (Bettis et al, 2010; Rovey et al, 2010; Fig. 2).

The lowermost weathering profile within the Quaternary section at USRB and CCB is encountered in various landscape positions (uplands and valleys), 60–100 m below the present land surface. The profiles are formed in variable thicknesses of sand, silt, gravel and rubbly diamicton, and lie directly on bedrock (Figs. 1 and 2). These sediments have a distinctive greenish gray to olive brown weathering color, may be leached, and generally contain distinctive clay mineral content and lower magnetic susceptibilities compared to the overlying glacial sediment. These sediments often contain some angular-shaped, oxidized and unoxidized clasts of the local bedrock.

In the USRB, the uppermost bedrock is Pennsylvanian and composed of alternating bands of shale, limestone, coal and underclay, with sandier lenses possible within the large shale bodies. Shale is the most volumetric lithology, and the most commonly encountered Pennsylvanian exposure surface when drilling. The shales may show a degree of lamination or stratification in the unweathered state, but this is obfuscated with weathering. Additionally, shales surfaces become soft and mushy. Consequently, material from the bedrock can be easily incorporated into the overlying unlithified sediments, making

distinguishing a precise surface of the bedrock difficult. In CCB the uppermost bedrock is variable and ranges from micaceous Pennsylvanian siltstone and sandstone to Devonian mudstone and limestone. Smears and clasts of local bedrock occur prominently in the oldest few tills of the Alburnett Formation and decrease in abundance up section.

The modern landscape in the IML-CZO is underlain by a variety of unlithified deposits altered to various degrees by several periods of weathering. Weathering profiles developed in bedrock are uncommon and, for the most part, the bedrock surface is a glacially scoured erosion surface. Initial materials in which the weathering profiles developed are dominantly wind-blown silt (the upper weathering profile) and dense, unoxidized matrix-dominated loamy glacial diamict. Fracture networks in these materials provide preferential pathways for movement of water and colloids in these otherwise slowly permeable materials.

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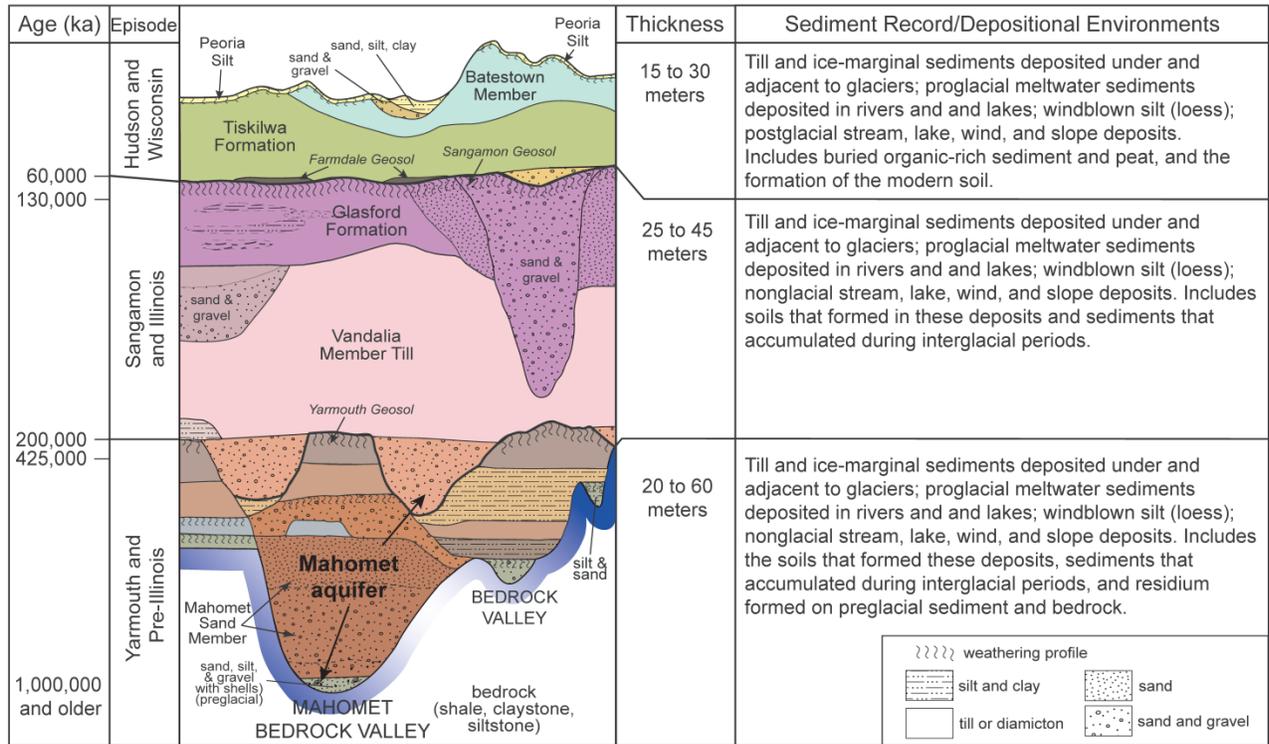


