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The role of fieldwork in rock decay research: Case studies from the fringe

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ABSTRACT

Researchers exploring rock decay hail from chemistry, engineering, geography, geology, paleoclimatology, soil science, and other disciplines and use laboratory, microscopic, theoretical, and field-based strategies. We illustrate here how the tradition of fieldwork forms the core knowledge of rock decay and continues to build on the classic research of Blackwelder, Bryan, Gilbert, Jutson, King, Linton, Twidale, and von Humboldt. While development of nonfield-based investigation has contributed substantially to our understanding of processes, the wide range of environments, stone types, and climatic variability encountered raises issues of temporal and spatial scales too complex to fit into attempts at universal modeling. Although nonfield methods are immensely useful for understanding overarching processes, they can miss subtle differences in factors that ultimately shape rock surfaces. We, therefore, illustrate here how the tradition of fieldwork continues today alongside laboratory and computer-based investigations and contributes to our understanding of rock decay processes. This includes the contribution of fieldwork to the learning process of undergraduates, the calculation of activation energies of plagioclase and olivine dissolution, the high Arctic, the discovery of a new global carbon sink, the influence of plant roots, an analysis of the need for protocols, tafoni development, stone monuments, and rock coatings. These compiled vignettes argue that, despite revolutionary advances in instrumentation, rock decay research must remain firmly footed in the field.

1. Introduction

Scientists publishing papers on the decay of rocks hail from archeology, architecture, astrobiology, botany, chemistry, civil engineering, geochemistry, geography, geology, hydrology, microbiology, microscopy, pedagogy, soil science, stone conservation, and zoology. Methods employed include a host of strategies including bench geochemistry, computer modeling, culturing microorganisms, DNA analysis, geographic information science, light and electron microscopy, modeling through physical experiments, numerical modeling, various theoretical approaches, and different field methods.

The authors of this paper, like many other researchers, have training in multiple disciplines and often use different methodological strategies—following the warning of Yatsu (1988, p. 150) "that many geomorphologists ensconse themselves comfortably in authoritative positions, merely on the basis of their field observations without any vigilant attention to knowledge in other sciences." While we use different research approaches, we all advocate the position in this paper that fieldwork offers unique and vital insight into theory building in rock decay research. We do not contend that every field-derived concept has maintained its value over the years. For example, in his influential textbook, Merrill (1906: 293) writes about a *Personal Memoranda* with Israel C. Russell:

> Professor I.C. Russell, who has devoted much attention to the subject of rock-weathering in both high and low latitudes, is of the opinion that rock *decay* [italics in the original] is a direct result of existing climatic conditions. He states that decay goes on most rapidly in warm regions where there is an abundant rainfall, and it is scarcely at all manifest in arid and frigid regions. Professor

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> Russell's observations are of more than ordinary value, since he has discriminated between decay and disintegration, which most writers have failed to do (Merrill, 1906).

We are of the opinion that this oft-repeated perspective is wrong (Dixon et al., 1984; Thorn et al., 1989; Pope et al., 1995; Dixon and Thorn, 2005) and has slowed our understanding of rock decay in warm deserts, alpine, and Arctic/Antarctic settings. In general, however, fieldwork by pioneers in geomorphology has provided much of the core knowledge we pass on to the next generation. Simply evaluate a basic course in geomorphology. Many of the basic concepts and terms presented in Table 1 derive from fieldwork.

The purpose of this paper is to highlight the continued importance of fieldwork in the study of rock decay. We accomplish this through presenting a series of vignettes, each emphasizing that fieldwork remains indispensible.

2. Case studies

A vital and vibrant field of academic research must contain a number of elements. The case studies presented below exemplify why field research in rock decay rests in no danger of becoming the academic equivalent of ice stagnation topography. Top undergraduate students must find research in the field relevant and exciting (Section 2.1). Basic research must not adher to untenable paradigms, even as this research includes iconic locations such as Kärkevagge (2.2), Petra (2.3), or Yosemite Valley (2.4). Basic research must connect with the interests of the general public that supports research (2.5 and 2.3) and yet must continue to invigorate core concepts taught in introductory courses (2.8). The research must connect with the bigger issues of science, such as global climate change in the early 21st century (2.6 and 2.7). Research must also be able to identify forks in the roadways of investigation, when ongoing efforts require a new vision (2.9).

In each case study, we have avoided the term weathering. We advocate the conclusion of Hall et al. (2012, p. 9): "given the inadequacies entrenched within the term and the current explosion in techniques and data availability, we need a term that reflects the reality of what is happening more accurately. Our choice would be 'rock decay' evaluated with the notion of energy transfer as the basis for considering process." More than a century ago, Merrill's (1906) treatise distinguished between decay and disintegration. While we understand the reasons for this differentiation, we agree that rock decay connotes the broad intent of weathering researchers as well as the subject that we all study.

2.1. Building a Rock Decay Nerd, by Casey D. Allen, Kaelin M. Groom, Tyler J. Thompson, Niccole Cerveny

Yatsu's (1988: 505) seminal work on *The Nature of Weathering* concludes: "YOUNG STUDENTS FULL OF **ENTHUSIASM** AND ENERGY WILL PLAY THE MOST ACTIVE PART IN THIS FIELD (capitalization and bold in the original)." Thus, we start with a vignette that illustrates fieldwork's importance in educating the general population about our field and recruiting future geomorphologists with interests in rock decay. University-level introductory texts, while providing minimal treatment of rock decay, usually accompany explanations with especially beautiful yet very static and flat imagery. This portrayal does not sit well with today's students raised on three-dimensional IMAX movies, interactive motion-sensing video games, or visual displays on their smartphones. In fact, when it comes to geomorphology in general and rock decay specifically, without fieldwork, the learning landscape can be uninspiring and two-dimensional, plain, and boring. Fieldwork helps create interest in subject matter, principles, content, and concepts, while at the same time creating a rich landscape of possibilities and endless tracks of interest that drive the budding rock decay nerd[1] (RDN). Indeed, *seeing* that same textbook rock decay form *in situ* enhances the understanding of process(es) that helped create it. Take case hardening as an example, notoriously difficult-to-explain. Imagery and textual explanation, no matter how illustrative and spectacular (Dorn et al., 2012), cannot express the feel a budding RDN gets when they tap on a case-hardened rock and hear its hollowness, or actually see the rock being eaten (decayed) from the inside-out. With undergraduate fieldwork, the important rock decay forms and processes are suddenly and intimately realized.

Those who have experienced it know: students learn concepts better by *doing* fieldwork rather than sitting in the classroom—and research certainly backs up this claim (Kent et al., 1997; Warburton and Higgitt, 1997; Hudak, 2003; Ellis and Rindfleisch, 2006; Fuller et al., 2006). Recent studies demonstrate the power of combining fieldwork with rock decay specifically, to deepen understanding of its complex forms and processes (Allen, 2008, 2011; Allen and Lukinbeal, 2011; Allen et al., 2011); these studies also note gender, ethnicity, content interest level, and learning style as nonfactors when engaging students in fieldwork using rock decay as an interface.

In the classroom, however, unless the instructor is an RDN themselves, the importance of this most foundational (yet highly complex) concept is lost on students, as many relate it specifically to atmospheric phenomena ("weather"/"weathering") and sometimes confuse it with erosion (Dove, 1997). Even if the instructor *is* an RDN, incorporating field time into the (perhaps required) pedagogy is often tedious at best. Following this logic then, it seems that many potential RDNs might not be recognized or, perhaps worse, never be inspired because they never get to experience fieldwork. Instead, students are left to peer/parental pressures, job market demands, and career counseling sessions to help them find their passion, which very likely will *not* include geomorphology. A potential solution to this stagnation rests in exposing undergraduates to rock decay with hands-on applications and research via fieldwork.

One way to accomplish this lies in using the local landscape as an introductory study site. As rock decay is ubiquitous, using campus buildings, sidewalks, and even building interiors provides the promising RDN access to understanding the connections between forms and processes (Fig. 1). Whether as part of an introductory class or a more in-depth independent research project, these experiences serve as a primer to "hook" students on rock decay concepts and principles. Then, given more time—and maybe for an advanced course or as part of the instructor's research agenda—students extend their rock decay prowess to nonlocal and more specialized settings.

Building upon these premises in the past few years, up-and-coming undergraduate RDNs at University of Colorado Denver have studied rock decay locally, but also regionally and internationally in such locations as the Painted Desert, Grand Tetons, the Wasatch Front, London, Paris, and the Caribbean—making grander connections (Allen, 2011; Allen and Lukinbeal, 2011). If you are fortunate to have rock art, old buildings or even old cemeteries near your campus, visit this instructor's guide on how to teach about rock decay in introductory courses: http://alliance.la.asu.edu/rockart/NSF/RASI_InstructorsGuide.html. Certainly, catching the RDN early in their undergraduate career remains key, but infusing rock decay fieldwork into our pedagogy, and by extension their studies, will help solidify the nascent RDN mold and, eventually, allow the undergraduate to emerge as a full-grown, experienced, rock decay nerd, ready—and excited!—to work at the forefront of cutting-edge rock decay science that integrates fieldwork.

As each new generation of students come to our classrooms with increasingly high expectations for stimulating (not boring) educational experiences, fieldwork offers a unique venue to connect faculty

[1] According to the *Urban Dictionary*, the term *nerd* is actually an acronym for Never Ending Radical Dude. We ascribe to this definition and see being called a rock decay nerd as having earned our varves (stripes, as it were) in the discipline.

