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Boulder weathering and erosion associated with a wildfire, Sierra Ancha Mountains, Arizona

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Abstract

An April–May 2000 "Coon Creek Fire" burned ∼ 37.5 km^2 of the Sierra Ancha Mountains, 32.3 km miles north of Globe, AZ—including 25 sandstone and 19 diorite boulders surveyed in 1989 and resurveyed after the burn, after the summer 2000 monsoon season, and after the winter 2001 season. When viewed from the perspective of cumulative eroded area, both sandstone and diorite displayed bimodal patterns with 79% of sandstone boulder area and 93% of diorite boulder area undergoing either no fire-induced erosion or fire-induced erosion >76 mm. When stretched over cumulative boulder areas, erosion due to the fire averaged >26 mm for sandstone and >42 mm for diorite. Post-fire erosion from thunderstorm summer rains averaged < 1 mm for 5 diorite and 1 mm for 10 sandstone boulders. While only a single diorite boulder eroded an average of 1.2 mm after the winter, winter erosion removed an average of 5.5 mm from 14 sandstone boulders. Thus, fire appears to increase a rock's susceptibility to post-fire weathering and erosion processes, as predicted by Goudie et al. [Earth Surf. Process. Landf. 17 (1992) 605]. In contrast to experimental research indicating the importance of size in fire weathering, no statistically significant relationship exists between erosion and boulder height or boulder surface area—a result similar to Zimmerman et al. [Quat. Res. 42 (1994) 255]. These data exclude 12 original sites and 85 boulders at sites impacted by the fire that could not be relocated, with a reasonable cause for the lack of relocation being boulder obliteration by the fire. Given evidence from ^{10}Be and ^{26}Al cosmogenic nuclides [Earth Planet. Sci. Lett. 186 (2001) 269] supporting the importance of boulders in controlling evolution of nonglaciated, bouldered landscapes [Geol. Soc. Amer. Bull. 76 (1965) 1165], fire obliteration of boulders could be an important process driving drainage evolution in nonglaciated mountains.

Keywords: Weathering; Fire; Sierra Ancha Mountains; Arizona; Erosion; Landscape evolution; Boulder; Geomorphology; Landforms

1. Introduction

Fire and mountains go together, especially in the North American west (Pyne, 1998). The collective North American vision of mountains as wilderness, enabled by the Columbian genocide (Diamond, 1997), encompasses the right conditions for wildfire (Pyne, 1998). Mountainous public lands with a long history of fire-suppression (Pyne, 1982; Kaye and Swetnam, 1999) host abundant vegetative fuel (Wadleigh and Jenkins, 1996). Fire only requires rhythmic wetting and drying (Swetnam and Betancourt, 1998), sparked by lightning or anthropogenically (Bird, 1995).

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From a pyrogenic perspective, geomorphology influences mountain wildfires at a variety of spatial scales (Brown et al., 2001). At a large scale of hill plots, slopes create moisture gradients that vary fuel and fire patterns (Bridge and Johnson, 2000). Fires in pre-European Wyoming, for example, tended to spread down a slope (Baker and Kipfmueller, 2001). Bare rock cover is particularly important in a variety of mountain contexts (McDonald et al., 1996; Donnegan and Rebertus, 1999; Moody and Meentemeyer, 2001). Topography and moisture variability at the watershed scale (Bian and Walsh, 1993) influences wildfire behavior (Heyerdahl et al., 2001). Of course, at the megageomorphic scale, orography generates moisture, thus facilitating growth of fuel (Allen et al., 1998).

From a geomorphic perspective, fire modifies a variety of mountain geomorphic processes and rates and at a variety of spatial scales (Swanson, 1981). Locally, fire alters pedogenesis and permafrost (Power and Power, 1995; Mazhitova, 2000), increases rates of soil erosion substantially (Morris and Moses, 1987; Shakesby et al., 1993; Prosser and Williams, 1998) plays a role in mountain slope asymmetry (Selkirk et al., 2001), and utilizes efficient pre-existing pathways of mountain sediment transport. Debris flows, for example, are important agents of mountain sediment transport (Butler and Walsh, 1994). Using debris-flow pathways, fires alter debris erosion and deposition (Soons, 1994; Cannon et al., 2001). Fire-induced episodic sediment erosion even modifies loci and timing of aggradation at distant lowland locations (Germanoskiy and Miller, 1995). Considered from a summary perspective of different mountain sites around the Mediterranean, fires list among the most important contemporary erosional influences—on par with grazing (Cerda, 1998).

At an interface of geomorphology and biogeography in mountains, Butler (2001) highlights two key mountain geomorphic processes that produce disturbance corridors: snow-avalanche paths and debris flows. Both corridors maintain feedbacks with mountain wildfire. Avalanche paths form important fuel breaks (Malanson and Butler, 1984; Suffling, 1993), while wildfires greatly increase frequency and magnitude of geomorphic activity in debris-flow corridors (Cleveland, 1977; Wohl and Pearthree, 1991; Soons, 1994; Meyer et al., 1995).

Viewed from a longer time perspective, fire events often end up being critical agents of Holocene debris slope destabilization (Marion et al., 1995). Analyses of tree fire scars provide excellent means of reconstructing fire frequencies (Allen et al., 1998; Swetnam and Betancourt, 1990). Even lacking tree rings, pedoanthracological methods permit analyses of longer-term fire histories (Carcaillet, 1998; Carcaillet and Thinon, 1996). Maceral, sedimentological, and organic geochemistry analyses of organic remains in soil, regolith, and lacustrine deposits also facilitate understanding of ancient fires (Siffedine et al., 1994; Lichtfouse et al., 1997; Lichtfouse, 1999; Edwards et al., 2000; Laird and Campbell, 2000).

Admitting the aforementioned is only a sampling of the literature, fire comprises a relatively small component of research on mountain geomorphology. Similarly, fire is not a significant part of the even smaller rock and mineral weathering literature in mountain geomorphology. Over the last quarter century, for example, no mountain weathering paper, cited more than 20 times in science citation and social science citation indices as of this penning, concerned fire (Thorn, 1976, 1979, 1980; Chinn, 1981; Matthews and Shakesby, 1983; McGreevy and Whalley, 1983, 1985; Dixon et al., 1984; Mahaney et al., 1988; McCarroll, 1989; Drever and Zobrist, 1992; Gislason et al., 1996; Raymo, 1994; Condie et al., 1995).

