

Cracks in desert pavement rocks: Further insights into mechanical weathering by directional insolation

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ABSTRACT

The formation of cracks is a fundamental first step in the physical weathering of rocks in desert environments. In this study we combine new field data from the Mojave (U.S.), Gobi (Mongolia) and Strzelecki (Australia) deserts that collectively support the hypothesis that *meridional* cracks (cracks with orientations not readily attributable to rock anisotropies or shape) in boulders or cobbles form due to tensile stresses caused by directional heating and cooling during the sun's daily transit. The new studies indicate that rock size, surface age, and latitude play important roles with respect to their influence on rock fracture. Rock size and pavement surface age exert an influence on the development of rock cracks as the average clast size of mature desert pavements may be at or below the threshold-clast size for thermal cracking of rocks. Latitude-controlled seasonal temperature variations play a key role, as demonstrated by: 1) tightly clustered mean resultant orientations that differ by latitude, as predicted in McFadden et al. (2005), and 2) very cold wintertime temperatures and strong diurnal gradients that may favor crack development in wintertime, given the likelihood for strong clast heating during early morning hours. The consistent evidence for *meridional* cracks in surfaces of diverse age and desert environments, climate, vegetation, and distance of clast transport indicate that directional insolation may play the key role in initially generating and propagating rock fractures, rather than a secondary role as implied in recent field and modeling studies of physical weathering in deserts.

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1. Introduction

The first stage of physical weathering unequivocally is the formation of an incipient crack. These cracks are essential in enabling or accelerating virtually all other types of subsequent physical and chemical weathering, processes that are in turn essential in many aspects of landscape evolution (e.g. Goudie et al., 1997). While some cracks can be linked to geological inheritance or to forest fires, surface boulders and cobbles, regardless of rock type, universally exhibit discrete vertical to subvertical cracks that extend beyond individual grain boundaries (hereafter referred to as "cracks") throughout a range of climatic and geomorphic settings (e.g. Yaalon, 1970; Ollier, 1984; Hall, 1999; McFadden et al., 2005). Cracks are even visible in rocks imaged in recent photographs of Mars (e.g. Arvidson et al., 2006). A large body of literature describes mechanisms for the growth and expansion of such cracks, but the mechanism for their initiation has been disputed for over a century (e.g. Blackwelder, 1933; Griggs, 1936). Textbooks addressing geomorphology and weathering (Summerfield, 1992; Watson, 1992; Cooke et al., 1993; Ahnert, 1996; Bloom, 1998; Easterbrook, 1999;

Ritter et al., 2002) and many researchers (e.g., Yaalon, 1970; Smith and Warke, 1997; Goudie et al., 2002) identify several processes as possible causes of cracks in surface rocks, yet offer no clear solution to the problem of how they form.

New data have begun to shed light on this fundamental problem. McFadden et al. (2005) hypothesized that boulders or cobbles crack due to tensile stresses caused by directional heating and cooling during the sun's east-to-west transit across the sky. Cracks produced by this process should have orientations that reflect the orientation of the largest of these recurrent thermal stresses. This proposition was tested by measuring the orientations of approximately 700 cracks observed in over 300 rocks in the desert southwest of the United States. A significant number of cracks (462 out of ~700) had orientations that were not readily attributable to rock anisotropies such as fabric, bedding or planar surfaces. The mean azimuthal orientation of these remaining cracks was $5^\circ \pm 12^\circ$. These north-south cracks were termed *meridional* cracks. Additional documentation of the presence of these cracks in desert environments has been provided by a recent study of desert pavements in northern Africa that documents the predominance of *meridional* cracks in pavement clasts located there (Adelsberger and Smith, 2009).

Meridional cracks provide strong evidence for the importance of directional solar heating (and cooling) as a fundamental cause of such

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cracking, because their preferential orientations are very difficult to explain by other mechanisms. For example, cracks caused by freeze–thaw, salt shattering or other wedging processes alone presumably should exhibit largely random orientations, because there is no inherent mechanism involved in these processes that would result in oriented cracks. Modeling suggests that preferential shading of cracks that are already open could lead to a disproportionate propagation by these mechanisms of certain favorably oriented cracks (Moores et al., 2008). The specific north–south array of observed *meridional* crack orientations, however, would be predicted to preferentially propagate through this shading process only for a limited range of crack depths (Moores et al., 2008). Some relatively recent studies do consider a possible role for insolation, but do not specifically address directional insolation (e.g. Hall, 1999; Goudie and Viles, 2000; Viles, 2005; Warke, 2007). These studies focus on a variety of thermal–mechanical processes that may lead to cracking including thermal shock and thermal fatigue. Moores et al. (2008) do specifically address directional insolation, but propose that its impact on weathering is attributable not to induced thermal stresses but is instead attributable to differential moisture retention in cracks of varying sizes and specific rainfall regimes. Most desert weathering studies, however, continue to regard salt weathering as an essential physical weathering mechanism in deserts (e.g. Goudie and Viles, 1995; Wright et al., 1998; Smith et al., 2005). The role of directional insolation in crack initiation and propagation remains virtually unexplored.

In this study we combine new field studies of crack development in three desert study areas, the Mojave Desert of southern California, the Gobi (Desert) of Mongolia and the Strzelecki Desert of Australia, in order to further elucidate the nature and fundamental causes of *meridional* cracks in deserts around the globe. This documentation of *meridional* cracks in rocks on desert pavement surfaces of different ages in a variety of deserts (cold deserts, different latitudes, etc.) should help to evaluate more rigorously the role of directionally induced thermal stresses in fracture initiation as compared to other proposed models for physical weathering. The following will be addressed:

1) Our study of pavements in the Mongolian Gobi, which is subject to very cold winters, enables a test of the effectiveness of directional insolation as compared to thermal shock weathering, which has

been proposed (e.g. Hall, 1999) as an important physical weathering mechanism in cold environments.

- 2) Our additional studies in the Mojave Desert, as well as those in Australia and the Gobi enable evaluation of the hypothesized key role of monsoonal moisture in crack propagation proposed by Moores et al. (2008), because these deserts lack a summer monsoonal precipitation regime.
- 3) Desert pavement studies in the Mojave can help to determine if and how crack characteristics might vary as a function of surface exposure age.
- 4) If directional solar heating is responsible for rock fracture, then there should be a terminal threshold below which thermal gradients are insufficient to crack rocks.

Thus, our overall goal in this study is to build on previous desert pavement and rock fracture studies in order to further illuminate the processes of thermal–mechanical rock cracking on Earth.

2. Field areas

We examine desert pavement rock cracking in three primary field areas, the Silver Lake region of the Mojave Desert in southern California, the Mundi Mundi Plains region of the Strzelecki Desert in Australia, and the Tavan Har region of the Mongolian Gobi (Desert). The Mojave site allows for detailed examination of pavements on different age surfaces within a warm, arid site that is similar to others examined in the McFadden et al. (2005) study, while the warm, semi-arid Australian Mundi Mundi Plains and the cold, arid, and moderately high-latitude Gobi sites provide overall variability in the temperature, precipitation regime and/or latitude of deserts in which pavements are found.