Table 1
Examples of fundamental rock decay concepts developed through fieldwork.

Concept	Explanation	Reference
Case hardening	Induration of the surface of rocks, especially siliceous sandstones, occurs through the accumulation of silica, carbonate, or iron oxides.	(Merrill, 1906)
Deep weathering	Most of the deeply weathered rock found in what are now deserts formed under more moist conditions, such as would be found in a tropical savanna setting today.	(Tricart and Cailleaux, 1965; Büdel, 1977)
Exfoliation	Although the use of this term was changed by later researchers, the intent of the original paper was to explain the origin of millimeter to centimeter-scale flaking of rock surfaces.	(Blackwelder, 1925)
Gnamma	The location of gnammas atop and aside granitic and sandstone bornhardts and slickrock outcrops indicates an initiation and development from a mix of environmental factors, petrology and structure.	(Twidale and Corbin, 1963)
Insolation hypothesis	High rock temperatures in warm deserts can generate fractures in rocks.	(Blackwelder, 1933)
Joint Density	The density of joints in granitic rocks plays a critical role in whether massive forms like bornhardts develop (low density) or smaller boulder forms such as tors (high density).	(King, 1948)
Pedestal rocks	Formation can occur through differential resistance to rainsplash of harder sandstone talus and the underlying weaker shale. Formation of pedestal rocks in granitic material occurs through disintegration and not wind erosion.	(Bryan, 1925, 1926; Leonard, 1927)
Quartzose karst	Dissolution of quartz rich rocks can generate karst forms.	(Twidale, 1956)
Rock coatings	Submillimeter accretions of mineral material like manganese and iron can drastically alter the appearance of rock surfaces.	(von Humboldt, 1812)
Salt decay	Crystallization of salts can fragment rocks.	(Jutson, 1918)
Spheroidal weathering	Tors are produced through subsurface rock rotting of joint-bounded parallelepipedal granitic blocks, where more rapid decay of the sides and corners generate spheroidal forms.	(Linton, 1955)
Tafoni	Salt-saturated sea sprays facilitate pitting development to form tafoni and alveolar weathering along Corsica's coastal strands.	(Reusch, 1882)
Weathering and transport-limited landscapes	Faster rates of rock decay than slope transport generates soil-covered landscapes. Conversely, faster rates of transport than rock decay generate bare-rock landforms.	(Gilbert, 1877)

to student. Ongoing research on geomorphology education will remain a vital key to the vibrancy of our field.

2.2. Kärkevagge, Swedish Lapland by John Dixon

This vignette illustrates how field-based perspectives remain vital to understanding the high Arctic rock decay system, whether it be the study of rock surfaces or solute loads. In order to understand the nature of the rock decay system in the Arctic/Alpine environment of Kärkevagge, Swedish Lapland fieldwork was essential, coupled with related laboratory analyses.

Chemical weathering in cold environments has long been regarded as being subordinate to physical weathering (Peltier, 1950). This “belief” was based largely on the apparent overwhelming abundance

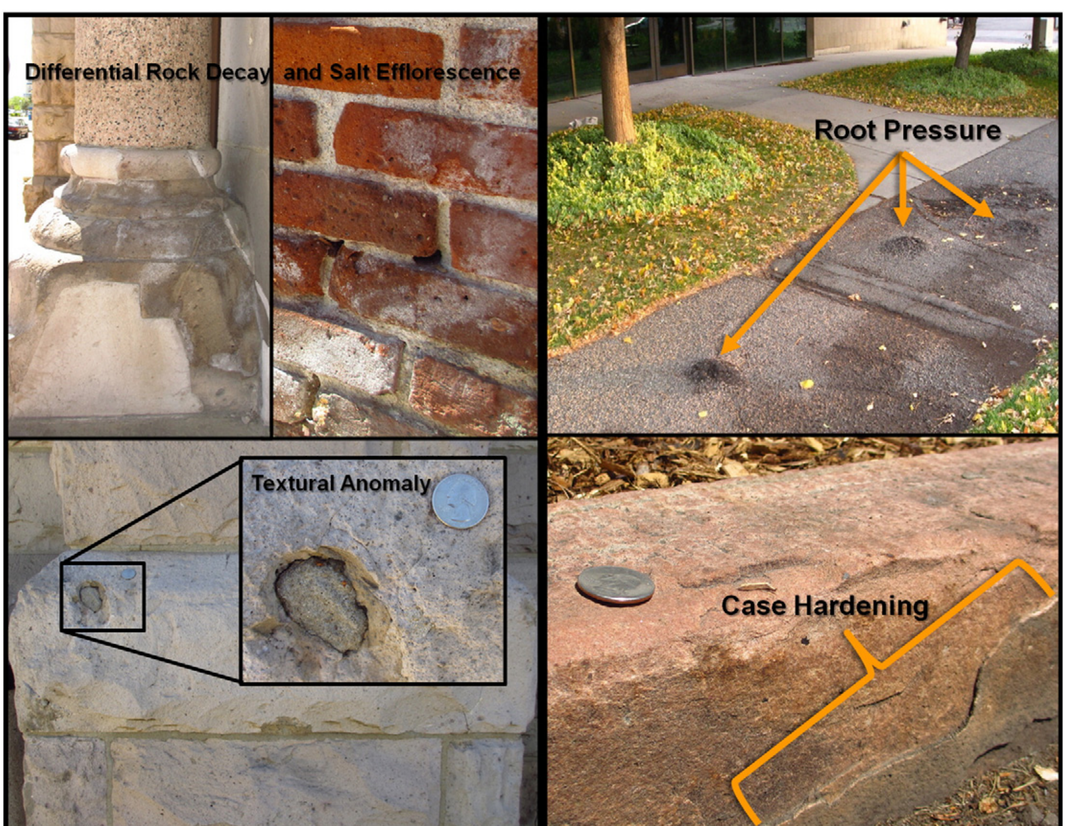

Fig. 1. A sampling of local rock decay easily accessible on the University of Colorado Denver campus used to “hook” undergraduate students on the importance of understanding rock decay. For internet alternative to generate ideas on educating a rock decay nerd, see http://alliance.la.asu.edu/rockart/NSF/RASI_InstructorsGuide.html.

of angular rock debris covering the landscape and the presence of apparently thin, poorly developed soils and minor features related to the decay of rock and regolith. Field observations show that, in addition to the presence of abundant coarse angular debris vast areas of the landscape are also covered by fine-grained regolith and associated soil development as well as the presence of abundant chemical decay features on bedrock surfaces. Further field observation in Kärkevagge quickly reveals the widespread occurrence of rock coatings of diverse appearances (Fig. 2) (Dixon et al., 2002). Subsequent laboratory analyses indicate a diverse range of chemical and mineralogical species, including minerals abundant in Fe, Si, K, Ca, and Al (Fig. 3) (Dixon et al., 2002). Identification and analysis of dissolution rinds show these elements derive from chemical decay of local bedrock.

In order to understand the fundamental spatial patterns of chemical decay as well as the general pattern of landscape evolution, one of the first undertakings of the Kärkevagge project was a comprehensive soil survey of the valley (Darmody et al., 2000) involving excavation and detailed field description of some 40 soil profiles developed in eight different vegetation communities and encompassing a comprehensive range of landform settings. The field soil survey accomplished several objectives. First, it provided insight into the range of degrees of soil development and hence chemical alteration of surficial deposits as well as insight into some fundamental vegetation/landform relationships. Second, it helped establish a fundamental understanding of the relative ages of landscape settings as reflected in the degree of soil development. Additionally, the soil survey provided opportunity to formulate initial hypotheses related to active hillslope and permafrost processes. Contrary to popular belief, Arctic/alpine soils are frequently deep and well developed. In Kärkevagge, detailed mapping of soils shows strong horizonation as a result of leaching under abundant snowmelt with associated leaching and transformation of mineral particles (Darmody et al., 2000).

Fig. 2. Al-rich (bassaluminite) rock coating on eastern wall of Karkevagge. Originally identified as “lime streaks” by earlier workers, but field testing with weak acid revealed they were not carbonate rich and subsequent laboratory analysis showed them to be sulfate dominated.

Between 1994 and 2004 a series of field experiments examined rates of breakdown of rock material on the landscape surface and at depth beneath tundra, forest, meadow, and other environmental settings (Thorn et al., 2006). Machined bedrock discs placed in diverse settings enabled assessments of rates and the nature of early stage rock decay. Field conditions, rather than laboratory experimentation, permit a more realistic assessment of natural factors affecting rock breakdown rates. This field experiment established the importance of chemical decay in an Arctic setting where expected factors of increased temperature and precipitation accelerated loss of mass of the placed disks. The significance of this research should not be lost among the various other field Kärkevagge results, because genuine field experiments in geomorphology both unusual and of critical importance (Slaymaker, 2009; Church, 2010).

An additional component essential for understanding the rock decay system includes the nature of waters draining the valley. Arctic and alpine streams typically appear clear and cold; yet, the importance of chemical decay is revealed by elevated abundances of cations and anions that exceed those abundances being contributed by precipitation (Campbell et al., 2001). While detailed chemical analyses are conducted in the laboratory, fundamental characterization of the water chemistry of the valley requires direct field measurement. In addition, determination of chemical flux for a water-year was obtained by direct measurement in the field. This latter measurement permitted an understanding of temporal patterns of chemical erosion that are simply unattainable outside a field setting.

Without systematic field observation and sampling, and associated laboratory analysis, a comprehensive and representative understanding of the rock decay system in an Arctic/alpine environment would simply not be possible. In the case of Kärkevagge, Swedish Lapland, fieldwork provides indispensible insight to contradict the predominate theory taught in classrooms of minimal chemical decay in cold regions.

