Breaking it Down: Mechanical Processes in the Weathering Engine

Suzanne Prestrud Anderson[1]

Title image Gneiss bedrock is riven with pervasive fractures in a cliff exposure on Skyscraper peak, Front Range (Colorado, USA). Fracture density increases near the cliff top, a manifestation of near-surface mechanical weathering. PHOTO: SP ANDERSON

ABSTRACT

The vast diversity of landscapes found on Earth results from interplay between processes that break rock down, produce mobile regolith, and transport materials away. Mechanical weathering is fundamental to shaping landscapes, yet it is perhaps less understood at a mechanistic level than chemical weathering. Ubiquitous microfractures in rock propagate and grow through a slow process known as

---

[1] INSTAAR and Dept of Geological Sciences
University of Colorado
Boulder, CO 80309, USA
E-mail: Suzanne.Anderson@colorado.edu

Elements, (2019) Vol. 15, pp. 247-252

subcritical cracking that operates at the low applied stresses common in the near-surface. Subcritical cracking is the most likely explanation for the mechanical processes associated with thermal stress, ice lens growth, mineral alteration, and root growth. The long timescales over which critical zone architectures develop require an understanding of slow processes, such as subcritical cracking.

KEYWORDS mechanical weathering, erosion, subcritical cracking, microcracks, thermal stress, roots, frost cracking, biotite expansion

INTRODUCTION

Earth's habitable surface environments are shaped by weathering and erosion, processes that renew and evolve the surface. Sitting at the interface between the rocky interior and the moist atmosphere, Earth's surface owes its character to the dynamism between the mantle and the atmosphere: tectonics builds topography, while solar radiation–driven water cycling tears it apart. These twin energy inputs provide the impetus for the weathering and erosion processes that produce sediments, sculpt landscapes, and affect geochemical cycling, most notably of carbon between lithosphere, biosphere, and atmosphere (see Kasting 2019 this issue). Weathering and erosion processes are intertwined, each reinforcing the other. This article will disentangle weathering and erosion, and delve into a new understanding of the mechanical weathering processes that break rocks down.

Earth's surface is littered with the products of the breakdown of its rocky interior, in everything from blocks in talus to the muds of marine sediments. Mechanical disaggregation of rock promotes chemical weathering by increasing the surface area available for reactions, and promotes erosion by generating particles that can be easily moved. Furthermore, removing material (erosion) uncovers less weathered material, effectively introducing fresh rock into the reactive environment of Earth's surface (see Frings 2019 this issue; Porder 2019 this issue). In this way, we can think of the surface as a "weathering engine", in which crustal rock is carried into the surface reactor and so used to sustain living organisms and geochemical cycles.

How does this process of removal and erosion begin? Globally, total denudation rates are composed of about 80% solid sediment fluxes and about 20% dissolved fluxes (Summerfield and Hulton 1994), implying that most erosion results from physical sediment transport processes. This is why mechanical disintegration has long been viewed as the starting point of erosion. Noted American geologist Grove K.

Gilbert observed that “All indurated rocks and most earths are bound together by a force of cohesion which must be overcome before they can be divided and removed” (Gilbert 1877). After carefully defining erosion, the concept of subcritical cracking, as advocated by Eppes and Keanini (2017), will be introduced as a new way to understand mechanical weathering in surface weathering environments. A familiar list of mechanical weathering processes enumerates ways to generate applied stresses: thermal expansion, crystal growth (either salt or ice), mineral volumetric expansion, root growth, or topographic stress (Gilbert 1877; Merrill 1897; Anderson and Anderson 2010). While the list of stressors has not changed much over the last century, the concept of subcritical cracking improves our understanding of the conditions under which these stressors act. Consequently, our understanding of weathering processes has grown in sophistication.

THE CRITICAL ZONE: WEATHERING, TRANSPORTATION, AND EROSION

Weathering and erosion occur in the *critical zone* (FIG**.** 1), which is the permeable layer of Earth’ surface, where bedrock is affected by water, air and life and where ecosystems are supported (Riebe et al. 2017). Weathered materials in the critical zone are what make up the regolith and can include in-place weathered material in the form of weathered rock or the more degraded saprolite, depending on degree of alteration. A layer of disarticulated and transported material, called “mobile regolith”, may overlie weathered rock. Soil horizons may form within mobile regolith and saprolite.

