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The influence of solar-induced thermal stresses on the mechanical weathering of rocks in humid mid-latitudes

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ABSTRACT: The role of solar-induced thermal stresses in the mechanical breakdown of rock in humid-temperate climates has remained relatively unexplored. In contrast, numerous studies have demonstrated that cracks in rocks found in more arid mid-latitude locations exhibit preferred northeast orientations that are interpreted to be a consequence of insolation-related cracking. Here we hypothesize that similar insolation-related mechanisms may be efficacious in humid temperate climates, possibly in conjunction with other mechanical weathering processes. To test this hypothesis, we collected rock and crack data from a total of 310 rocks at a forested field site in North Carolina (99 rocks, 266 cracks) and at forested and unforested field sites in Pennsylvania (211 rocks, 664 cracks) in the eastern United States. We find that overall, measured cracks exhibit statistically preferred strike orientations (47° ± 16), as well as dip angles (52° ± 24°), that are similar in most respects to comparable datasets from mid-latitude deserts. There is less variance in strike orientations for larger cracks suggesting that cracks with certain orientations are preferentially propagated through time. We propose that diurnally repeating geometries of solar-related stresses result in propagation of those cracks whose orientations are favorably oriented with respect to those stresses. We hypothesize that the result is an oriented rock heterogeneity that acts as a zone of weakness much like bedding or foliation that can, in turn, be exploited by other weathering processes. Observed crack orientations vary somewhat by location, consistent with this hypothesis given the different latitude and solar exposure of the field sites. Crack densities vary between field sites and are generally higher on north-facing boulder-faces and in forested sites, suggesting that moisture-availability also plays a role in dictating cracking rates. These data provide evidence that solar-induced thermal stresses facilitate mechanical weathering in environments where other processes are also likely at play. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: weathering; insolation; thermal stress; rock cracking

Introduction

Mechanical weathering comprises a key component of critical zone processes and overall landscape evolution in all environments. The majority of existing physical weathering studies, however, have focused on dry and/or cold climates. Few studies have specifically examined physical weathering in humid mid-latitude climates, despite the fact that there is a growing appreciation for the role of moisture, and moisture-associated mechanical weathering in dictating surface processes (Hancock *et al.*, 2011; Pelletier and Baker, 2011). Furthermore, a majority of Earth's population lives in these areas, and there is increasing interest in their long-term landscape evolution (e.g. Gallen *et al.*, 2013; West *et al.*, 2013; Jin *et al.*, 2014).

A compilation of published orientations (McFadden *et al.*, 2005; Adelsberger and Smith, 2009; Eppes and Griffing, 2010; Eppes *et al.*, 2010a; D'Arcy *et al.*, 2014) of over 4000 cracks, on a broad range of common rock types, from mid-latitude desert locations around the globe reveals that measured macro-cracks are steeply dipping and strike northeast (Eppes *et al.*, 2015). These preferred orientations of cracks have been interpreted as being the result of differential stresses that arise due to repeating diurnal patterns of directional heating and cooling of the rock surface by the sun (McFadden *et al.*, 2005; Eppes *et al.*, 2010a; Eppes *et al.*, 2015). It is furthermore hypothesized that the repeating geometry of thermal stresses imparted by diurnal solar cycles results in preferential propagation of microfractures with favorable orientations with respect to this stress (Eppes *et al.*, 2015). If this hypothesis is correct, then a majority of microfractures within any given rock on Earth will be densest in these preferred orientations due to the ubiquitous and continuous nature of diurnal insolation. As such, this denser population of fractures will have a higher probability of being propagated by other mechanical weathering processes such as freezing, biological processes or salt shattering. Thus, we hypothesize that preferred crack orientations may be found in a range of environments besides deserts, even where other mechanical weathering processes readily proceed.

Here we examine for the first time rock crack data for boulder fields located in the humid temperate mid-latitude climates of North Carolina and Pennsylvania, USA (Figure 1), the latter of which has been long-postulated to have been influenced by the sun (Wherry, 1912). We find that, as with mid-latitude

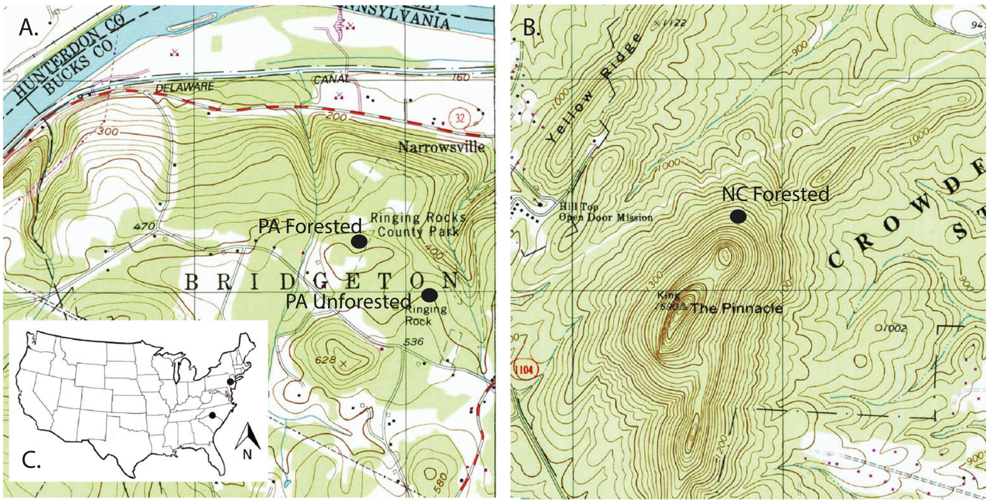

Figure 1. Field site locations. Both topographic maps are 1:24 000 scale. (A) Ringing Rocks County Park, Pennsylvania (unforested site UTM zone 18 4490200.02 m N 489030.10 m E, and forested site UTM zone 18 T 4490442.09 m N 489008.12 m E). (B) Crowders Mountain State Park, North Carolina (forested site UTM 17S 471599 E 3896219 N). (C) Eastern United States. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

deserts, boulders in these locations also exhibit cracks with preferred orientations. As such, these data provide evidence of the potential importance of insolation-induced thermal stresses in cracking rocks even in climates where other processes are typically thought to dominate.

Field Sites

Kings Pinnacle, Gastonia, North Carolina

Kings Pinnacle is an erosion remnant (monadnock) that stands about 240 m above the surrounding piedmont with 30–45 m vertical cliffs (Sarver, 1993). Located in Gaston County, North Carolina within the Kings Mountain belt, the peak is comprised primarily of Paleozoic meta-sedimentary and meta-volcanic rocks of the Battleground Formation. The selected field site is a ~2000 m^2 coarse debris fan that outcrops as a boulder field (Figure 2A) located in a deciduous forest on the north-facing slope of Kings Pinnacle with a gradient of ~22° (Horton, 2008). Tree canopy cover at the site is ~80–90% and is a mix of deciduous hard wood trees with sparse conifers. Topographic shading to the south by Kings Pinnacle decreases direct sunlight by a total of about one hour (½ hour later sunrise and ½ hour earlier sunset) during winter months. We have observed that any given boulder in the field site receives periodic direct sunlight in all seasons with higher overall direct sunlight in the winter months due to lack of foliage.