Figure 1. The geological framework for the Upper Sangamon River Basin (USRB); from Stumpf and Dey (2013).

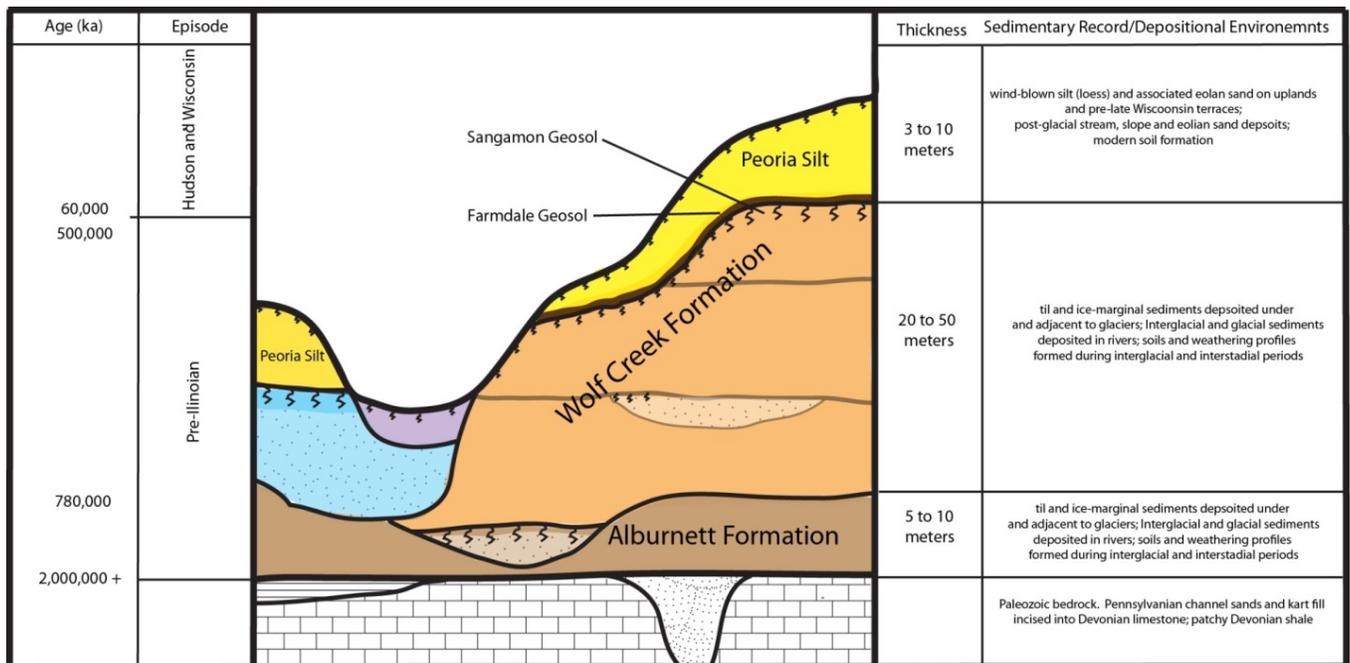


Figure 2. The geological framework for the Clear Creek Basin (CCB) in eastern Iowa.