Consider a vertical column through regolith on a hillslope (FIG. 1). Ignoring tectonic or isostatic movements, the ground surface lowers (*erosion* occurs) by thinning the mobile regolith layer (of thickness h_{mr}). Lowering may occur via mass losses in solution, but, judging from river material loads, more commonly lowering results from losses of solid material by physical transport processes (Summerfield and Hulton 1994). Only two fluxes involve transport of solid material: (1) sediment flux in the mobile regolith (Q_{solid}); (2) the flux or advection associated with the transformation of weathered rock into mobile regolith, designated the “production” of mobile regolith (P_{mr}). Thinning of the mobile regolith layer (expressed as negative mobile regolith thickness change rate; $\partial h_{\mathrm{mr}}/\partial t < 0$) occurs when the solid flux out of the column exceeds the combined influxes of solid material from upslope and from mobile regolith production:

$$\frac{\partial h_{\mathrm{mr}}}{\partial t} = \frac{\rho_{\mathrm{sap}}}{\rho_{\mathrm{mr}}} P_{\mathrm{mr}} - \frac{1}{\rho_{\mathrm{mr}}} \left(\frac{dQ_{\mathrm{solid}}}{dx} \right) \tag{1}$$

where ρ_{mr} and ρ_{sap} are bulk density of mobile regolith and saprolite, respectively, and *x* is the distance downslope.

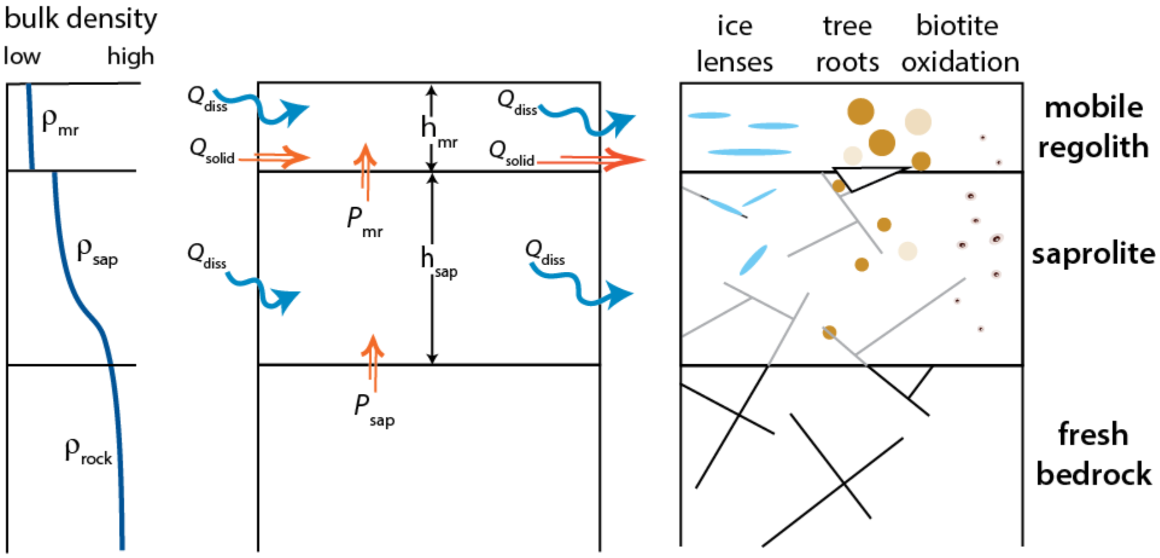

FIGURE 1 The critical zone includes the regolith, consisting of altered but in-place weathered rock, and saprolite (lumped as saprolite, subscript "sap"), and disaggregated material released from rock into mobile regolith (subscript "mr"). **LEFT PANEL** A profile of bulk density (ρ) of mobile regolith, saprolite, and fresh bedrock (subscript "rock"). **MIDDLE PANEL** The layer thicknesses (*h*), and fluxes that affect the thickness and density of regolith layers. A hillslope gradient down to the right (*x*-direction) is implied. The fluxes in question are production rates (*P*), which describe incorporation of material into a layer from below, and mass fluxes (*Q*) of dissolved solutes ("diss") and mobile regolith ("solid"). **RIGHT PANEL** Some possible agents of mechanical weathering: ice lenses, tree roots, and biotite oxidation.

Erosion is not the movement of sediment (Q_{solid}) itself, whether by transport processes such as soil creep, frost creep, tree throw, or landsliding. Rather, erosion is a result of greater mass losses than mass inputs in a column. Mathematically, erosion occurs when $\partial h_{\mathrm{mr}}/\partial t < 0$. Deposition or mobile regolith thickening, $\partial h_{\mathrm{mr}}/\partial t > 0$, is another possible net outcome when the solid flux into the column (from upslope and mobile regolith production) exceeds the solid flux out.