2.3. Petra, Jordan by Tom Paradise

This vignette illustrates that fieldwork generates unique and vital insight into the processes that decay world heritage sites.

The now-ruined city of Petra lies hidden in a deep valley surrounded by steep, impassable sandstone cliffs and winding faulted defiles in the arid expanse of Jordan's great southern desert. However, the allure of Petra's rock-hewn architecture, in addition to its dramatic geology, draws tourists to the site. Although its archaeology indicates occupation since 7000 BCE, the brilliant urban setting of the Nabataeans two millennia ago ensured the city's place in history. Since this unique architecture was mostly hewn directly from the sandstone cliffs and not constructed,000 years ago, Petra represents an ideal laboratory for the empirical study of sandstone breakdown (Paradise, 1999, 2002; Pope et al., 2002; Paradise, 2005; Turkington and Paradise, 2005; Wedekind and Ruedrich, 2006; Heinrichs, 2008; Paradise, 2010) because the structures in Petra have (i) known construction period, (ii) well-researched petrology, (iii) record of past conservation applications (either through documentation or relict application), and (iv) have never been moved. Few sites on Earth surpass the value of Petra as a superlative outdoor laboratory for rock decay, landscape change, and architectural conservation research (Fig. 4).

Prior research in the ruined city and surroundings is well documented over its 100 years, from visiting geographers, scholars,

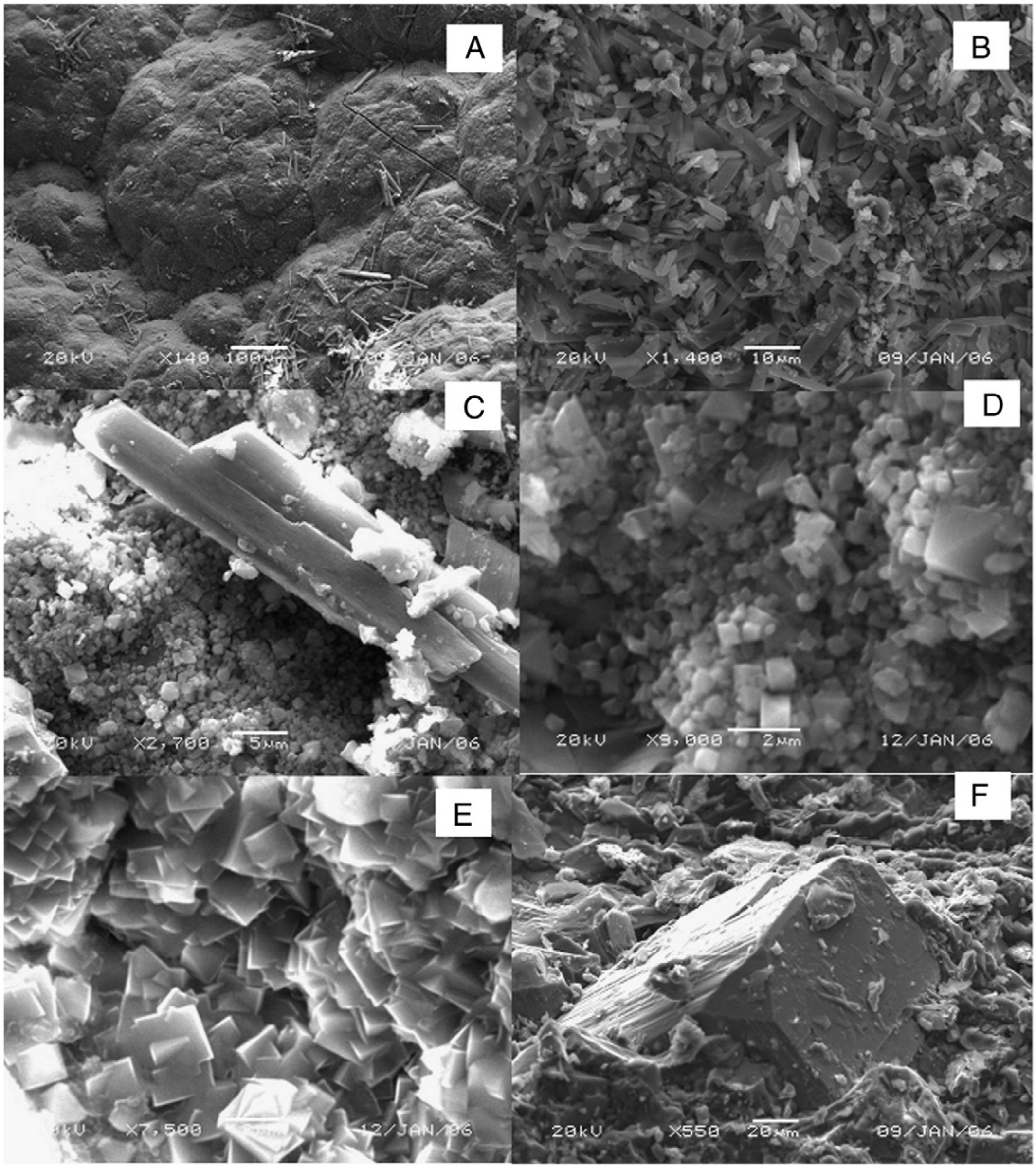

Fig. 3. Field investigations identified protected boulder sites where a variety of rock coatings occurred. Subsequent electron microscopy and X-ray diffraction analysis showed these coatings to contain gypsum (A and B), often associated with jarosite (C–E), and all of the coatings to be associated with pyrite and its oxidation (F).

geologists, archaeologists, and artists. Research about the petrology, botany, architecture, history, culture, and climate have been published since the early nineteenth century, and this represents a superlative archive and resource to use Petra as an invaluable laboratory for empirical studies.

Also, with the increasing utilization of laboratory simulation in architectural and rock decay research, Petra represents an ideal site for the 'crossover' investigations of 'natural stone' (outcrops) and 'dressed stone' (structural façades) in this natural setting (Fig. 5). Where climatic cycles of wetting-drying and freezing-thawing can be replicated in laboratory settings, nature here represents the surrogate for the laboratory simulation over 2000 years, where conventionally the lab represents the surrogate for the natural processes. Direct field observations measured rates of surface recession ranging from 0.015 to 0.070 mm/year on horizontal surfaces and 0.010–0.020 mm/year on vertical surfaces in the Roman Theater. Careful field observations also reveals that calcareous cementation at sites with more intense solar radiation enhances recession rates because of the greater sensitivity of calcite to thermal expansion and contraction, while iron cementation reduces recession rates to minimal amounts (Paradise, 2005).

Moreover, as tourism increased dramatically from 30,000 (1990) to nearly 1,000,000 (2012) visitors, not only is Petra a consummate outdoor laboratory for the study of natural and dressed sandstone and limestone, but it also represents a very special venue for the investigation of anthropogenic-touristic influences on sensitive arid landscapes like Petra and nearby Wadi Rum. With such a steep increase in tourism in the last decade, this site represents a truly unique 'laboratory' and opportunity for empirical investigations to assess and quantify the influence of large visitor numbers on anthropogenic factors including landscape denudation, tomb chamber humidity spikes (Fig. 6), architectural façade deterioration, and even effective cultural heritage management policies and infrastructure strain.

Finally as increasing numbers visit the Valley of the Crescent Moon the attention of global agencies has increased as well. UNESCO, USAID, World Monument Fund, and ICOMOS-ICAHM all have an increased

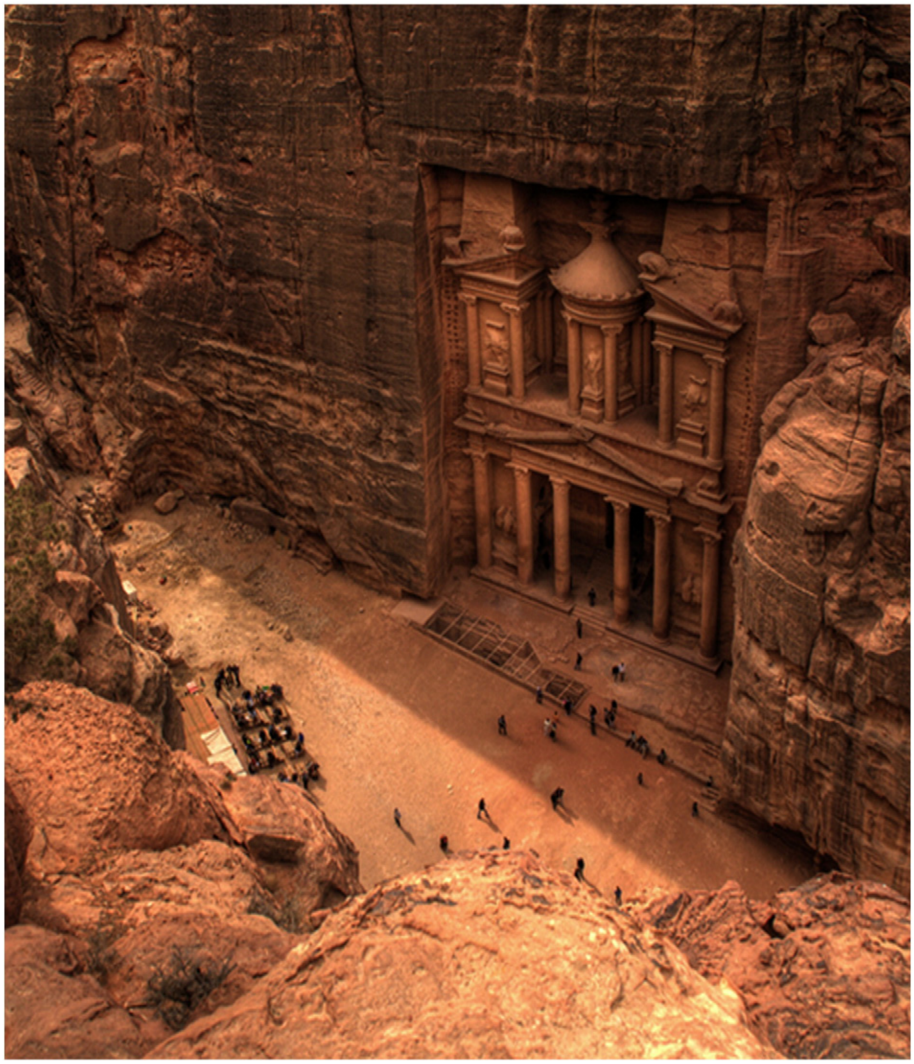

Fig. 4. al-Khazneh (Treasury) at the Inner and Outer Siqs, from high above Jebel Khubtha.