Similar debris fans located in nearby regions are thought to be most active during extreme precipitation associated with hurricane activity, and they are commonly mid- to mid-late Holocene in age (Kochel and Johnson, 1984). A soil pit dug for this study on the debris fan exhibits Bt soil horizonation that is similar in development to a mid-Holocene aged soil described for a nearby chronosequence of river terraces (Layzell *et al.*, 2012). Radiocarbon dating of a piece of charcoal found within the pit returned an age of 3600 ± 29 calibrated years before present (cal yr BP). Rocks within the boulder field are derived from the Kings Pinnacle and are fine to coarse grained, foliated aluminous quartzite.

Modern climate is characterized by hot, humid summers and moderate, short winters. Annual precipitation is about 109.1 cm with 3 cm of snowfall on average per year. Average temperatures range from 10.6 °C in January to 31.9 °C in July, with a mean annual temperature of 15.75 °C (http://www.usclimatedata.com). Vegetation in this area is dominated by mature deciduous hardwoods with minimal understory.

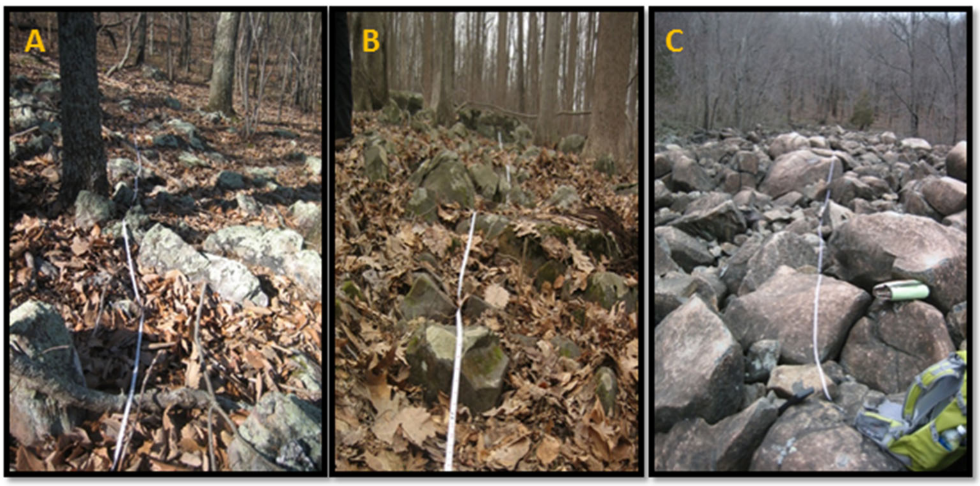

Figure 2. Photographs of representative transects where data was collected in each boulder field. Tape measure in all photographs is ~1 cm wide. (A) North Carolina Forested site. (B) Pennsylvania Forested site. (C) Pennsylvania Unforested site. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Ringing Rocks Park, near Allentown, Pennsylvania

Ringing Rocks is a 7–8 acre boulder field located in east-central Pennsylvania in Bucks County within the Triassic Gettysburg-Newark Lowlands. Boulder fields such as Ringing Rocks and the nearby Hickory Run are attributed to peri-glacial processes acting during the latest Pleistocene (Potter and Moss, 1968; Psilovikos and Van Houten, 1982). Ringing Rocks is comprised of rocks from the Coffman Hill diabase sill which outcrop about 100 m above the current channel of the nearby Delaware River. The field area consists of a boulder-strewn area located in a decidiuos forest with sparce conifers (Figure 2B) located to the north-northwest of a large open, unforested boulderfield with a ~~gentle~~ (8) northwesterward oreinted slope (FIgure 2C). Tree canopy cover at the unforested site was zero and at the forested site was ~80–90%. Topographic shading at the forested site reduces direct sunlight by about one hour (½ hour later sunrise and ½ hour earlier sunset) during all seasons.

Climate in this region is humid subtropical with hot and muggy summers and cold winters. Annual average precipitation is 115.2 cm while annual average snowfall is 84 cm. Average monthly temperatures range from 2.2 °C in January to 29 °C in July with a mean annual temperature of 10.6 °C (http://www.usclimatedata.com, 2015). Vegetation in the forested portion of the boulder field consists of several deciduous hardwoods, including red maples, black birch, black cherry, and American elm (Smith *et al.*, 2004) with minimal understory.

Methods

We collected rock and crack data in three locations, the forested Kings Pinnacle boulder field in North Carolina (NC Forested), the forested Ringing Rocks boulder field (PA Forested) and the unforested Ringing Rocks boulder field in Pennsylvania (PA Unforested). For each of these sites, we established four ~30 m transects across representative portions of the boulder fields (Figure 2). For each transect, we selected the boulder closest to every 0.5 m interval which met a size criteria of 10 to 50 cm maximum diameter for a total of about 100 rocks per location. These criteria allowed us to avoid small rocks that were more likely to be rotated or disrupted through time as well as very large rocks that would be outliers in the datasets. For every boulder, we recorded rock type, dimensions (length × width × height), and long axis orientation. In addition, we noted if the rock exhibited evidence of granular disaggregation (individual crystals that easily popped off of the surface of the rock, indicating cracking along intergranular boundaries), fabric such as foliation or bedding, or spalling (surface-parallel fractures within a centimeter of the surface). We avoided clasts that were notably wobbly or loose and therefore may have been recently disturbed. We recorded the percentage of the rock surface that was covered in lichen or dirt and removed any that could be gently brushed away with our fingers.

For every boulder, we collected data for all visible cracks, defined as any linear void greater than 2 cm in length. The geometry of cracks smaller than this length is difficult to measure accurately (Eppes *et al.*, 2010a), however, we made note if we observed any other crack < 2 cm in length on the rock. For each boulder, we divided the rock up into geographically oriented quadrants by drawing north–south and east–west trending gridlines on the top surface of the rock (Figure 3). We then recorded the total number of cracks that fell in each of the quadrants. If a crack crossed two quadrants, it was counted twice. We further recorded the total number of cracks located in the upper versus lower hemispheres of the rock (defined by 50% of the rock height above the surface).