Fluxes of solid material (Q_{solid}) are limited to the mobile regolith layer and define it. Fluxes of water and of dissolved solutes (Q_{diss}) from chemical weathering occur throughout the critical zone. The chemical and mechanical weathering reactions throughout the critical zone alter rock properties such as strength, porosity, and hydraulic conductivity. These material property changes probably affect the mobile regolith production rate (P_{mr}), and so may affect erosion (negative $\partial h_{\mathrm{mr}}/\partial t$) indirectly. Of the fluxes involved in erosion, mobile regolith production (P_{mr}) is the least well understood. We lack a mechanistic theory for this important process. It is likely that P_{mr} is controlled by multiple processes, including processes that (a) weaken rock by mechanical and chemical weathering, and processes that (b) mobilize the weakened material by sediment transport.

SUBCRITICAL VS. CRITICAL CRACKING: A NEW APPROACH TO MECHANICAL WEATHERING

Mechanical weathering breaks rock, a process commonly understood to occur when applied stress (force per unit area) exceeds material strength (the stress at which failure—breakage—occurs). If you hit a rock with a hammer with sufficient force, the rock breaks or shatters. This is *critical cracking*, a process in which fractures grow so rapidly that the result is catastrophic failure. But consider a fractured outcrop or cliff. No hammer blows have been applied, yet pervasive fractures are present, often with closer spacing near the cliff top. This implies that these fractures form preferentially near the surface. In weathering, the less familiar process of *subcritical cracking* is important (Eppes and Keanini 2017).

In subcritical cracking, rock fractures propagate slowly at low, subcritical stresses. Crack extension rates of $\mathrm{m \cdot s^{-1}}$ to $\mathrm{nm \cdot s^{-1}}$ or lower are considered slow (Lawn 1993) and can occur at applied stresses much lower than the critical values at which catastrophic crack growth occurs (FIG. 2). In materials with preexisting flaws, subcritical cracking may occur because the effects of external applied stresses are amplified at the tips of cracks—precisely the location where bonds must be broken. Microscopic cracks, or microcracks, are found in all rocks (Anders et al. 2014). Microcracks are long (on the order of 100 μm or less) relative to their apertures, and are present within grains, between grains, and at grain boundaries. Given the ubiquity of microcracks, rock mechanics focuses more on crack propagation than on crack initiation.

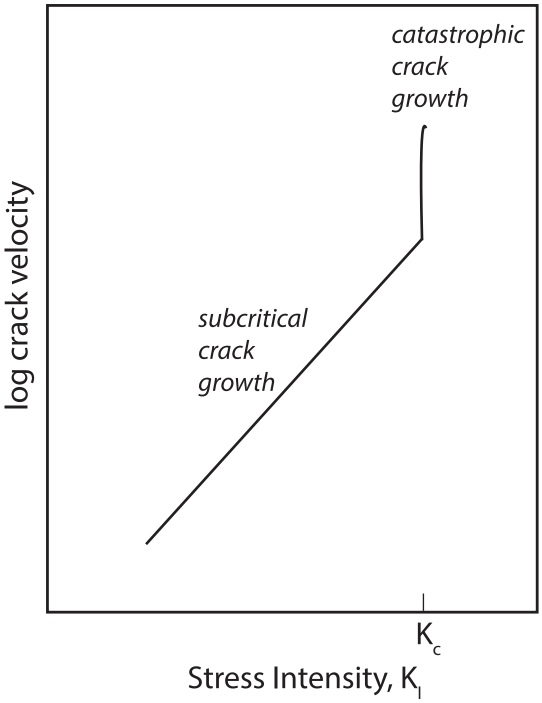

FIGURE 2 Schematic plot of crack growth velocity versus the crack driving force (stress intensity, K_I) for rocks. Above a lower limit for subcritical cracking, crack growth rate (velocity) increases with stress intensity. When K_I exceeds the critical stress, K_c, the crack grows catastrophically, and critical cracking occurs.

Theoretically, microcracks are treated as traction-free planar slits. A nonuniform stress field, described by linear elastic theory, develops around a crack in a rock mass subjected to an external applied stress. A key descriptor is the *stress intensity factor*, K_I, which is the magnitude or amplification of the stress field around a crack tip. The stress intensity factor expresses the driving force for crack growth. For a simple opening (tensile, or Mode I) fracture (i.e., the mode expected in near-surface weathering environments), K_I takes the form:

$$K_I = \sigma\sqrt{\pi a} \qquad (2)$$

where σ is the external applied stress (load) and a is the crack half-length (Atkinson 1987). Note that because K_I depends on crack length, the stress intensity factor increases as a crack grows under a fixed external stress (σ). Effectively, the material weakens as fractures lengthen (Anders et al. 2014) because the same external stress produces a much greater local stress at the crack tip.