interest, presence, and investment in Petra's effective management and longevity. Although, permission and permits to work within the Park are increasingly difficult to obtain, this accelerated deterioration behooves the field researcher to look at empirical investigation with even more dedication and passion than before. The very nature of fieldwork can divulge associations beforehand unseen and unknown—the very thrust of inquiry and science and the very nature of life—building a better understanding of rock decay processes of disaggregation, surface recession, tafoni and surface coating development, and denudation in the arid lands of southern Jordan. Without direct empirical observation, measurement, assessment, and analysis in Petra, that vital bridge from empiricism to theory to application could not be constructed.

2.4. Painting the rocks by Ronald I. Dorn

This vignette illustrates that even subfields of rock decay that rely on high powered electron microscopy must remain contextualized by field setting in order to remain relevant to geomorphic research.

Rock coating research has been revolutionized by modern electron microscopy. Whereas geomorphologists once used field observations and laboratory analyses to conclude that features like "desert varnish" derived from solutions sweated out of the rock (Longwell et al., 1950; Engel and Sharp, 1958), scanning and then transmission electron microscopy showed unequivocally the external origin of a wide array of rock coatings (Dorn, 1998, 2009) through a clear contact of varnish accreted on the underlying rock surface (Fig. 7). Even though I am a strong advocate for the power of multiple microscopic tools to study rock decay (Dorn et al., in press), the theme of this vignette is that field insight remains vital in the interpretation of even the most advanced analytical methods.

Losing field context ends up being so easy in rock coating research. The journals that publish new insights often do not insist on including substantive site collection details or even a photograph to understand the field context of the collection site (Kuhlman et al., 2006; Garvie et al., 2008; Fabero-Longo et al., 2011; Hoar et al., 2011). Yet, the point-to-point variability of rock coatings can be extreme. Substantive differences can occur from meter to meter (Dorn, 1998; Sanjurjo-Sanchez, 2010). Scholarship on rock coatings in rock decay research can only benefit from the clarity of a field setting. Consider, for example, Fig. 7, from Half Dome in Yosemite National Park, California. Many different types of rock coatings can be found within close proximity and also interlayered. Just showing microscopic views misses the field setting of understanding the geographic implications of rock coatings for changing the fundamental appearance of landform surfaces.

The visual feast of strange forms produced by case hardening (Merrill, 1906) fascinates the general public and geomorphologists alike. A simple photograph indicates the field context of breaching case hardening and the erosion of the decayed weathering rind (Fig. 8A). While secondary and back-scattered electron microscope imagery reveal processes of induration of the weathering rind (Fig. 8B) and of the

Fig. 5. Looking toward the Royal Tombs from the Colonnaded Road in the Main Valley, Petra.

outermost rock coating (Fig. 8C), the field generates trust in these microscopic perspectives. The field setting makes clear that breaching case hardening is the vital process (Turkington and Paradise, 2005), while microscopy simply reveals the processes of indurating a sandstone petroglyph panel in the Petrified Forest National Park, Arizona (Fig. 8).

Trust in results derives, in part, from the ability to observe processes at different scales. A difficulty derives, in no small part, from the need for multiple random samples analyzed at micron and submicron scales to be matched with field hand lens observations at the millimeter scale, and then correlated with field observations of decay forms. Two of those three scale jumps require unique and indispensible field insight.

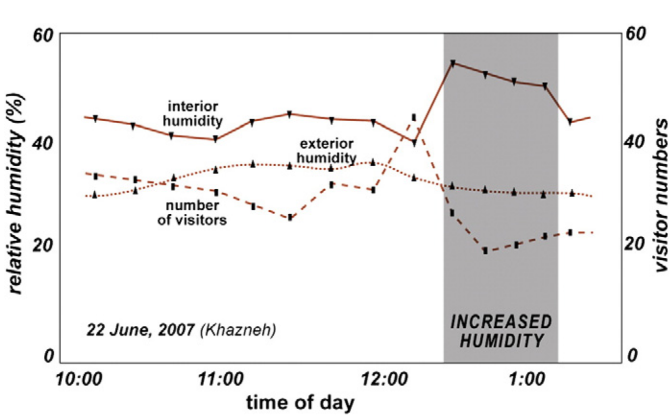

Fig. 6. The relationship between in-chamber humidity and the number of visitors reveal a substantial increase in humidity during peak visitation times.

2.5. Tafoni by Lisa Mol

This vignette digs deeper into the iconic rock decay form of tafoni, highlighting the continued relevance of new field methods in extracting new insights.

Tafoni features result from a diverse set of processes found in a large range of materials and settings. In the natural environment they can be stunning visual enhancers, while in building materials they can carry the far more negative connotation of stability-decreasing features (Fig. 9), often requiring extensive repair work. Despite extensive research on these cavernous features, their origins and development are still debated (Strini et al., 2008). Fundamental processes could either be physical or chemical or a combination of the two (French and Guglielmin, 2000), but no overarching theory covers all recorded forms of tafoni.

Lithologies range from decay-resistant material such as granite (Yatsu, 1988; Matsukura and Tanaka, 2000; Guglielmin et al., 2005) to far more friable sedimentary rock like sandstone (Mol and Viles, 2012) and limestone (Hirsch et al., 1995; Norwick and Dexter, 2002). Tafoni occur in the arid, extremely hot conditions of the Sonoran Desert (Campbell, 1999), the coastal environments of Devon (UK) (Mottershead and Pye, 1994), and the extremely cold conditions observed in Antarctica (Hall and André, 2006). In effect, one could almost go as far as to state that the only common feature is the tafoni's cavernous form (Yatsu, 1988).

The plethora of conditions and properties lays the foundation for a challenging question: what are the processes that form the basis of tafoni development? As Turkington and Phillips (2004, p 666) state: "[a] problem that has beset studies of tafoni rock decay has been the tendency to relate it to one single formative process, whereas in many cases cavern development can only be satisfactorily explained by invoking the operation of a range of processes". Primary processes suggested as the driving processes behind tafoni formation have ranged from wind regimes (Futterer, 1897; Bartrum, 1936; Hall, 1989; Gillies et al., 2009) to fluctuations in moisture availability and relative humidity (Pope et al., 1995; Mellor et al., 1997). "[There is] a general agreement that an arid period during the year is essential for the formation of tafoni … and salt rock decay is generally accepted as the main process in the formation of tafoni" (Brandmeier et al., 2011, p. 840). So there appears to be some consensus within the research community, but complexities and contradictions are found in equal measure.

While computer simulations and mathematical approaches help model processes such as growth rate (Sunamura, 1996) and salt weathering (Huinink et al., 2004), fieldwork contributions have unearthed the complexities associated with fluctuating temperature regimes, salt transport and accumulation, and internal moisture interactions. Early work by Futterer (1897), Bartrum (1936) and Dragovich (1969) laid the foundations for the current understanding of cavernous feature formation, identifying amongst other processes the importance of microclimates within the tafoni in differential rock decay.