Figure 3. Photograph example of a rock marked for measuring cracks within different locations on the rock surface. Pencil is ~15 cm long. Each rock was divided into quadrants using chalk and a compass. We recorded the quadrant(s) location of all measured cracks, as well as if the crack was located in the upper or lower hemisphere of the rock. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

For every crack > 2 cm in length, we measured its length, maximum width and its orientation including both strike (right-hand rule) and dip. After McFadden *et al*. (2005), we noted if the crack was parallel to the rock's surface or longitudinal axis or to any visible heterogeneity such as a vein or foliation. We were unable to collect crack strike data for the PA Unforested site because of the strong magnetic properties of this portion of the boulder field. Measured compass readings were clearly disrupted within about 0.5 m of the boulder field surface. After noticing the anomaly, a series of about a dozen tests were conducted in different sites on the boulder field by team members. One person would stand with the Brunton Compass pointing towards 0° north, as verified by a distant observer with a second compass, and then the person would slowly kneel down keeping the compass steady and pointing north. As the kneeler approached within about 20–30 cm of the boulder surface, the needle would wildly shift and would not stabilize. Such compass disruption has been anecdotally noted for the Ringing Rocks Boulder field, and is likely attributed to the high iron (Fe) content of the diabase. We repeated these experiments and observed no such compass disruption for the PA Forested site, likely due to the fact that individual boulders are isolated from one another by soil matrix and thus their Fe mass is insufficient to disrupt the compass.

Statistics

Using Oriana 3 software, we plotted circular data using both bidirectional and unidirectional circular histograms, and calculated circular statistics. Given that we collected all strike data using the right-hand rule, the former also depicts the dip direction of cracks, whereby crack down-dip direction is 90° to the right (clockwise) of the strike in a rose diagram. Vector mean, similar to a linear regression but for circular data, is calculated for all orientation datasets. We also tested orientation data for uniformity using both Raleigh and Rao's tests, which apply to unimodal and multimodal data respectively. Low p-values indicate preferred orientations or non-uniformity (e.g. Mardia and Jupp, 2009).

Results

We measured 930 cracks on 310 clasts. The average number of cracks per clast varied from one per rock at the PA Unforested site to three per rock at NC Forested site and six per rock at PA Forested site (Table I). Cracks observed at the PA Forested site were on average longer than cracks observed at the NC Forested site or the PA Unforested site (Table I). Both the PA and NC Forested sites exhibited significantly more cracks overall including those < 2 cm than the PA Unforested site (Table I).

The vector mean and 95% confidence interval of the strikes for all cracks in both forested sites ($n = 879$), is 47 ± 16° with both Raleigh and Rao *p*-values indicating statistically preferred orientations (Figure 4 and Table II). This mean crack strike reflects the combination of the more northeast 42 ± 17° vector mean of the PA Forested sites (Figure 4C and Table II) and the more east-west 61 ± 31° vector mean of the NC Forested site (Figure 4B). For the PA Forested site, the vector mean calculated only for cracks that are not parallel to rock heterogeneities such as foliation or planar facets is very similar to the crack dataset as a whole (Figure 5). When cracks related to rock heterogeneities are removed from the NC Forested site data set, the remaining crack orientations are strongly bimodal with cracks striking in the north–south direction and in the east–west direction, and thus strongly favored dip directions to the south and to the west (Figure 5B).

In order to examine orientations of cracks as a function of both crack size and rock size, we divided our data sets into three groups of crack and rock sizes. Overall at both the PA and NC Forested sites, cracks exhibit far more orientation variance when they are relatively short and thin (less than 1 cm^2 in area) and when they are found in smaller boulders (less than 10,000 cm^3; Figure 6). Intermediate size cracks, and cracks found in intermediate size rocks exhibit vector means whose variance and orientation (Figures 6B and 6E) are similar to that of all cracks (Figure 4A). Larger cracks (>3 cm^2) and larger rocks (>30,000 cm^3) with cracks are less common, and tend to exhibit more of a bi- or tri-modality (Figures 6C and 6F).

The average dip angle and standard deviation of all cracks, including the PA Unforested site is (52° ± 24°) (Figure 7). This average was similar for all sites: NC Forested site (50° ± 25°, $n = 262$), PA Forested (53° ± 24°, $n = 610$) and PA Unforested (56° ± 22, $n = 54$) sites (Figure 7). There appears to be a slight east dipping preference for cracks in the Pennsylvania data set (slightly more cracks with northerly strikes; Figure 4F) and a slight west-dipping preference in cracks from the North Carolina data set (slightly more cracks with southerly strikes; Figure 4E); therefore these preferences cancel out in the overall data set (Figure 4D).

Spalling was commonly observed at all sites; however rocks at the PA Forested site much more commonly exhibited spalls in comparison to the PA Unforested site or the NC Forested site (Table I). No rocks observed in the PA Unforested site exhibited evidence of granular disaggregation, whereas the coarse-grained quartz-rich portions of the boulders at the NC Forested site showed common evidence of active granular disaggregation (crystals loosening along grain boundaries), and some rocks of the PA Forested site did as well (Table I).

The cardinal location of cracks on boulder surfaces varied somewhat by site, with a slight preference for the northern and eastern hemispheres in the PA Forested site and a slight preference to the northern and western hemispheres for cracks measured in the NC Forested site (Figure 8). Cracks measured at the PA Unforested site exhibit a slight preference towards southern and eastern hemispheres. Overall, we observed more cracks in the upper hemispheres of boulders than in the lower, however as we did not turn rocks over to examine their undersides, this difference is likely attributable to surface area exposed.

Discussion

Here for the first time, we demonstrate that a majority of cracks in rocks found in boulder fields of humid temperate mid-latitudes exhibit preferred orientations that are similar to those observed in mid-latitude deserts. As with prior data sets, these orientations provide strong evidence that diurnal insolation plays a role in driving rock fracture in these moister climates. Here we explore the possible stresses and mechanisms that give rise to these preferred orientations, doing so in the context of pre-existing fracture mechanic concepts, instrumentation data, and numerical models of solar-induced thermal stresses in rock. We also discuss the potential differences in weathering processes that may arise in these temperate sites compared to previously reported desert sites that exhibit similar rock-cracking characteristics.

Insolation-related crack growth under humid-temperate conditions

Overall, preferred crack orientations in rocks found in humid climates might be somewhat unexpected, in that most geomorphologists would assume that in the moisture-rich environment of these relatively cool-temperature forests, other mechanical weathering processes such as biological activity or freezing would dominate the manifestation of cracking observed there. Or, given that there might be an overall higher potential for larger diurnal temperature cycles in deserts (particularly high-altitude ones), or for more rapid rates of temperature change and thus the potential for thermal shock, rocks found in deserts might be expected to be more prone to thermal weathering. Increasingly, however measurements of rock surface temperatures in a variety of climates reveal an azonality of diurnal temperature ranges and rates of temperature change (e.g. Sumner *et al.*, 2004). Also, there is little if any field data which supports the often-cited 2 °C/min threshold for cracking by thermal shock (Boelhouwers and Jonsson, 2013); and it is likely that rates of temperature change of much lower magnitude can lead

Table I. General rock and crack characteristics for each site. ± is 1 standard deviation for all calculations