The critical stress intensity factor, K_c, at which rock fails catastrophically, defines the fracture toughness. Subcritical cracking is the noncatastrophic fracture growth that occurs when $K_I < K_c$ (FIG. 2). Low stress intensities of around 0.1 K_c may constitute a lower limit for subcritical cracking, although whether there is a lower limit is debatable (Atkinson 1987).

Environmental Effects on Subcritical Fracture Propagation

Subcritical cracking is extremely sensitive to the magnitude of the stress at the crack tip and to environmental conditions, such as temperature or the presence of water and its chemistry (Lawn 1993; Atkinson 1987). At the atomic scale, the mechanical process of fracture propagation is facilitated by chemical reactions at the stressed crack tip because fracture propagation proceeds by breaking chemical bonds. The reaction is facilitated by water in fractures, an effect called *stress corrosion*. Consider a crack in silica glass (FIG. 3) as a model system. The siloxane –Si–O–Si– bonds at the crack tip are stretched due to the enhanced stress around the crack tip. Water molecules within the fracture preferentially react with the stressed part of the lattice via a dissociative reaction

$$(\mathrm{H{-}O{-}H}) + (\mathrm{{-}Si{-}O{-}Si{-}}) \rightarrow (\mathrm{{-}Si{-}OH \cdot OH{-}Si{-}})$$

The reaction breaks one of the bonds in the siloxane sheet, forming terminating hydroxyl groups and extending the fracture. As the fracture lengthens (slowly), the stress intensity at the fracture tip increases, providing a positive feedback on fracture propagation.

The reaction is thought to progress through three stages (Lawn 1993). First, adsorption of water on the siloxane surface, with the water molecule H-bonding to the siloxane O, and the water lone-pair orbitals attracted to the siloxane Si. Second, reaction of the stretched siloxane bonds with the adsorbed water molecule. The water molecule donates an electron to Si and a proton to the linking siloxane O, forming two new O–H bonds. Third, separation, impelled by repulsive forces between the hydroxyl groups.

Water can, therefore, directly affect mechanical subcritical fracture propagation rates, an observation that implies an environmental—in fact, climatic—control on mechanical weathering rates (Eppes and Keanini 2017). Stress corrosion is the most likely mechanism driving subcritical cracking in superficial levels of the crust (Atkinson 1987). Over the long residence time of rock in the critical zone (10^4–10^6 y), relatively small external stresses are, therefore, sufficient to slowly break rock, modulated by climatic parameters that include temperature and water.

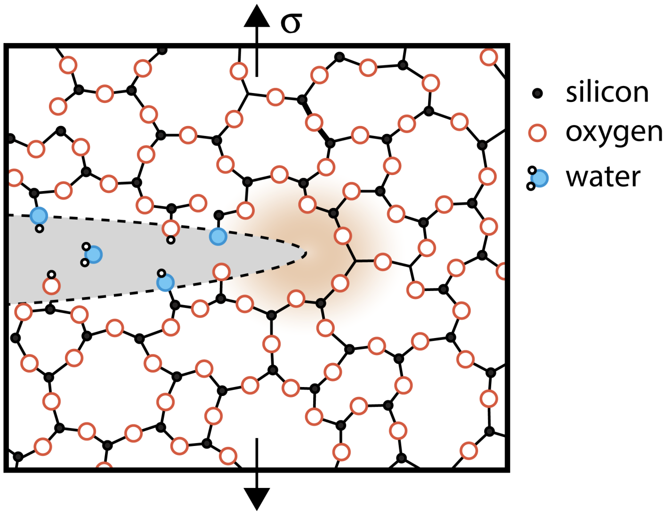

FIGURE 3 Representation of water-promoted crack propagation in silica glass that is being subjected to an applied tensile stress (σ). The dissociative reaction between water in the crack (gray shading) and a siloxane bridging bond is favored where the –Si–O–Si– bonds are stressed around the crack tip. Pink shading represents the distribution of high stress intensity at the crack tip. BASED ON LAWN (1993).

MECHANICAL WEATHERING PROCESSES

The concept of subcritical cracking elevates the importance of modest, but persistent, stresses that are either steadily or frequently applied on the rock to ultimately produce rock breakdown (Eppes and Keanini 2017). Local stress intensification around crack tips can drive slow subcritical cracking under a wider range of conditions than those predicted from a traditional critical stress–strength analysis. Accordingly, the conditions under which subcritical cracking may occur, as well as its potential contribution to rapid failures, must be accounted for.

A dramatic example of this principle occurred during the unusually hot summer in 2014. During August, there were several brief periods of explosive exfoliation fracture propagation on a granite dome at Twain Harte (California, USA), and some were captured on video (FIG. 4). Detailed investigations in the aftermath revealed that these spontaneous exfoliation events ruptured bridges of fresh rock between existing macrofractures (Collins et al. 2018). Topographic stress combined with cumulative damage by thermal subcritical stresses, as revealed by monitoring, preceded the apparent "spontaneous" rock burst (or spalling) events.