The alluvial fan piedmont of the deeply embayed eastern flank of the Soda Mountains adjacent to Silver Lake Playa in the southern Mojave Desert (Fig. 1) has been the focus of numerous geomorphic and pedologic studies (Wells et al., 1984, 1987; Ritter, 1987; McFadden et al., 1989; Reheis et al., 1989; McFadden et al., 1998). A new model for accretionary desert pavement and soil development was developed on the basis of studies of these fans and adjacent

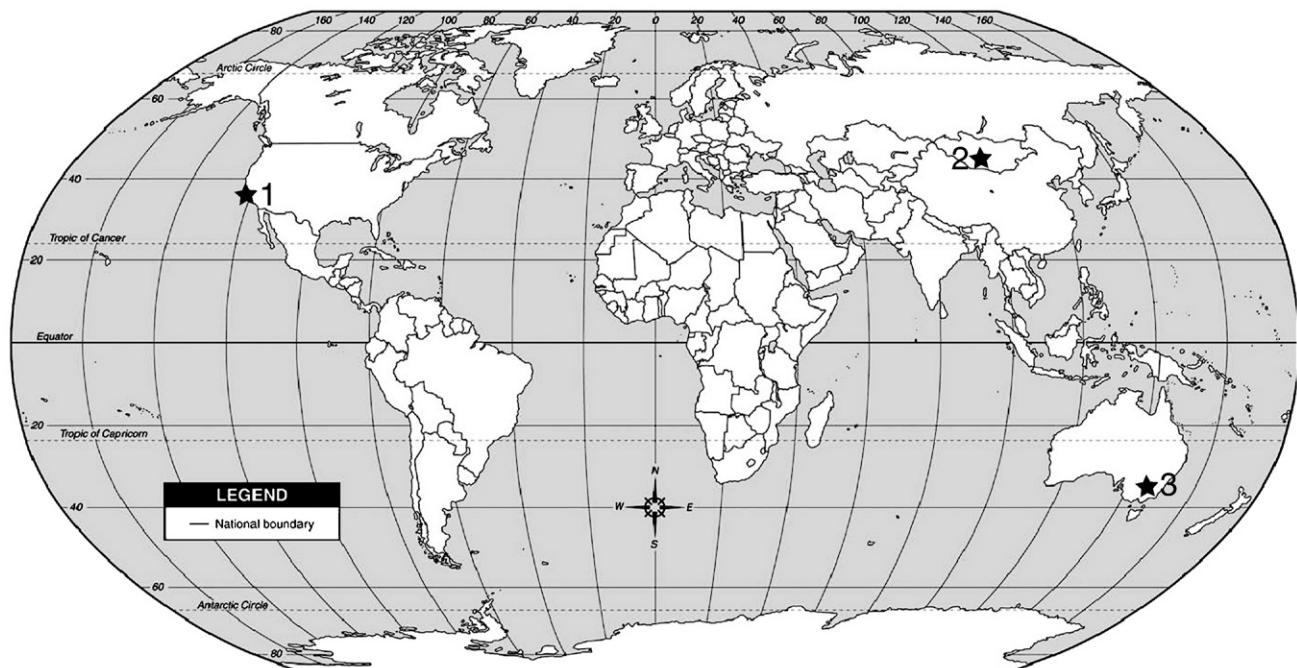


Fig. 1. Location map of the three field sites: Mojave Desert, California USA $35^{\circ} 19' N$, $116^{\circ} 07' W$), Strzelecki Desert, Australia ($31^{\circ} 48' S$, $141^{\circ} 12' E$), Gobi Desert, Mongolia ($43^{\circ} 57' N$, $109^{\circ} 25' E$).

landscapes in the Mojave Desert (McFadden et al., 1987). Silver Lake alluvial fans span ~2.5 km from ~375 m elevation at the mountain front to ~275 m elevation where they interfinger with Silver Lake Playa. Alluvial fan sediments are composed of gravely-sand size and poorly sorted plutonic and sparse volcanic clasts derived from the adjacent Soda Mountains. Six alluvial fan units have been distinguished based on stratigraphic relations, gravel bar relief, soil development, and pavement particle size and weathering characteristics (Wells et al., 1984, 1987; Ritter, 1987; McFadden et al., 1989). The ages of alluvial fan units have been assigned on the basis of interfingering ^{14}C -dated playa shorelines and sediments (Wells et al., 1987; McFadden et al., 1989). The two fans in the Silver Lake field area that were chosen for this study are Qf1, which is overlain by lacustrine deposits ^{14}C -dated at ~22,000 yr B.P., and Qf5 that is estimated to be around 1000–2000 yrs old based on rock varnish coatings and other soil features (McFadden et al., 1989). Qf5 is also certainly much less than 3300 yr B.P. based on a ^{14}C age obtained from a packrat midden in an exposed portion of the older Qf3 fan. The Qf5 surface is characterized by well-preserved bar and swale topography with unweathered clasts and minimal observable soil or desert pavement development (Wells et al., 1987; McFadden et al., 1989). In contrast, bar and swale topography is almost unobservable on the Qf1 surface; well-weathered clasts with robust varnish and rubification are common; and soils are marked by strong translocated clay (Bt) and soil carbonate (Bk) enriched horizons and desert pavement development. The climate of the area is warm and arid. The mean annual temperature is 29.7 °C with mean maximum temperatures exceeding 39 °C for June, July and August and mean minimum temperatures above freezing for all months (1971–2000; Western Region Climate Center, 2009). Mean annual precipitation is 9.4 cm with most precipitation falling during winter months.

The Australia field site is located northwest of the town of Broken Hill on the eastern margin of the Strzelecki desert of south central Australia (Fig. 1) (elevation 204 m, 31.805° S, 141.202° E). Previous detailed work on the geomorphology and Quaternary geology of this area has primarily focused on the northern end of the Barrier Range near Fowlers Gap (Hill, 2002) with general studies of the Broken Hill Region including the work of Gibson (1997, 1998) and Hill (2005). Visual interpretation of high resolution imagery and geologic maps of the region (Australian Department of Mines, 1970) suggests that the field site has reasonably “young” surfaces in a dryland setting characterized by relatively large surface clasts and a limited vegetation cover. Hill's (2005) mapping of the entire Broken Hill range confirms this interpretation and shows significant areas of both alluvial and colluvial deposits. Our field site is characterized by a dissected colluvial/alluvial bajada with a relatively steep gradient extending laterally for 40 km along the western edge of the Barrier Range, where it transitions to the low gradient Mundi Mundi Plains. The bajada spans an elevational range from ~240 m at the mountain front to ~200 m, where it interfingers with the floodplain and aeolian sands of the Mundi Mundi Plains. The Quaternary alluvial fan sediments are relatively young (as indicated by relatively weak desert pavement development) with limited vegetation and large surface clasts composed of poorly sorted gneiss, schist, amphibolite granite and pegmatite derived from the Barrier Range which rises to a local maximum elevation of 450 m. The regional climate is hot and semi-arid with an annual precipitation spread equally throughout the year and ranging from 20.5 cm at Umberumberka Reservoir (elevation 226 m; 1.66 km to the SE, 1911–2009) to 25.3 cm at Broken Hill, (elevation 315 m; 30.1 km to the NE, 1889–2009; Australian Government Bureau of Meteorology, 2009). Mean annual temperature at both sites is ~25.8 °C with mean maximum temperatures exceeding 30 °C most of December, January and February and mean minimum temperatures above freezing for all months (1889–2009, Australian Government Bureau of Meteorology, 2009). Frosts are rare at this site.

The Mongolian field site (43.9559° N, 109.4253° E) is located in the Tavan Har massif of the eastern Gobi, 175 km north of the Chinese border and about 100 km southwest of the regional capital, Sainshand. The Tavan Har massif, a basement high of Paleozoic metamorphic rocks within the Late Jurassic – Early Cretaceous East Gobi basin (Johnson, 2004), has subdued topographic relief of about 275 m. Discontinuous and abandoned, undated pediment surfaces of presumed late Pleistocene age encircle the massif between elevations of 900 and 925 m. Holocene ephemeral alluvial channels and fans are incised (inset) into these pediment surfaces. The soils developed on the pediment surfaces have thin Av (~2.5 cm) and moderate Bt and Bk horizons beneath well-developed pavement surfaces. Climate of the Tavan Har area is arid continental. About 70% of the mean annual precipitation (11.3 cm) occurs during the summer months. The mean annual temperature is 3.6 °C with mean maximum temperatures exceeding 27.5 °C for June, July, and August, while the mean minimum temperature is below 0 °C from October through April, and below –20 °C for December through February (1961–1990; World Meteorological Organization, 1998).