The literature on fire as a weathering process is, by itself, still underdeveloped. When it comes to field observations, geomorphologists have long known of the importance of fire in rock and mineral weathering (Blackwelder, 1927; Emery, 1944). However, the literature suffers from a paucity of data and hence consists of anecdotal observations (Ollier, 1983; Birkeland, 1984, p. 64; Bierman and Gillespie, 1991; Dragovich, 1993). Consider just the interface between fire and epilithic organisms. While the weathering literature on organisms matured enough to host excellent review papers (Viles, 1995), very little is known about how fire influences biochemical activity of lithobionts (Garty, 1992). The state of field research is such that quantitative observations on a single sagebrush range fire justifies publication of rare insights into rates of boulder erosion (Zimmerman et al., 1994). When averaged over the entire exposed boulder surface area, Zimmerman et al. (1994) found that erosion rates averaged 0.9 mm, median erosion was 0.4 mm, and the range varied from < 0.1 to 6.1 mm.

Archaeologists, ecologists, and experimental geomorphologists dominate attempts to develop theories on the effects of fire on rock weathering. Archaeologists make important field observations on surface effects of fire (Kelly and McCarthy, 2001) and also develop general models of thermolithofractography as a means to characterize and interpret "fire cracked" rock (House and Smith, 1975; McFarland, 1977; Kritzer, 1995; Rapp et al., 1999; Wilson, 1999). Ecologists acquire data on the importance of fire-related weathering in nutrient cycles such as potassium (Brais et al., 2000) and phosphorus (Brundrett et al., 1996). Working in the long tradition (Tarr, 1915) of controlled experimental (McGreevy and Whalley, 1985; McGreevy et al., 2000; Warke and Smith, 1998) and field (Warke et al., 1996) weathering studies, experiments on fire (Goudie et al., 1992; Allison and Goudie, 1994; Nealson, 1995; Allison and Bristow, 1999) reveal substantive insights. For example, erosion of rocks in response to fire depends heavily on rock physical properties and varies with different rock types, inversely with rock size and positively with water content.

Given this research interface of mountains, fire, and rock weathering, this paper rests in the tradition of providing a rare dataset of field observations. Following advice given by Bob Sharp (California Institute of Technology) and Luna Leopold (University of California, Berkeley) to get to know a new region by surveying field sites, upon arriving at Arizona State University, I surveyed rock surfaces in a wide variety of different settings around Arizona—thinking I would return decades later to detect small amounts of erosion in only a small percentage of surveyed rock faces. One of the field sites, however, experienced a major forest fire in April–May 2000—offering a unique chance to resurvey fire-impacted boulders. Because the literature contained the hypothesis that field outcrops should have a greater degree of susceptibility to weathering and erosion processes after a fire (Goudie et al., 1992), I also monitored boulder erosion after the fire.

2. Field setting

Mountain ranges in the SW United States host repeated forest fires. No data are available, unfortunately, on the last time the "Coon Creek" site burned in the Sierra Ancha Mountains. In regional terms, however, fire-scar analysis reveals periodic high fire decades (e.g., 1740-80 and 1830-60 in Fig. 1) that occur during rapid switching from extreme wet to dry years in the southwest (Swetnam and Betancourt, 1998). Thus, prior fire events undoubtedly influenced the study site.

The Workman Creek SNOTEL site in the lower end of the study area recorded winter snowfall since 1983.

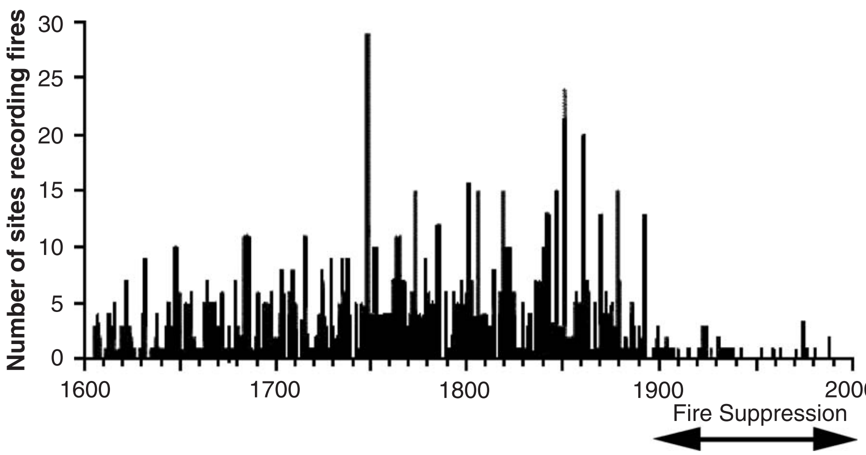

Fig. 1. Summary of fire-scar chronologies of 27 mountain ranges of the SW United States, modified from Figs. 9 to 12 in Allen et al. (1998). This chronology does not include the study site, but derives from the surrounding region.

The long-term winter average is 635 mm (25 in.) of precipitable water. During the winter season preceding the burn, the SNOTEL site received only 20% of normal (http://www.aracnet.com/cgi-usr/cpacheco/cdbs_tbl)—indicating conditions were extraordinarily dry in spring 2000.

The Coon Creek fire started at a campfire on April 26, 2000. The April–May fire burned approximately 37.5 km^2 in the Sierra Ancha Mountains, Tonto National Forest, 32.3-km miles north of Globe, AZ. In contrast to a natural lightning-strike fire, which would have started near crests and moved slowly downhill, this fire started near the base of the drainage basin. The fire moved upslope rapidly with rising flames. Winds of 6–12 m/s helped produce a large, hot, and destructive fire. Ground temperatures are not known.

In 1989, I surveyed 129 boulders in 20 sites in the burned area. Thirty-seven boulders were also surveyed at five sites not burned in the fire. Surveyed boulders range from 2070 to 2290 m on slopes hosting ponderosa pine (*Pinus ponderosa*), Gambel

