PHYSICAL WEATHERING IN ARID LANDSCAPES DUE TO DIURNAL VARIATION IN THE DIRECTION OF SOLAR HEATING

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ABSTRACT

Despite the prominent role of physical weathering in arid and semi-arid landscapes, there has been little study of the specific processes responsible for the rapid breakdown of subaerially exposed rocks. For example, many boulders and cobbles in deserts exhibit fine near-vertical cracks. Although workers have hypothesized that these and other cracks are initiated by diurnal heating and cooling, no convincing specific mechanism for their formation has been proposed. We have characterized these cracks at eight sites on surfaces of different ages in the Mojave, Sonoran, Chihuahuan Deserts and the high desert of central New Mexico. Our data reveal four basic types of cracks: longitudinal, surface-parallel fabric-related, and meridional. The orientations of the former three types are associated with clast shape and rock fabric. The azimuths of meridional cracks, however, are preferentially aligned north-south, typically with a nonrandom multi-modal distribution. We propose that these cracks are caused by tensile stresses that arise in the interior of clasts due to strong radial gradients in temperature that evolve and rotate in alignment with the sun's rays. We suggest that the multi-modal nature of crack orientations may be in part attributable to the seasonally varying, latitude-dependent solar elevation angle. Over millennial time scales, we suggest that this thermal cracking is an efficient weathering

process that, together with cumulic soil epipedon development, creates the key attributes of most desert pavements. In addition to individual clasts exposed on desert surfaces, this mechanism of cracking is potentially significant in other climates and on other planets, as well as for rock outcrops and for man-made structures.

INTRODUCTION

Physical weathering is the mechanical breakdown of rock materials into smaller particles. Together with chemical weathering, it plays a key role in the rock cycle by forming regolith, colluvium, sediment and soils at the Earth's surface. For example, in arid and semi-arid environments, in-situ physical weathering of pre-existing surface materials (e.g., boulders, lava flow surfaces) plays a critical role in desert pavement formation (McFadden et al., 1987, 1998; Amit et al., 1993; Wells et al., 1995), and in the decrease in boulder frequency and size on moraine crests (Birkeland, 1999). Physical weathering of these exposed clasts is often evident from granular disintegration. Near-surface or surface clasts of diverse rock types are commonly cracked throughout arid and semi-arid landscapes, evidently representing the initial stages of rock disintegration (Fig. 1). A large body of literature exists that describes mechanisms for growth and expansion of such cracks, but their *origin* has been debated for decades. Most recent textbooks addressing geomorphology and weathering (Ahnert, 1996; Bloom, 1998; Easterbrook; 1991; Cooke et al., 1993; Birkeland, 2000; Watson, 1992; Ritter et al.; 2002; Summerfield, 1992**)** and many researchers (e.g., Yaalon, 1970; Smith and Warke, 1997; Goudie et al., 2002) identify several processes as possible causes of cracking of surface rocks. None of these seems adequate to produce the vertical cracks (hereafter: "cracks") observed in deserts around the globe.

Salt weathering is often cited as a highly effective physical weathering process in deserts (e.g., Yaalon, 1970; Smith, 1988; Amit et al., 1993), but it seems more effective in propagating cracks than in forming them. Only after salts are introduced into the clast's interior, where small cracks existed or have formed by other processes, can the crystallization, differential expansion, or hydration of salts induce the internal stresses leading to rock fracture (Amit et al., 1993).

The potential importance of thermal stresses in the breakdown of rocks was recognized long ago (Bartlett, 1832; Branner, 1896, Merrill, 1906). In response to surface heating, steep gradients in temperature and thus stress develop in the outer few centimeters of a clast (e.g., Warke and Smith, 1994). If such stresses exceed the tensile strength of the rock, brittle failure should occur; fire-induced fracturing is an example. However, most fire-induced fractures tend to be parallel (spalls) rather than perpendicular to the rock surface (Evenson et al., 1990; Bloom, 1998). Diurnal cycles of solar heating and cooling can also cause expansion and contraction. Although of a much smaller magnitude, these thermal cycles are frequent (daily), and they penetrate more deeply than typical fires, down to decimeters.

The studies of Blackwelder (1927, 1933) and especially the often-cited, negative experimental findings reported in the classic papers by Griggs (1936a, b) cast lasting doubt on the notion that thermal stresses produced by insolation are important in rock cracking. In the latter studies, 244 years of simulated diurnal cycling with maximum temperatures up to 110 °C produced no cracking in small samples. Similarly, Ide (1937) showed that temperature fluctuations of 100°C did not produce irreversible microfracturing, although heating at 250 °C did. Since these studies, the debate concerning the effectiveness of insolation as a cause of physical weathering has continued. On the basis of field evidence, some geomorphologists (e.g., Ollier, 1963; Rice, 1976) continued to propose insolation as an important weathering process in arid regions, but others just as strongly ruled it out (Twidale, 1968). In the last few decades, the conclusions of many studies are primarily that thermally induced cracks can form, but probably only in association with other processes or in the presence of significant levels of moisture and/or various surface salts (Gray, 1965; Rice, 1976; Ahnert, 1996; Ritter et al., 2002; Bloom, 1998). Recently, studies in very cold, dry environments strongly suggest that physical weathering due to thermal stresses can be substantial (Hall, 1999; Hall and Andre, 2003). The intergranular stresses documented in these studies, however, produce granular disintegration near the clast surface, not deeply penetrating cracks along which subsequent separation occurs. Nearly seventy years after Griggs's research, geologists and geomorphologists continue to dispute the effectiveness of solar insolation in the mechanical breakdown of rocks (Gillespie, 1982; Yatsu, 1988; Cooke et al., 1993; Smith, 1994).

In natural environments a clast on the Earth's surface is not subject to uniform heating such as that studied by Griggs. In this study we test the hypothesis that rocks crack due to tensile stresses caused by the directional heating and cooling that result from the sun's transit across the sky (Fig. 2). In the absence of strong fabric or other mechanical anisotropy, the orientation of cracks caused by these stresses should reflect the orientation of the largest thermal differences that occur repeatedly. Thus we propose that cracks should be vertical and should strike north-south. If other processes such as uniform thermal heating, hydration or salt weathering are responsible for rock cracks, we would expect crack orientations in surface clasts to be random or to reflect jointing and rock fabric.

METHODS AND FIELD SITES

We selected eight sites in the Mojave Desert of southern California, the Chihuahuan Desert and high (1800 m) deserts of New Mexico and the Sonoran Desert in Arizona largely where numerous cracked boulders and cobbles were known to exist and where the distribution, age and soils associated with Quaternary surficial deposits had already been characterized (Fig. 3 and Table 1). Surfaces ranged in age from Late Holocene to Late or Middle (?) Pleistocene. Active channels were not studied because cracking there could be attributed to joint inheritance and transport. Our general observations of cracked rocks in active channels indicated that inheritance and transport cracks could be recognized by the evidence of abrasion along the edges of the crack surface. Plant communities at the study areas are characterized by sparsely scattered shrubs, cacti and grasses with few if any larger trees. Climate ranges from arid to semi-arid.

Within each study area, we collected data primarily in well-expressed fluvial bars or debris-flow levees, areas where cobbles and boulders were concentrated. Within any particular bar or debris flow, we collected data from the population of clasts that fell within predetermined size and/or shape specifications. For most sites these specifications were all clasts whose intermediate diameters exceeded 10 cm and that projected at least 5 cm above the ground surface. We also generally restricted sampling to approximately equidimensional, rounded to sub-rounded clasts. We collected data for clasts with diameters between 5 and 10 cm at the Cima volcanic flow site, because of the overall prevalence of small clasts on that desert pavement surface. Examination of this clast population provided preliminary information concerning the relations between clast size and crack formation.

We obtained crack and clast data from a total of nearly 300 clasts and approximately 700 total cracks within those clasts. Crack-orientation data were collected with a Brunton compass. Often a single orientation (± 5º) was represented by more than one crack on any given stone. In these cases, we took one representative measurement for a group of cracks with similar orientations. If crack orientations were parallel to rock features such as bedding, foliation, the long axis of the clast, or a flat side of the clast, they were noted. Four crack-width types were defined: incipient (< 0.1 mm wide); thin (0.1 - 1 mm); moderately wide (1-3 mm) and large (> 3 mm). Rock fragments that could readily be recognized as having been separated completely along a former crack were classified as "separated." We defined five degrees of crack length: discontinuous cracks limited to a portion of the subaerially exposed surface, discontinuous cracks that extended to the ground surface, but not beyond it, discontinuous cracks that extended below the ground surface; and continuous cracks that completely encircled the clast. If present, spalling was noted. Finally, clast size (long and intermediate axis lengths) and rock type were measured for all clasts.