Site	Number of rocks	Average cracks/rock	Average rock length (cm)	Percentage of rocks with cracks	Percentage of rocks with spalling	Percentage of rocks with granular disaggregation	Percentage of rocks with < 2 cm cracks	Average crack length (mm)
NC Forested	99	3 ± 2	31 ± 9	79	35	20	95	67 ± 45
PA Forested	109	6 ± 5	30 ± 11	95	74	0.9	92	89 ± 63
PA Unforested	102	1 ± 0.9	30 ± 8	35	23	0	34	66 ± 40

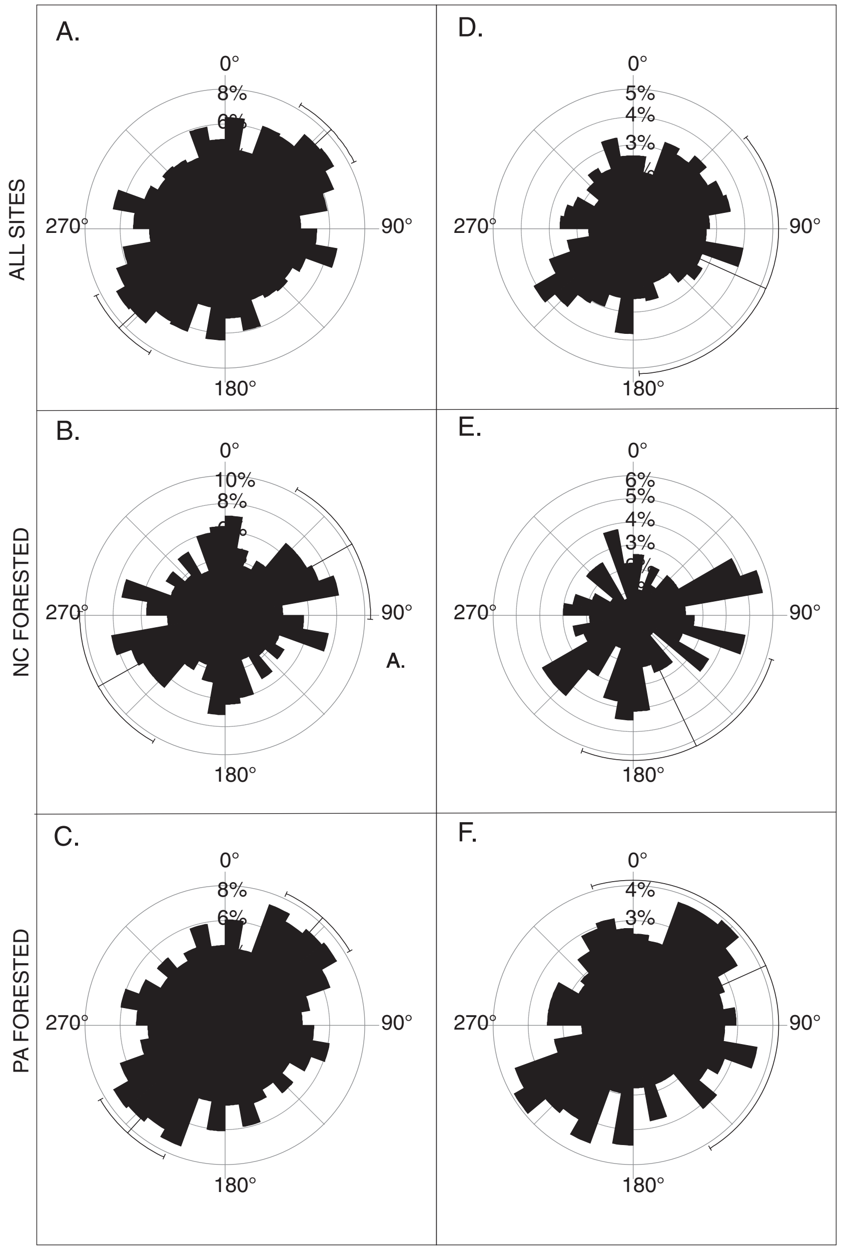

Figure 4. Rose diagrams of crack strike orientations. Lines and brackets indicate vector mean and 95% confidence interval. Statistics are available in Table II. (A) Biaxial orientations for at all locations. (B) Biaxial orientations at NC Forested site. (C) Biaxial orientations at PA Forested site. (D) Uniaxial orientations at all locations. (E) Uniaxial orientations for NC Forested site. (F) Uniaxial orientations for PA Forested site.

Table II. Crack orientation data and statistics (Figures 4–6)

Site	Total cracks observed	Strike (vector mean and 95% confidence interval)	Raleigh *p*-value	Rao *p*-value	Average dip
All sites	930	46.9 ± 15.7	0.002	<0.01	52.8
NC Forested	266	60.6 ± 31	0.194	<0.01	50.7
PA Forested	610	42.1 ± 17.2	0.005	<0.01	53.7
PA Unforested	54	NA	NA	NA	NA
All Sites SLF Removed	436	174.1 ± 149.4	0.754	<0.01	NA
NC Forested SLF Removed	105	160.3 ± 51.2	0.093	$0.10 > p > 0.05$	NA
PA Forested SLF Removed	331	312.5 ± 254.7	0.907	$0.50 > p > 0.10$	NA
All Sites Small Cracks	551	52.1 ± 35.2	0.278	<0.01	NA
All Sites Medium Cracks	221	52.6 ± 15.7	0.002	<0.01	NA
All Sites Large Cracks	103	30.8 ± 26.2	0.104	<0.05	NA
All Sites Small Clasts	445	61.7 ± 32.2	0.22	<0.01	NA
All Sites Medium Clasts	352	44.5 ± 41.3	<0.01	<0.01	NA
All Sites Large Clasts	78	9.9 ± 73.6	0.748	$0.10 > p > 0.05$	NA

Note: NA, not available.
SLF = Surface- Longitudinal- and Fabric- parallel cracks as defined by McFadden *et al.* (2005).