With the further development of field techniques, our understanding of tafoni formation has grown. Equipment such as high-resolution data loggers—including humidity, resistivity (Sass, 2005), temperature (Hall, 2006a; Smith et al., 2011), rock surface hardness measurements (Matsukura and Tanaka, 2000; Mol and Viles, 2010; Viles et al., 2011), infrared thermometry (Hall et al., 2007a), laser scanning (Birginie and Rivas, 2005; Wasklewicz et al., 2005; McCabe et al., 2011), photogrammetry (Fujii et al., 2009), and salts analysis (Rodriguez-Navarro et al., 1999)—enabled researchers to assemble multivariate data sets that shed light on the complex and often

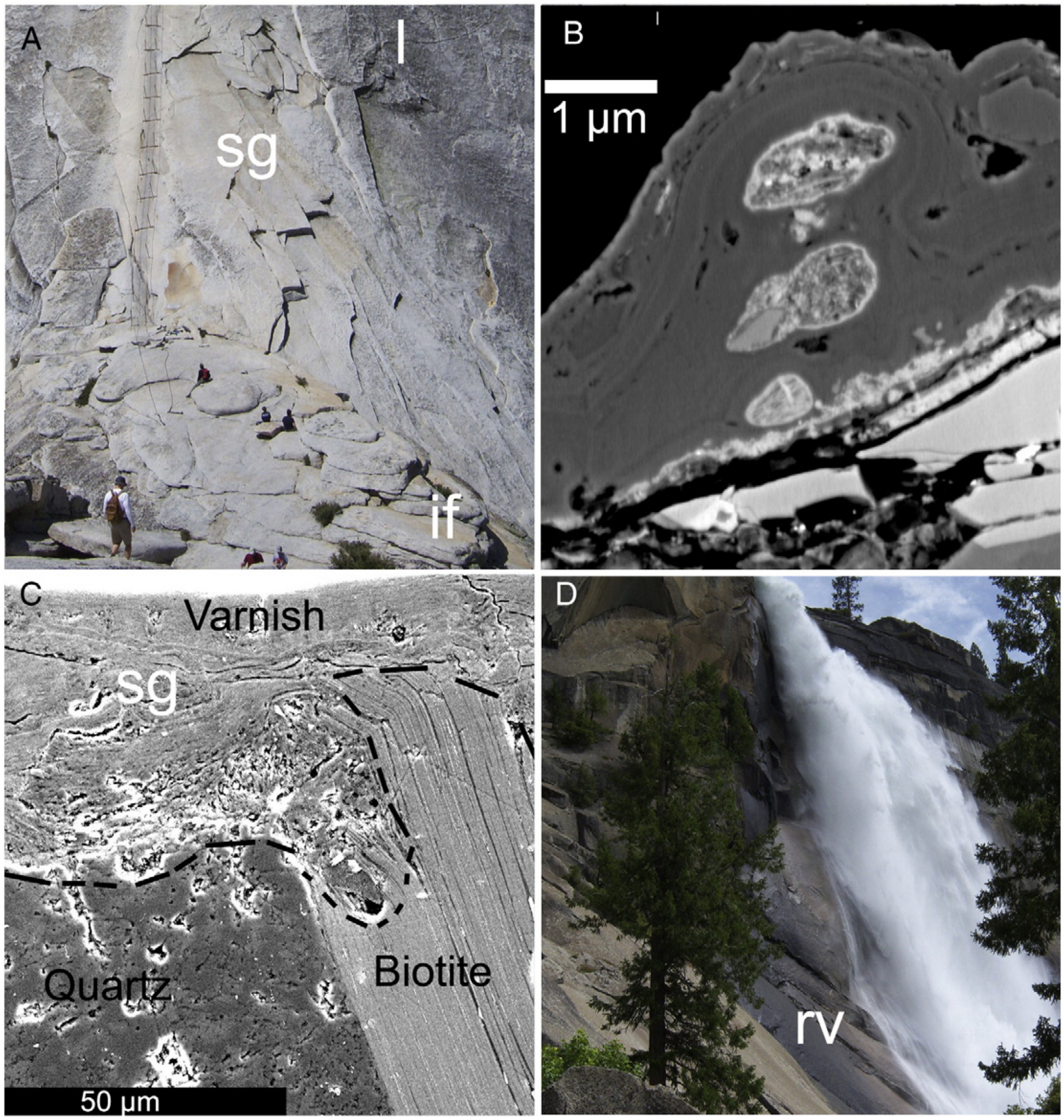

Fig. 7. Connecting field setting to electron microscopy of rock coatings on Half Dome, Yosemite National Park, California. (A) Many different types of rock coatings can be found at the base of the Half Dome ladder, including iron films (if), silica glaze (sg), and lithobionts (l). (B) Bacterial-sized cocci form encapsulated by the silica glaze seen in image A. The outermost portion of the cocci form is bright because it contains the most manganese and iron enrichment. (C) Rock varnish found in a dark streak on Half Dome (image D). Note how the rock varnish forms a distinct contact on both quartz and biotite. However, other types of rock coatings can interrupt varnish accretion, such as the small pocket of silica glaze (sg). (D) The dark stains in Yosemite Valley are composed of many different types of rock coatings, including rock varnish (rv).

nonlinear interactions between processes. In addition, these data sets may enable researchers to compare case studies collected in the field to find the underlying processes that drive tafoni formation.

One technique that may be of particular use to field researchers studying tafoni development is electric resistivity tomography. This technique enables the user to build up a two-dimensional pseudosection of the resistivity distribution within a cavern wall. It is especially useful for investigating the relationship between case softening, case hardening, and tafoni development, which represents an ongoing debate within tafoni research (McAlister et al., 2003).

Recent work has shown that moisture movement within the rock body can be very influential in the formation of these cavernous features (Mol and Viles, 2010, 2012). The development of case hardening on a surface can create a changing interplay between subsurface moisture accumulations and loss of surface material. The relationship changes over time as permeability of the surface decreases with development of case hardening and moisture is forced along set pathways. While these new insights by no means solve the tafoni puzzle, they contribute to ongoing research to map, monitor, and analyze tafoni development processes. Field based analyses on tafoni provide insight not available from alternative approaches. Indispensible insight derives from field deployment of such tools as electric resistivity tomography, laser scanning, infrared thermometry, and hardness measurements.

2.6. Sorting the relative roles of moisture, temperature, and biota by Steven J. Gordon and Ronald I. Dorn

This vignette explores the role of a field-based, site-specific sampling strategy in revising fundamental empirical values used in understanding carbon dioxide drawdown through rock decay.

Theoretical, laboratory, and computer modeling-based research all concluded that chemical reactions led to the drawdown of CO_2 through the "Urey reaction" (Urey, 1952):

$$CO_2 + Mg, CaSiO_4 \rightarrow Mg, CaCO_3 + SiO_2 \quad (1)$$

where the temperature-dependent carbon dioxide drawdown occurs (Berner et al., 1983; Suchet et al., 2003) through carbonic acid interaction with silicate minerals that contain calcium. Ultimately, this process made possible the diverse biosphere of Earth, starting with the Cambrian

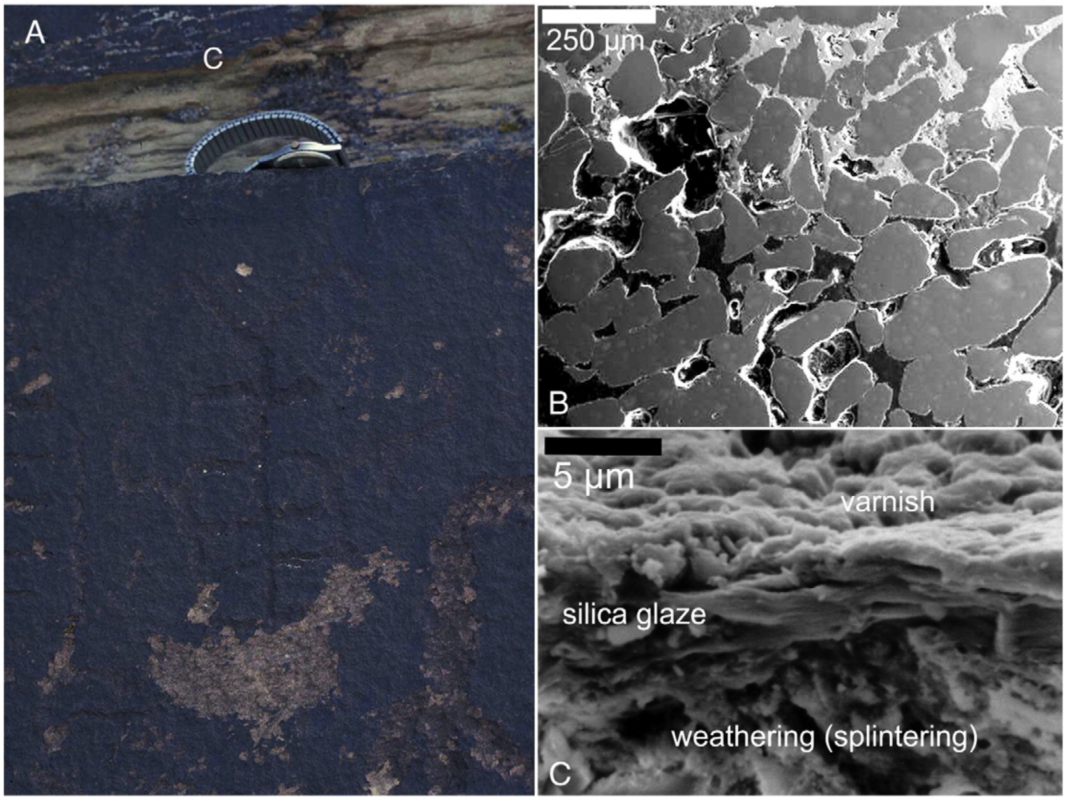

Fig. 8. Case hardening of sandstone at Petrified Forest National Park. (A) A case hardened joint face forms a stable surface used for carving of a bird motif and an earlier anthropomorphic image. Note, however, that the case hardening has been breached—with wristwatch for scale. (B) Back-scattered electron microscope image of a cross section collected at location "c" in image (A). The bright material between the grains is a heavy metal skin of iron and manganese constituents, likely dissolved from rock varnish and mobilized into the sandstone to stabilize the upper millimeter of a surface. Note, also, the abundant porosity underneath the case hardened heavy metal skin. Once the case hardening is breached, this porosity makes erosion rapid. (C) Another type of case hardening exists at the very surface of this panel. A mixture of silica glaze and rock varnish can offer additional stability in the upper few microns, where this secondary electron image was from a sample also collected from the letter C above the watch in image A.

explosion (Peters and Gaines, 2012). Approaches to obtain fundamental empirical data used to understand the activation energies involved in the Urey reaction typically involves laboratory studies of ground-up minerals (Oelkers et al., 1994) or watershed studies (Velbel, 1993; White and Blum, 1995) measuring the net output of a drainage basin.