Some studies show that the positions of at least some surface clasts on Late and Middle Holocene surfaces and on older Holocene and Pleistocene desert pavements change (e.g., Cooke et al., 1993; Haff and Werner, 1993). We avoided all clasts showing obvious signs of recent movement. Certain characteristics of soils and surface clasts associated with geomorphic surfaces in arid regions provide evidence that their position has remained stable for many centuries or millennia. For example, the depth of clast burial in soils on older surfaces is an indicator of sustained stability. Also, collars of pedogenic calcium carbonate that form at or very near the clast-soil surface contact require up to a few thousand years to form (McFadden et al., 1998). Similarly, many studies of desert-varnish formation (e.g., Bull, 1994) show that a minimum of several centuries are required to form the dark subaerial surface varnish and the reddish subsurface varnish; therefore, the spatial pattern of varnish accumulation can be used as another indicator of clast stability. The presence of any or all of these indicators of stability was noted for clasts observed in this study.

Thin sections of four rocks: a basalt, a weakly metamorphosed sandstone, and two metagranite clasts with surface cracks were made for microscopic examination of cracks in the rock interiror. Cracks were preserved with epoxy resin before processing. The thin sections were made both perpendicular to and parallel to the clast surface for each crack.

Statistical analysis of crack orientations

At each area within the study sites, we collected between 30 and 160 crack measurements. We used the program GEOrient to evaluate crack orientation data statistically. The spherical and circular statistics reported in this program are based on procedures from Mardia (1972), Mardia and Jupp (1999), Fisher et al. (1987), and Fisher (1993). Of the data provided by GEOrient, we report vector means and circular variances. The vector mean is analogous to the slope in a linear regression. The circular variance is a simple measure (0-1) of the scatter of recorded crack azimuths; values close to 0 indicate low variance, and values close to 1 indicate high variance.

We attempted to minimize sample bias by collecting data for all clasts within a given site. We recognize, however, that our selection of a sub-set of large clasts from a few, isolated areas on spatially limited geomorphic surface remnants could introduce bias. At two sites, the geomorphic character of the surficial materials enabled collection of orientation data in a manner that minimized sample collection bias. On the densely packed desert pavement of the Cima Volcanic field, we collected crack orientations from all clasts within a randomly chosen 2 by 2 m area located 20 m from the pavement margin. At the San Lorenzo Wash, New Mexico, site and the site in Arizona, the presence of exceptionally long boulder bars on a relatively young (Late Holocene) terrace enabled collection of data in the following manner. A 50-m tape was placed along the surface of the bar and staked at each end. At every meter mark, the clast closest to the meter mark (within 2 m of the line) with a minimum diameter of 20 cm and projecting at least 5 cm above the ground surface was selected and evaluated as described above. We compared these data with a data set collected from the same area in the fashion **described in the previous section.**

Collection of Clast Surface Temperature Data

Our goal in obtaining clast temperature data was to gain general insights into the spatial patterns and magnitudes of temperature differences that can form across a rock surface during a day. We used thermometers specifically designed to record surface rather than ambient air temperatures (Pacific

Transducer Corporation) to monitor daily spatial and temporal fluctuations in the surface temperatures of eight clasts. Thermometers were coupled with silicone gel to flat surfaces in the centers of the approximate north, west, south and east clast-surface quadrants and on the apex of eight boulders of various sizes (15 – 150 cm diameter), shapes (round, elongate, etc.), and rock types (limestone, granite, metasedimentary, etc.). These temperature data were collected at the San Bernardino study site during the summer, with one exception (Table 1). For one day in January, temperature data were collected at the San Lorenzo Study site. Temperatures were recorded once an hour from morning until late afternoon. The ranges of temperatures measured were similar to those documented in other studies in hot desert settings (Cooke and Warren, 1973; Summerfield, 1991); they recorded heating and cooling rates similar to those observed recently using other methods (e.g., microthermocouples, Hall and Andre, 2003). Hence, in our view, our measurements are a useful proxy for spatial variability of, and daily changes in, rock surface temperatures.

RESULTS

Crack Orientations

On all geomorphic surfaces we studied, virtually all clasts, regardless of rock type or grain size, exhibit at least incipient vertical cracks. Four basic crack orientation types can be readily recognized in the field: meridional[1], fabric-related, facet-parallel, and longitudinal cracks (Fig. 4). The orientation of 73% of the 688 cracks observed in this study fell into one of these categories.

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[1] The Glossary of Geology (1997) defines meridional as: Pertaining to a movement or direction between poles of an object (e.g., the Earth).

Meridional Cracks

A large number of all cracks have a non-random, moderately strong north-south orientation (Fig. 5). Rose diagrams and statistical data (Table 2) of crack populations for each site show that all sites yield vector mean orientations that range from 2 to 30º, and average 8º (Fig. 6, A-J; Table 2). Also, the statistical data for the Cima volcanic field site and the San Lorenzo site demonstrate that this same generally north-south alignment of cracks is observed regardless of the method of clast selection used (Tables 2 and 3). Of all cracks measured (688), 462 could not be assigned to the longitudinal, fabric, or surface-parallel categories discussed below. These 462 cracks (Fig. 6D) are generally steeply dipping, and the vector means for the orientation of these cracks at individual sites ranges from 344° to 13° (Fig**.** 7A-J**,** Table 4). The vector mean of the orientations of all these cracks is 5°, virtually north south (Fig. 8). We provisionally defined those cracks within 33° of north-south (57% of the 462) as "meridional" cracks.

Fabric-Related Cracks

Rock fabric and the orientation of many cracks are often strongly associated (Fig. 4A). 32% of all sedimentary rocks and metamorphic rocks examined exhibited one or more cracks parallel to planar discontinuities in the rock. Besides bedding and foliation, flow banding in volcanic rocks and even the orientation of favorably aligned vesicles in scoriacious basaltic clasts were parallel to some cracks.

Surface-Parallel Cracks

Spalls were observed on many clasts, and there was a correlation between spalling and rock type (GSA Data Repository). 86% of quartzite clasts exhibited spalling in addition to vertical cracks. 49% of granite clasts studied exhibited spalling in addition to vertical cracks. 14% of the remainder of clasts exhibited spalling in addition to vertical cracks. In some cases, particularly in granite clasts, spalls terminate into vertical fractures, and could be removed in sheets from the clast surface. Examination of the exposed surfaces showed no evidence of penetration of the vertical crack through the basal spall surface. These relationships provide evidence that the vertical crack post-dated the spall, and initiated above the spall relatively close to the rock surface.

In addition to spalls, which are typically parallel to curvilinear rock surfaces, we observed many cracks that were parallel and in close proximity (<10 cm) to major planar surfaces or facets (Fig. 4B). Early in the study (Cima and Providence study sites), we did not record data concerning planar surface orientation. However, 30% of the clasts for which we did record the orientations (n=228) exhibited one or more of these planar "surface-parallel" cracks.

Longitudinal Cracks

19% of relatively elongated clasts (with long-to-intermediate axis ratios ≥1.5) exhibit cracks parallel or approximately parallel to the long axis of the clast (Fig. 4C). 54% of clasts with ratios >2 exhibited one or more cracks parallel to the long axis, and 6% of clasts with ratios <1.5 exhibited cracks parallel to the long axis. We define cracks that were parallel to a clast's long axis as "longitudinal" cracks.

Other Crack Characteristics

Although the orientation of many cracks was parallel to rock features such as fabric or a major flat face, cracks were also observed to cross-cut rock fabric or bisect large crystals (e.g., Fig 9A & 9B). In many cases a single crack would change orientation along strike, from fabric-normal to fabric-parallel. Crack dip and/or orientation was often observed to change near the ground surface. Cracks often appeared to terminate at adjacent cracks. One thin section provides evidence that cracks can bifurcate below the rock surface (Fig. 9C).

The intermediate diameter of clasts that exhibited meridional cracks ranged from 3.5 to ~2 m (GSA Data Repository). The average size of all clasts studied was 33 cm. Only 25 clasts studied had diameters <10 cm: however, 60% of those clasts exhibited meridional cracks.

Crack width and length appear to increase in a time-dependant manner, suggestive of an evolutionary sequence of crack development. On surfaces younger than Late Holocene, only two clasts exhibited cracks that encircled the clast completely (GSA Data Repository). Only nine total clasts exhibited incipient cracks that are continuous over more than half of the stone circumference. With the exception of three clasts, complete separation of a clast along a former crack was observed only on Early Holocene or older surfaces (Fig. 6A). In some cases, rock fragments in close proximity could easily be matched along former crack surfaces, although in most cases, especially on older surfaces, the fragments are presumably widely dispersed.