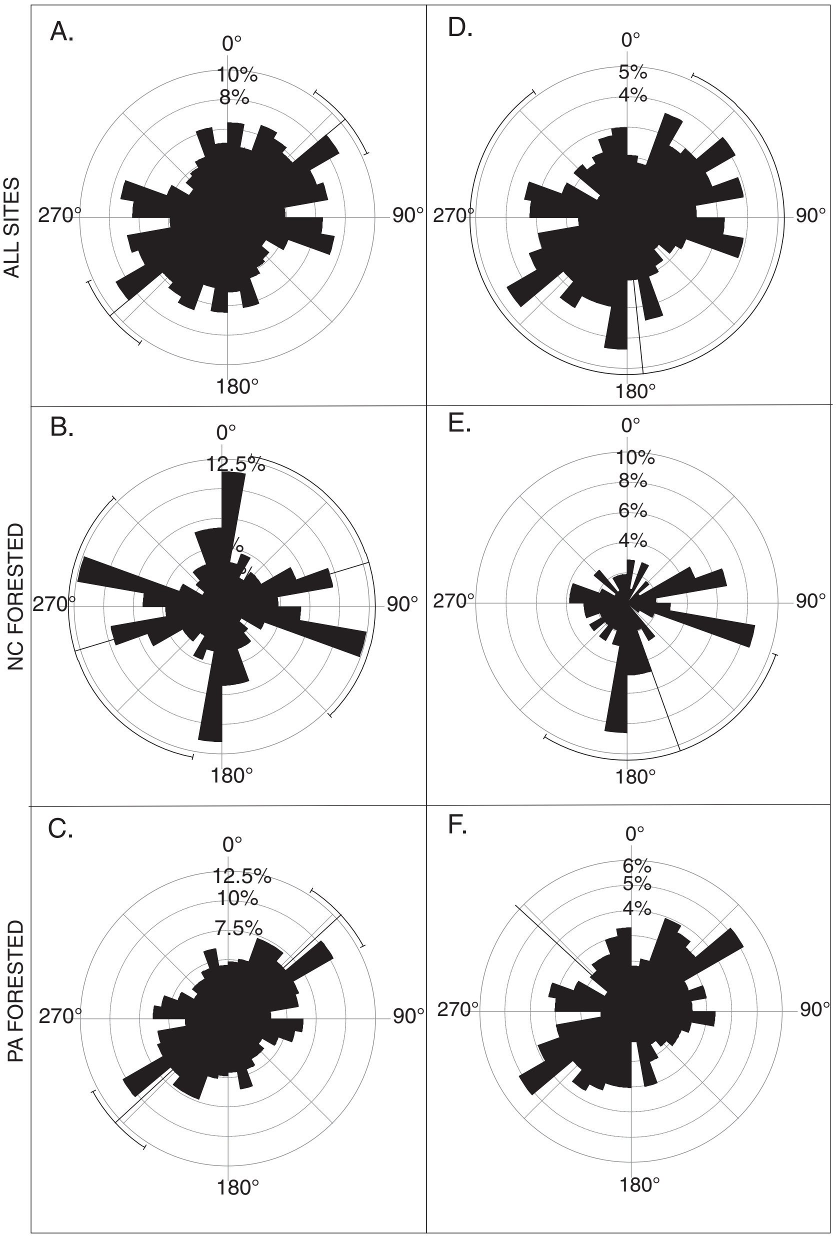

Figure 5. Rose diagrams of crack orientations with rock characteristics with cracks that were found to be parallel to rock heterogeneities (e.g. foliation, joint faces) removed from the dataset. Lines and brackets indicate vector mean and 95% confidence interval. Statistics are available in Table II. (A) Biaxial orientations for all sites. (B) Biaxial orientations for NC Forested site. (C) Biaxial orientations for PA Forested site. (D) Uniaxial orientations for all sites. (E) Uniaxial orientations for NC Forested site. (F) Uniaxial orientations for PA Forested site.

to cracking by fatigue. If insolation-related cracking is proceeding primarily due to slow-subcritical crack growth by fatigue, then the number of stressing cycles as well as their magnitude should influence cracking rates over long timescales. Forested sites such as that described herein have been demonstrated to experience more temperature cycling (Gómez-Heras *et al.*, 2008) than open sites that are typical in deserts. Thus, we propose, that due to the ubiquitous and constant influence of diurnal thermal cycles, cracks formed through diurnal temperature cycling might be expected regardless of climate or of the relative efficacy and activity of other processes.

Numerical modeling of thermal stresses that arise due to simple diurnal insolation without any influence of water due to both grain scale (Holzhausen, 1989; Molaro and Byrne, 2015) and rock scale (Shi, 2011) heterogeneities and/or differential heating indicate that solar-induced thermal stresses arise in rock daily. These stresses scale, at least in part, with diurnal temperature range (Holzhausen, 1989; Molaro and Byrne, 2015), and are thus likely higher in deserts than in more humid environments. Nevertheless, despite the overall low magnitudes of thermal stresses (generally less than 15 MPa) calculated using humid-temperate climate data as inputs (Shi, 2011), these stresses are likely sufficient for slow, time-dependant crack growth (also known as sub-critical crack growth in the manner of Atkinson, 1984).

Furthermore, calculated times of peak solar-induced rock scale (Shi, 2011) and grain-to-grain (Eppes *et al.*, 2015) stresses coincide with peaks in the magnitude of observed cracking, as measured by acoustic emissions in boulders placed in humid temperate sites within 20 km of the NC Forested site (Eppes *et al.*, 2012; Warren *et al.*, 2013). Warren *et al.* (2013) also observed that cracking was typically coincident with short-term temperature cycling driven by weather such as wind or cloud-cover. Such short-term temperature cycling has been observed in a range of climates (e.g. Jenkins and Smith, 1990; Hall and André, 2001) and direct correlations have been made between the frequency of such short-term thermal cycling and visible rock degradation (Gómez-Heras *et al.*, 2008). Thus all of