A very different strategy in sorting out the role of temperature, moisture, and biota in the decay of calcium-silicates involves starting with a place-specific field perspective. By analyzing basalt samples from dated lava flows (Fig. 10), we have been able to measure the percentage of plagioclase dissolved over time (Dorn and Brady, 1995; Brady et al., 1999; Gordon and Brady, 2002; Gordon and Dorn, 2005).

A field approach involves selecting sites lichen-coated and lacking lichens or fungi, by selecting sites along the same isohyet but with different isotherms, by selecting sites along the same isotherm but with a different isohyet, and by analyzing the minerals that have undergone in situ dissolution. With multiple random samples collected over an outcrop several square meters on lava flows dated by radiocarbon analysis of lava burnt charcoal, the uncertainties associated with climate change shifting the locations of isohyets and isotherms imply that the precise location of a site is less important than insuring age and mineralogical controls (Dorn and Brady, 1995; Brady et al., 1999; Gordon and Brady, 2002; Gordon and Dorn, 2005).

Analyzing place-specific samples reveals that (i) lichens enhance plagioclase dissolution by an order of magnitude, especially under more moist conditions; (ii) by varying temperature and controlling moisture the recalculation of the activation energy for plagioclase dissolution in the field is higher than solute-budget and laboratory measurements; and (iii) that moisture availability can overshadow the effects of age, elevation, and temperature (Dorn and Brady, 1995; Brady et al., 1999; Gordon, 2005). Thus, using *in situ* measurements of field-constrained sampling sites was vital to refining key values used in the modeling carbon dioxide drawdown through rock decay.

2.7. Potential for a new global carbon sink by Emma Harrison

This vignette explores how keeping one's eyes open in the field can lead to the discovery of a global carbon reservoir, even in the most unlikely of places—desert mountain ranges.

The "Urey reaction" (Urey, 1952) illustrates that limestone, dolomite, travertine, calcrete, and other carbonate deposits represent stored atmospheric carbon dioxide. Three decades ago Schlesinger (1982) first estimated the reservoir of carbon stored in the carbonate of desert soils using data from Arizona soils, concluding that "accumulations of pedogenic carbonate in desert soils endow these regions with a greater importance in the global carbon cycle than the amount of soil organic matter, biomass and proportional land area would otherwise suggest" (p. 295). Schlesinger's findings were then replicated in Arizona (Rasmussen, 2006) and in Spain (Diaz-Hernandez, 2010), leading to the conclusion that global soil inorganic carbon stores between 780 and 940 gigatons of carbon (GtC), the same approximate amount of the living terrestrial biomass of 500–1000 GtC.

Diagrams in the literature show veins of carbonate well beneath the soils analyzed by Schlesinger (1982) penetrating into bedrock, both decayed and relatively fresh into gneiss in south India (Durand et al., 2006), sandstone in Utah, USA (Heilweil et al., 2007), basalt in the Middle Atlas of Morocco (Hamidi et al., 1999), granite in central Spain (Chiquet et al., 1999), and different rock types in southeastern Australia (McQueen et al., 1999). These fractures filled with carbonate go meters deep into desert bedrock (Fig. 11). However, no prior

Fig. 9. Tafoni formation on the outside walls of Durham Cathedral, UK (Photo: Lisa Mol).

research has attempted to quantify the amount of carbon stored within the bedrock of desert mountains.

A random process selected four road cuts into the Gila Range, Phoenix. Mapping of the carbonate veins penetrating into bedrock (e.g., Fig. 11) yields a range from 25.42% to 39.60% in just the upper 2 m. A Perkins-Elmer PE-2400 analyzed the carbon content of samples at $8.71 \pm 1.76\%$ with a bulk density of 2.45 ± 0.32 g/cm^3 measured by water displacement in a graduated cylinder. The following equation was then used to calculate the grams of carbon per square meter to a depth of 2 m:

$$\mathrm{g\,C/m^2} = bvCD$$

where b is the percent of bedrock fracture fills composed of calcium carbonate In the upper 2 m of the bedrock exposure; v – volume in cm^3 of a rectangular solid that is 2 m deep with a surface area of 1 m^2, or 2×10^6 cm^3; C – carbon content of the BFFCs at a site, measured in percent C by weight; and D – density of the BFFCs, measured in g/cm^3. The g C/m^2 is then converted into mT C/m^2, with an estimate of 4.9 mT in a rectangular solid of 1 m × 1 m (area) × 2 m (depth). Extrapolating these sites to the Gila Range as a whole yields a first estimate of about 139,000 ± 2 8,000 metric tons C stored in this small Sonoran Desert mountain range with an area of 15 km^2.

Urban sprawl associated with migration to USA cities has generated a great many dynamited or bulldozed fresh exposures in mountain bedrock. Field observations at dozens of these sites reveals that the measurements made at the Gila Range sites are not particularly anomalous, but reflect the potential for storing carbonate in desert bedrock deep beneath desert soils—a discovery only made possible through fieldwork.

2.8. Tree roots by Alice Turkington

This vignette demonstrates the importance of fieldwork in generating new ideas and new insights into rock decay at the interface of physical and chemical processes involved in the action of roots.

The question of how trees can weather bedrock, and raise those clasts released from the bedrock mass to the surface, was investigated in the Ouachita National Forest in Arkansas (Phillips et al., 2008a,b). Clearly, trees can play a significant role in the development of soil and regolith profiles (Samonil et al., 2010) and in breaking down bedrock (Gabet and Mudd, 2010). Following a tornado outbreak in the Ouachita Mountain Range, fieldwork examined the effects of treethrow on bedrock mining and soil development (Phillips et al., 2008a). This study showed that the majority of overturned trees had roots growing deep into bedrock, and tornado activity brought large amounts of root-impregnated rock to the surface. While the bedrock mined was most often a friable, easily decayed shale, the trees also decayed a significant amount of sandstone, a resistant silica-cemented rock.

While in the field—especially when alternating between repeated measurements, digging, and note-taking—an opportunity exists to make new observations and reflections on the landforms in the field. In this case, the forest floor (away from the blowdown site) was littered with large sandstone clasts, that had partly rounded, sinuous channel forms evident on their surfaces (Fig. 12). These forms did not follow structural or lithological discontinuities in the rock, and were not exclusive to one face or one orientation of the clasts. These sandstone clasts apparently had not been on the forest floor for long; bioturbation by tree throw in this area is extensive. Further excavation of sandstone clasts and bedrock surfaces under trees quickly showed that these grooves were associated with tree roots, and were actively forming where trees grew in shallow soils over sandstone (Fig. 13). Root grooves have been described on limestone surfaces (Viles, 1988), but not on noncalcareous sandstone surfaces. Further, sandstone is not typically thought of as soluble enough to sustain such a decay form, although some studies have suggested that silica-cemented sandstone may be dissolved under particular environmental conditions (Young et al., 2009). Subsequent fieldwork in the area revealed that root grooves were ubiquitous on sandstone in this area of the Ouachita National Forest.

The formation of root groves on sandstone is presumably a biochemical process, given the microbial communities that must colonise the rock around roots to facilitate nutrient and water uptake. However, they do not appear to be equivalent to root grooves on limestone, which are predominantly solutional, as there is evidence to suggest that abrasion is important in their formation and development at the scale of the plant. At the microscale, biophysical processes seem to also be contributing to the development of the grooves; tiny fractures are colonized by root mats and fungi, and roots can clearly penetrate and enlarge incipient fractures in the sandstone (Fig. 14).

Hall et al. (2012) suggested that we might usefully look to expand our set of known decay processes, or at least think about new combinations of processes. Further investigation of biophysical and biochemical processes in rock decay, especially if expanded to include the microbial contribution to interactions (Viles, 2011), will likely offer new insights into rock decay processes through field observations—followed up with laboratory studies.

2.9. In pursuit of protocols by Paul Sumner

This vignette analyzes the value of the pursuit of protocols in making field measurements of rock decay by asking the key questions of can we? do we? and should we pursue protocols?

Scientific protocols are ubiquitous and serve, amongst other objectives, to standardize laboratory and field research in disciplines. A successful geomorphic example is the recent approach to permafrost monitoring under the International Permafrost Associations'