FIGURE 4 Spontaneous exfoliation event at Twain Harte (California, USA) in August 2014. Note rock fragments flying into the air. Dust traces the edge of the exfoliation sheet. Image from a video available as a supplement to Collins et al. (2018), covered by a Creative Commons license: http://creativecommons.org/licenses/by/4.0/.

Thermal Stresses

Heating and cooling have long been recognized as a cause of expansion and contraction of minerals and rocks, such that "each and every constituent … crowds against its neighbor" (Merrill 1897). Writing over a century ago, Merrill reports measurements of thermal expansion coefficients for granite, marble, and sandstone made more than sixty years before him. Thermal expansion coefficients (α, the fractional change in volume with temperature) are on the order of $1\text{–}10 \times 10^{-6}$ °C^{-1}. However, values vary between minerals, and often display anisotropy (Anderson and Anderson 2010). Of the common rock-forming minerals, quartz has the highest α values, whereas calcium feldspars are among the lowest. In calcite, as an extreme example, α differs in sign with crystallographic axis. The magnitude of thermally induced stresses from temperature gradients and mineralogical differences increases with crystal size and may explain the propensity of coarse crystalline rocks to weather by surficial granular disintegration.

Extreme thermal stresses are one of the rare mechanisms of critical stress fracture (i.e., rapid and catastrophic) in rock. Fire spall (breaking off of rock fragments) energetically removes centimeter-scale slabs from exposed rock surfaces (Shakesby and Doerr 2006; Kendrick et al. 2016) and can affect tens of percent of exposed rock surfaces in a single fire (FIG. 5). While highly localized, lightning strikes can produce outsized effects by instantaneous expansion and heating of air by up to 30,000 °C (Knight and Grab 2013). These large, but brief, temperature perturbations induce steep gradients in volumetric strain, producing the stress needed to spall off flakes.

FIGURE 5 Abundance of spall scars on an outcrop surface seen in the immediate aftermath of the September 2010 Fourmile Canyon Fire, near Boulder, Colorado, USA. The rock surface is fire blackened except where centimeter-thick flakes have spalled by thermally driven critical cracking. The rock debris that was generated is scattered around the base of the outcrop. PHOTO: SP ANDERSON

In contrast, heating from insolation on rock surfaces activates the less dramatic process of subcritical cracking. Eppes et al. (2016) used acoustic emissions and net strain to detect insolation-driven microcrack growth in boulders. Insolation-induced subcritical cracking is slow, but occurs at high frequency over the residence time of rock within ~0.15 m of the surface, where daily insolation-driven temperature swings are significant. The ubiquity of solar-driven heating on rock surfaces elevates this to a major driver of near-surface weathering.

Frost Cracking

Rocks crack under moist freezing conditions through the open-system process of frost cracking (Hallet et al. 1991). Rather than volumetric expansion from the phase change, frost cracking occurs due to growth of ice lenses within rock, fed by water migrating at subzero °C temperatures. Water moves in unfrozen films on fracture surfaces and along thin "premelted" films on ice (Rempel et al. 2016), even under considerable confining stresses (Radd and Oertle 1973). Increasing pressure from the growing ice lenses drive subcritical cracking of the surrounding rock. Steady cold conditions rather than freeze–thaw cycles are conducive to frost cracking. Laboratory experiments revealed propagation of microfractures in rock, detected by numerous acoustic events, under steady subfreezing temperatures (Hallet et al. 1991). Ice lens growth and frost cracking is favored by temperatures sustained in the range −3 °C to −8 °C (the so-called "frost cracking window"), a range in which both thin, unfrozen water films on mineral and ice surfaces, and ice bodies in large pores are thermodynamically stable. At lower temperatures, the water films are too thin and too viscous to support sufficient water migration.

A consequence of water flow through thin films as a driver of frost cracking is that stable or slowly changing thermal environments, rather than rapid temperature oscillations, favor the process (Rempel et al. 2016). Conditions that maximize the time in the frost-cracking temperature window are optimal (Anderson et al. 2013). Although subzero mean annual temperatures are not a requirement for frost cracking, lower mean annual temperatures extend the process to greater depths (FIG. 6). Climate history, therefore, matters. Marshall et al. (2015) showed >90% of the Oregon Coast Range landscapes were influenced by Quaternary frost cracking processes, despite the lack of glaciation or permafrost.

