GEOPHYSICS

Pinched topography initiates the critical zone

Geophysical imaging provides a clearer picture of how rock turns into soil

By **Robert S. Anderson**

In Earth sciences, the critical zone represents the intersection of the biosphere with the atmosphere, hydrosphere, and lithosphere (*1*, *2*). The myriad interactions and feedbacks among these systems assure us of a world with considerable complexity, in which the critical zone varies in thickness, mineralogy, permeability (*3*), and structure of ecosystems (*4*). It is no wonder, then, that we lack a general theory of how the critical zone works. On page 534 of this issue, St. Clair *et al.* (*5*) argue that we must take the broadest possible view of, and acknowledge a role for, large-scale tectonic stresses in guiding the pattern of cracking of rock in the subsurface.

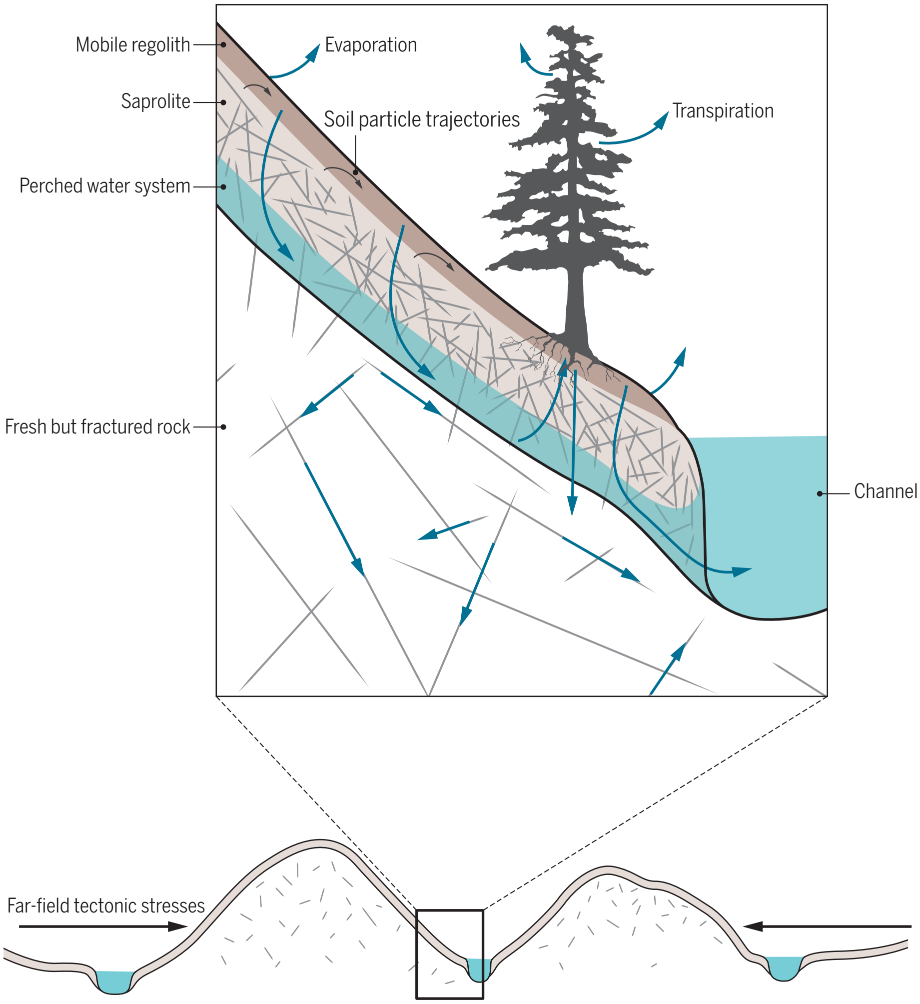
Consider a hillslope bounded by stream channels (see the figure). Rock is released as transportable particles into the soil on its surface, which then carries the particles through physical and biological transport processes to streams. Water, by contrast, is poured onto the landscape from above, either as rain or as snowmelt, with chemistry that is effectively distilled through evaporation from its source. The water travels downward through the soil, and through rock fractures that ultimately deliver it to the stream. As the water travels, interaction with the minerals of the soil and rock, catalyzed by biological interactions, both changes the strength, porosity, and permeability of the rock, and charges the water with ions that constitute the nutrient supply for plants. The generation of porosity transforms the rock into a substrate capable of sustaining an ecosystem, which in turn, through the action of roots, aids in the breakdown of rock (*2, 3*). These two trajectories, of rock particles and of water molecules, tangle in the critical zone, where their manifold interactions are indeed critical to life—hence the "critical zone."