**Appendix 10: Dating Alteration and  
Exhumation in the Deep Critical Zone, by A.  
Joshua West and Pete Reiners.**

## Dating alteration and exhumation in the deep Critical Zone

*White paper for NSF Workshop on Drilling, Sampling, and Imaging the Depths of the Critical Zone, Thursday October 24<sup>th</sup> – Saturday October 26<sup>th</sup>, 2013, Denver, CO*

*Josh West (University of Southern California) and Pete Reiners (University of Arizona)*

### Motivation: Why dates are likely to be important

There is wide agreement about the need to understand chemical reaction and rock alteration that takes place beneath the depth of identifiable soil. Drilling and other deep sample collection provide the opportunity to directly sample alteration at depth, and alteration minerals such as clays and oxides are likely to provide particularly valuable information about the chemical processes in recovered material (e.g. Buss et al., 2008). But clays and oxides in many rocks reflect processes that range widely in age, with some clays and oxides forming millions of years ago, or even earlier, and others forming as recently as the past decades (e.g. Vasconcelos et al., 1999). Moreover, there is little *a priori* information about when rock in the deep Critical Zone was exhumed to depths where alteration occurs. Properly understanding the geochemical records of drill cores or other samples from the deep Critical Zone, and accurately interpreting what they mean about the nature and rates of geochemical and biogeochemical reactions, will depend on determining both when rock was brought to the shallow crustal depths where alteration occurs, and when key alteration reactions actually took place. *This brief white paper summarizes some ideas for adding age information about clays and oxides recovered from the deep Critical Zone, as well as constraining the timing and rate of shallow exhumation.*

### Dating by K/Ar, Ar-Ar, and Rb-Sr

Ar-Ar dating has been successfully applied to Mn-oxides (e.g., Vasconcelos, 1999), and K-Ar and Rb-Sr methods have proved useful in dating clay minerals (e.g. Gilg et al., 2003). The long half-lives of these systems generally have restricted their application to **clays and oxides >100,000 years in age**. This means that they are not well suited for the study of recent (Holocene or similar) alteration, which may be most relevant for understanding active Critical Zone processes. However, older alteration, which may be reflected in ancient oxides and other minerals, is important for setting the stage for more recent chemical reaction and shaping the physiochemical characteristics of the bedrock. Indeed, much remains to be understood about how the older history of rock alteration shapes present-day processes. Ar dating would be a potentially valuable tool for gaining older age information from alteration phases, although (U-Th)/He chronology, described below, may also provide valuable insights into the history of deep Critical Zone samples.

### Dating by (U-Th)/He

Radiogenic He dating may be valuable for understanding deep CZ evolution for two reasons:

- First, (U-Th)/He thermochronology of common primary minerals can **constrain the timing and rate of exhumation of bedrock into the shallow crust** (1-2 km for apatite), where it is exposed to chemical alteration and the initiation of CZ processes (e.g. Reiners et al., 2005). Knowing the timing of the initiation of the CZ context would provide a valuable interpretive baseline. For example, as noted above, CZ processes occurring in a modern setting may be influenced by previous or ancient exposure episodes that initiated bedrock weathering.
- Second, ongoing studies show significant potential for this method to **date the timing of formation of secondary oxides** (e.g., hematite, goethite, Mn-oxides) in bedrock (e.g. Shuster et al., 2005). This is useful because it constrains the timing of flow of oxidized fluids in the uppermost crust and therefore the timing of chemical weathering in the deep CZ (e.g. Buss et al., 2008).

### Dating by U-series disequilibrium

There are several ways in which the  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  system can be used to date alteration processes. This system can cover a useful range from a few thousands of years to >350 ka. Perhaps the most robust use of this system is in **dating of specific individual phases**, and several alteration phases have been successfully dated this way, including:

- *Secondary carbonates and opal rinds*: These are obvious targets and there has been considerable use of this tool especially on carbonate rinds from soils in arid environments (e.g. Ludwig and Paces, 2002; Sharp et al., 2003).
- *Oxides*: Fe-oxides including goethite are datable; most applications have focused on concretions (Short et al., 1989; Augustinus et al., 1997; Bernal et al., 2006).
- *Clays*: Dequincey et al. (1999) dated the <0.2mm fraction of laterite soils, which they viewed as a clay fraction and which exhibited quasi-closed system behavior sufficient to yield a clay formation age at the bottom of the profile. This approach has not been widely used but may be promising.

If appropriate secondary phases can be recovered from samples from the deep Critical Zone, these kinds of phase-specific  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  work have the potential to provide valuable age information.