Although cracks of all widths are present in clasts on geomorphic surfaces of all ages, cracks tend to be wider on clasts on older surfaces. For example, only twelve clasts with widths of medium or larger were observed on surfaces younger than Middle Holocene. These temporal changes in the appearance, width and length of cracks are generally consistent with the metamorphosis of bouldery bar-and-swale alluvial-fan surfaces and debris-flow levees into relatively flat, pebble-dominated pavement surfaces in tens of thousands of years or less (McFadden et al., 1989; Amit et al., 1993; Al-Farraj and Harvey, 2000; Quade, 2001).

Changes in Daily Clast Surface Temperature

Several key observations are evident from clast surface temperature data (Figure 10, GSA Data Repository) First, the amplitude of the diurnal oscilation in clast surface temperature is between 40 and 45°C, which is at least double the ambient air temperature average diurnal range of about 20° C. These temperature ranges and relationships with air temperature are similar to those documented in past studies in desert settings (e.g., Cooke and Warren, 1973). In most cases, maximum differences in surface temperatures occur between the east and west rock surface quadrants. The temperature difference between east and west faces of individual boulders ranges from 10 to 26ºC, and exceed the maximum north-south temperature difference by 40 to 300%. With the exception of the winter data set, the east-west temperature difference peaks in mid morning (9-10 am). In nearly all cases by early afternoon, the west side temperature exceeded the east side. As sunset approaches, all surface temperatures gradually decrease, and the differences between sides diminish.

We observed the same general features in the winter rock temperature data set as in the summer data sets, although surface temperatures are lower. The timing of the surface temperature maximums for different sides of the clast also varied. For example, the maximum east-to-west surface temperature difference occurred at noon (33ºC) and exceeded all of those measured in the summer.

Other factors also influenced measured rock surface temperatures. For example, during the afternoon on the day we measured winter surface-rock temperatures, it became windy. Rather than increasing during the still sunny, early afternoon, the temperature of rock surfaces that directly faced the sun decreased rapidly. Some studies suggest that other weather conditions such as cloudiness and rainfall,can also significantly and quickly affect surface temperatures (Capin et al 1981; Hall and Andre, 2003). Clast shape also appears to influence surface temperature patterns. In the case of the two angular clasts (GSA Data Repository), the maximum differences in surface temperatures are achieved along the north-south parts of the surface, but they are only 4.5° to 5°C more than the maximum east-to-west temperature differences.

DISCUSSION

Mechanisms for crack initiation

Meridional Cracks

A statistically significant fraction of vertical to sub-vertical cracks on clasts observed at all study sites are aligned in an approximately north-south orientation, regardless of study area location or surface age. We hypothesize that steeply dipping north-south cracks are genetically linked to thermal stresses produced by the recurrent directional diurnal heating and cooling of the clast surface.

Tensile stresses are generally thought of as the most effective stresses for causing rock fracture. Thermal expansion is one way to produce tensile stress. When a clast begins to heat up, its interior is relatively cool. Surface parallel expansion of its outer layer is inhibited by this cool interior and thus the outer portion of the clast is in a state of tangential (parallel to the surface) compression, rather than extension (e.g., Kingery, 1954). Indeed, analyses of the thermal stresses produced in elastic spheres exposed to stationary or rotating heat source (Cheung et al., 1974) indicate that, upon heating, tangential tension actually develops in a large domain of the interior of the sphere, while tangential compressive stresses develop near its surface. Thus we hypothesize that in subareal environments at mid-day, when the tendency for the outer shell of a clast to expand is greatest relative to its cooler interior, internal tension will peak, and vertical cracks will initiate in the interior of the clast and propagate to the surface. With spatially uniform surface heating, radial cracks resulting from this tensile stress would be randomly oriented. Modeling suggests, however, that when a sphere is heated by a rotating source, maximum stresses are centered on the heat source and are oriented within the plane of the heat source orbit (Tanigawa and Takeuti, 1983). The daily movement of the sun across the sky introduces similar asymmetrical stresses, favoring the growth of cracks perpendicular to its track. We suggest that this non-uniform diurnal heating of a surface clast's exterior accounts for the preferred orientation of observed cracks.

Following sunrise, the zone of maximum surface heating of an equidimensional clast progresses in an east- west direction across the clast surface. Presumably, the area of the rock surface that is compressed also expands from east to west across the rock surface. As rock surface temperatures continue to rise through the morning and the thickness of the heated outermost shell increases, internal tensile stresses also increase. Eventually, the internal tensile stresses are near-horizontal in the east-west direction, and hence resulting cracks tend to be vertical and to strike north-south.

The observed relationship between vertical cracks and spalls suggests that least some cracks do form within a few millimeters to a few centimeters of the rock surface. This observation contrasts with the proposed mechanism for crack initiation in clast interiors. However, we also attribute the formation of these cracks to insolation. Vertical surface fractures might arise from contraction while the rock surface is cooling in various ways: a) rapid, short-term cooling of a hot rock surface, by rain or episodic cloud cover that will cause contraction of a thin surface zone of the clast, and b) cooling at night fall that will generate surface-parallel tensile stresses deeper into the clast because the cooling occurs over a longer time scale. Many workers have suggested that brittle failure can be triggered by sudden and extreme changes in surface temperature (thermal shock) (Birch, 1937; Ide, 1937; Nur and Simmons, 1969; Bloom, 1998; Hall and Andre, 2003). Such short-duration (seconds or minutes) surface temperature variations can evidently cause superficial cracking and granular disintegration (e.g., Hall and Andre, 2003), but they cannot be important in causing through-going fractures in boulders because they do not penetrate deeply (only mm's or cm's). Sustained surface cooling, on the other hand, could cause steeply dipping contraction cracks, much like those that form in a layer of elastic material as its surface cools (e.g,. Lachenbruch, 1958). A notable example of the latter is the development of columnar basalt.

As with columnar basalt, given spatially uniform cooling, these cracks would tend to grow and intersect to form polygonal arrays. Surface fracture patterns observed on the clasts in our study sites do not resemble the typically observed polygonal pattern, however; instead, the cracks are oriented north-south. We suggest that the cumulative effect of large numbers of diurnal cycles of compression and decompression due to east-west oriented heating and cooling cycles on the rock surface preferentially favors surface cracks in a north-south direction. Repeated stress cycles are known to cause fatigue in solid materials, and cracks may simply form and grow progressively when internal stresses repeatedly approach the rock strength (threshold of "thermal fatigue"), as suggested by the studies of Hall and his coworkers (Hall, 1999; Hall and Andre, 2003).

Although the overall state of compressional stress below the contracted outermost surface layer would prevent deeper propagation of contraction surface cracks at the time they initially form, sequential cooling and warming phases can be synergetic in causing stresses (Chen et al., 1975) and therefore crack growth. Thus, the propagation of such north-south surface-initiated cracks would be favored because they may potentially merge with existing north-south oriented internal cracks. These concepts help elucidate field observations showing incipient cracks on sub-aerially exposed rock surfaces that do not penetrate the entire clast. Subsequently, these cracks propagate and widen, eventually extending vertically completely through the clast.

Fabric, Surface-Parallel, and Longitudinal Cracks

Facet-parallel, fabric and longitudinal cracks may also initiate as a result of solar insolation. For example, the generally uniform heating of a large, planar rock surface and its consequent tendency for surface-parallel expansion may be sufficient to cause formation of a surface-parallel crack, a form of spallation. Once surface-parallel cracks form, subsequent crack growth could cause sheets of rock to eventually detach along the crack surface. This process favors the formation of a subsequent generation of surface-parallel cracks.

Longitudinal cracks may also be due to variation in solar heating. For example, during much of the year strongly oblong clasts with long-axis orientations that are within about 45°of north-south will be strongly illuminated during the early hours of the morning on one side of the clast and during the late afternoon largely on the other. In such a case, the largest temperature difference would be approximately perpendicular to the clast's long axis, and thus cracks would tend to initiate parallel that axis.

The orientation of fabric-related cracks is probably attributable to crack propagation being most favored in areas of least resistance to rupture. The orientation of some surface cracks in foliated rocks is, however, approximately north-south, although the crack orientation typically changes to become generally parallel with rock foliation. This suggests that the orientation of thermally induced internal stress at the scale of the clast (much larger than the grain scale), which are largely independent of fabric, is the primary factor controlling the orientation of many of these cracks. Once cracks propagate, however, field evidence suggests that crystal or grain shape and orientation may increasingly influence propagation behavior.

Other factors that influence cracking

Clast Size

Although a significant portion of small clasts exhibited meridional cracks, it is likely that below a certain diameter this mechanism for cracking becomes less efficient. Small clasts with a radius smaller than the maximum depth of heating should not be as significantly affected by the proposed mechanisms of cracking because temperature differences either within the clast or across the clast surface cannot become very large, and, hence, large thermal stresses cannot arise. Relative to larger clasts, smaller clasts also tend to be shaded for a longer period during the day by their neighbors, which tends to reduce thermal stresses. Temperature gradients in clasts sitting on a surface are also affected by soil temperature in proportion of the extent to which clasts are embedded in the soil. Ultimately, with decreasing size, the thermal behavior of a clast should approach that of the fine matrix in which it is embedded.