The most difficult of these processes to document are those that herald the arrival of rock into the surface environment and initiate its transformation from unweathered fresh rock. Any debate about the relative importance of processes tied to the surface, and those initiated at much greater depths (*6*), in promoting the transformation of fresh rock must ultimately be informed by field data.

Institute for Arctic and Alpine Research, University of Colorado, Boulder, CO 80303-0450, USA. E-mail: robert.s.anderson@colorado.edu

Seismic refraction and electrical resistivity methods, often used in deep crustal studies, are seeing greater use in shallow settings (*7, 8*). St. Clair *et al.* undertook a campaign-style geophysical characterization of the subsurface across ridge-channel pairs in multiple landscapes. They leveraged the geologic and climatic diversity of accessible, well-studied sites within the U.S. Critical Zone Observatory network. Using sites in the humid eastern United States and in the Rockies of the arid western United States, the team found surprisingly different patterns of seismic velocities across the ridge-slope-channel transects. In some sites, low seismic velocities, interpreted as high density of cracks in the subsurface, were confined to a thin surface-parallel layer. In others, the zone of low-velocity, cracked rock extends more deeply beneath the ridges than below the stream chan-

The critical zone



The critical zone. Transformation of fresh rock into soil involves cracking of the rock and chemical attack of its minerals. Coevolution of the permeability of the rock mass, the pattern of water flow (blue arrows), and the ecosystem constitute a complex system that varies in time and location as a result of rock type and climate. St. Clair *et al.* argue that the pattern of cracking of the rock as it nears the surface also depends on topographic stresses, reflecting the interplay between the topography itself and the far-field stresses that pinch the topography (arrows).

ILLUSTRATION: P. HUEY/*SCIENCE*

nels, generating a "bowtie" image. These very different patterns of deep critical zone structure are not easily explained with climate. The authors used a numerical model of the state of stress in an elastic rock mass into which a landscape has been carved (*9*) to calculate the pattern of expected cracking of the rock. The topographic stresses arise from both the topography itself, and the far-field horizontal stresses imposed by the tectonic setting (arrows in figure) constrained by an existing world map of stresses. As the far-field stresses are increased, the pattern of expected cracking morphs from the surface-parallel to bowtie patterns, capturing both end-members of the observed seismic images. This is indeed an encouraging result.

Are we to believe their results? In many mountain ranges, the rock arriving in the near-surface zone is already riddled with flaws that have accumulated as it moved through the tectonic stress fields of present and past orogenies (*10*). To what degree does the presence of such preexisting flaws violate the assumption that the rock behaves as a uniform elastic medium? How well does the present state of stress reflect the long-term history of stress to which a rock has been subjected? One can also imagine situations in which other processes that generate near-surface cracks [for example, frost-cracking (*11*)], or that chemically weather the rock as it nears the surface (*12*), are instead the rate-limiting steps in damaging the rock.

Whatever the answers, the results reported by St. Clair *et al.* will challenge the broader community to entertain a role for the state of stress imposed by the topography itself and its tectonic setting. They have also demonstrated the utility of classical geophysical methods and of a network of sites to test their ideas. ■

REFERENCES

1. S. P. Anderson, F. von Blanckenburg, A. F. White, *Elements* **3**, 315 (2007).
2. D. deB. Richter, S. A. Billings, *New Phytol.* **206**, 900 (2015).
3. R. C. Graham, A. M. Rossi, K. R. Hubbert, *GSA Today* **20**, 4 (2010).
4. D. T. Milodowski, S. M. Mudd, E. T. A. Mitchard, *Ecology* **96**, 31 (2015).
5. J. St. Clair *et al.*, *Science* **350**, 534 (2015).
6. D. M. Rempe, W. E. Dietrich, *Proc. Natl. Acad. Sci. U.S.A.* **111**, 6576 (2014).
7. A. D. Parsekian, K. Singha, B. J. Minsley, W. S. Holbrook, L. Slater, *Rev. Geophys.* **53**, 1 (2015).
8. K. M. Befus, A. F. Sheehan, M. Leopold, S. P. Anderson, R. S. Anderson, *Vadose Zone J.* **10**, 1342, (2011).
9. M. Slim, J. Taylor Perron, S. J. Martel, K. Singha, *Earth Surf. Process. Landf.* **40**, 512 (2015).
10. P. Molnar, R. S. Anderson, S. P. Anderson, *J. Geophys. Res.* **112**, F03014, (2007).
11. R. S. Anderson, S. P. Anderson, G. E. Tucker, *Earth Surf. Process. Landf.* **38**, 299 (2013).
12. M. I. Lebedeva, S. L. Brantley, *Earth Surf. Process. Landf.* **38**, 1793 (2013).