There have also been many efforts to infer **ages of initial alteration of bulk material** (the “weathering timescale” of soils and sediments) using  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  disequilibria. This includes isochron methods using co-genetic samples with varying detrital component (e.g. Rosholt, 1976), and modeling of leaching timescales (e.g. Vigier et al., 2001; Dossetto et al., 2008; Chabaux et al., 2012). These methods may often provide useful information, and they may be useful in application to deep CZ samples, but there are several uncertainties and the context of their application requires careful attention in order not to yield ages that may be biased, for example by complex leaching behavior (e.g. Keech et al., 2013).

### Summary

U-series disequilibrium and (U-Th)/He geo- and thermochronology offer geochemical techniques that may be particularly useful in providing age information about alteration in the deep Critical Zone. Planning sample recovery with these techniques in mind will help to maximize the information gained from drilling and other recovery efforts, because understanding the age of alteration will be critical to interpreting other geochemical, geophysical, and geobiological information.

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**Appendix 11: The Deep Critical Zone (DCZ)  
Need Not Go “Unmeasured”: Advancing  
Process-Based Geophysical Characterization  
and Monitoring, by Lee Slater**

## **The Deep Critical Zone (DCZ) need not go “Unmeasured”: Advancing Process-Based Geophysical Characterization and Monitoring**

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Although the Deep Critical Zone (DCZ) has been nicknamed the “unmeasured zone” (Dietrich, 2010) it is actually highly accessible with well-established geophysical imaging technologies. This misrepresentation of the DCZ highlights a pressing need for more collaboration between near surface geophysicists and the hydrologists, geochemists and geomorphologists currently studying critical zone processes. Dramatic advances in near surface geophysical techniques have occurred over the last decade, resulting in improved spatiotemporal resolution of subsurface structure and processes. The information content of geophysical measurements with respect to hydrogeological and biogeochemical properties of the Earth has also increased through theory and observation. Geophysical imaging of the DCZ is not new: The current opportunity is to better perform geophysical imaging in a manner that helps to unravel how the DCZ structure regulates biogeochemical processes observed in the shallow critical zone and at the Earth surface. In a nutshell, near surface geophysicists need to better understand the significance of their trade with respect to advancing understanding of critical zone processes. This requires new thinking on geophysical sensors, instrumentation and petrophysical interpretation.

A new era of geophysical instrumentation: Geophysical characterization and monitoring of the DCZ should be better coupled with other sensors being used to understand critical zone processes. Such coupling of geophysical images to surface observations offers the solution to understanding how shallow CZO processes are linked to the DCZ. This strategy has already led to [1] improved understanding of hydrogeological controls on focused groundwater discharge into rivers, and [2] geological controls on peatland formation and carbon cycling within peatlands. This new era requires development of geophysical instrumentation that overcomes the inflexibility of instruments designed for traditional exploration geophysics. Instead geophysical sensors and monitoring systems that maximize the information content retrievable from the DCZ are needed. Integration of these geophysical sensors with instrumentation for monitoring shallow CZ processes must be considered. Autonomous geophysical monitoring platforms should ultimately be developed to provide invasive proxy measurements of chemical, physical, and biological processes operating in the DCZ over long time scales. For example, electrical geophysical monitoring systems have recently been deployed to determine the control of geological structure on surface water-groundwater interactions.

A new era of “petrophysical” research: Petrophysics is a petroleum geophysics term for the science defining the relations between geophysical properties measured with imaging and the physicochemical properties of the Earth. Existing petrophysical relations generally consider static systems i.e. they are parameterized with the physicochemical properties of rocks that are primarily determined by processes acting on geological timescales. However, the DCZ is dynamic in that biogeochemical transformations modify both the physicochemical and geophysical properties of earth materials on much shorter timescales. Recent studies have repeatedly demonstrated the sensitivity of geophysical techniques to biogeochemical processes and transformations occurring in the DCZ. Consequently, we foresee a need for research on time-variable petrophysics to develop robust relations that will improve the information content of geophysical signatures resulting from natural biogeochemical processes, and allow better quantitative coupling of deep CZO processes to the shallow zone.