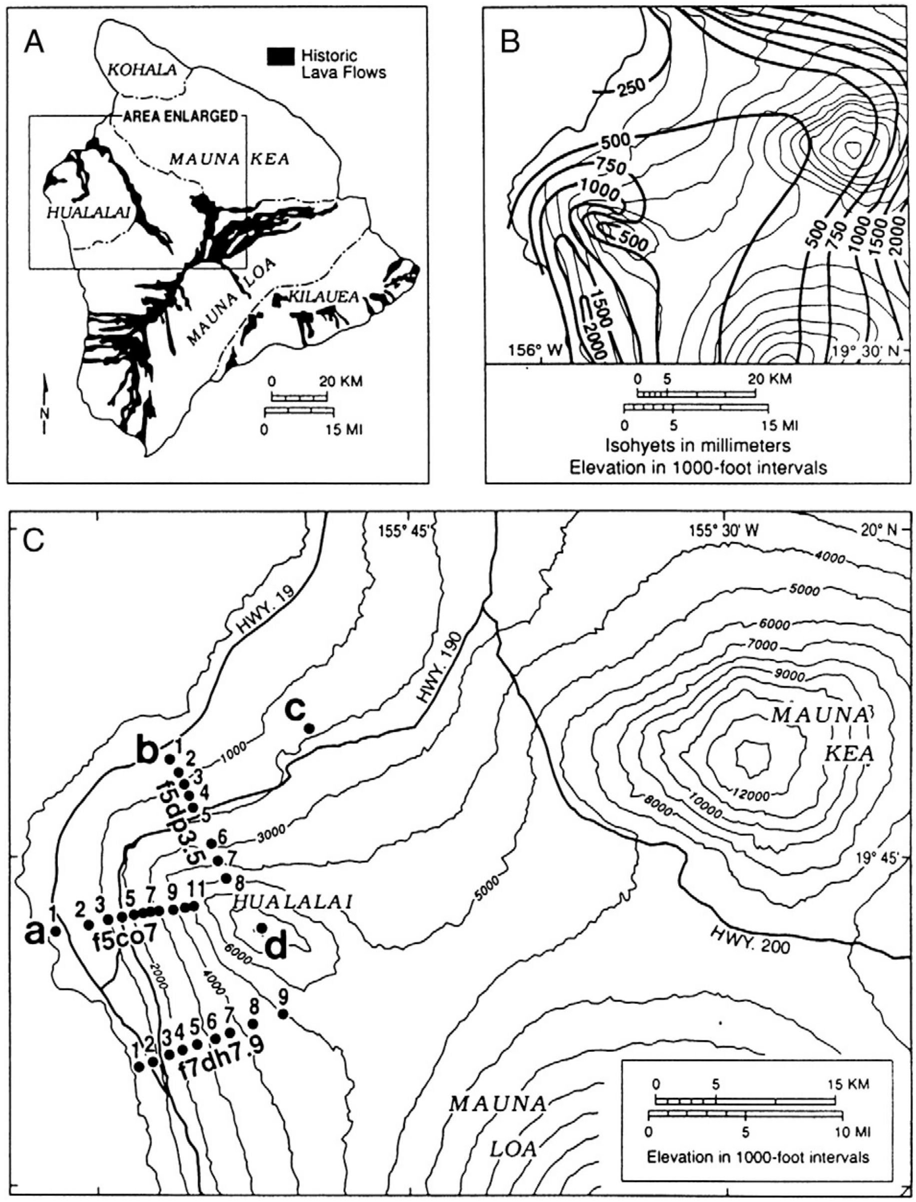

Fig. 10. The dated lava flows of Hualalai volcano (A) Hawaii (Moore and Clague, 1991) provide varied field sites where rainshadow effects allow isohyets to cross different elevations (B) allowing the sampling of lava flow surfaces (C) along different isotherms, different isohyets, under lichens, and also avoiding lichens and fungi.

Circumpolar Active Layer Monitoring Network (CALM) project protocols (Brown et al., 2000). Although a substantial component of rock decay research involves detailed field monitoring, we appear to deliberately avoid or simply ignore such a framework—one that would probably facilitate intersite and study comparisons and thus provide global impetus in the field. But, given our state of knowledge and the tools available *can* we, and *do we want to*, pursue protocols in rock decay research?

Field monitoring typically makes use of automated loggers with an array of sensors monitoring several environmental and rock-related parameters. The diversity in equipment used in studies is too substantial to present fully here. Experience with a handful of workers in southern Africa and the Antarctic highlights, for example, the array of temperature sensors available for use. Position of sensor, type and size of sensor, depth from rock surface, sensor accuracy and response time, and monitoring intervals are tailored for each project and can vary considerably between sites (Sumner et al., 2004). As technology advances and funding levels change, the scale and detail of temperature monitoring will change. Microsensors can now monitor intergrain temperature profiles and, again drawing on the southern African experience, measure light penetration into rock while bead-type microthermocouples resolve grain-scale surface temperatures (Hall et al., 2007b, 2010). Similarly, determining and monitoring rock moisture can also range from the simple to the complex (Hall et al., 2007b); *how* to measure rock moisture, as well as *when* and *where* thus poses a serious challenge. A quick scan of the international literature confirms the diverse approach to monitoring in the field and this then begs the questions: are any of these field data comparable or even truly representative of reality?

Not only has the technology improved substantially, but the monetary budgets required have increased accordingly. Pressure for results (and funding limitations) inevitably restricts monitoring durations. This is aptly highlighted by environmental monitoring in rock decay associated with rock art where monitoring projects can span periods from as short as 6 weeks to 15 years (Sumner et al., 2009). Equipment security and limited accessibility can further constrain the monitoring period, or logger interval, and servicing requirements. Some devices also simply will not operate in the diverse and extreme

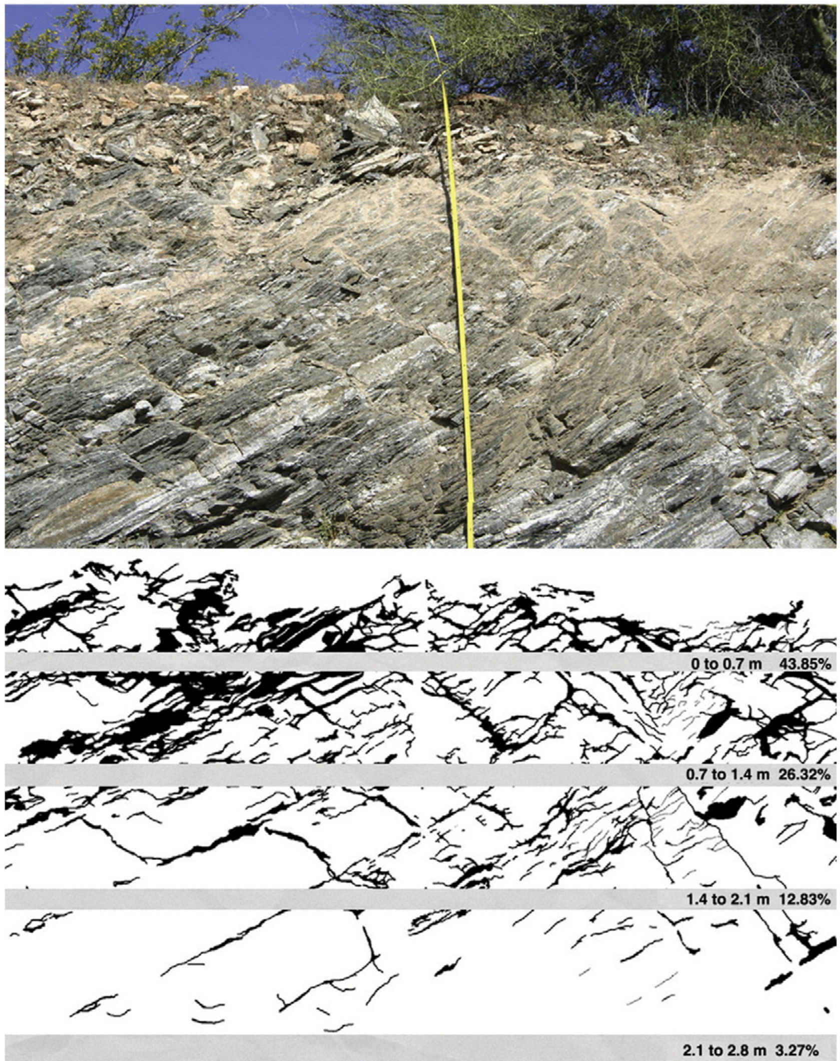

Fig. 11. Road excavation cut into the Gila Range, central Arizona, where digital image processing generated a map of the carbonate veins in bedrock. The decrease in abundance is typical of this carbon pool.

weather settings, particularly when contrasting hot, arid desert environments with cold, arid (e.g., Antarctic) and cold, wet (e.g., sub-Antarctic) settings. In other words, we tailor our projects to suit the funding duration, budget constraints, access, and equipment exposure and security—all while acknowledging noble and justified individual project objectives.

Fig. 12. A small root groove on siliceous sandstone, Ouachita National Forest, Arkansas. The scale is in inches.

Perhaps the practical difficulties can be overcome. However, the quick answer to both the "*can* we" and "*do we want to*" pursue protocols question is probably a resounding "No" from most people active in the field. In any case, *who* will decide and *what* (and probably also *when*) do we measure? Rock decay monitoring guidelines have been proposed (Matsuoka, 2006), for example, but have not been widely followed; perhaps wider consultation will circumvent feelings of imposition. As to *what* to measure, Hall et al. (2012) argued that we have an outdated theoretical framework within which we are attempting to fit current technology and that in many instances we design procedures according to what we want to find. A preoccupation with temperature monitoring alone for the freeze-thaw rock decay process demonstrates such a predetermined and simplistic approach to what is in reality a complex interaction of processes and rock properties (Hall and Thorn, 2011; Hall et al., 2012).

The pursuit of protocols thus appears to be a nonstarter, but a final question is posed: *should* we pursue protocols? My answer here would be a firm yes but not within our current theoretical framework. Our increasingly reductionist approach to rock decay assessments and the complexity we see in the field has highlighted the disparity between our understanding of, and allocation of, traditional decay processes. Our paper theory cannot hold in the face of recent advances. Perhaps the

Fig. 13. A large root groove developing along a main root of a small pine tree on a sandstone ridge top, Ouachita National Forest, Arkansas (root has been severed and removed).

proposal to consider rock decay from the perspective of energy transfer and rock properties (Hall et al., 2012) will be a way forward, or possibly the theory will be redirected toward a different framework. Either way, we stand on the brink of reconceptualizing rock decay from a theoretical perspective and this is the opportunity to firmly link new theory and practice by clearly deciding *what*, *how*, and *when* we measure. A call for protocols will thus be hard to ignore in future discussions of fieldwork and its role in theory building.