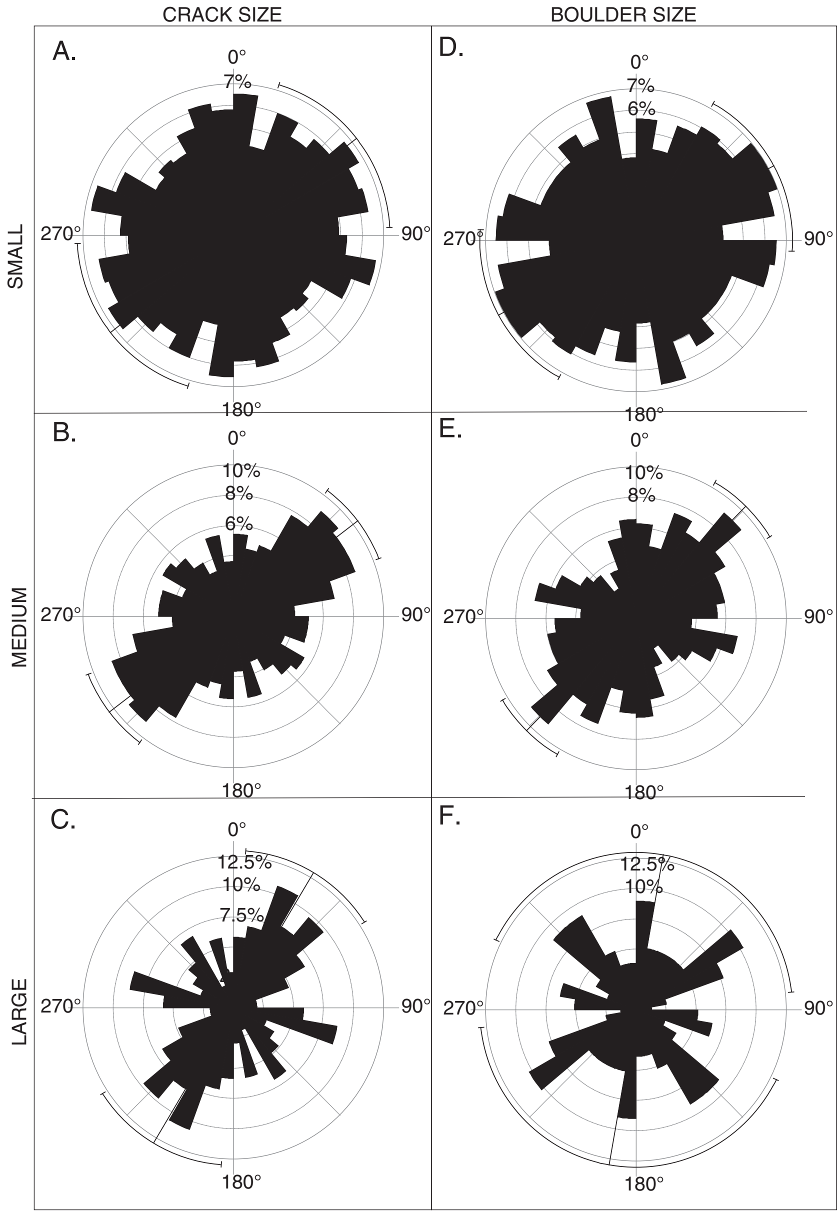

Figure 6. Rose diagrams of crack orientations by crack size and by boulder size. Lines and brackets indicate vector mean and 95% confidence interval. Statistics are available in Table II. (A) Small (>0 and < 1 cm^2), (B) medium (>1 and < 3 cm^2), and (C) large (>3 cm^2) cracks. (D) Small (>0 and < 10 000 cm^3), (E) medium (>10 000 and < 30 000 cm^3), and (F) large (>30 000 cm^3) boulders.

these data and numerical models support the potential of diurnal thermal cycling in driving rock fracture in the humid-temperate climates of the field sites described herein.

Directional cracking

The recurrence of a majority of cracking at specific times of day as predicted by numerical modeling using temperate-climate weather data as inputs (Shi, 2011) and as observed in instrumentation data (Warren *et al.*, 2013) leads to an explanation of how insolation contributes to directionality of visible cracks in subaerially exposed boulders. Instrumentation studies show that for boulders exposed to diurnal insolation, unique temperature fields are imparted across the rock surface throughout the day (e.g. Hall, 1997; Hall and André, 2001; Eppes *et al.*, in preparation) as the sun traverses the sky. Thus, insolation-driven, recurring peak thermal stresses themselves should also be manifest in particular and repeating orientations at given times of day, regardless of climate. It is hypothesized that such repeating geometries of maximum thermal stresses will result in preferential subcritical growth (very slow) of pre-existing cracks whose orientations are favorable with respect to the geometry of these peak stresses (Eppes *et al.*, 2015). Our data support this conceptual model for the growth of cracks with preferred orientations in that we see high variance in the orientations of relatively small fractures that gives way to more preferred orientations with larger fractures (Figure 6). These results suggest that at least some population of macrofractures arise relatively quickly after the initial deposition of the boulders similar to what has been observed in desert environments (D'Arcy *et al.*, 2014). The field dataset presented herein suggests that through time, however, both microfractures and macrofractures with certain orientations propagate preferentially over others.

We also observe that cracks in smaller boulders exhibit a higher variance in crack orientation. Such boulders are more prone to disturbance from tree root growth, or frost heaving changing the orientation of the rock over time. Also, however, calculated solar-induced diurnal stresses increase with rock size within the range of sizes for which we collected data (Shi, 2011). As such, cracks in small rocks may not as readily

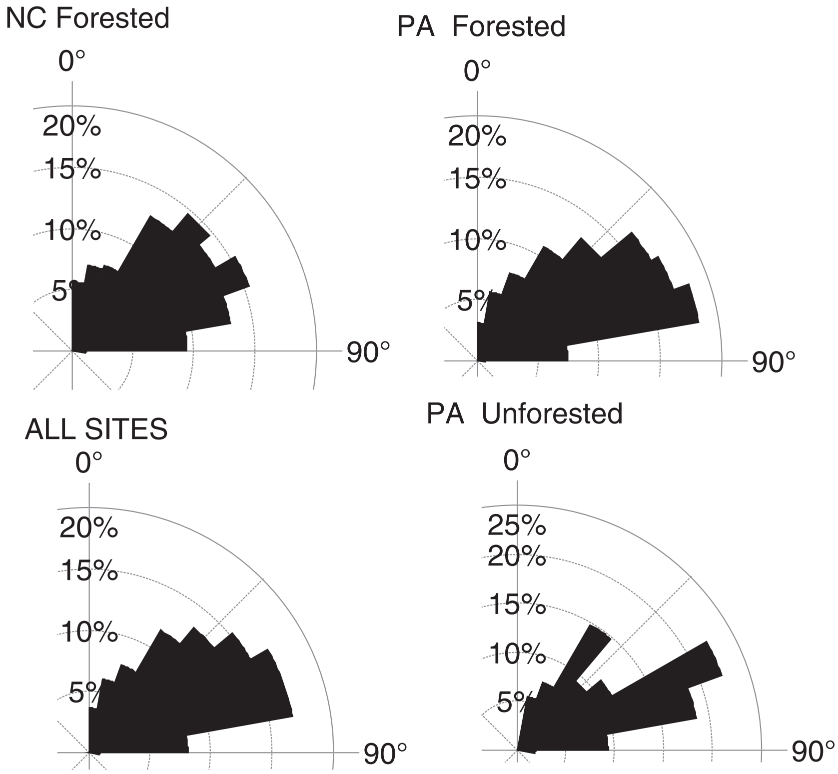

Figure 7. Dip angles plotted as circular histograms for all field sites. See text for statistics.