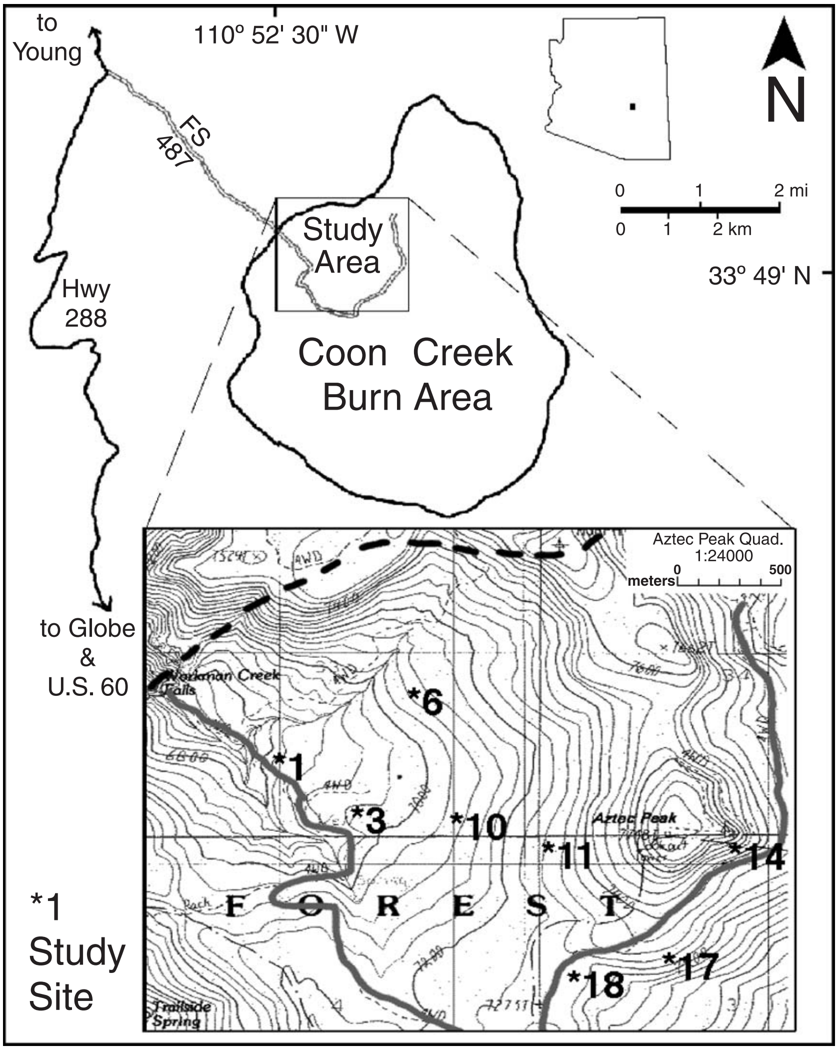

Fig. 2. Coon Creek burn study area, Sierra Ancha Mountains, central Arizona. Numbers designate clusters of surveyed boulders and correspond with tables, figures, and in-text discussions. For example, Boulder 18.6 in Fig. 3 refers to boulder 6 from site 18.

oak (*Quercus gambelii*), mixed-conifer woodland with blue spruce (*Picea pungens*), Douglas-fir (*Pseudotsuga menziesii* var. glauca), white fir (*Abies concolor*), corkbark fir (*A. lasiocarpa* var. arizonica), southwestern white pine (*P. strobiformis*), and quaking aspen (*Populus tremulodies*).

In June 2000, I relocated 25 sandstone boulders and 10 diorite boulders at eight sites (Fig. 2). The 44 refound boulders were resurveyed twice more, in October 2000 after the summer monsoon precipitation season and again in May 2001 after the winter snow season.

Summer thunderstorm precipitation values are not recorded at the SNOTEL site in the surveyed basin; however, at drier Globe, "Arizona Monsoon" rains were extensive. The Globe area received more than 300 mm of precipitation in Summer 2000. Because Coon Creek is higher and more susceptible to monsoon precipitation, totals were likely much higher. The Workman Creek SNOTEL site had a slightly above

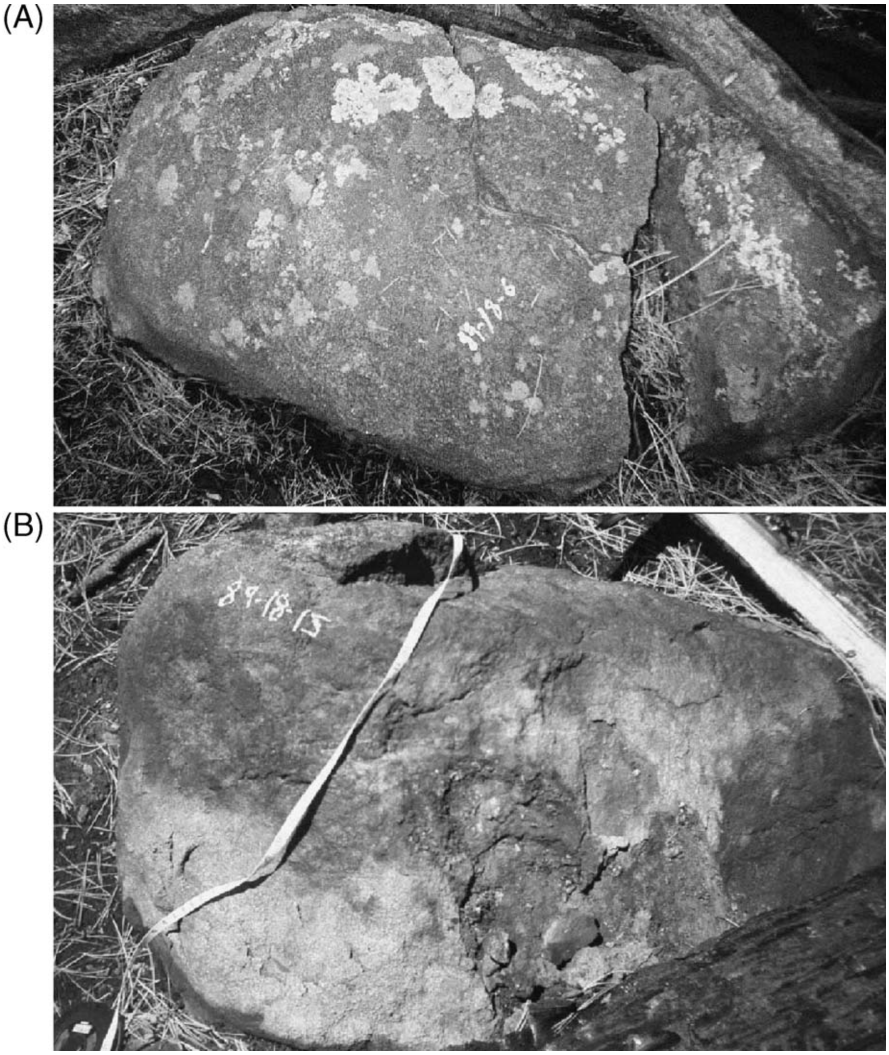

Fig. 3. Example of two extremes in erosion behavior within a few meters of each other at site 18 (see Fig. 2). (A) Diorite boulder 18.6 (50 mm across) did not experience erosion after the fire, and its epilithics still coat the boulder. (B) Diorite boulder 18.15 (1500 mm across) lost all but 10% of its original surface.

average snowfall of 685 mm of precipitable water from October 2000 through April 2001—the winter after the fire (ftp://ftp.wcc.nrcs.usda.gov/data/snow/snotel/reports/water_year/arizona/10s01s.gif).