3. Methods

At the Mojave field site, we collected data along four transects from the Qf1 and Qf5 alluvial fan surfaces in medial fan positions (Fig. 2; Table 1). We chose areas of the fan surfaces with the highest stone density for all transect locations. On each of the two surfaces, we completed an ‘all rock’ survey in which we laid a 100 m tape parallel to the fan slope and examined every stone with intermediate diameters equal or greater than 1 cm that fell under each 20-cm tick mark. If the stone under the tick mark was loose on the pavement or showed signs of recent disturbance, it was skipped. The following data were collected for each rock: rock type, width, length, depth, and azimuthal orientation (using a declination of 13° East for Baker, California) of the rock's longest axis. Cracks were defined as any visible, linear void greater than 0.5 cm in length. The following data were collected for every crack with a unique orientation for 50 rocks on each surface: crack width as defined by 4 categories, incipient – <0.1 mm, thin – 0.1–1 mm, medium – 1–3 mm, thick – >3 mm; crack strike (azimuthal°); crack length as defined by 4 categories related to how the crack encircles the stone, 1 – crack found only on the exposed portion of the stone and does not continue to the ground surface, 2 – crack extends across the rock to the ground surface but not beyond, 3 – crack extends beyond the ground surface but does not bifurcate the rock, and 4 – crack bifurcates the entire rock; crack type as defined by 4 orientation categories that were observed in the McFadden et al. (2005) study, fabric cracks – cracks parallel ($\pm 10^\circ$) to rock fabric such as bedding or foliation, longitudinal cracks – cracks parallel ($\pm 10^\circ$) to the orientation of the rock's long axis, surface cracks – cracks parallel ($\pm 10^\circ$) to an exterior surface of the rock, and ‘other’ cracks – those cracks not falling into one of the three other categories; and finally whether or not additional cracks on the rock were parallel ($\pm 10^\circ$) to the measured crack. For each of the two fan surfaces data were also collected for a 2nd ‘boulder’ transect in an adjacent location. For these transects, however, we examined the largest clast with an intermediate diameter greater than 20 cm that was within 1.5 m of each 1 m increment on the tape. In addition, we collected the same clast and crack data as the ‘all rock’ transect for 12 boulders on each of the two surfaces in this manner.

For the Strzelecki field site our methodology for collecting crack data was still evolving. At that time, we therefore had a slightly different strategy for data collection than in the Mojave. We did not collect an ‘all rock’ dataset, however, we examined a ‘boulder’ transect in a similar manner to that described above, where we examined the largest clast greater than 10 cm within 2 m of every 1 m incremental tick mark on a tape. We collected the same data as above for both rocks and cracks at the Strzelecki site for a total of 17 rocks. Here,

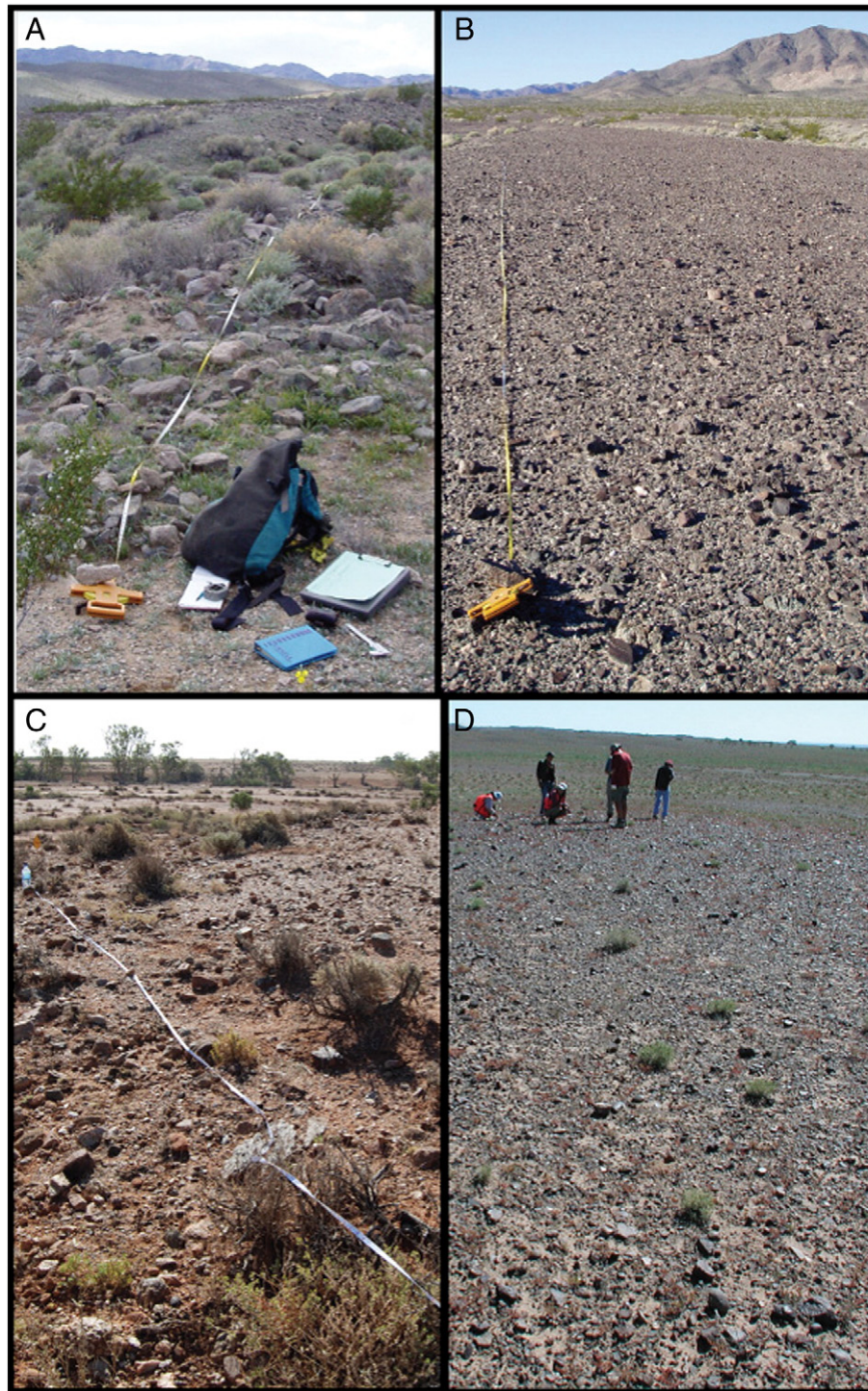


Fig. 2. Photographs of field transect locations. A) Qf5 – latest Holocene age fan Mojave field site B) Qf1 – 14–22 ka age fan Mojave field site C) late Quaternary age fan Strzelecki field site and D) middle- to late Pleistocene age pediment surface, Gobi field site. Scale is roughly the same in all 4 photographs.

however, we defined cracks as any linear void greater than 10 cm in length. Despite these minor differences in data collection strategy, due to the fact that in all sites we examined cracks on cobbles and boulders, we feel that the datasets are rigorous and comparable.