With increasing clast size, significant thermal stresses are expected. We observed cracks on the surface of many very large boulders (diameters >2 m), suggesting that thermal stresses developed in such large boulders sufficient to cause such cracks. Diurnal thermal stresses are expected to become less effective in breaking larger boulders, however, because 1) the local curvature of progressively larger boulders will reduce differential azimuthal heating, and 2) the penetration depth of diurnal heating (decimeters) is only a small fraction of the boulder diameter, and hence the magnitude of thermal tension in the boulder is limited. Additional field and modeling studies will be required to evaluate the proposed influences of clast size on thermal stresses and to determine the size range over which the proposed process of solar weathering is likely to be most effective.

Rock Color

Rock color influences rock surface temperature primarily due to surface albedo effects. Maximum surface temperatures of some dark rocks as high as 80°C, for example, have been measured, higher than those measured on lighter rocks (Summerfield, 1992). We generally observe, however, that cracks are present in all rock types, regardless of color. Although we did not specifically evaluate the influence of rock color on surface temperatures, we suspect that color is not of primary importance in the generation of cracks in subaerial environments.

Inheritance of Rock Surface Micro-cracks

Micro-cracks may be present in surface clasts inherited from bedload transport or other processes that caused their formation prior to deposition. Pervasive pre-existing micro-cracks in coarse-grained igneous plutonic rocks, for example, may facilitate the observed, relatively rapid intergranular decomposition of such rocks, although some research suggest that the presence of water (Roth, 1965) or salts (Amit et al, 1993) play critical roles in this process. Granular disintegration by thermal processes (Hall and Andre, 2003) may also be an important origin of microcracks in desert environments. In these circumstances, such rapid surface disintegration might even preclude the development of larger scale vertical cracks. Because the presence of microcracks substantially decreases the tensile strength of rocks and the magnitude of thermal stresses, microcracks likely play a key role in any type of physical weathering, including that resulting from recurrent solar heating. These inherited microcracks may account for the orientation of some cracks that are not meridional, fabric, surface-parallel or longitudinal cracks.

Possible Cause of the Bimodal Crack Orientations

Although the strongly nonrandom crack populations nearly always have a vector mean orientation value within only a few degrees of north-south, the bins closest to north–south bin (350-360º and 0-10º) do not typically constitute a single, clearly dominant population mode. This is especially evident in the populations of cracks that exclude cracks in the shape- or fabric-associated types; the orientations of many cracks are typically in the 330 to 350°range or the 10 to 40°range, and usually both modes are represented (Figs. 7a-h, 8). The approximate symmetry of crack distribution modes about the north-south direction is largely responsible for the mean resultant vector that is very close to north-south. In a few areas, another more weakly expressed mode with a near east-west orientation is evident (Figure 7), but this mode is not expressed in the summary rose diagram (Fig. 8).

Evaluation of solar position for the latitude of the field sites as a function of different seasons (Fig. 11) suggests a possible explanation for this pair of modes. At all sites in this study, between sunrise and mid-morning during a significant fraction of the year (summer), the most strongly heated part of round clast surfaces is not that directly facing east or west. Instead, the southeast side of the clast will be most strongly heated at this time, presumably producing internal tensile stresses in a northeast-southwest direction. This may explain the northwest-southeastern crack orientation mode. Although observed evening surface temperature differences are smaller than morning differences, any cracks that might form in response to these thermal differences would produce essentially the mirror image of those that form in response to the morning thermal difference.

An interesting latitude effect on crack orientations seems evident. The angle subtended by the pair of orientation modes associated with the north-south meridian should progressively increase at higher latitudes and decrease at lower latitudes, disappearing at the equator. Thus the observed range of orientation of cracks defined as Meridional should vary as a function of latitude. Testing this prediction in the field should be relatively straightforward.

Implications of Solar-generated Cracking for Desert Pavements and Weathering in Other Subaerial Environments

The proposed model of solar breakdown of surface clasts helps elucidate aspects of desert pavement formation. Studies of desert pavements in the past two decades have provided the basis for the development of a model of pavement formation that differs substantially from most previous models (Ritter et al., 2002). In the current model, the role of desert dust incorporation is emphasized (1) in the development of the soil horizons closely associated with the pavement (McFadden et al., 1986; Amit and Gerson, 1986; Gerson and Amit, 1987) and (2) as a means of lifting surface clasts as dust infiltrates into the underlying soil (McFadden et al., 1987; Wells et al., 1995). The cumulic soil processes that explain the coarse surface clast layer of desert pavements, however, do not address other documented features of desert pavements. For example, the solar-weathering mechanism proposed in this study can account for the breakdown of volumetrically abundant massive, basalt blocks or large boulders into the well-sorted relatively small (5-15 cm) angular pebbles and cobbles that are common in well-developed pavements. The prevalence of these clasts in desert pavements precludes ascribing their primary origin to other thermal processes (Hall and Andre, 2003) that tend to produce granular disintegration.

Our observations suggest that any subaerially exposed clast will continue to break down until a limiting clast size is ultimately attained. This suggests that the increasing angularity of clasts on older pavements which has been noted in other recent studies (e.g.Al-Farraj and Harvey, 2000), is due to the loss of inherited roundness after two and probably more generations of cracking. Clast breakdown along largely planar cracks produces a generation of clasts with abundant planar facets, which would promote future generations of both meridional and facet-parallel cracks. Ultimately, a surface layer of well-sorted and strongly interlocking, subangular to angular cobbles and pebbles of all rock types, which constitutes the maximum stage of pavement evolution, is obtained. Finally, Quade (2001) has recently suggested that the formation of desert pavements in the western United States is presently limited to elevations below about 1700 m. This is because at higher elevations, a generally cooler, effectively more humid climate favors the presence of a shrub-woodland community, and shadowing of vegetation on clast reduces thermal and stress gradients (and therefore cracking), just as clouds do.

Solar-generated thermal stresses are not, of course, restricted to individual clasts on desert surfaces. Such stresses will develop, and presumably solar-generated physical weathering will occur in any subaerial environment where canopy cover is limited. Thus we predict that meridional cracks potentially form 1) in both colder as well as wetter subaerial environments than those of this study, 2) in rock outcrops, and 3) in man-made structures. These predictions have interesting implications for the studies of the orientations of joints or fractures at the outcrop scale. A limiting factor for the development of meridional cracks in all of these cases will be, as suggested above, the presence of any other surface weathering processes that act more quickly to break down rocks. For example, the thermal-induced granular disintegration of rocks that has been documented in Antarctica (Hall et al., 2002, Hall and Andre, 2003), is perhaps such an efficient process for physical weathering in cold environments that cracking generated by directional heating and cooling is precluded, or at least rendered a far less important weathering process than in hot deserts. The tendency for certain rock types to spall may also preclude the preservation of meridional cracks. An important step of future work will be documenting the range of conditions under which significant populations of north-south cracks can be observed.

In addition to terrestrial environments, solar-generated physical weathering could be of importance on other planets. The large temperature variations over the 24.5-hour-long Martian diurnal cycle, for example, should produce large thermal stresses in surface boulders. Interestingly, some photos of the Martian surface taken during past missions, including the most recent Spirit rover mission, depict features that strongly resemble desert pavements. The high resolution photographs from Spirit clearly reveal clasts with vertical cracks. Given the recognition of the significance of eolian processes on Mars, the formation of Martian surface pavements may be even more similar to terrestrial desert pavements than has been suspected.

CONCLUSIONS

The preferred north-south and near vertical orientations of many rock-surface cracks we have observed in boulders and cobbles are hypothesized to be fundamentally related to thermal stresses that arise daily from non-uniform solar heating. We propose that this process, operating singly or in concert with other processes, plays a key role in the physical weathering of rocks exposed to the sun. Once cracks form, they extend, widen and ultimately may breakdown the entire clast, either through the formation of later generations of such cracks or by facilitating salt-weathering or other physical weathering mechanisms. We suggest that this mechanism for physical weathering is viable in other climates as well as for rock outcrops and rocks in non-terrestrial environments.

Future research addressing the generation of cracks by directional solar heating in subaerial environments should include: 1) Determination of the range of climates over which a significant population of meridional cracks are present; 2) Determination of the range of clast size and shapes over which the hypothesized mechanism is feasible; 3) Testing the hypothesis of latitudinal control on the azimuth distributions of meridional cracks; 4) More detailed studies of the subsurface cracks using both conventional petrographic microscopes and scanning electron microscopes, which should help determine why and where cracks initially form and how they propagate; 5) Instrumental studies to acoustically detect rupture events, as well as measure temperature, strain and moisture content continuously in field settings; 6) Laboratory experiments designed to simulate daily variation in insolation, and perhaps even the generation of cracks; and 7) Development of numerical models to simulate thermal stresses and fracture propagation due to daily heating of a partly buried, clast as a function of clast size, shape, moisture content, lithology, and fabric.