**Appendix 12: Exploring Weathered Bedrock  
Characteristics: A Pedologic Approach, by  
Toby O'Geen, Craig Rasmussen, Bob  
Graham, and Peter Hartsough.**

# Exploring Weathered Bedrock Characteristics: A Pedologic Approach

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## Introduction

Weathered bedrock plays a critical role in the hydrologic cycle and directly influences ecosystem productivity (Graham et al., 2010). Its ability to store water is especially relevant in arid and semi-arid environments, yet equally important in the midst of climate uncertainty in humid regions. Remarkably, very little is known about the spatial variability of weathered bedrock characteristics. Geophysical investigations are promising, but alone do not provide information about ecologically important characteristics such as water and nutrient availability, propensity to accommodate roots, and carbon storage. On the other hand, deep coring provides direct point observations, but of limited spatial extent and questions of representative sample collection arise. In combination with geophysical techniques and deep drilling, pedological approaches can be applied to describe deep regolith characteristics across catchment scales.

In many landscapes, repeating patterns of soil forming factors (usually overlapping) give rise to predictable patterns in soil characteristics. This phenomenon and its application define a paradigm for mapping soils using field observations coupled with contextual data (aerial imagery, topographic maps, geologic maps, etc.) that are hypothesized to have a connection with active soil forming factors: time, topography, organisms, climate and parent material (Jenny, 1941 & 1980). The fairly recent digital implementation of this approach, supported by widely available, high-resolution spatial data coupled with statistical and mapping software, has resulted in effective quantification techniques that document soil variability and their influence on near surface processes (Moore et al., 1991; McBratney et al., 2003; Grunwald, 2009).

Most digital mapping studies focus on external “drivers” of soil formation (e.g. hillslope processes that affect the redistribution of water, sediment, and mineral weathering), with an inferred relationship to digital proxies for these drivers. This approach relies on fitting statistical models to soil and environmental covariates (i.e. proxies for soil forming factors), followed by prediction at un-sampled locations. Terrain-based attributes calculated from digital elevation models such as slope shape, exposure, and compound metrics describing flow (water or energy) or sediment accumulation are some of the common proxies used to describe soil forming processes (Moore et al., 1993).

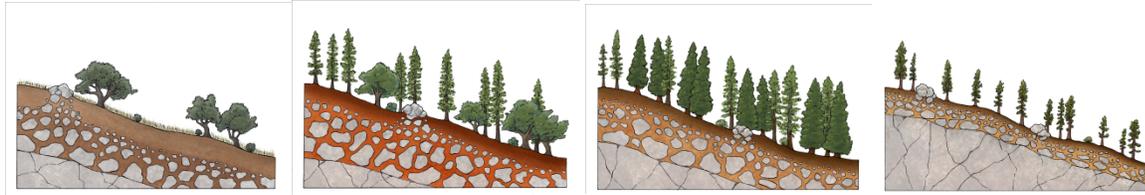
Quantitative models that describe weathered bedrock characteristics are needed in order to understand critical zone processes operating at catchment and hillslope scales. We believe that digital soil mapping and other pedologic approaches should be included as part of the toolkit for deep CZ research. The following questions are examples of how the characteristics and spatial distribution of weathered bedrock might be addressed from a pedological perspective.

1. Do soil forming factors, (Time, Topography, Parent material, Organisms, and Climate) explain spatial variability of weathered bedrock characteristics? Are some factors more or less important?
2. To what degree do digital soil mapping techniques and their digital proxies (terrain attributes, airborne gamma ray mapping, remote sensing) explain weathered bedrock thickness and mineralogical, chemical, biological and physical characteristics?
3. To what extent does soil variability as documented by the Cooperative Soil Survey relate to spatial trends in weathered bedrock characteristics?
4. What other observational techniques are possible to sample and describe important characteristics of weathered bedrock?
5. Can traditional soil analyses be applied to deep regolith to help interpret their ecosystem and hydrologic functions?
6. How does the degree of soil development influence the nature and dynamics of processes in weathered bedrock?
7. Is there a fundamental scaling relationship between the depth of regolith, canopy height, and depth of chemical alteration of bedrock?

### **Case Studies**

*Study 1:* Preliminary evidence at the Southern Sierra CZO suggests that a linkage exists between the degree of soil development and characteristics of weathered bedrock. Spatially explicit patterns of soil forming factors give rise soil sequences that correspond to an altitudinal gradient. This gradient imposes a weathering environment that is limited by moisture at low elevations and by low temperature at high elevations. A zone of high weathering intensity exists across the entire Sierra Nevada at mid elevations, between ~800 to 1600 m. This belt of intense soil development occurs in many parent materials throughout Sierra Nevada and reflects the combined influence of mild temperatures and high precipitation, predominantly as rain (Dahlgren et al., 1997; Rasmussen et al., 2007).