In the Gobi field site, the azimuth (using a declination of 13 E for the Tavan Har region) of ~100 cracked rocks from two pediment surfaces was measured. Cracks were defined as any linear void bisecting the rock either to the ground surface or completely through the clast. If cracks were parallel to a rock's fabric or bedding, they were not counted. The average clast size of rocks examined in the Gobi was

about 20 cm in diameter. Gobi data were collected prior to publication of the methodologies established in the [McFadden et al. \(2005\)](#) study, and therefore does not include the same amount of detail as the other three datasets presented here. We feel, however, that the large number of stones examined (101) and the unique opportunity to present data from this ancient, remote cold desert justify the inclusion of this dataset.

We utilized the open-source GEOrient © v9.4.2 software ([Holcombe, 2009](#)) to plot crack orientation data as Rose Diagrams ([Fig. 3](#)). [Fisher \(1993\)](#) proposed that a more objective, visual indication of preferred

Table 1
Crack data for all transects in all field sites.

Field site	Surface	Age (ka)	total # rocks examined	total # cracks with unique orientations	% of crack orientations that were parallel (+/−10) to other cracks on the same rock	% of rocks with no cracks	Crack width			Crack length relative to rock							Crack type		
							'i' cracks (<5 mm)	't' cracks (>5 mm, <1 mm)	'm' cracks (>1 mm, <3 mm)	'L' cracks (>3 mm)	% 1	% 2	% 3	% 4	% 5	B cracks	% o cracks	s cracks	% s/B/F cracks
Mojave All Rock	Alluvial Fan Qf5	1000–2000 yr	50	96	19	16	68	20	3	7	23	60	11	4	0				
Mojave Boulder	Alluvial Fan Qf5	1000–2000 yr	12	39	26	0	56	23	13	8	85	15	0	3	13	74	13	0	0
Australia Boulder	Alluvial Fan	late Holocene	17	54	63	0	46	33	7	13	17	76	4	2	2				
Mojave All Rock	Alluvial Fan Qf1	20–30 kyrs	50	108	18	14	85	11	3	0	7	83	7	1	0				
Mojave Boulder	Alluvial Fan Qf1	20–30 kyrs	12	54	33	0	50	22	17	11	80	17	4	0	7	70	20	2	0
Gobi All Rock	Pediment	Late Pleistocene	101	120	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**

orientations for circular data is a quantile–quantile plot of $i(n - 1)$ vs. $X_i/180$. Where n = total number of data, X_i are the orientation values of the data that have been converted to 0–180 for axial data, and i is the ranking of those data from 1 to n . If data are perfectly uniform and random, then they will fall on a line that intersects the origin at 0,0. Systematic, periodic deviations from this straight line indicate preferred orientations in that azimuthal quadrant. All data are plotted in this manner in Fig. 4.

Using Oriana © v 3.0 software, we report statistics for the circular data (Table 2). The statistics provided in Oriana are based on procedures from Mardia (1972), Mardia and Jupp (2000), Fisher et al. (1987) and Fisher (1993). Here we report 'mean resultant direction' (sometimes called vector mean or mean vector), and the 99% confidence interval of that mean resultant direction. The mean resultant direction is analogous to the slope in a linear regression with the 95% confidence interval providing the ± error for that mean.

Using Oriana © v 3.0 software, we also report circular variance as well as the Rayleigh Uniformity Test, and Rao's Spacing Test (all after Fisher, 1993; Mardia and Jupp, 2000). Circular variance is a simple measure (0 to 1) of the scatter of recorded crack azimuths; values close to 0 indicate low variance, and values close to 1 indicate high variance. This statistic is based on a von Mises distribution (in circular statistics, a normal distribution is referred to as a von Mises distribution) of data about a single mean (i.e. unimodal data). Therefore, for multi-modal data, the variance might be high, but the data might nevertheless be non-uniform. The Rayleigh Uniformity Test calculates the probability of the null hypothesis that the data are distributed in a uniform manner. Again, this test is based on statistical parameters that assume that the data are clustered about a single mean. If p-values for this test are <0.05 then data are considered non-uniform or non-random. Rao's Spacing Test is also a test for the null hypothesis that the data are uniformly distributed; however, the Rao statistic examines the spacing between adjacent points to see if they are roughly equal (random with a spacing of $360/n$) around the circle. Thus, Rao's Spacing Test is appropriate for multi-modal data and may find statistical significance where other tests do not. If the p-value for this test is <0.05, then the data are considered to be non-random.

4. Results

4.1. Numbers of cracks per rock

Almost all rocks on all examined surfaces exhibited cracks. In the Mojave and Strzelecki sites, all rocks from the *boulder* transects exhibited cracks, and ~85% of the *all rock* Mojave transects exhibited cracks. We do not have data to determine what percentage of Gobi rocks have cracks, however, they were sufficiently distributed across the two pediment surfaces that the azimuths of cracks on 100 rocks were collected within a small area (~500 m²) in a short period of time (~1 h each).

The old Qf1 and the young Qf5 surfaces in the Mojave site exhibited comparable total numbers of unique crack orientations for the 50 rocks examined in the *all rock* transects (Table 1). On average, rocks observed for both of these Mojave *all rock* transects exhibited about two unique orientations of cracks. In addition, around 17% of those cracks had other cracks that were parallel to them on the same rock for both datasets. These percentages were slightly higher for the Mojave as well as the Strzelecki *boulder* transects. The average rock in all *boulder* transects contained 3–5 unique orientations of cracks, with many (26–33% Mojave; 63% Strzelecki) of those cracks having others that were parallel on the same rock. The Gobi rocks had the fewest crack orientations per rock of all sites, with an average of 1.2 unique crack orientations per rock; however, only relatively large cracks that reached the ground surface or bifurcated the rock were measured. No data were collected for the numbers of parallel cracks in the Gobi.

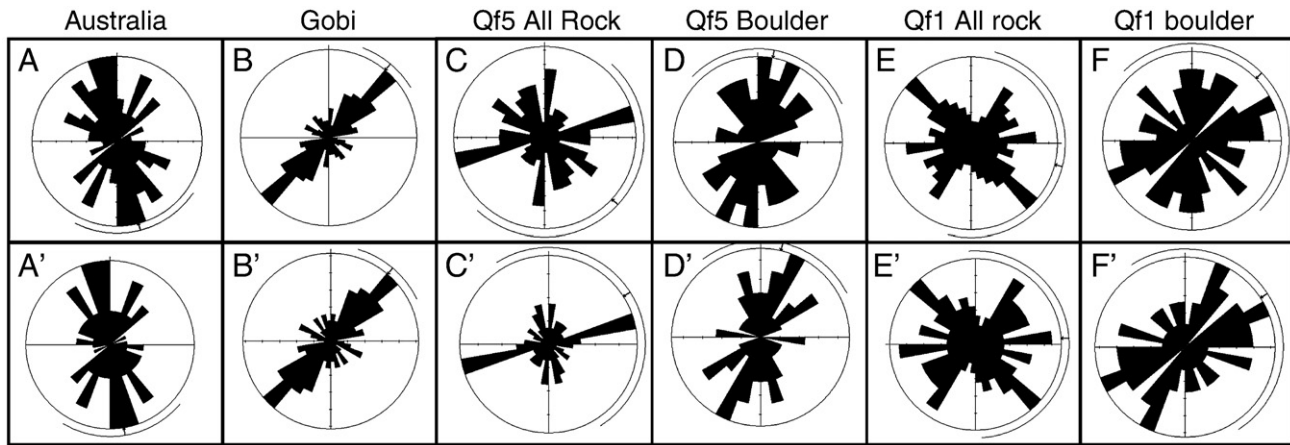


Fig. 3. Rose diagrams (circular histograms) of crack orientation data created with GEORient © v9.x software. Arrows point to the mean resultant direction. Arcs represent the error on the mean to 95% confidence as calculated in GEORient. See text for explanation of statistics calculations and Table 2 for statistics for these orientation data. A) Strzelecki site all cracks, $n = 54$; A') Strzelecki 'other' cracks, $n = 40$; B) Gobi site all cracks, $n = 120$; B') Gobi site all cracks for igneous rocks only (71 of 101 rocks examined), $n = 84$; C) Mojave site Qf5 All Rock Transect all cracks, $n = 96$; C') Mojave site Qf5 All Rock Transect other cracks, $n = 58$; D) Mojave site Qf5 Boulder Transect all cracks, $n = 39$; D') Mojave site Qf5 Boulder Transect other cracks, $n = 29$; E) Mojave site Qf1 All Rock Transect all cracks, $n = 108$; E') Mojave site Qf1 All Rock Transect other cracks, $n = 90$; F) Mojave site Qf1 Boulder Transect all cracks, $n = 54$; F') Mojave site Qf1 Boulder Transect 'other' cracks, $n = 38$.