3. Methods

All 37 boulders surveyed at five sites outside the burned area in 1989 had a complete cover of epilithic lichens and other lithobionts. Similarly, 129 boulders surveyed at 20 sites in the burn area in 1989 had a complete or almost complete cover of epilithic organisms (e.g., Fig. 3) with the original intention of monitoring the effects of weathering over a period of decades. Most of the sites occur along broad ridge lines. Selected boulders had no clear orientation. With permission of the Forest Service, holes were drilled into boulders with 76-mm steel nails emplaced with epoxy to establish baselines for future surveys.

My efforts after the April–May 2000 fire failed to relocate 85 boulders at 12 of the original sites. Since GPS technology was not available during the original survey, relocation was to be aided by additional surveying with respect to particular trees and landforms such as slope breaks and drainage features. With no success, I attempted relocation at each subsequent visit to the site after the monsoon season in October 2000 and after the snowfall season in May 2001. Although metal detectors found nails at sites with missing boulders, the presence of nails is certainly not conclusive evidence for complete boulder obliteration at these nonrelocated sites.

Scanning electron microscopy also analyzed rock samples collected in the field before the fire and samples of the host rock and spalled fragments collected after the fire. Wavelength and energy dispersive X-ray spectrometry supplemented secondary electron microscopy and backscattered electron microscopy imaging techniques.

Employing 76-mm-long nails, while facilitating resurveys, resulted in several important limitations for this study. First, many spalls exceeded nail length. In these cases, 76 mm is an obvious minimum amount of boulder erosion. Second, the steel and epoxy may have altered internal thermal gradients and could bias results. Third, nail emplacement could have increased water content within the boulders, at least around the nails.

In order to understand the possible influence of nails as a monitoring device, an experiment was conducted on diorite and sandstone clasts removed from the field area. Blow torches heated 24 diorite and 24 sandstone clasts that were spheroidal in shape with diameters of about 10 cm. Three cm-long nails were emplaced with epoxy in half of the clasts (12 diorite, 12 sandstone). Half of the clasts (6 diorite, 6 sandstone) soaked in distilled water for 1 h prior to torching, while 12 clasts (6 diorite, 6 sandstone) air dried for 24 h prior to torching. Blow torches heated rocks until the backsides (away from the torch) reached a temperature of approximately 400 °C as measured by thermocouples and verified by optical microscope examination of commercial temperature pellets that melt at specific temperatures, in this case melting at 371 °C but not 427 °C.

4. Results

Only two of the diorite and sandstone boulders outside of the fire-impacted region experienced detectable erosion. Obviously, erosion and weathering occurs under the epilithic cover. However, those changes are the subject of a study emphasizing microscopic techniques and beyond the scope of this paper.

Table 1
Field observations on Boulder 1.2 (sandstone), at about 2070 m, a boulder with a maximum height of 500 mm and a surface area of 1,560,000 mm^2 (italic, bold, and underline formatting helps track what happened over time to the different surfaces)

After April–May fire (June resurvey)		After monsoon (October 2000 resurvey)		After winter (May 2001 resurvey)	
Surface erosion	Area in mm^2	Surface erosion	Area in mm^2	Surface erosion	Area in mm^2
>76	**312,000**	**>76**	**312,000**	**>76**	**312,000**
32	*468,000*	*32*	*468,000*	*32*	*156,000*
				>76	*312,000*
0	780,000	0	312,000	0	312,000
		5	468,000	5	312,000
				8	156,000
Average after fire = 24.8 mm		Average after monsoon season = 26.3 mm		Average after winter = 35.4 mm	

Table 2
Erosion of diorite boulders, averaged over the entire exposed boulder surface area (blank entries indicate no change; entries are sorted from least to most average erosion over the year of monitoring)

Site.Boulder number	Boulder height (mm)	Boulder Area (mm^2)	After fire	After monsoon	After winter
11.6[a]	500	300,000	0.0		
11.9	600	275,000	0.0		
18.20	1000	900,000	0.0		
18.6	600	340,000	0.0		1.2
14.1	1450	1,150,000	4.6	5.0	
14.13	690	627,000	7.9	8.7	
17.2	700	840,000	9.1	9.7	
17.12	300	675,000	22.7		
17.3	300	240,000	24.8	25.0	
18.1	300	865,800	60.8		
11.3	1950	1,500,000	68.4		
18.15	400	1,350,000	68.4		
11.12	200	202,500	75.8		
11.15	250	152,000	76.0		
11.16	300	105,000	76.0		
11.2	400	360,000	76.0		
17.1	600	1,760,000	76.0		
17.6	600	1,260,000	76.0		
18.25	300	1,200,000	76.0		
Number of boulders			19	19	19
Number of boulders eroded			15	5	1
Percentage of boulders changed			79	26	5
Average change			>53.2[b]	0.5	1
Median change			68.4	0.5	

[a] Site 11, boulder 6.
[b] Because the maximum amount that could be recorded was 76 mm, this is a minimum average change.

The two unfired sandstone boulders that eroded appear to have been chipped mechanically by bullets.

Each boulder in the area impacted by the Coon Creek wildfire experienced its own complex erosional history. Consider, for example, Boulder 1.2 in Table 1. After the fire, ~ 50% of this sandstone boulder retained its epilithic surface cover, albeit charred in places. A portion of this section of the boulder then eroded in relatively thin 5-mm sheets after the monsoon season. Then after the winter, the surface changed again: another 3 mm eroded from the monsoon-season spall. Also after the winter, 30% of the boulder that had a post-fire surface loss of 32 mm then spalled a large-enough block to erode a nail and exceed the 76-mm monitoring depth.

Rather than present a series of similar case studies for all 44 boulders, I followed Zimmerman et al.

Table 3
Erosion of sandstone boulders, averaged over the entire exposed boulder surface area (blank entries indicate no change; entries are sorted from least to most average erosion over the year of monitoring)

Site.Boulder number	Boulder height (mm)	Boulder area (mm^2)	After fire	After monsoon	After winter
10.3[a]	500	160,000	0.0		
14.9	1250	1,350,000	0.0		
6.15	400	325,000	0.0		0.7
6.11	3450	850,000	5.5		5.8
3.9	1100	1,680,000	3.8	5.3	6.7
14.10	2000	3,120,000	7.8	8.3	
14.12	820	1,054,000	8.8	9.7	
6.6	800	440,000	10.5		
14.3	600	1,960,000	12.0		
14.6	1300	2,310,000	12.2	12.4	12.9
1.4	300	1,166,300	19.2	19.6	20.2
6.12	650	921,200	23.2		24.3
3.11	400	495,000	24.8	24.8	26.1
10.7	650	330,000	21.5		30.4
6.16	1100	1,125,000	23.3		31.3
3.4	400	990,000	3.9	5.0	34.0
10.10	800	1,320,000	33.6	35.1	
1.2	500	1,560,000	24.8	26.3	35.4
10.12	1050	560,000	24.2	24.8	38.6
6.5	300	270,000	47.4	49.2	50.1
10.4	600	525,000	56.7		
3.12	350	840,000	61.2		62.4
1.13	300	317,400	76.0		
1.3	150	917,900	76.0		
10.11	1100	1,150,000	76.0		
Number of boulders			25	25	25
Number of boulders eroded			22	10	14
Percentage of boulders changed			88	40	56
Average change			>39.4[b]	1.0	5.5
Median change			24.8	1.0	1.2

[a] Site 10, boulder 3.
[b] Because the maximum amount that could be recorded was 76 mm, this is a minimum average change.