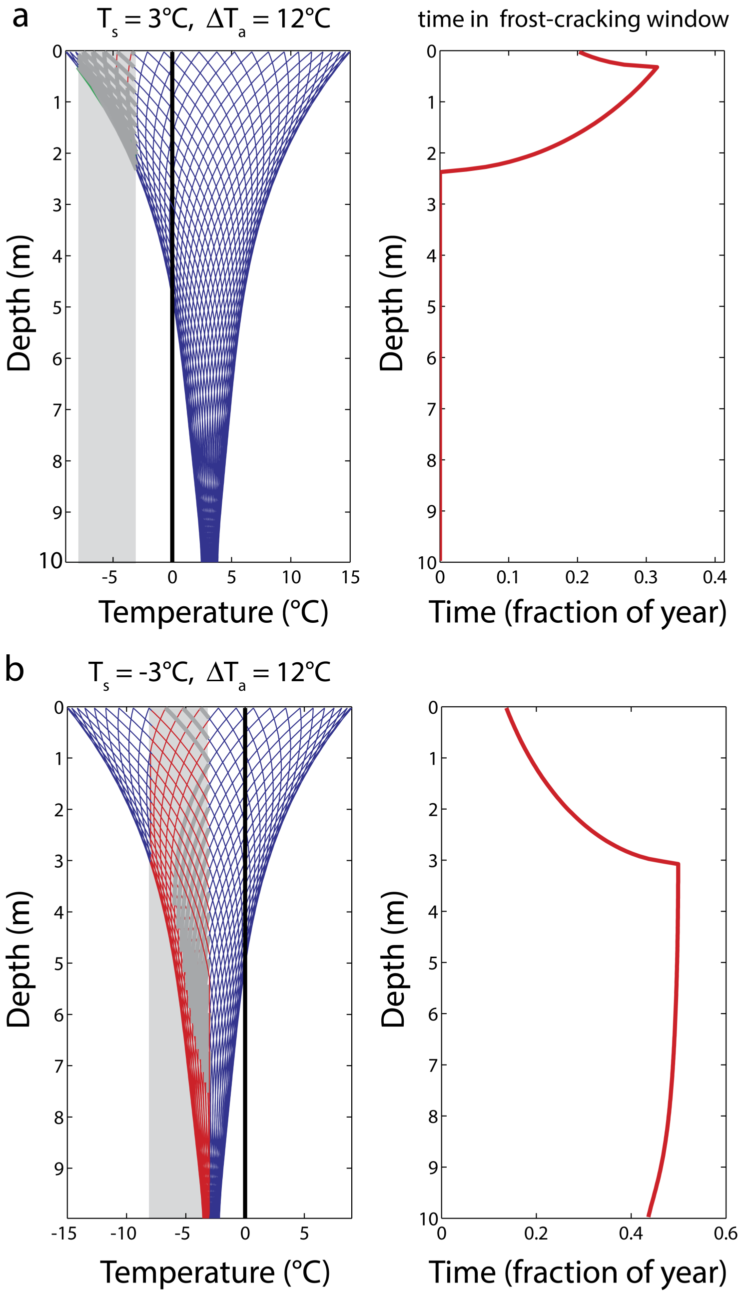

FIGURE 6 Modeled profiles of subsurface temperature (left panels) and of integrated time in the frost cracking window (−3 °C to −8 °C) (right panels). (**A**) Modeled profiles for mean annual temperature of 3 °C. (**B**) Modeled profiles for mean annual temperature of −3 °C. In both models, surface temperatures vary sinusoidally, with an amplitude of 12 °C. Gray shading highlights the frost-cracking temperature window; portions of weekly temperature profiles in the frost-cracking window are colored red. BASED ON ANDERSON ET AL. (2013)

Mineral Volumetric Expansion

Physical expansion of minerals during chemical weathering has been fingered as significant in disintegrating rock. Many studies (e.g., Isherwood and Street 1976) suggest that hydration of biotite to vermiculite is the cause of rock breakdown. More recently, Buss et al. (2008) and Goodfellow et al. (2016) found that the initial weathering reaction in biotite involves oxidation of Fe(II), as observed with synchrotron X-ray fluorescence maps of samples. This alteration precedes detectable alteration of other minerals in the rock, and is accompanied by expansion of ~5% in biotite (001) basal plane separation (Buss et al. 2008). While the oxidation step produces only modest chemical alteration, it is significant because the physical change leads to accumulation of strain energy that generates microfractures. This initial mechanical alteration leads to greater porosity, water flow, and further chemical weathering processes that ultimately transform the rock into pervasively altered soft saprolite. Goodfellow et al. (2016) consider biotite oxidation the "profile controlling reaction", due to its mechanical effects.