In the Mojave *all rock* transects, only 8 rocks out of 50 on the younger Qf5 surface and 7 rocks out of 50 on the older Qf1 surface did not exhibit any cracks. Two of these 15 rocks were granites that exhibited friable surfaces and were actively disintegrating along intergranular boundaries. The remaining 13 rocks exhibited no cracking at all. The maximum size of these 13 rocks with no observed cracks was 5 cm; however, rocks as small as 1 cm diameter commonly exhibited cracks on both the Qf5 and Qf1 surfaces. In many instances we observed that these smaller rock fragments could be replaced onto their parent rock like a puzzle piece. Upon refitting these pieces, it became obvious that cracks present on smaller fragments lined up with cracks on the parent rock, suggesting that the crack on the smaller rock had been inherited.

4.2. Crack types

We observed somewhat similar crack types and characteristics in our Mojave and Australia transects as were observed in the McFadden et al. (2005) study (Table 1) (crack type data are not available for the

Gobi dataset). Only two rocks in the Mojave and Strzelecki transects exhibited some type of fabric (metamorphic rocks in the Strzelecki desert), and so only these two rocks exhibited fabric cracks. In the Gobi, 32 of the 101 rocks examined were either metamorphic or sedimentary; however, as we collected this data, we did not measure cracks that were visibly parallel to any rock fabric.

Around 11% of rocks in both the *all rock* and *boulder* transects for Qf5 exhibited surface-parallel cracks, however, this percentage varied for the Qf1 *boulder* (20%) versus *all rock* (7%) transects (Table 1). In the Strzelecki *boulder* transect only 3% of rocks exhibited surface-parallel cracks.

For all but the Qf1 *boulder* transect, the largest percentage (range 30–75%) of rocks with longitudinal cracks were boulders with the highest length to width ratios (generally >2). For the Qf1 *boulder* transect, only 4 boulders out of 12 exhibited cracks parallel to the long axis of the boulder and all of these exhibited length/width ratios less than 1.5. For all transects on all surfaces the large majority (60–80%) of cracks were 'other' cracks that did not fall into one of the three non-meridional crack categories of McFadden et al. (2005).

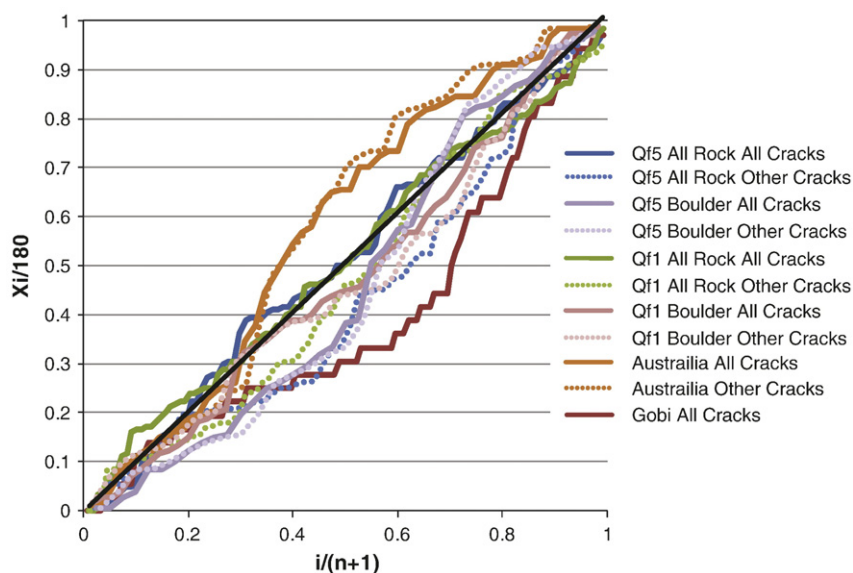


Fig. 4. Quantile-quantile plot of crack orientation data. See text for explanation of variables. Deviations from a straight line indicate non-random, preferred orientations.

Table 2
Statistical data for crack orientations for all transects and sites. See text for statistics explanations.

Variable	Australia all cracks	Gobi all cracks	Qf5 all rock all cracks	Qf5 boulder all cracks	Qf1 all rock all cracks	Qf1 boulder all cracks	All sites/transects all cracks
Number of observations	54	120	96	39	108	54	471
Mean resultant direction ^a	345°	40°	133°	10°	104°	46°	26°
99% confidence interval ^a	± 25°	± 13°	± 90°	± 31°	± 90°	± 90°	± 30°
Circular variance ^a	0.36	0.33	0.46	0.37	0.46	0.46	0.46
Rayleigh test (p) ^a	0.01	7.10E–07	0.54	0.06	0.58	0.74	0.05
Rao's spacing test (p) ^a	0.50 > p > 0.10	< 0.01	< 0.01	0.95 > p > 0.90	0.50 > p > 0.10	0.99 > p > 0.95	< 0.01
Variable	Australia other cracks	Gobi all rock minus fabric rocks	Qf5 all rock other cracks	Qf5 boulder other cracks	Qf1 all rock other cracks	Qf1 boulder other cracks	All sites/transects other cracks
Number of observations	40	84	58	29	90	38	339
Mean resultant direction ^a	351°	40°	57°	13°	86°	57°	34°
99% confidence interval ^a	± 24°	± 17°	± 90°	± 29°	± 90°	± 90°	± 22°
Circular variance ^a	0.33	0.33	0.45	0.33	0.43	0.42	0.44
Rayleigh test (p) ^a	0.01	5.93E–05	0.56	0.04	7.79E–01	0.38	0
Rao's spacing test (p) ^a	0.50 > p > 0.10	< 0.01	0.50 > p > 0.10	0.90 > p > 0.50	0.90 > p > 0.50	0.90 > p > 0.50	< 0.01

^a Calculated with Oriana © v3.0.

4.3. Crack sizes

There is no remarkable pattern for crack widths and lengths in terms of surface age for any of the Mojave transects (Table 1). Cracks were slightly wider and longer on the older Qf1 surface than the Qf5 surface for the *boulder* transects, but slightly thinner and shorter on the older surface for the *all rock* transects (Table 1). The Strzelecki *boulder* transect was comparable to that of the Qf5 *boulder* transect in terms of crack width. This transect contained significantly more separated rocks (15%), however, than any other transect examined (0–3%).