(1994) in averaging erosion over each exposed boulder surface area. Thus, for Boulder 1.2 (Table 1), two-thirds of the net boulder erosion took place as a result of the fire and subsequent cooling. Very little change took place during the monsoon season. However, one third of this boulder's erosion occurred during the winter.

Table 2 summarizes erosion history of the 19 resurveyed diorite boulders. Almost 80% of these diorite boulders experienced some fire erosion, with almost a third averaging more erosion than the nail penetration of 76 mm. After the monsoon, only a quarter of the diorite boulders eroded with an average of < 1 mm. Only one diorite boulder experienced additional spalling after the winter.

Table 3 summarizes a much more active erosion history for 25 resurveyed sandstone boulders. All but three sandstone boulders experienced some fire erosion, and one of those three eroded after the winter. Like the diorite, erosion rates dropped precipitously after the fire. However, 40% of the boulders eroded an average of 1 mm during the monsoon season, with more than 50% eroding an average of 5.5 mm during the winter.

The blow torch experiment resulted in fragmentation of 19 of the 24 clasts into smaller centimeter and subcentimeter-sized pieces. All 12 of the water-soaked clasts fragmented (3 diorite with nail, 3 sandstone with nail, 3 diorite without nail, 3 sandstone without nail). Of the air-dried clasts, 4 with nail (3 sandstone, 1 diorite) and 3 without nail (3 sandstone, 0 diorite) fragmented. Only 5 non-soaked diorite clasts did not break apart, although millimeter-scale surface spalling took place on these 5. These results suggest that wetting and lithology may be more important in eroding clasts than the presence of nails.

5. Discussion

The results of this study generate several distinct points of discussion relevant to different aspects of the prior literature.

5.1. Bimodal erosion

The June 2000 survey after the fire revealed a strongly bimodal pattern to boulder erosion. Instead of aggregating data by each separate boulder (cf. Tables 2 and 3 and Zimmerman et al., 1994), Figs. 4 and 5 aggregate spalling thickness by the total area of a given spall thickness. Viewed in this cumulative fashion, more than half of the area of all of the sandstone boulders did not erode after the fire, but a little more than 20% of the sandstone surface area eroded >76 mm (Fig. 4). Diorite boulders displayed even stronger bimodal behavior, but in a reverse pattern (Fig. 5): >60% of the surface area eroded >76 mm, while almost a third of the diorite surface did not erode after the fire. Fig. 3 photographically illustrates these extremes of no erosion and extensive erosion.

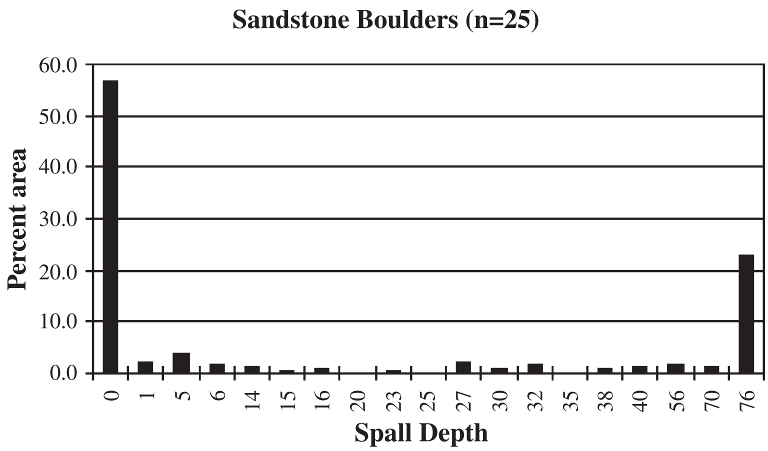

Fig. 4. Erosion of sandstone boulder area, graphed by spalling depth for all sandstone boulders resurveyed after the burn.

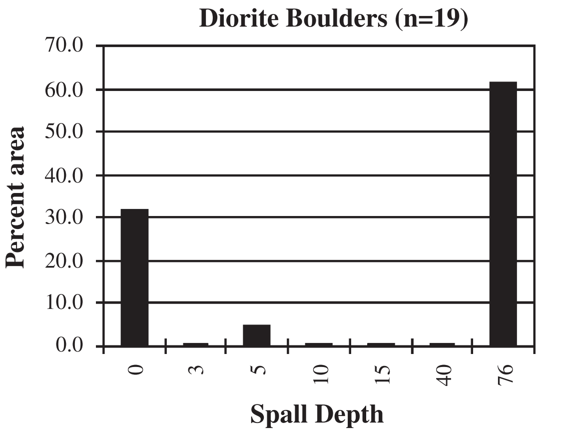

Fig. 5. Erosion of diorite boulder area, graphed by spalling depth for all diorite boulders resurveyed after the burn.

The general bimodal pattern for diorite does not change substantially after the monsoon and winter seasons. The pattern for sandstone also remains bimodal after summer and winter, but changes slightly. Total sandstone surface area with zero erosion declines to 43% after the monsoon and 38% after the winter, and total surface area with erosion >76 mm increased to 22% after the monsoon and 27% after the winter.

I am not sure why diorite tended to erode in the fashion of spalling fairly thick blocks. One possible explanation is the presence of laminar calcrete in boulder fractures (Fig. 6), rock coatings that could be seen on open spalled rock faces after the fire. Laminar calcrete is common in arid and semiarid settings (Goudie, 1996), but it also occurs in humid contexts (Reams, 1990). Carbonate responds differently to thermal stress than silicate minerals (Gaffey et al., 1991), and organic material in laminar calcrete (Chitale, 1986; Klappa, 1979) further changes the response to firing. Thus, the laminar calcrete coatings may have facilitated diorite spalling along these internal fractures.