Weathered bedrock thickness coincides in part with the degree of soil development along the altitudinal gradient. Generally, weathered bedrock thickness is limited at low elevations because of a lack of water and at high elevations due to glaciation, which has limited the amount of time the material has been exposed to weathering processes. There is a greater elevation range of landscapes with deep regolith (~800-2000 m) compared to landscapes with highly weathered soils (~800-1600 m) (Figure 1.). Elevations between 1600-2000 m appear to have deep regolith, but relatively weakly developed soils. Additional factors that influence regolith thickness appear to be at play. For example, physical weathering plays a significant role in weathered bedrock thickness. Physical weathering in Sierran granitic materials is largely controlled by mica exfoliation. Hence, higher mica contents result in thicker weathered bedrock, if enough water is present and the terrain has not been glaciated.



Oak savannah 400 m      Pine/oak forest 1100 m      Mixed conifer 2000 m      Subalpine forest 2700 m

Figure 1. Soil development and regolith thickness across an altitudinal gradient in the Sierra Nevada. The intensity of redness reflects the degree of soil development.

*Study 2:* Numerical and digital soil mapping models of soil properties in the Marshall Gulch catchment of the Santa Catalina Mountain CZO indicate clear relationships between terrain attributes (wetness index and annual solar radiation) and properties such as the depth of potentially mobile regolith (defined here as the depth of refusal when excavated by hand) and chemical depletion (Pelletier and Rasmussen, 2009; Holleran, 2013). The Marshall Gulch study area focused on a small 6 ha basin at ~2,200 m a.s.l. with a mixed conifer forest underlain by dominantly granitic parent materials, characterized by an assemblage of quartz, alkali and plagioclase feldspars, and muscovite.

Pelletier and Rasmussen (2009) used a mass transport numerical model that incorporates an exponential form of the “soil production function” (Heimsath et al., 1997) and a non-linear depth and slope dependent sediment transport function using 1-m resolution LiDAR data and an assumption of topographic steady-state to model the depth of the potentially mobile regolith with a reasonable degree of accuracy based on field observations (Fig. 2a). The modeled depth expresses strong correlation with topographic divergence and convergence as expected based on the sediment transport model.

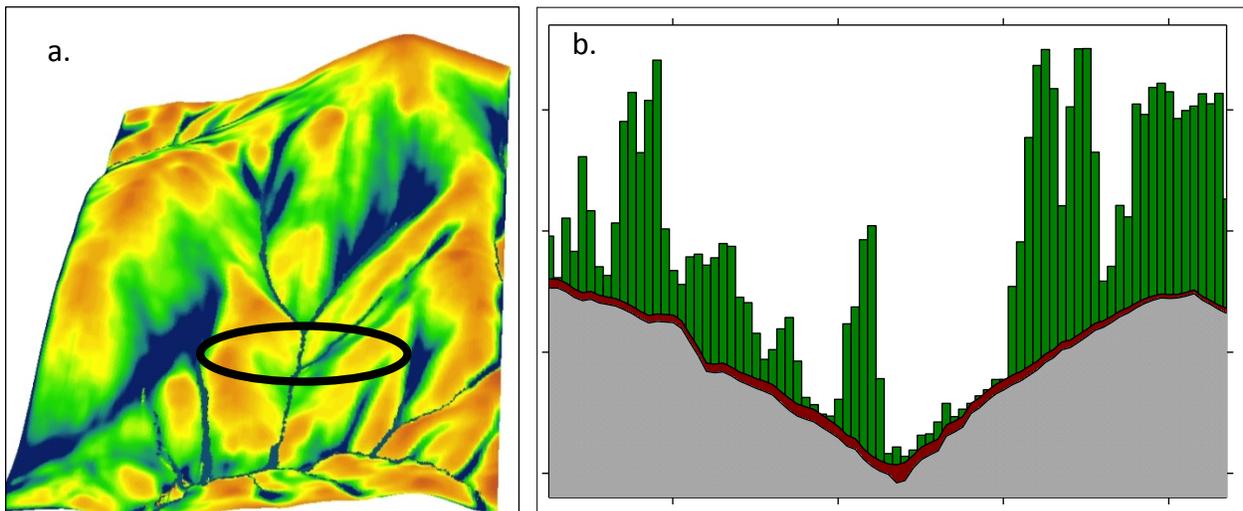


Figure 2. Numerically modeled depth of mobile regolith (defined here as depth to refusal when excavated by hand) (a) indicates clear relationship between depth and topography, namely deep soils in convergent portions of the landscape (dark blue ~2 m depth) and shallow soils in divergent landscape positions (red and orange < 0.15 m depth). The second panel (b) overlays the LiDAR derived canopy