4.4. Clast sizes

In a manner similar to data collected in other Silver Lake studies (e.g. McFadden et al., 1989), clast size varied in the Mojave site as a function of surface age. The average maximum diameter of all clasts in the *all rock* transect on Qf1 was 4.2 ± 2.7 cm, and the largest clast encountered was 11 cm. The average maximum diameter of all clasts in the *all rock* transect of Qf5 was 10.4 ± 8.6 and the largest clast encountered was 36 cm (Fig. 5). The maximum diameter of over half of the rocks examined on Qf1 fell in the size range of 3.2 to 6.4 cm, whereas the maximum diameters of rocks on Qf5 were significantly more varied (Fig. 5). Although we do not have quantitative data, in general the relatively young Strzelecki site is characterized by rocks of variable sizes, whereas those of the Gobi site are consistently smaller

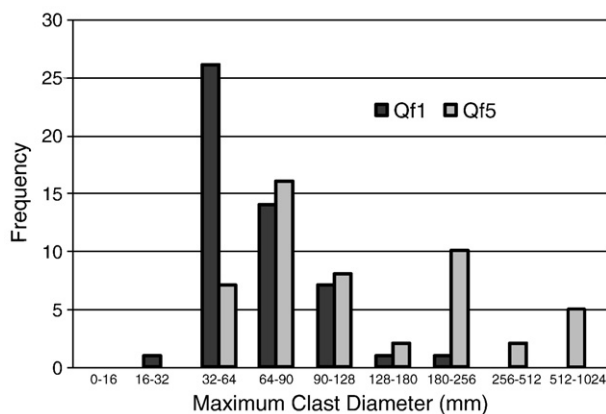


Fig. 5. Histogram of the maximum diameters (length of longest axis in mm) of all clasts measured in the 50-rock transects completed on the Qf1 and Qf5 surfaces at the Mojave field site. Size categories are based on the Udden-Wentworth grain size scale.

and qualitatively more similar to the clast sizes measured from the Mojave Qf1 than Qf5 (Fig. 2).

4.5. Crack orientations

The mean resultant direction for all cracks in all sites is $26^\circ \pm 30^\circ$ ($n = 471$) with both Rayleigh and Rao's Spacing tests as well as visual inspection of the quantile–quantile plot indicating that the orientations are not random (Table 2; Fig. 4). When surface-parallel, longitudinal and fabric cracks are removed from the entire dataset, the mean resultant direction becomes $34^\circ \pm 22^\circ$ ($n = 339$; Fig. 6) with both the Rayleigh and Rao's Spacing tests indicating that the orientations are not random (Table 2). The individual mean resultant directions for the 6 datasets examined ranged from $345^\circ \pm 25$ to $46^\circ \pm 90$ with 4 out of 6 transects characterized by mean resultant directions to the northeast (Fig. 3). The Gobi dataset was strikingly unimodal with a smaller 99% confidence interval ($\pm 13^\circ$) compared to the remainder of the datasets (Fig. 3; Table 2). The remainder of the datasets exhibited varying modality, often with two to three general modes of varying strength roughly centered about north–south (i.e. Fig. 3 A, D, E and F). Variance for all transects and sites was less than 0.5 (Table 2). With no exceptions, orientation variance stayed the same (Gobi) or decreased (all others) when surface-parallel, longitudinal and fabric cracks were removed from the dataset. The Rayleigh Uniformity test showed statistically significant, non-random distributions for the Strzelecki, Gobi, and Mojave Qf5 *boulder* transects when all cracks were considered, and for those sites plus the Mojave Qf1 *all rock* transect when surface-parallel, longitudinal and fabric cracks were removed from the datasets. The Rao's Spacing Test indicated a non-random distribution for the Gobi and Mojave Qf5 *all rock* transects when all cracks are considered, and for the Gobi transect when sedimentary and metamorphic rocks were removed from the datasets.

5. Discussion

5.1. Minimum clast size for meridional cracking on desert pavements

The systematic, in-situ breakdown of volumetrically abundant, massive blocks or large boulders into well-sorted relatively small (5 to 15 cm) angular pebbles and cobbles is well documented for strongly-developed pavements. Increasing angularity, sorting and/or decreasing clast size with progressive surface age are commonly observed features of desert pavements (e.g. McFadden et al., 1998; Al-Farraj and Harvey, 2000). This comminution of rocks on the original desert surface is a geomorphically-significant process that favors an important pavement

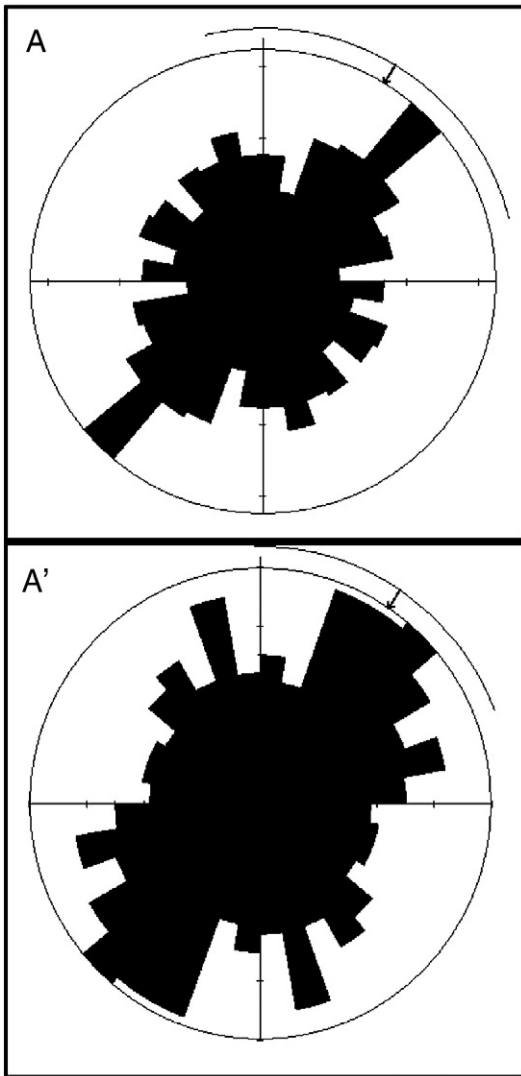


Fig. 6. Rose diagrams (circular histograms) of crack orientation data created with GEOrient © v9.4 software. Arrows point to the circular mean direction (CMD). Arcs represent the error on the mean to 95% confidence. Circular Variance (CV) is reported herein. See text for explanation of statistics calculations. A) All sites combined all cracks, $n = 471$, $\text{CMD} = 31^\circ \pm 44^\circ$, $\text{CV} = 0.91$; A') All sites combined 'other' cracks, $n = 339$, $\text{CMD} = 34^\circ \pm 35^\circ$, $\text{CV} = 0.87$.

formation feedback by increasing clast density, surface cover, and subsequently decreasing water infiltration into the underlying Av horizon (Wells et al., 1985; Abrahams and Parsons, 1991; Wood et al., 2005). This decrease in infiltration can lead to exceptionally high nitrates and overall soluble salt concentrations within the upper soil horizons of desert pavements, thus posing a potential environmental threat if the pavement is disturbed (Wood et al., 2005; Graham et al., 2008). Despite its importance, the relatively rapid breakdown of initial surface materials (e.g., boulders, or basalt flow tops) into a well-sorted, cobble- to pebble-rich pavement has received considerably less attention than other aspects of desert pavement formation and is consequently poorly understood.