The style by which rock surfaces weather and erode has implications for interpretation of cosmogenic nuclides that build up in situ in rocks. Although the current perspective (Hancock et al., 1999; Heimsath et al., 1999; Jackson et al., 1999) assumes that rock erosion or soil production from bedrock behaves in a fashion that can be readily modeled with simple modeling assumptions, such as 5-mm erosion per 1000 years, these bimodal findings reveal the opposite. Some boulders are clearly susceptible to fire-related weathering, and others are not. A wide degree of irregular behaviors exists in rock weathering, with the need for cosmogenic models to interface with scalable weathering conceptual models (Trudgill, 2000). The point is that weathering research can help generate a realistic, field-contextualized, weathering error term that does not now exist in any reported cosmogenic dating result.

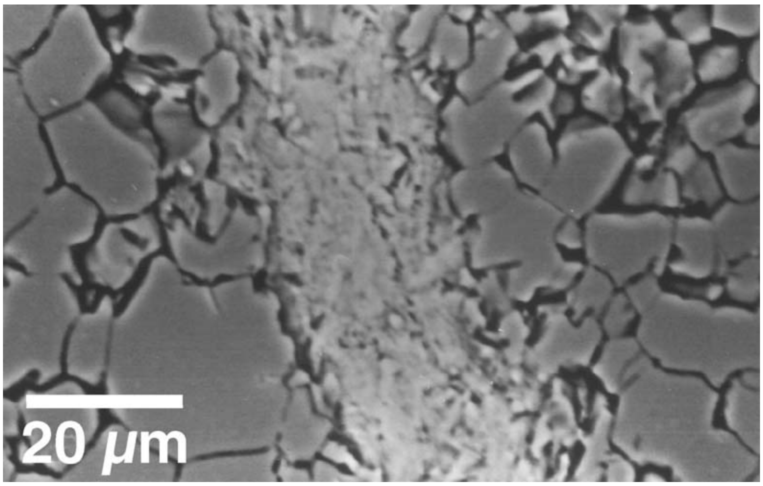

Fig. 6. Humid laminar calcrete lining fractures in diorite boulders, as seen in this backscattered electron microscope image of the calcrete surrounded by plagioclase.

5.2. Why did sandstone erode more in winter?

According to laboratory research, field outcrops should have a greater degree of susceptibility to weathering and erosion processes after a fire (Goudie et al., 1992). Field data for the weathering of sandstone boulders (Table 3) supports this experimental insight. More than half of the sandstone boulders eroded an average of 5.5 mm during the winter. Four sandstone boulders that did not erode after the monsoon eroded after the winter. Five sandstone boulders experienced substantial additional losses after the winter, including Boulder 1.2 exemplified in Table 1.

Initial fire erosion revealed a pattern of erosion that cut across bedding planes and individual minerals. Microscopic observation in the field and laboratory frequently revealed individual quartz grains breaking by conchoidal fracturing (Fig. 7). At first glance, this did not make sense. Quartz expands approximately four times more than the feldspar in the sandstone (Winkler, 1975), suggesting that post-fire breakage should occur along grain boundaries. I speculate that internal quartz weakness (Pope, 1995b) or perhaps internal fractures in quartz (Pope, 1995a) aided fracturing of quartz grains.

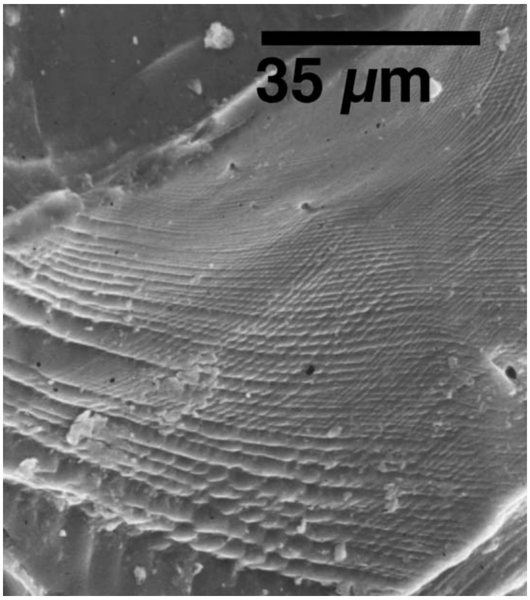

Fig. 7. Erosional processes from the fire event include internal breakage of quartz grains, as evidenced by the conchoidal fracture pattern in this quartz grain from Boulder 1.2 collected after the fire in June 2000.

In contrast, sandstone spalling faces examined after the winter were dominated by breakage along bedding planes, grain boundaries, and especially cutting across weathered feldspar (Fig. 8). The general condition seen in Fig. 8 is based on SEM examination of eight comparative samples from June 2000, October 2000, and May 2001 collections. Feldspar discongruent dissolution probably did not occur during the fire event; measurements of feldspar weathering over time in different circumstances (Dorn and Brady, 1995; Gordon, 1996) indicate that the swiss-cheese appearance in Fig. 8 likely takes tens of thousands of years to develop. Thus, observed internal feldspar weathering likely developed in situ long before the fire, perhaps even during a prior rock cycle.

Warke and Smith (1994) emphasized that ‘‘inherited’’ weathering can greatly influence weathering behavior, and inherited weathering may indeed be very important in explaining the erosion behavior at Coon Creek. In this case, inherited porosity may have helped support hygroscopic and capillary water, that in turn helped produce micro-environmental conditions (cf. Warke and Smith, 1998) prompting fracturing along feldspar-rich bedding planes. Experimental studies revealed the importance of moisture in fired rocks (Allison and Goudie, 1994), suggesting that the fire may have helped weaken previously weathered feldspar grains—making them more susceptible to post-fire weathering processes such as winter-time frost weathering (McGreevy and Whalley, 1985).

Inherited weathering may also play a role in the limited diorite erosion experienced during the monsoon and winter seasons. Only one of the diorite boulders eroded during the winter, and only an average 1.2 mm. A comparison of the face of a fire spall with the face of the winter spall (Fig. 9) revealed the fire spall to be cut across minerals that were not very weathered. In contrast, winter spalling cut grains with substantial internal porosity (Fig. 9). These SEM insights are anecdotal because I only examined spalling from one winter boulder and four fire-spalled diorite boulders. Still, these diorite observations indicate the importance of ‘‘inherited’’ weathering (cf. Warke and Smith, 1994).