height (green bars), modeled regolith depth (red-brown layer), and topography (all scaled to meters a.s.l.). Data from a 6 ha basin in Marshall Gulch SCM-CZO (Pelletier and Rasmussen, 2009).

Application of digital soil mapping techniques to the same basin similarly indicated strong statistical relationships between topographic wetness index and solar radiation to mobile regolith depth and degree of chemical denudation (Fig. 3) (Holleran, 2013). It is encouraging to note that two independent modeling techniques (a numerical mass transport approach and a statistically based digital soil mapping approach) yield very similar patterns in mobile regolith depth and degree of chemical alteration. However, the large scale difference and relative lack of spatial correlation in modeled and measured mobile regolith depth and LiDAR derived canopy height (Fig. 2b), suggests the mixed conifer forest must rely on water from depths much greater than those that can be excavated by hand. We suggest there may be a scaling relationship among terrain attributes, mobile regolith depth, canopy height, and depth of weathered bedrock that would facilitate coupling these techniques and data to model the depth of weathered bedrock.

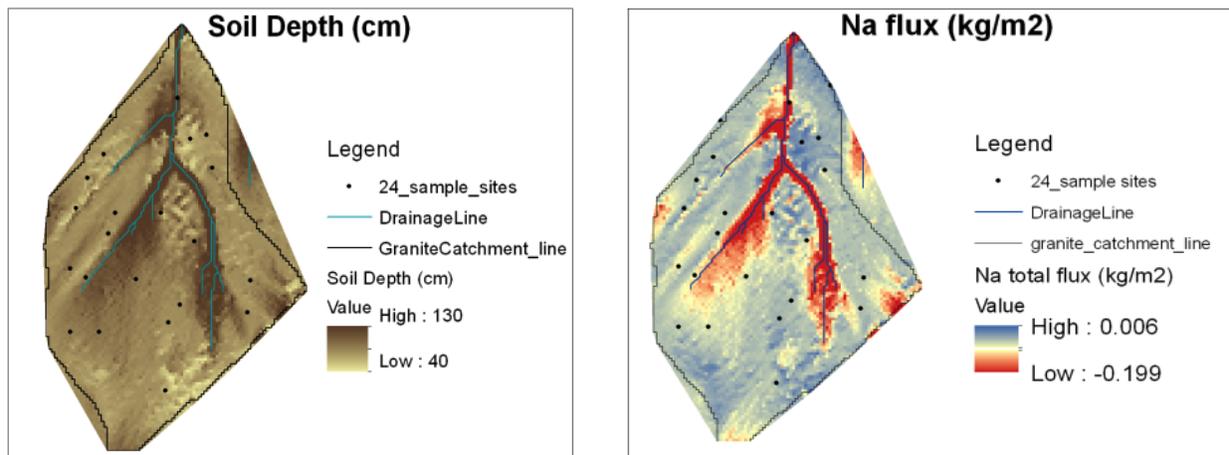


Figure 3. Modeled mobile regolith depth (defined here as depth to refusal when excavated by hand) and Na mass loss for the 6 ha basin in Marshall Gulch SCM-CZO using statistically based digital soil mapping techniques (Holleran, 2013).

### Summary

The opportunity to incorporate the pedologic method with other disciplines for deep, weathered bedrock CZ investigations appears promising. Soil landscape relationships such as those described here are commonly used in pedologic investigations. Moreover, these types of models serve as the foundation for how soil surveys are made. Thus, the possibility of using soil survey as an upscaling mechanism for weathered bedrock characteristics is conceivable. To fully understand the characteristics of weathered bedrock, and the processes it mediates, a joint-CZO effort is needed that involves a variety of disciplines.

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