Numerical modeling (Mackenzie-Helnwein et al., 2009) predicts that in rocks smaller than about 5 cm in diameter, maximum temperature gradients between the rock surface and its interior would be insufficient to produce stresses that might cause cracking. Therefore if thermal-mechanical processes related to directional insolation are the primary cause of cracking of desert pavement rocks, then there should be a terminal clast size below which desert pavement rocks do not crack. On the basis of this hypothesis, we

developed a field-based strategy to attempt to document a clast size below which no cracks were evident on desert pavement surfaces. Our initial results indicated, however, that cracks are inherited from parent rocks and that, as demonstrated in many previous studies of pavements, the subsequent likely disturbance of and probable changes in the orientation of these small clasts would preclude conclusions about directional heating based on such an observation. However, we note that only 13 of the 141 rocks that we observed did not contain cracks, and that all of these 13 rocks were less than 5 cm in diameter. This diameter is similar to the average clast size of the older Qf1 Mojave desert pavement surface. There is an abrupt drop in the frequency of clasts below the 3.2 cm maximum diameter for this surface (Fig. 5). We know from trench data (McFadden et al., 1989) that the limited size range of clasts on the surface of the ~20 ka Qf1 surfaces (Fig. 5) is not an inherited trait of the original alluvial fan deposit, which exhibits variability in clast size comparable to younger deposits, for example the Mojave Qf5 surface (Fig. 5). Also, data from other studies suggest that the median desert pavement clast size does not continue to diminish significantly for older surfaces, suggesting that indeed the terminal clast size for pavements is in the 3 to 5 cm range. For example, Wood et al. (2005) document dominant average clast sizes from 2.2 to 4.5 cm from a pavement developed on a 580 ka basalt flow in the Cima Volcanic Field, also in southern California. We suggest that the average clast size on mature desert pavements is controlled partly by the strongly diminished efficacy of directional thermal cracking below this clast size that has been suggested in modeling studies (Mackenzie-Helnwein et al., 2009). Differential shading of pre-existing microfractures (e.g. Moores et al., 2008) does not readily provide a mechanism for producing this observed terminal clast size in desert pavements.

5.2. Evolution of cracking

A second goal of this study was to further document the evolution of meridional cracking by examining rocks on desert pavement surfaces of different age. With few exceptions, we were unable to document significant trends in crack properties as a function of surface age (Table 1). We did observe a slight increase with surface age in the number of unique crack orientations per rock on all transects, as well as a slight increase in crack widths with surface age for the Mojave *boulder* transects. The latter is similar to general observations presented in McFadden et al. (2005), however, they did not directly compare different aged surfaces within the same field area in that study as we did. We did not see any significant increase, however, in the size of cracks for the *all rock* transects, nor did we observe any significant trends in crack types or orientations with age. These results suggest that perhaps a steady-state of crack initiation and propagation is reached relatively quickly once rocks are deposited and the surface stabilized. Cracks form, propagate and completely separate rocks quickly enough, such that an evolution is not apparent when observing two surfaces of significantly different age. The proposed evolution in cracking might be more apparent in future data sets if more surfaces that are closely spaced in age were included in the study.

Another complicating factor is that rates and processes of crack widening such as salt shattering or frost wedging will probably vary from site to site and temporally through time. These differences might account for the variability that we observed in crack size and orientations from transect to transect. For example, the climate of the Strzelecki site is wetter than that of the other sites examined. This could possibly account for the greater abundance of separated clasts. Conversely, there could possibly be more bioturbation or swelling and shifting of the underlying Av horizon at the Mojave sites that would ultimately serve to relatively rapidly separate two halves of a rock to such an extent that they were no longer recognizable as a single clast. The evidence for less strongly expressed preferred crack orientations

in the older Qf1 dataset at the Mojave site supports the idea that other processes probably play increasingly important roles in influencing rock fracture orientation and propagation, as discussed in the next section. Finally, the inclusion of very small cracks (<1 cm length) in the Mojave transects possibly led to a greater variance in these datasets if those small cracks were present in the stone as it was deposited. If cracks on small rocks are being inherited from parent rocks, the orientation of the crack should not be related to the shape of the small rock.

5.3. Preferential orientation of cracking

Our data unambiguously show that cracks exhibit preferred orientations in deserts of varying latitudes and climates around the globe. These data suggest that the comminution of desert pavement clasts can be largely attributed to processes of physical weathering related to directional insolation. Although the datasets are not extensive in these locations, some preliminary comparisons may be made between the new datasets from Australia and Mongolia and those of the southwestern United States. In particular, we observe interesting similarities and differences in both the modality and the mean resultant direction for data from different localities in our study as well as those of others (e.g., [McFadden et al., 2005](#); [Adelsberger and Smith, 2009](#)).

First, the lack of tight clustering as indicated by intermediate circular variance statistics for almost all of our datasets is largely attributable to the bi-modality or multi-modality of the orientation data. The primary exception to this multi-modality is the Gobi data, which is markedly unimodal ([Fig. 3](#)). Crack orientation bi-modality was evident in the rose diagrams for all field sites across the Southwestern U.S. desert in the [McFadden et al. \(2005\)](#) study. [Adelsberger and Smith \(2009\)](#) examined crack orientations on pavement rocks for slopes of varying aspect in the hyperarid Libyan Plateau of Central Egypt. In their data, the east and south-facing slopes exhibited strongly unimodal orientations, while the flat slopes exhibited unimodal orientations with slightly more variance, and north-facing slope data exhibited a bi-modality or multi-modality similar to that of other datasets described herein. They did not present data for west-facing slopes.

The majority of mean resultant directions of crack orientations in our studies as well as those in [McFadden et al. \(2005\)](#) and [Adelsberger and Smith \(2009\)](#) is towards the northeast. In our data, all mean resultant directions are to the northeast with the exception of Strzelecki and the Mojave *all rock* transects ([Fig. 3](#)). In the [McFadden et al. \(2005\)](#) study, 9 of the 10 datasets collected at different sites throughout the southwestern United States were also characterized by a mean resultant direction of crack orientations towards the northeast or less than 5° west of north. The lone exceptions to this northeast trend are a dataset with only 24 cracks observed (mean resultant direction = 30° west of north; [McFadden et al., 2005](#)). Data from Egypt exhibit mean resultant directions to the northeast with the exception of very small datasets (12 cracks) and north-facing slopes ([Adelsberger and Smith, 2009](#)). It has been suggested that the northeast offset in the mean resultant direction of field data could be explained by a preferential retention of summer monsoon moisture by ENE–WSW facing cracks ([Moores et al., 2008](#)), however we observe similar offset for data collected in the Mojave which does not receive summer monsoonal precipitation. Furthermore, our Strzelecki site also does not experience a monsoonal climate, nor does the Gobi site. If preferential shading were responsible for the orientations of these cracks, then symmetry about N–S would be expected ([Moores et al., 2008](#)). We suggest instead that the observed differences in mean resultant directions and modality reflect the times of year and day which are most influential in producing these directional cracks at different latitudes through thermal–mechanical cracking due to directional insolation.

The strong unimodality of the mean orientations of our Gobi dataset and that of the Egypt data ([Adelsberger and Smith, 2009](#))

have interesting implications for understanding the most important solar conditions for crack development. The Gobi field site is located at ~44° N. If cracks are forming perpendicular to the principal thermal stresses arising from directional heating in the Gobi site, then cracks are forming due to stresses that arise when the sun is at a 90° angle from the 40° ± 13° mean resultant direction of the data, (i.e. when the sun is either in the southeastern sky at 130° ± 13° or in the northwest at 310° ± 13°). The solar path for the latitude and longitude of the Gobi site, however, includes the 130° ± 13° portion of the sky for 3–4 h/day all year long, whereas it is never in the 310° northwestern portion of the sky and only within the westernmost portion of the northwestern ± 13° window for <1 h/day in the summer months (May, June, July; [Fig. 7](#)). Thus, cracks are probably forming due to stresses that arise during clast heating in the morning hours in this setting because the sun is never in a position in the afternoon to produce the thermal stresses necessary to produce cracks of the observed orientation. In the Gobi winter, average overnight minimum temperatures are well below 0 °C. Fractures induced by morning thermal conditions are consistent with observed times of maximum temperature gradients across the surface of the rock from the [McFadden et al. \(2005\)](#) study.