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Figure Captions

1. Photographs of two cracks. A. A vertical surface crack on a boulder on a fan surface in the Cima volcanic field in the Mojave Desert, California. Nickel for scale. B. A vertically cracked boulder on an early Holocene alluvial fan surface on the northern flank of the San Bernardino Mountains, California. Brunton Compass to the right of the crack at the top of the boulder for scale. Note the shaded western side of the boulder.

2. Cartoon depicting the diurnal pattern of solar heating of a clast on the Earth's surface. Boulder is cracked in a direction perpendicular to the direction of the sun's rays in the morning and afternoon.

3. Map showing location of the study areas in the southwestern United States. 1) Southwestern Providence Mountains, California, 2) Cima Volcanic field, California; 3) North flank of the San Bernardino Mountains, California; 4) Sevilleta Wildlife Refuge, NM; 5) Palo Duro wash, New Mexico; 6) West flank of the Los Pinos Mountains, New Mexico; 7) West flank of the Sandia Mountains, New Mexico; 8) San Lorenzo Wash near Socorro, New Mexico; 9) Harqualala Mountains, Arizona See Tables 1 and 2 for selected attributes of the study areas.

4. Photographs of the 4 primary crack-types observed in this study (see text for further explanation) A. Fabric-related cracks, including cracking ranging from thin to separated. B. Surface-parallel crack that is not a spall. C. Longitudinal crack D. Meridional crack.

5.Rose diagram showing abundance of orientations of all measured cracks representing all types. Arrow indicates vector mean. Maximum vector value is 57 points in a 10-degree bin.

6. Rose diagrams showing abundance of orientations of cracks associated with all types from rocks from different study sites. Arrow indicates vector mean of the data set. Vector scales vary; see Table 2 for maximum vector value for each site. A. Providence Mountains piedmont. B. Cima volcanic field. C. San Bernardino Mountains piedmont. D. Sevilleta Wildlife Refuge, western area E. Palo Duro wash. F. Sevilleta Wildlife Refuge, Los Pinos Mountains, Late Pleistocene terrace. G. Sevilleta Wildlife Refuge, Los Pinos Mountains, Middle (?) Pleistocene fan surface. H. Sandia Mountains piedmont. I. San Lorenzo Wash, New Mexico. J. Harquahala Mountains piedmont. Locations of all sites indicated in Table 1 and Figure 3.

7. Rose diagrams showing abundance of orientations of cracks unrelated to fabric or rock shape from different study sites. Arrow indicates vector mean of data set. Vector scales vary; see Table 2 for maximum vector value for each site. Locations of all sites indicated in Table 1 and Figure 3. See Figure 6 caption for locality symbols.

8. Rose diagram showing abundance of orientations of all measured cracks unrelated to fabric or rock shape. Cracks with orientations within 33°of the N-S meridian are referred to as meridional cracks. Arrow indicates vector mean of data set. Maximum vector value is 40 points in a 10-degree bin.

9. Photomicrographs showing characteristics of the selected cracks in different rock types. A. Vertical crack in basaltic rock from the Cima volcanic field. The crack cuts large xenolith and plagioclase phenocrysts. Section oriented perpendicular to rock surface. Horizontal scale: 4 mm. Cross-polarized

light. B. Vertical crack in granitic gneiss from the Los Pinos Mountains, New Mexico, showing apparent spatial relationship between foliation and crack. The crack cuts some larger crystals. Section oriented parallel with rock surface. Horizontal scale: 8 mm. Cross-polarized light. C. Vertical, bifurcating crack in basaltic rock from the Cima volcanic field. Section oriented perpendicular to rock surface. Horizontal scale: 8 mm. Cross-polarized light.

10. Changes in rock surface temperature from two selected rocks, showing summer (San Bernardino Mountains study site) and winter (San Lorenzo wash study site) data sets. Temperatures for all four rock-surface quadrants are shown to demonstrate the impact of the stronger illumination of the south quadrant of rocks given the solar path during the winter at the 35° latitude of this part of New Mexico. See GSA Data Repository for all rock surface temperature data.

11. Solar path during summer solstice (A) and Winter solstice (B) at 35º 9′ N latitude (Albuquerque, New Mexico).

Tables

TABLE 1. STUDY AREA LOCATIONS AND GEOMORPHIC SURFACE CHARACTERISTICS.

Study Area	SW Providence Mountains CA (1)	Cima Volcanic field CA(2)	North Flank San Bernardino Mtns, CA (3)	Sevilleta Wildlife Refuge NM (4)	Palo Duro Wash, NM (5)
Latitude, Longitude	35° 0', 115° 45'	35° 45', 115° 45'	34° 23', 116° 52'	34° 24', 106° 59'	34° 17', 106° 45'
Elevation (m)	115	115	100	185	170
Surface Age	Early Holocene	Late Pleistocene	Early Holocene	Early-MIddle Pleistocene	Middle-Late Holocene
Principal Rock Types	granite, gneiss	volcanic, limestone	granite	sandstone, basalt	limestone, volcanic
# of clasts	59	30	22	23	34
Soil Profile	Av-Bw-Bwk	Av-Btk	A-Bw-C	A-Bw-Bk-C	A-Bwk-Bk
Varnish	weak to strong	strong	rarely present, weak	weak to strong	none to moderate
Carbonate Collars	rarely present	rarely present	rarely present	typically present	typically present
References	McDonald (1994)	Wells et al. (1985) McFadden et al.(1987)	Eppes (2002), Powell et al. (2000)	McMahon, (1998)	Treadwell (1994)

Study Area	West Flank, Los Pinos Mtns (inset) NM (6)	West flank Los Pinos Mtns NM (6)	West flank, Sandia Mtns. NM (7)	San Lorenzo Wash near Socorro NM (8)	Harquahala Mountains AZ (9)
Latitude, Longitude	34° 22, 106° 36	34° 22, 106° 36	35° 09', 106° 31'	34° 17', 106° 57'	33° 52', 113° 11'
Elevation (m)	180	180	190	170	80
Surface Age	Early Holocene	Middle-Late Holocene	Late Pleistocene	Late Holocene	Late - Early Holocene
Principal Rock Types	granites	granites	granite	volcanics	granite, gneiss
# of clasts	11	38	13	54	24
Soil Profile *	A-Bt-Bk-C	A-Bt-Bk	no soil material present	A-Ck-C	A-Ck-C; A-Bw-Ck
Varnish $	weak-moderate	weak	weak	rarely present, weak	rarely present weak
Carbonate Collars	typically present	rarely present	rarely present	rarely present	not present

References	McFadden This Study	McFadden This Study	Connell (1995)	this study	Ruzicka, 1994

TABLE 2. CIRCULAR STATISTICS OF CRACK ORIENTATIONS USING GEORIENT.

Study Area	Southwesten Providence Mountains CA (1)	Cima Volcanic field CA(2)	North Flank San Bernardino Mtns, CA (3)	Sevilleta Wildlife Refuge NM (4)	Palo Duro Wash, NM (5)	
n	96	31	44	43	53	
Vector Mean	17º	10º	11º	4º	13º	
Circular Variance	0.35	0.33	0.42	0.2	0.3	
Max # pts per 10º bin	10	3	8	5	7	
Study Area	**West Flank, Los Pinos Mtns (inset) NM (6)**	**West flank Los Pinos Mtns NM (6)**	**West flank, Sandia Mtns. NM (7)**	**San Lorenzo Wash near Socorro NM (8)**	**Harquahala Mountains AZ (9)**	**All Data**
n	24	86	30	160	79	694
Vector Mean	150º	2º	8º	12º	5º	7º
Circular Variance	0.3	0.3	0.34	0.35	0.46	0.36
Max # pts per 10º bin	4	9	4	16	5	57

TABLE 3. CIRCULAR STATISTICS OF CRACK ORIENTATIONS: TWO SAMPLE COLLECTION METHODS.