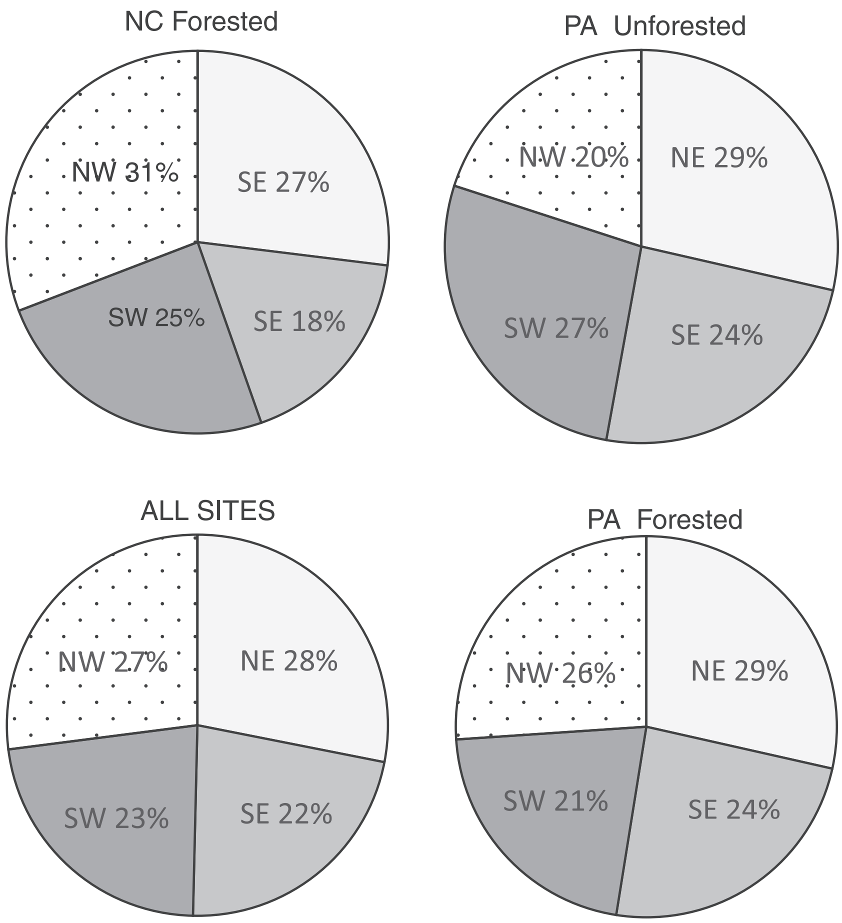

Figure 8. Pie graphs, plotted by site, of the percentage of measured cracks located within different rock quadrants (see text for methods). The majority of observed cracks overall were located within the northern hemisphere of rocks.

propagate due to thermal stresses, leading to less preference in crack orientations; our data are consistent with this modeling result.

Coincident and related weathering processes

We postulate that observed preferred fracture orientations are not necessarily the result of crack propagation solely by thermal stresses. Instead, it is likely that other mechanical weathering processes are exploiting weathering that is initiated by thermal cycling. We hypothesize that the preferential, albeit slow, propagation of certain cracks that are favorably oriented with respect to solar-induced maximum thermal stresses will result, over long (century–millennia) timescales, in an oriented heterogeneity that will act as a directional weakness in the rock much like a bedding plan or joint set. Rock's overall propensity for cracking in directions parallel to such heterogeneities or in directions with higher densities of microfractures is supported by both field observations (e.g. McFadden *et al*., 2005; Eppes *et al*., 2010a) and laboratory experiments (e.g. Nara and Kaneko, 2006). Thus, we suggest that any simultaneously- or alternatingly-acting mechanical weathering processes such as freezing (e.g. Hallet, 2006), biological processes (e.g. Viles, 2012), or salt-related processes (e.g. Grossi *et al*., 2011), that affect a rock exposed to diurnal insolation will be more likely to propagate fractures within this denser, thermal-related population of sub-parallel cracks over fractures that fall in other orientations that occur less frequently in the rock. For example, the PA Forested site exhibits a higher fracture density overall, which is possibly reflective of the stronger efficacy of freezing processes acting on cracks with preferred orientations at this location compared to the more-southerly NC sites. Although no rock temperature data is available for this region, the climate of the Pennsylvania site, located just outside of the Laurentide Ice Margin, would be expected to be characterized by sufficiently long periods of sufficiently cold and moist (due to snowfall) conditions to lead to weathering by either freezing or segregation ice growth (summarized in Hallet, 2006) throughout the Holocene, and particularly in the late-Pleistocene. Pennsylvania's modern climate suggests that even today, there are extended periods of time when air temperatures are below freezing. The climate of the North Carolina boulder field was likely characterized by much shorter duration and lower magnitude annual cold periods throughout the Holocene. For example, an 11-month study of rock surface temperatures collected for a granite boulder within 20 km of the field site during a colder than average year (Eppes *et al*., in preparation) reveals that rock surface temperatures fell within the 'frost cracking window' (−3 to −8 °C) for only 7% of the period of record. These data suggest that at a minimum freezing cycles and extended periods of freezing temperatures in North Carolina are much less common under current climate conditions than in Pennsylvania. In addition, however, given the likely latest Pleistocene age of the PA Forested boulder field, compared to the mid-Holocene age of the NC Forested boulder field, it might be expected to have higher crack densities due simply to its age. Also, the higher moisture-availability in the forested sites overall, will enhance the efficacy of freezing processes (see later). Finally, the differences between rock types at the two sites also precludes drawing strong conclusions from the overall differences in crack populations, because numerous factors including mineral composition and crystal size will play a roll overall in any weathering process.

In addition to the potential exploitation of thermal-related cracks by other mechanical weathering processes, many of these processes themselves are potentially influenced by thermal cycling. For example, the potential for salt-phase transitions, a metric employed to approximate the efficacy of salt-related processes in rock break-down, is sensitive to both the seasonality and the magnitude of thermal fluctuations as measured in different climates (e.g. Grossi *et al*., 2011). Although not applicable to the intrusive rocks of this study, wet–dry cycles and associated mudstone mechanical degradation has also been shown to be temperature-cycle sensitive (Zhang *et al*., 2015). Thus the fact that we observe higher crack densities in the forested field sites (Table I) could be attributable to the fact that these sites experience more, and more-varied, temperature cycling due to canopy shading (Gómez-Heras *et al*., 2008). These higher numbers of thermal cycles could in turn, serve to accelerate fracture propagation via a number of different loading mechanisms, not just insolation. It has long been recognized that different weathering mechanisms can result in an equifinality of rock crack form (e.g. Cooke and Warren, 1973).

The role of moisture

For both the NC and PA Forested sites, we observe slightly higher crack densities on the northern side of boulders. These data are consistent with observations from numerous weathering studies that indicate that more moisture-rich portions of outcrops tend to have evidence of more intense weathering (e.g. Sass, 2005; Twidale and Romaní, 2005). In addition to the potential influence of rock geometry on moisture conditions, rock surface cracks oriented in certain directions may retain water more effectively than others due to a higher degree of shading by the crack flanks, (Moores *et al*., 2008). Thus, higher degrees of weathering on high-moisture portions of rock, as well as of moisture-rich cracks, are often cited as evidence that insolation plays a lesser role than moisture-dependent processes (e.g. Twidale and Romaní, 2005).

Moisture, however, is one of the least-characterized and understood properties with respect to mechanical weathering processes (e.g. Hall, 1986; Sass, 2005). Weathering studies rarely if ever consider that the fracture mechanics of crack propagation itself, particularly for sub-critical crack growth, is moisture-dependent regardless of the loading mechanism (e.g. Atkinson, 1984; Brantut *et al*., 2013). Thus, if a rock experiences stress induced by thermal loading, those fractures with higher moisture content will tend to propagate more rapidly than drier cracks subject to the same magnitude of stress, due to the higher efficacy of moisture-dependent subcritical crack growth processes like stress corrosion. This tendency will be true for any and all loading mechanisms including other moisture-dependent stress-loading mechanisms themselves like freezing, salt crystallization or mineral hydration.