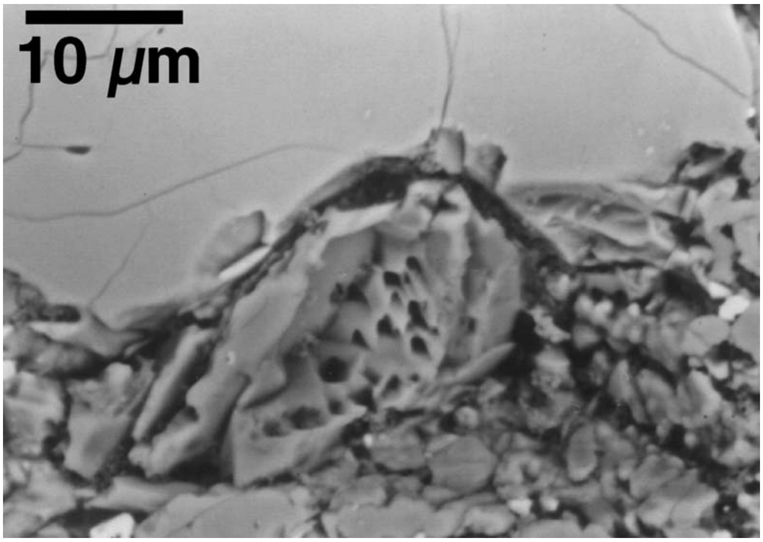

Fig. 8. Spalled grain from sandstone Boulder 1.2 collected after the winter season in May 2001. The less-weathered upper part of the image is quartz, and the heavily porous lower part of the image is plagioclase feldspar. The spall face cut across the bedding plane of heavily weathered plagioclase.

5.3. Does size matter?

Size should matter in a boulder's erosional response to wildfire. Changes in rock modulus of elasticity should generate differences in weathering and erosion. Experimental studies reveal strong correlations between rock size and the amount of spalling; the percentage of rock mass eroded in one study was proportionally higher for larger rocks, explained by differences in temperature gradients (Nealson, 1995). Similarly, some field research also revealed that size matters, with fire rounding larger boulders the most (Hellborg, 1995).

My data, however, did not reveal any statistically significant relationship between boulder height or boulder surface area and erosion. Results that are not statistically significant reveal a weak negative relationship between boulder height and erosion rates for sandstone and diorite, where higher boulders tend to experience proportionally less erosion than boulders closer to the ground (Fig. 10).

I have no explanation for size not mattering, except to stress the obvious that each boulder has a long and individual history of prior weathering. That ground huggers eroded more could reflect the importance of prior weathering at the ground surface or the importance of more internal water in pore spaces closer to the ground. But considered overall, size was not a significant factor at the Coon Creek burn, just like size did not matter on a glacial moraine in Wyoming (Zimmerman et al., 1994).

5.4. Lost boulders, slope armoring, and climate change

My failure to relocate two-thirds of the originally surveyed boulders could be attributed to incomplete care in taking field notes in 1989, complete erosion of boulders at a site, or some combination. Based on finding nails with metal detectors at locales where the boulders should have been, my subjective opinion is that fire obliterated many, if not most, of these boulders (Fig. 11). The upper frame shows a half-decimated boulder. The lower frame shows a site that formerly hosted boulders.

Although the blow torch experiment was not conclusive regarding the importance of nail emplacement in boulder fragmentation, results suggest that the presence of water and the role of lithology may be more important than the occurrence of an epoxied nail. Birkeland (1984, p. 64) did not use nails in a qualitative analysis of fire weathering,

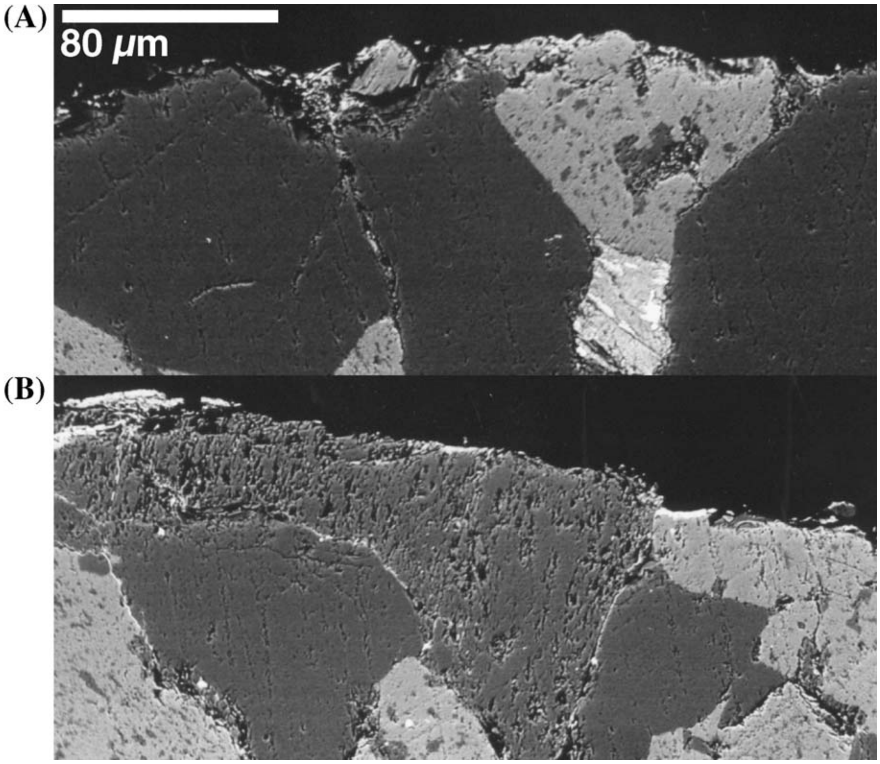

Fig. 9. Comparison of backscattered electron microscope images of (A) diorite boulders only eroded from the fire (from Boulder 17.12) with (B) the single monitored diorite boulder experiencing winter erosion (from Boulder 18.6). Note the greater degree of internal weathering in (B). Hygroscopic and perhaps capillary water stored in the pores may have promoted wintertime frost weathering of Boulder 18.6.

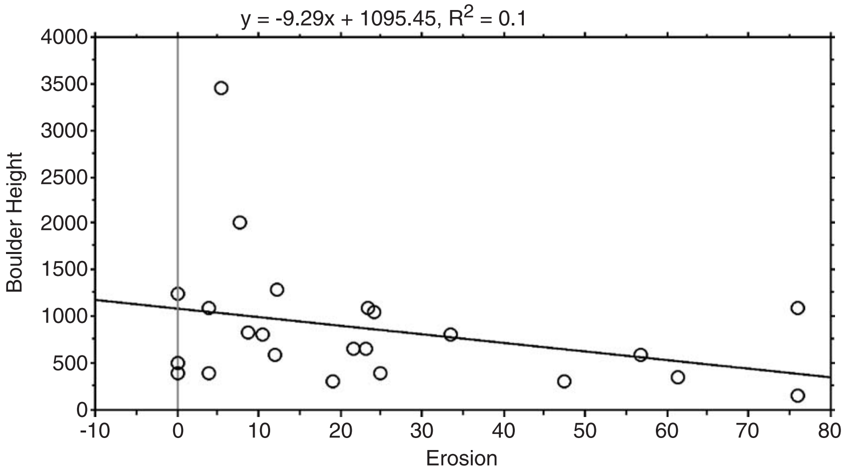

Fig. 10. Strongest relationship between erosion and boulder size, in this case between sandstone boulder height and erosion averaged over the boulder surface. This relationship is not statistically significant, with a p value of 0.15.