Study Area	Method 1 All Data	Method 1 All Data minus I	Method 2 All Data (transect)	Method 2 All Data minus I (transect)
n	51	35	109	67
Vector Mean	14	14	11	9
Circular Variance	0.31	0.3	0.37	0.22
Max # pts per 10º bin	6	5	10	9

4. CIRCULAR STATISTIC OF ORIENTATIONS OF CRACKS. DATA MINUS FABRIC-RELATED, FACET-PARALLEL AND LONGITUDINAL CRACKS.

Study Area	**Southwestern Providence Mountains CA**	**Cima Volcanic field CA**	**North Flank San Bernardino Mtns, CA**	**Sevilleta Wildlife Refuge NM**	**Palo Duro Wash, NM**
n	71	26	25	32	31
Vector Mean	13	3	0	6	2
Circular Variance	0.29	0.26	0.15	0.19	0.22
Max # pts per 10º bin	10	3	7	5	5

Study Area	**West Flank, Los Pinos Mtns (inset) NM**	**West flank Los Pinos Mtns NM**	**West flank, Sandia Mtns. NM**	**San Lorenzo Wash near Socorro NM**	**Harquahala Mountains AZ**	**All Data**
n	24	86	30	160	39	392
Vector Mean	150	2	8	12	7	5
Circular Variance	0.3	0.3	0.34	0.35	0.31	0.25
Maximum number of points in bin (10 degree)	4	9	4	16	6	40

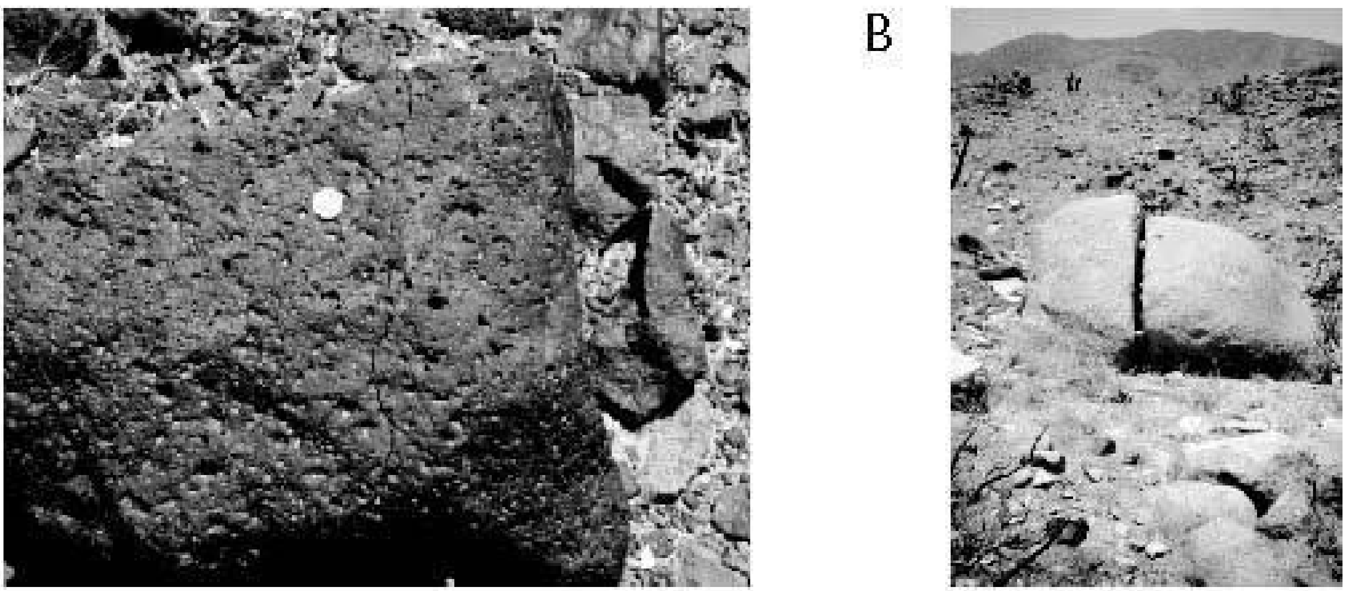
Note: ~43% of others are not meridional

5. ROCK SURFACE TEMPERATURE MEASUREMENTS

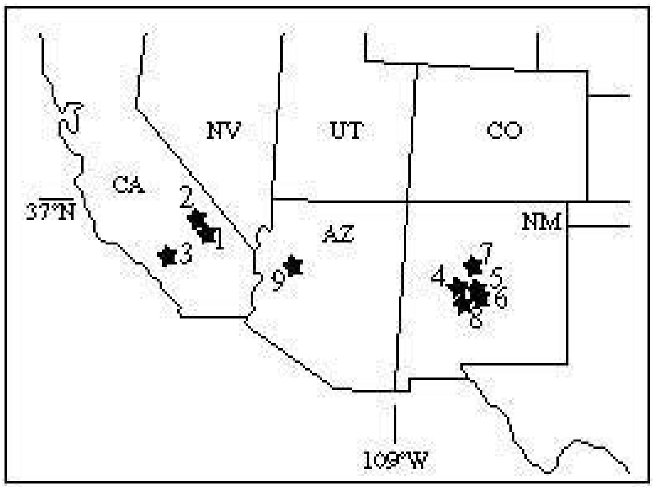
Rock	**Rock Type**	**w,l,h (cm)**	**Maximum E-W temp. range**	**Time**	**Maximum N-S temperature range**	**Time**	**Temp Differe Revers Time**
1	metasedimentary	25 x 38 x 93	10	11 a.m.	14.5	11 a.m.	2:30 p
2	metasedimentary	26 x 33 x 17	13	10:00 a.m.	4	1 p.m.	1 p.m
3	limestone	19 x 21 x 12	16	9:00 a.m.	8	9:00 a.m.	12:30 p
4	limestone	14 x 15 x 8	22	9:30 a.m.	16	1:00 p.m.	12:30 p
5	quartzite	15 x 20 x 6	10	10:00 a.m.	6	8 a.m.; 4 p.m.	2:30 p
6	granite	20 x 40 x 20	18	10:00 a.m.	23	9 a.m.	after 1 p
7	granite	150 x 200 x 150	26	10:30 a.m.	11	6 p.m.	~ 2:30 p
8	rhyolite	38 x 46 x 28	33	11 a.m.	27	11:30 a.m.	3:30 p