Biomechanical Processes

Roots of trees may provide another means of exerting stresses at depth within the critical zone. Relatively little attention has been paid to the biomechanical work of tree roots within rock. Trees as weathering agents, particularly as mechanical actors, present a frontier (Brantley et al. 2017). Tree roots anchor plants, transport water and nutrients both up and down, and support biogeochemical activities of the plant. Their roles in soil transport, both as an agent of transport and as a stabilizing source of soil cohesion, and in soil production are well explored (Pawlik et al. 2016). An open question, however, is whether roots are capable of breaking rocks (FIG. 7).

Data on tree roots in rock is hard to collect, so datasets are few. An 18-year study of *Thuja occidentalis* (eastern white cedar) on the limestone cliffs of the Niagara

Escarpment (Ontario, Canada) found that seedling survival over an 18-year period was highest in the rocky crevice and narrow ledge sites (Matthes and Larson 2006). Most of the trees grew in locations without soil, favoring rock fissures, especially those in weathered rock. Although the root:shoot biomass ratio was normal (about 0.48), rooting depths were shallow (average 9 cm, maximum 30 cm). Hasenmueller et al. (2017) examined roots in soil and saprolite developed on shale bedrock in excavations up to 1.8 m deep. Although most abundant in the mobile regolith, roots were present at all depths. Root density correlated with volume concentration of fractures in the rock, suggesting that void space limited root growth. Hasenmueller et al. (2017) found no definitive evidence that the roots had created the fractures in which they grow; Matthes and Larson (2006) did not address the question.

Figure 7 Road cut exposure showing the roots of a Ponderosa Pine growing in granodiorite bedrock in Colorado (USA). Photo: SP Anderson

From a mechanical perspective, it seems unlikely that roots can break rock. Roots generate radial pressures from 0.51–0.9 MPa, while the tensile strength of rock ranges from 1–25 MPa (Pawlik et al. 2016). However, as emphasized herein, subcritical cracking occurs at stresses as low as one-tenth of the tensile strength of rock (Eppes and Keanini 2017). Over the decades-to-centuries of the growth of individual trees, subcritical cracking coupled with the undisputed geochemical interactions of the root rhizosphere may, indeed, promote rock fracture.

SMALL STRESSES, SLOW PROCESSES, BIG RESULTS

Chinese philosopher Lao-Tzu wrote that "nature does not hurry, but accomplishes everything", an observation that captures the essence of the imperceptible but inevitable breakdown of rock at Earth's surface. The stresses from processes such as the slow growth of an ice lens or the even slower growth of a tree root, solar warming of rock surfaces, or the oxidation of a biotite grain are insufficient to cause catastrophic rock fracture. Yet these small but pervasive stresses can, nonetheless, provide enough impetus for subcritical cracking. Eppes and Keanini (2017) highlight that hydroclimate control on mechanical weathering is implied because of the importance of the reaction of water with the siloxane microcrack walls in breaking the bonds to propagate cracks.

Subcritical cracking proceeds slowly, in contrast to the rapid and catastrophic failure of critical cracking. Yet time is generally not a limitation in weathering systems. Total denudation rates are low enough that rock spends on the order of 10^5 years within a few meters of the surface, where these mechanical weathering processes operate. This time span means that modern critical zone profiles in many areas are shaped by Quaternary glacial climates (Marshall et al. 2015). The upper 0.1 m will experience on the order of 10^4 daily insolation cycles, and 10^2–10^3 generations of trees may extend their roots into bedrock. The changes in fracture density, porosity, and hydrologic connectivity produced by microcracking clearly influence subsequent chemical alteration (Goodfellow et al. 2016).

SUMMARY

The introduction of subcritical cracking processes into the weathering lexicon (Eppes and Keanini 2017) expands the applicability of mechanical weathering processes into a much broader set of weathering conditions because of the lowering of the stress intensity requirements for crack propagation. A clear frontier in critical zone science lies in documenting the roles of various stressing agents in damaging intact rock, transforming it into saprolite, and releasing it into the mobile regolith layer. The environmental factors of temperature and moisture availability, long appealed to as the drivers of most weathering processes, can now be seen afresh through the lens of subcritical crack growth. The long timescales over which we must integrate to generate critical zone architectures and drive geochemical cycles imply that we must know deeply the effects of the available weathering processes, including individual mechanical and chemical processes, as they change in rate and relative importance.

ACKNOWLEDGMENTS

I thank Missy Eppes, Brad Goodfellow, Patrick Frings, and John Eiler for thoughtful reviews that guided revisions and improved the text. This work was supported by the Boulder Creek Critical Zone Observatory (Colorado, USA) (NSF grant 1331828).