2.10. Summary

Nine vignettes offer support to the position of this paper that fieldwork remains indispensible in modern research about rock decay. Five general themes on the fundamental importance of the field emerge from the case studies related to: jumping scales from the microscopic to the visual; fundamental discoveries made possible through field based insight; identification of new research problems; unique insights generated from genuine field experiments; and moving away from armchair theories to field realities.

Each jump in electron microscope technology brings with it the risk of detaching high resolution observations of rock decay processes from forms seen in the field. The case study on *sorting the relative roles of moisture*, *temperature*, and *biota* started with micrometer-scale measurements of olivine and plagioclase porosity, from meter-scale field sites with established age, temperature and rainfall, and then combined these different scales to derive new insight on the importance of lithobionts, temperature and moisture on the activation energy for mineral dissolution. The *painting the rocks* vignette emphasizes how micrometer-scale observations of rock coatings and case hardening can directly explain different appearances of coatings and indurated rocks.

A geomorphic epiphany can derive from many sources, ranging from modeling to microscopy. Certainly, seeing something as common as a road cut as the *potential for a new global carbon sink* exemplifies the role of fieldwork in coming to a sudden realization about the nature or meaning of a rock decay feature. Carbonate veins shoot through the bedrock of metropolitan Arizona, exposed through excavations of homes, water towers, roads and other infrastructure.

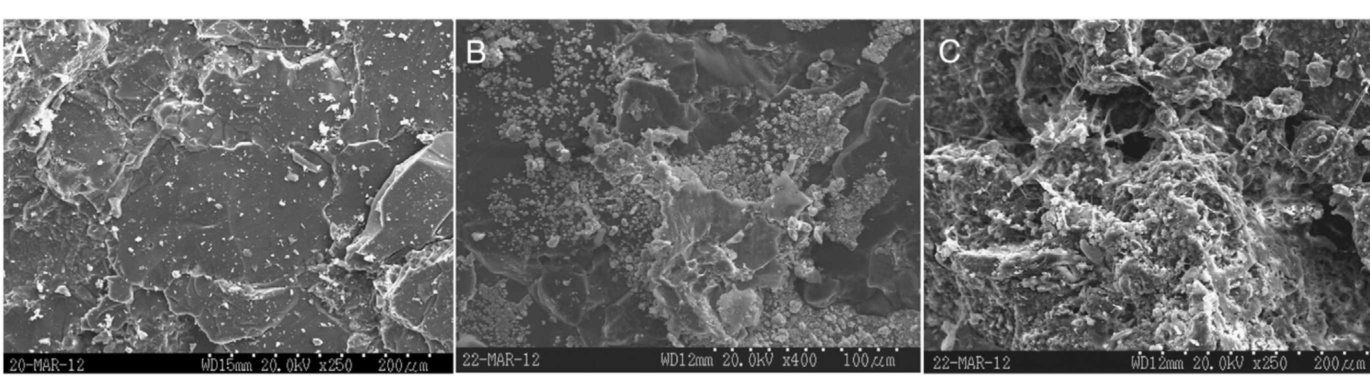

Fig. 14. Scanning electron micrographs of sandstone samples from the Ouachita Mountains, Arkansas, showing (A) the surface of a fresh sandstone clast removed from an upturned root wad (<10 years old); (B) the surface of a root groove on a large sandstone boulder, which has an abundance of organic material, iron-rich florets, and pitted sand grains; (C) 1.5 mm below the root groove surface, where the rock has been bleached, and the sand grains are heavily pitted in association with the endolithic microbes and roots.

Through simple field and laboratory measurements of the carbon abundance in these veins, a pilot research project revealed the possibility that a global carbon sink exists in desert mountain ranges.

Fieldwork plays a vital role in the identification of research problems in rock decay. *Tafoni* explores the role of field deployment of new tools in identifying problems related to nonlinear complexities of microclimatic fluctuations in temperature and humidity, salt transport and accumulation in relation to internal moisture, and linking case hardening and core softening. *Roots* emphasizes that the examination of the breakdown of bedrock by roots helps maintain focus on the broader research question of the impact of tree growth on regolith and soil development, as well as the impact on bedrock and soil characteristics on tree rooting patterns and on water and nutrient pathways.

Genuine field experiments on rock decay are rare, but a couple vignettes jump two orders of magnitude in time to obtain unique insights. Machined bedrock disks placed in *Kärkevagge, Swedish Lapland* over a 10 year period revealed sensitivity of chemical decay to both temperature and precipitation, even in an Arctic environment. Stone masonry construction of the Roman Theatre at *Petra, Jordan* allow a 2000 year long experiment on rates and factors influencing decay, reveals the clear role of insolation in causing differential thermal expansion and contraction of calcite and iron cementing agents in the sandstone. At the same time that these studies exemplify the importance of field experiments, *in pursuit of protocols* gets at a vitally important, yet often ignored issue of scientific protocols in rock decay research. The rarity of genuine field experiments emphasizes the importance of a call for protocols, but with the caveat of a need for a new theoretical framework that moves from reductionistic studies to an approach linking research through the perspective of energy transfer and rock properties.

Two vignettes speak to the problem of overcoming the residue of armchair geomorphology. An exploration of today's textbooks and posted online course notes abound with the theory that mechanical processes like frost wedging dominate cold climate rock decay—a theory developed under the comfort of a soft chair and an idealized graph of precipitation and temperature. Nothing could be further from the truth, as viewed through the lens of fieldwork carried out in the Swedish Lapland. *Kärkevagge*. Fieldwork on chemical decay of machined bedrock disks, soil surveys, stream water sampling and linked laboratory studies all emphasize the reality that chemical decay is a vital geomorphic process in cold regions. Questioning the textbook or the lecture notes handed down from previous generations is best achieved through the role of fieldwork in the education of a future geomorphologist and rock decay specialist, explored in *Building a Rock Decay Nerd*. As future students come to geomorphology classes expecting multimedia, multidimensional, and rapid-fire stimulating material, fieldwork offers common ground to encourage critical thought over what is being learned.

3. Concluding remarks: A broader view by Kevin Hall

The thought of geomorphology, particularly in regard to the ubiquitous processes of rock decay, without recourse to fieldwork, brings to mind the meeting of the Little Prince with the "Geographer" (Saint-Exupéry, 1943). Upon meeting the Geographer, the Little Prince asks about features on the planet only to be told "I couldn't tell you" to each question. In essence, the Geographer states (p. 50) "[i]t is not the geographer who goes out to count the … rivers, the seas, the oceans and the deserts. The geographer is much too important to go loafing about." Ultimately, the Geographer decides what information may be used based on the "moral character" of the person bringing the information and upon 'proofs' commensurate with the finding (e.g., large stones in respect to the finding of a large mountain). This latter attribute, the 'moral character,' can be reconstituted as "anonymous refereeing" wherein the researcher is told by someone who clearly has not just done this work (i.e., not out 'loafing around') all the things they should have done and, in some remarkable cases, what they should have found. Further, without ever visiting the places (the 'field'), the Geographer makes judgments on the veracity of the findings by others, especially as (Saint-Exupéry, 1943, p. 52) the Geographer deals only with "matters of consequence" and problems such as an 'extinct' volcano erupting again does not matter for "[t]he thing that matters to us is the mountain. It does not change." In understanding what motivates the next generation of rock decay researchers, vignette 2.1 takes the very different perspective of Strabo AD 22 "to see the world with the eyes of gods is geography—to know cities and tribes, mountains and rivers, earth and sea, this is our gift."

The Little Prince experiences many of the frustrations experienced by us who work primarily in the field. As case studies based in Kärkevagge (2.2), Petra (2.3), Yosemite (2.4), and Hawaii (2.6) illustrate, the realities of fieldwork (i.e., what can actually be done) constrain the 'proof' that is available from such work when trying to present it to the "old gentlemen who wrote voluminous books" (Saint-Exupéry, 1943, p. 49) and who had no experience of that field situation (the journal/referee): this is the more so when trying to challenge long-cherished notions regarding rock decay often constructed in the fantasy world of conceptual diagrams.

That said, the obverse of the coin would be fieldworkers investigating rock decay who seem blinkered to that which surrounds them (e.g., the 'observation' that frost-shattered rocks are always 'angular'—and so all angular rocks must be caused by frost action?) or who are not even close to measuring that which they purport to measure; consider, for example, those who use weather station data as an analogue for rock surface microclimatic data (Hoerle and Salomon, 2004). In contrast, case studies exploring a global carbon sink (2.8), root rock decay (2.8), and tafoni (2.5) all exemplify new strategies to avoid perceptual blinders.

Too often the fieldwork provides little more than a self-fulfilling prophecy (see the paradox of the "Self-fulfilling Belief"; Hall (2006b, p. 188)) because it was so structured it could do no other, and so it but further enshrines the concept that it has, in fact, failed to test. Such might be said of the pursuit of protocols with the contemporary reductionistic thinking in desperate need of reconceptualization (2.9).

So here, like others, while writing in defense of fieldwork, recognition must be made that the fieldwork in itself is not a universal panacea; indeed, some work perpetuates the myths written down by the Geographer (e.g. frost shattering is the ubiquitous cold region process: see Hall and Thorn (2011)). So, while writing in defense of fieldwork, for some, the response by the Geographer to the question by the Little Prince regarding where he should now visit is apropos: "The planet Earth" (Saint-Exupéry, 1943, p. 53).

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