A

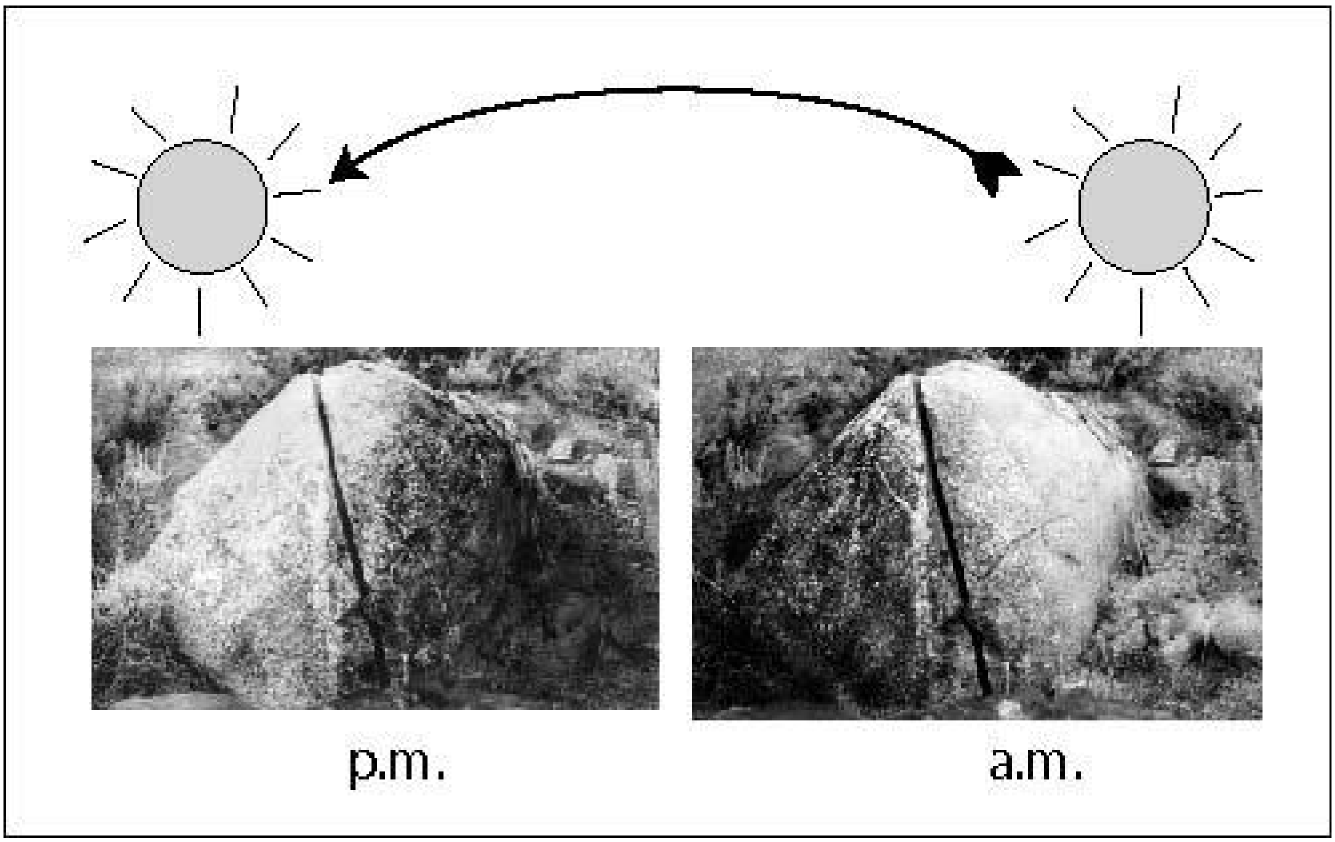
B



McFadden et al., Fig. 1



McFadden et al., Fig. 2

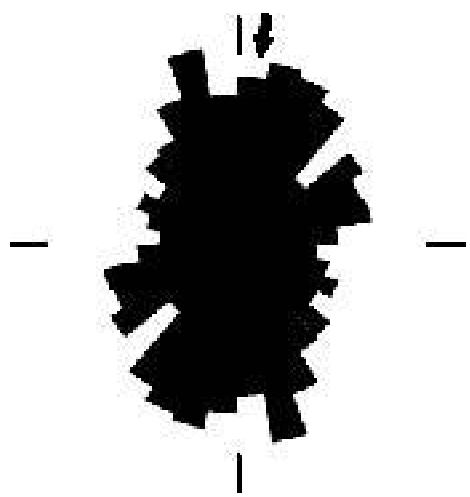

p.m.
a.m.