The fact that the PA Unforested site has overall fewer fractures than both other sites may be reflective of the fact that these rocks are likely characterized by much lower moisture content throughout the year due to minimal shading (and thus higher evaporation potential) and lower biological activity (lichens, leaf litter, etc.). This lack of moisture will lower the efficacy of all potential weathering processes. Also, as previously mentioned, this open site experiences fewer overall thermal cycles given its lack of tree canopy. Thus, crack growth rates by thermal-stress loading and/or other moisture-dependent stress-loading mechanisms like freezing would be expected to be much lower. Nevertheless, the fact that the PA Unforested fractures are most commonly found on the south-facing aspect of boulders, which experience higher diurnal temperature ranges (e.g. Sumner *et al*., 2007) and thus higher thermal stress (Holzhausen, 1989; Molaro and Byrne, 2015) gives rise to the possibility that in this relatively unusual moisture-limited unforested site in a humid-temperate climate, crack growth by thermal stress dominates over other processes.

Rock cracking style

In addition to the through-going fractures with preferred orientations that we measured in all sites, our data also provide evidence that the manifestation of mechanical weathering in both the North Carolina and Pennsylvania sites is characterized by additional crack types. Although we did not commonly observe the tell-tale polygonal-morphology of cracking that is commonly attributed to thermal shock (Hall and Thorn, 2014), we did observe crack types similar to those described in McFadden *et al*. (2005) and Eppes *et al*. (2010a): surface parallel fractures (spalling), fabric parallel fractures, longitudinal fractures (those parallel to the long-axis of the rock), and intergranular fractures. For the latter cracks, thermal stress is known to lead to granular disaggregation, particularly in coarse-grained rocks (Gómez-Heras *et al*., 2006; Eppes and Griffing, 2010), and we see evidence for such cracking along mineral grain boundaries in this study, particularly in the relatively coarse, quartz rich metamorphic rocks of the North Carolina site. We see less granular disaggregation and more spalling in the fine grained, darker rocks of the Pennsylvania sites overall, as would be expected from this previous work. We do not observe any evidence of granular disaggregation in the PA Unforested site, possibly due to case hardening (e.g. Conca and Rossman, 1982) by the varnish that characterizes these rocks in the open boulder field (Figure 2). In contrast, surface-parallel cracking is particularly dominant in the darker, and finer grained intrusive rocks of both the PA Forested and PA Unforested sites. Again, it is recognized that thermal stress, particularly induced by wildfires, can lead to such spallation (Goudie *et al*., 1992). Additionally, not only would such spalls have less chance to be preserved if the comprising crystals were being removed by disaggregation, but these finer, darker rock types are also thought to be more susceptible to thermal-cycling-related spalling (Gómez-Heras *et al*., 2006).

Comparisons with desert data

If we compare our boulder crack data with that of mid-latitude deserts, we see both similarities and differences. Crack density in the NC Forested and PA Unforested sites are on par with those determined for an ~140 ka surface in the Mojave Desert of southern California (Eppes *et al*., 2010b); whereas the PA Forested site has crack densities that are roughly double any of those observed in the same study. Few published studies, however, have collected data for all cracks, and instead have typically focused on larger cracks (e.g. McFadden *et al*., 2005; D'Arcy *et al*., 2014), or the orientations of sub-parallel cracks (Eppes *et al*., 2010a) so additional direct comparisons are difficult. Future research should address the relative efficacy of predicted higher solar-induced stress magnitudes versus higher moisture content.

A compilation of mid-latitude desert rock-crack data yielded a vector mean crack strike of 23° ± 11° (Eppes *et al*., 2015). The vector mean of our measured crack strikes (47° ± 16°) is more easterly. There are several possible explanations for this difference. First, the higher latitude of location of the PA Forested site, for which the majority of our crack data was collected would be predicted to result in more east–west oriented cracks given latitude differences in solar pathways (McFadden *et al*., 2005). Cracks measured in rocks at a relatively high-latitude site in the Gobi desert exhibit a vector mean orientation of 40° ± 13° (Eppes *et al*., 2010a). Thus our data also are consistent with the idea that latitude will play a role in insolation stresses due to the fact that the timing of peak stresses will be associated with different sun positions at different latitudes. A more dominant east–west mode could also indicate preferential moisture retention of pre-existing cracks that are generally larger in these humid sites compared to desert sites; or a difference in timing of summer precipitation between some previously studied desert sites and those studied herein (Moores *et al*., 2008). Examination of summer diurnal precipitation patterns for North Carolina (Prat and Nelson, 2014), however, reveals that afternoon precipitation dominates at the North Carolina site, similar to the monsoon-affected desert sites of the south-western United States, making the latter hypothesis less viable.

It is also expected that topographic shading will play a strong role in solar-induced thermal stress magnitude, as well as the timing of potential peak stresses that arise in any given rock (Leask and Wilson, 2003), and thus potentially in crack orientation. In general variations in topographic shading might therefore be predicted to generally add variance to crack orientations. Rocks from the NC Forested site, however, exhibit a strong bimodal distribution of crack orientations. These orientations are somewhat similar to bi- or multi-modal orientations of cracks on chert from desert pavements found on north-facing slopes in Egypt (Adelsberger and Smith, 2009). It is possible that this bi-modality is specifically reflecting southerly topographic shading that changes the timing of insolation, as well as its intensity during mid-day hours, resulting in two distinct times of cracking that in turn result in two distinct orientations. Topographic shading might also increase moisture retention of shade-parallel cracks (in the manner of Moores *et al*., 2008); however, additive shading to the south would be predicted to result in an increase in moisture-retention in north–south cracks rather than east–west ones. More detailed modeling results or additional field data from other slopes might provide insights into all of these possible effects.

Finally, dip angles measured in this study are similar to those measured in desert field sites, however dip direction in the deserts site was primarily to the southeast whereas herein we see more evidence of west dipping cracks. A more detailed examination of the orientation of rock scale stresses that arise in such topographically shielded locations would perhaps shed more light on these data.

Conclusions

The fact that cracks exhibit preferred orientations in boulders found in late-Pleistocene and Holocene aged deposits of humid-temperate mid-latitude locations provides evidence that solar-induced thermal stress-related processes may have played a significant role in the mechanical weathering of rocks in these locations during most of the Holocene. Specifically, we conclude that diurnally repeating geometries of thermal-stresses impart a directional heterogeneity in the propagation of rock microfractures within any given rock. Thus through time, other mechanical weathering processes acting in these humid environments have a higher probability of propagating the relatively denser population of insolation-related microfractures, resulting in the observed population of macrofractures whose orientations are related to insolation. The ubiquitous and continuous nature of insolation-related thermal cycling, compared to conditions necessary for other mechanical weathering processes, leads to the conclusion that thermal-stresses may represent a rate-limiting influence on mechanical weathering processes in humid regions and beyond. This conclusion contrasts with that of most geomorphic studies which commonly assume freeze–thaw to be the default physical weathering process that limits erosion and/or drives sediment supply in similar climates.

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