REFERENCES

Anders MH, Laubach SE, Scholz CH (2014) Microfractures: a review. Journal of Structural Geology 69: 377-394

Anderson RS, Anderson SP, Tucker GE (2013) Rock damage and regolith transport by frost: an example of climate modulation of the geomorphology of the critical zone. Earth Surface Processes and Landforms 38: 299-316

Anderson RS, Anderson SP (2010) Geomorphology: The Mechanics and Chemistry of Landscapes. Cambridge University Press, Cambridge, 651 pp

Atkinson BK (1987) Fracture Mechanics of Rock. Academic Press, London, 534 pp

Brantley SL and 12 coauthors (2017) Reviews and syntheses: on the roles trees play in building and plumbing the critical zone. Biogeosciences 14: 5115-5142

Buss HL, Sak PB, Webb SM, Brantley SL (2008) Weathering of the Rio Blanco quartz diorite, Luquillo Mountains, Puerto Rico: coupling oxidation, dissolution, and fracturing. Geochimica et Cosmochimica Acta 72: 4488-4507

Collins BD and 5 coauthors (2018) Thermal influences on spontaneous rock dome exfoliation. Nature Communications 9, doi: 10.1038/s41467-017-02778-1

Dixon JL, Heimsath AM, Amundson R (2009) The critical role of climate and saprolite weathering in landscape evolution. Earth Surface Processes and Landforms 34: 1507-1521

Eppes M-C, Keanini R (2017) Mechanical weathering and rock erosion by climate-dependent subcritical cracking. Reviews of Geophysics 55: 470-508

Eppes M-C and 6 coauthors (2016) Deciphering the role of solar-induced thermal stresses in rock weathering. Geological Society of America Bulletin 128: 1315-1338

Frings PJ (2019) Palaeoweathering: how do weathering rates vary with climate? Elements 15: XXX-XXX

Gilbert GK (1877) Report on the Geology of the Henry Mountains. Government Printing Office, Washington, DC, 160 pp

Goodfellow BW and 5 coauthors (2016) The chemical, mechanical, and hydrological evolution of weathering granitoid. Journal of Geophysical Research: Earth Surface 121: 1410-1435

Hallet B, Walder JS, Stubbs CW (1991) Weathering by segregation ice growth in microcracks at sustained subzero temperatures: verification from an experimental study using acoustic emissions. Permafrost and Periglacial Processes 2: 283-300

Hasenmueller EA and 8 coauthors (2017) Weathering of rock to regolith: the activity of deep roots in bedrock fractures. Geoderma 300: 11-31

Isherwood D, Street A (1976) Biotite-induced grussification of the Boulder Creek Granodiorite, Boulder County, Colorado. Geological Society of America Bulletin 87: 366-370

Kasting JF (2019) The Goldilocks planet? How silicate weathering maintains earth “just right”. Elements 15: XXX-XXX

Kendrick KJ, Partin CA, Graham RC (2016) Granitic boulder erosion caused by chaparral wildfire: implications for cosmogenic radionuclide dating of bedrock surfaces. Journal of Geology 124: 529-539

Knight J, Grab SW (2013) Lightning as a geomorphic agent on mountain summits: evidence from southern Africa. Geomorphology 204: 61-70

Lawn B (1993) Fracture of Brittle Solids. 2nd edition. Cambridge University Press, Cambridge, 378 pp

Marshall JA and 7 coauthors (2015) Frost for the trees: did climate increase erosion in unglaciated landscapes during the late Pleistocene? Science Advances 1, doi: 10.1126/sciadv.1500715

Matthes U, Larson DW (2006) Microsite and climatic controls of tree population dynamics: an 18-year study on cliffs. Journal of Ecology 94: 402-414

Merrill GP (1897) A Treatise on Rocks, Rock-weathering and Soils. The MacMillan Company, New York, 411 pp.

Pawlik Ł, Phillips JD, Šamonil P (2016) Roots, rock, and regolith: biomechanical and biochemical weathering by trees and its impact on hillslopes—a critical literature review. Earth-Science Reviews 159: 142-159

Porder S (2019) How plants enhance weathering and how weathering is important to plants. Elements 15: XXX-XXX

Radd FJ, Oertle DH (1973) Experimental pressure studies of frost-heave mechanisms and growth-fusion behavior of ice. In: 2nd International Conference on Permafrost, Yakutsk, USSR, July, 1973. National Academy Press, Washington, DC, pp377-384

Rempel AW, Marshall JA, Roering JJ (2016) Modeling relative frost weathering rates at geomorphic scales. Earth and Planetary Science Letters 453: 87-95

Riebe CS, Hahm WJ, Brantley SL (2017) Controls on deep critical zone architecture: a historical review and four testable hypotheses. Earth Surface Processes and Landforms 42: 128-156

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74: 269-307

Summerfield MA, Hulton NJ (1994) Natural controls of fluvial denudation rates in major world drainage basins. Journal of Geophysical Research: Solid Earth 99: 13871-13883