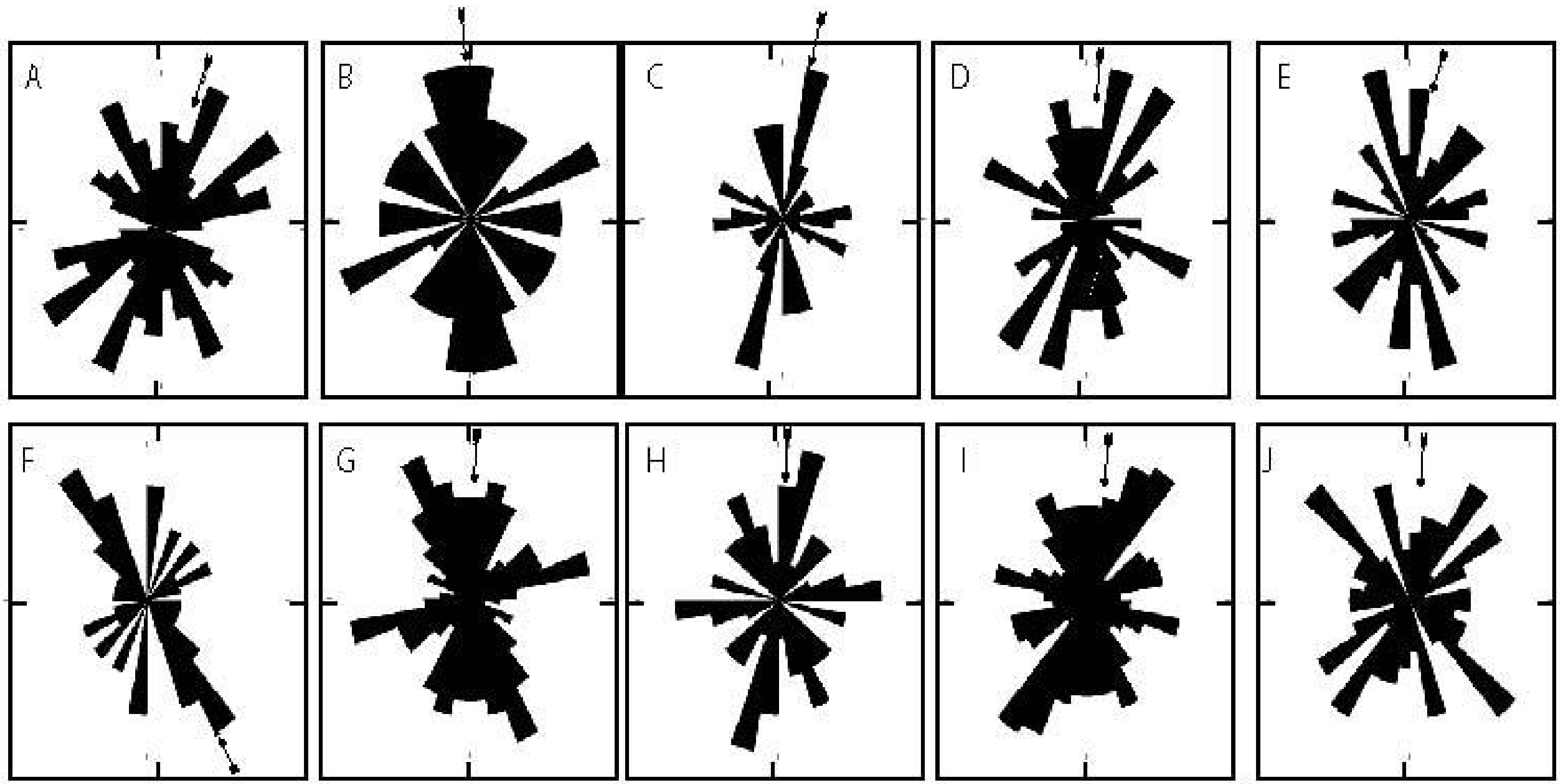
A

B

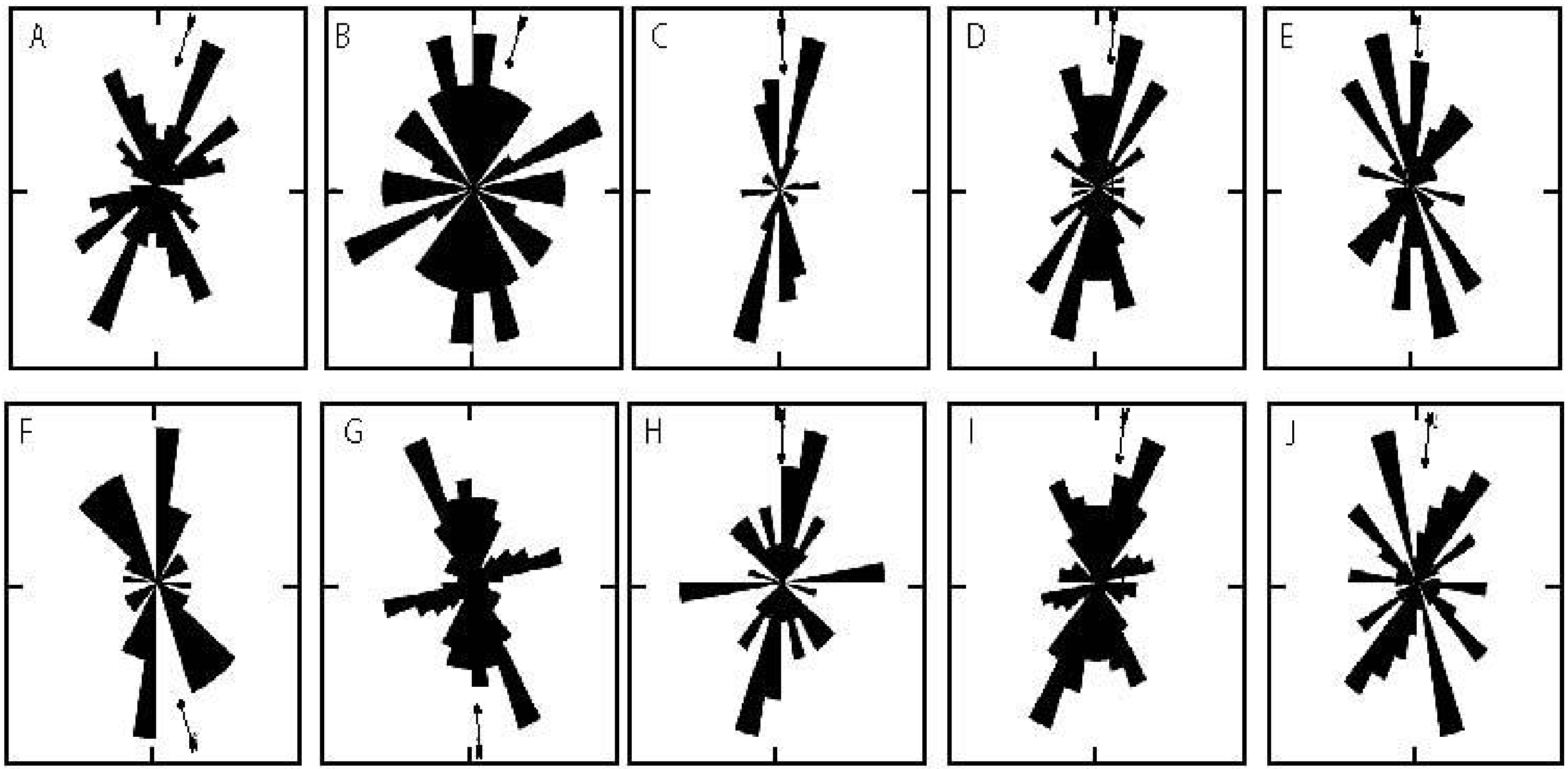
C

D

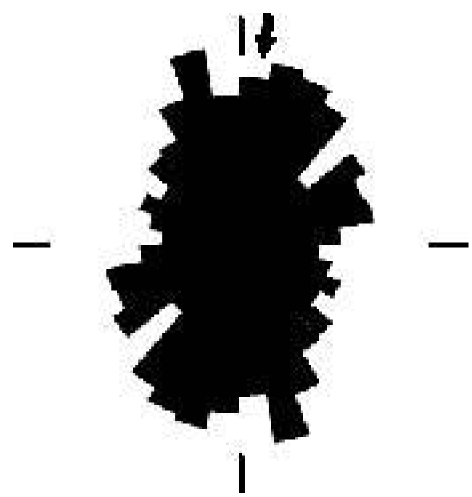


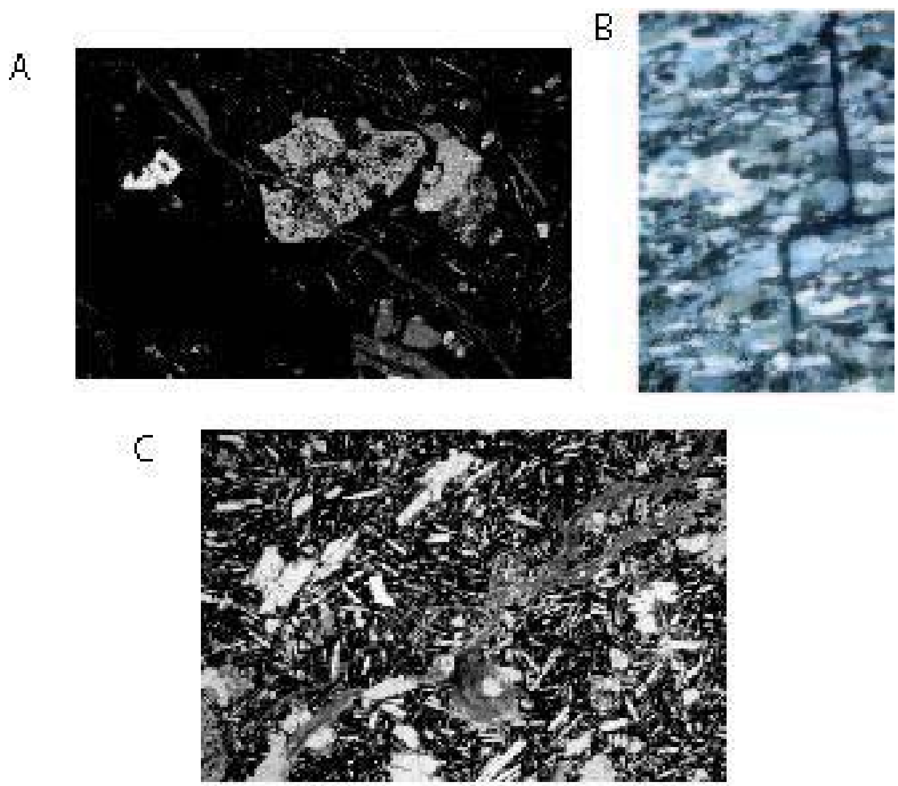


McFadden et al., Fig.6

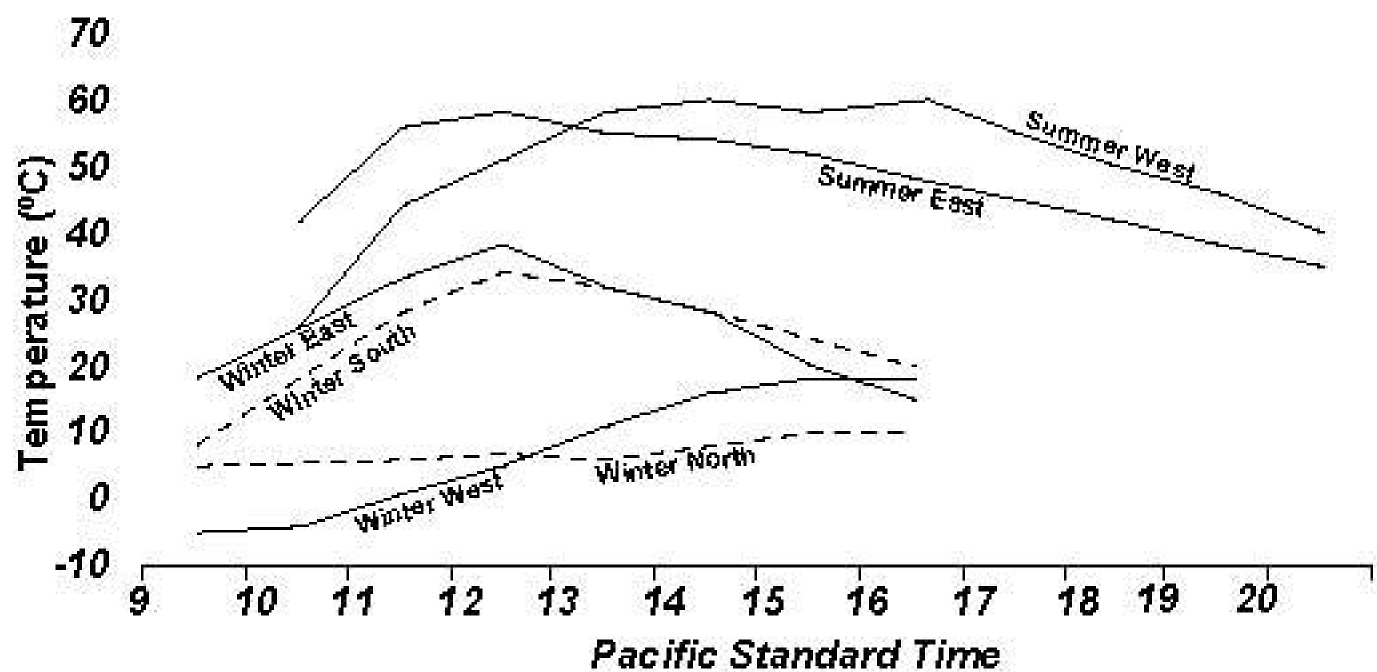


McFadden et al., Fig. 7

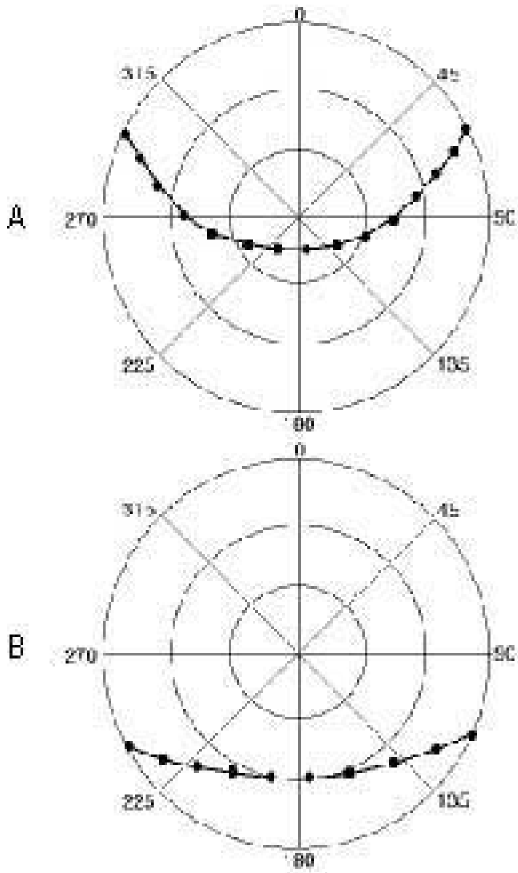




McFadden et al, Fig. 9



Temperature (°C)
70
60
50
40
30
20
10
0
-10
9
10
11
12
13
14
15
16
17
18
19
20
Pacific Standard Time
Summer West
Summer East
Winter East
Winter South
Winter North
Winter West


A
0
315
45
270
90
225
135
180
B
0
315
45
270
90
225
135
180