(A)
(B)

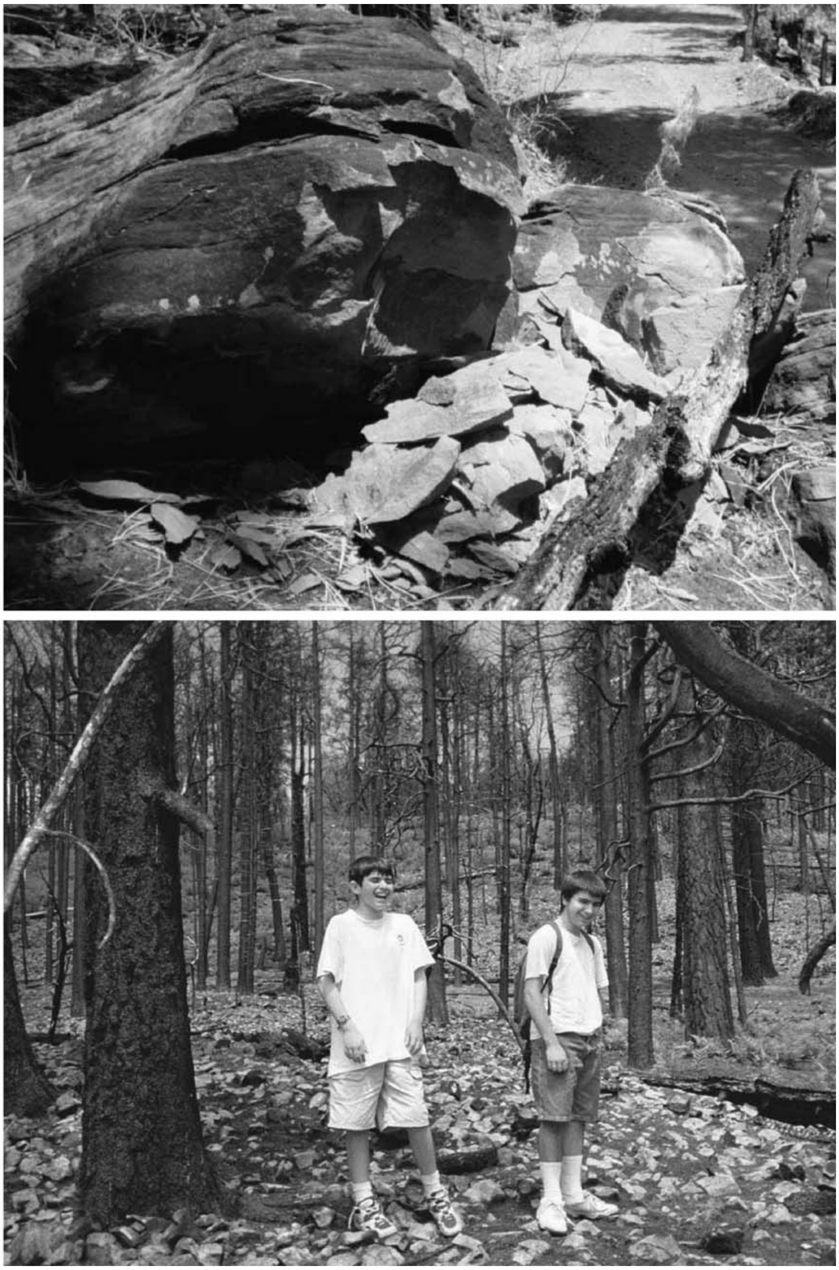

Fig. 11. The potential for fire shattering of entire boulders. (A) This image illustrates shattering of half of a 2-m diameter sandstone boulder near site 14. (B) This image illustrates the position of site 12, creating a humorous condition for field assistants brought to help survey fire-shattered boulders.

and yet he observed that fires are able to turn boulders into rubble. Thus, fire may be a key agent in pre-paration of 10–20-cm diameter clasts for fluvial transport.

If fires do obliterate boulders, producing clasts more readily transported by slope and fluvial processes, then wildfires become extraordinarily important agents of landscape evolution. The importance of boulders influencing slope evolution (Wahrhaftig, 1965; Abrahams et al., 1985; Allison and Higgitt, 1998) received new support from a study of ^{26}Al and ^{10}Be nuclides (Granger et al., 2001). Granitic boulders and bedrock emerge as fine sediment erodes rapidly; because boulders erode more slowly than do regolith-covered catchments, boulders control overall rates of erosion and drive morphogenesis (Granger et al., 2001). If agents, such as fire, can obliterate boulders in a single mountain wildfire event, then wildfires have the potential to be key limiting agents in the geomorphic evolution of bouldered slopes—essentially allowing drainages to develop more rapidly in fired locations.

Processes of wildfire erosion of boulders are not limited to currently forested mountains. Consider, for example, the granitic pediment and inselberg mountain landscapes of the Mojave and Sonoran Deserts (Abrahams et al., 1985; Oberlander, 1989). The Holocene is a hyper-arid anomaly in the western USA (Smith et al., 1983). Woody plants were far more abundant in wetter phases of the Quaternary (Spaulding, 1990; McAuliffe and Van Devender, 1998). Wildfire, thus, may have been an important geomorphic agent in desert geomorphology, creating locally important patterns of hillslope erosion through degrading boulders into sizes more compatible with hydraulic transport (Abrahams et al., 1988, 1990; Allison and Higgitt, 1998).

6. Concluding argument for controlled burn studies

This study was made possible by the serendipity of a major wildfire in a location of a prior survey of rock surfaces. Results highlight both agreements and complexities in comparisons between field results and experimental research on the effects of fire on rock weathering.

One scaling solution to link wildfires and laboratory studies would be to institute controlled studies of rock weathering at planned burns. Controlled burns do not have the intensity or longevity of wildfires. However, since we are all in the very early stages of this science, currently driven by data generated from "endpoints" of intense wildfires and controlled experimental research, the sort of intermediate data gathered by monitoring the effects of controlled burns on carefully planted and monitored rock samples might allow researchers to link experimental studies and serendipitous studies of wildfires.

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