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MICROBIOME

A unified initiative to harness Earth's microbiomes

Transition from description to causality and engineering

By **A. P. Alivisatos,* M. J. Blaser, E. L. Brodie, M. Chun, J. L. Dangl, T. J. Donohue, P. C. Dorrestein, J. A. Gilbert, J. L. Green, J. K. Jansson, R. Knight, M. E. Maxon, M. J. McFall-Ngai, J. F. Miller,† K. S. Pollard, E. G. Ruby, S. A. Taha, Unified Microbiome Initiative Consortium**

POLICY

Despite their centrality to life on Earth, we know little about how microbes (*1*) interact with each other, their hosts, or their environment. Although DNA sequencing technologies have enabled a new view of the ubiquity and diversity of microorganisms, this has mainly yielded snapshots that shed limited light on microbial functions or community dynamics. Given that nearly every habitat and organism hosts a diverse constellation of microorganisms—its "microbiome"—such knowledge could transform our understanding of the world and launch innovations in agriculture, energy, health, the environment, and more (see the photo). We propose an interdisciplinary Unified Microbiome Initiative (UMI) to discover and advance tools to understand and harness the capabilities of Earth's microbial ecosystems. The impacts of oceans and soil microbes on atmospheric CO_2 are critical for understanding climate change (*2*). By manipulating interactions at the root-soil-microbe interface, we may reduce agricultural pesticide, fertilizer, and water use enrich marginal land and rehabilitate degraded soils. Microbes can degrade plant cell walls (for biofuels), and synthesize myriad small molecules for new bioproducts, including antibiotics (*3*). Restoring normal human microbial ecosystems can save lives [e.g., fecal microbiome transplantation for *Clostridium difficile* infections (*4*)]. Rational management of microbial communities in and around us has implications for asthma, diabetes, obesity, infectious diseases, psychiatric illnesses, and other afflictions (*5*, *6*). The human microbiome is a target and a source for new drugs (*7*) and an essential tool for precision medicine (*8*).

The National Science Foundation's Microbial Observatories, the U.S. Department of Energy's Genomic Sciences program, the National Institutes of Health's Human Microbiome Project, and other efforts in the United States and abroad have served as critical first steps in revealing the diversity of microbes and their communities. However, we lack many tools required to advance beyond descriptive approaches to studies that enable a mechanistic, predictive, and actionable understanding of global microbiome processes. Developing these tools requires new collaborations between physical, life, and biomedical sciences; engineering; and other disciplines.

AREAS OF EMPHASIS. A central purpose of the UMI is to develop cross-cutting platform technologies to accelerate basic discovery and translation to applications. We highlight key needs and opportunities.

Decrypting microbial genes and chemistries. Approaches for characterizing microbiomes increasingly rely on whole-community metagenomic sequencing, yet roughly half of the genes identified in these studies encode products of unknown function, and existing functional annotations are often incomplete or inaccurate (*9*). Technologies for resolving roles of uncharacterized genes with high throughput and high accuracy are needed. These approaches must integrate improved computational methods for in silico prediction of protein and RNA functions, rapid mutagenesis of model organisms or native strains under natural conditions, multi-omics and high-resolution phenotyping platforms to test functional predictions in vitro and in situ, and improved capture of information in the literature.

"we envision...evidence-based, model-informed microbiome management..."

Deciphering chemistries of microbiomes is essential. In untargeted metabolomics studies using mass spectrometry, less than 2% of data can be matched to known chemical compounds, and only a fraction of those map to recognized biochemical pathways (*10*). Advances have been made in predicting structures from mass spectra, but improvements are needed in both in silico and physical

*See the supplementary materials for authors' affiliations.
†Corresponding author. E-mail: jfmiller@ucla.edu