The strong unimodality of the Gobi data suggests that a thermal regime associated with this early-morning temperature gradient is most important for cracking rocks in this setting. The unimodality of portions of the Egypt data ([Adelsberger and Smith, 2009](#)) also suggest that morning thermal conditions are important for fracture initiation. In that dataset, east-facing slopes are characterized by rocks with fractures oriented virtually north–south. Because these east-facing slopes do not receive afternoon sun, the implication is that fractures are forming due to stresses that arise during morning hours when the sun is perpendicular to the orientation of the observed cracks. Data from south-facing and ‘flat’ surfaces in the same field area exhibit similar mean resultant directions but with slightly more variance, suggesting that although these landscape positions receive more variable directions of insolation, the easterly morning sun dominates in terms of importance for crack formation. Similarly, cracks formed due to early morning summer or late-morning winter thermal stresses could account for the northeast trend of the Mojave *BOULDER* datasets and the *northwest*-majority trend of the Strzelecki dataset. Very late afternoon winter thermal conditions could also, however, contribute to these orientations, and both the Strzelecki and Mojave datasets exhibit much more variance than the Gobi and Egypt datasets, suggesting that other diurnal and/or annual conditions often lead to rock fracture in these settings.

Overall, based on the above data, we feel that thermal conditions resulting in maximum temperature gradients on the rock surface are most important for inducing rock fractures with preferred orientations. In particular, there is a general correlation in sites such as the Strzelecki desert in Australia between maximum diurnal range and the lowest relative humidity values (as would be expected with a dry atmosphere). This condition would lead to a rapid warming early in the morning peaking with high insolation induced gradients on a rock's surface in the early morning. Such an effect would be especially pronounced in the summer months in Australia (late December to mid March). Thus, we attribute the mean resultant direction of cracks from this dataset to those formed during early morning summer hours. Temperature data from other studies corroborate that overall maximum gradients occur in morning hours when ambient air temperatures are low, and insolation of sunrise rapidly heats one side of a rock surface (e.g. [McFadden et al., 2005](#)). Other diurnal and/or seasonal conditions, however, might also result in repeated cycles of large temperature gradients. Wind has been shown, for example, to rapidly reduce rock surface temperatures (e.g. [McKay et al., 2009](#); [Molaro and McKay, 2010](#)), If winds pick up at a particular site during similar times of day throughout a season, then the repeated gradients associated with cooling of what was a well-heated rock in the late

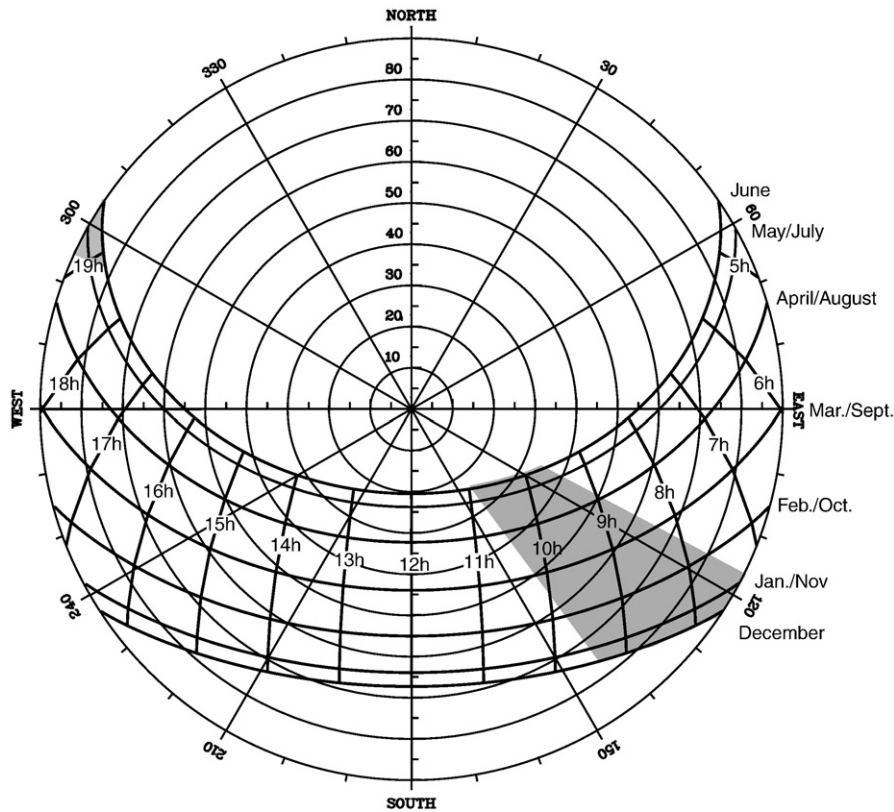


Fig. 7. Solar Path Chart for the Gobi field site. Modified from a chart created through the University of Oregon Solar Radiation Monitoring Laboratory website. Shaded areas represent times and days when the sun would be at a 90° angle from the mean resultant observed crack angle of 40° .

afternoon might induce sufficient preferential stress to cause fracture. These and other temporally-controlled diurnal and seasonal conditions will have likely been variable in the past, particularly for older surfaces that have survived through pre-Holocene conditions. In this manner, crack populations with varying preferred orientations may develop for a particular field site, resulting in the multi-modality that we observe at most sites. The evidence supporting a key role for the timing and magnitude of development of surface and sub-surface temperature gradients also indicates that induced thermal stresses associated with differential insolation play a key role in causing brittle failure, rather than only the presence of water retained in crack tips due to annual patterns of shading as proposed by Moores et al. (2008). In particular, because the Gobi site does not currently experience a summer monsoon, and has only experienced weak monsoonal moisture in the past (e.g. Yang and Scuderi, 2010), and the Egypt site receives less than 1 mm/year precipitation (Shahin, 1985), it is difficult to explain the unimodality of fracture orientations by preferential shading of crack tips that are oriented to keep afternoon monsoonal rainwater from evaporating. Our data do not preclude a shading effect; however, they are difficult to explain by a shading effect alone.

The relatively high variances observed in the Mojave *all rock* datasets and their associated NW-oriented mean resultant directions may also be explained by considering the currently accepted model for desert pavement formation and soil development. The mechanical weathering of surface clasts that produces the lower mean particle size range of Desert pavements compared to much younger bar and swale deposits documented in this study and the McFadden et al. (1989) study on the Soda Mountains piedmont means that most of the boulders initially present on the Mojave Qf1 surface have been both diminished in size and separated from their initial depositional position by accretionary soil development. These processes can influence crack orientations in two ways. First, as noted above,

although differential insolation probably produces a new generation of *meridional* cracks in smaller fragments detached from larger boulders, these fragments will likely retain at least some inherited cracks, many of which will be shifted to non-*meridional* orientations as described above. Additionally, it is likely that a majority of original crack orientations are not well-preserved at any time when smaller rocks are measured, because smaller rocks characteristic of this and other pavements worldwide are more subject to jostling by wind or bioturbation (e.g., Valentine and Harrington, 2006). Rodents and other animals (e.g., desert tortoise) are capable of disturbing surficial deposits in desert regions; however they are too small to dislodge larger clasts in interlocking boulder-rich deposits. It is notable that in contrast to the *all rock* datasets, the Mojave Qf5 *boulder* datasets exhibit a mean resultant direction (10 to 13° east of north) and associated relatively low circular variance (tighter clustering) that are consistent with those observed in the datasets of the McFadden et al. (2005) study and in the Gobi and Strzelecki datasets presented here. We attribute this clustering to the more mechanically stable conditions associated with large boulders embedded in well-developed channel bars. The evolution of a virtually boulder-free, texturally fine grained accretionary Bt horizon, however, eventually enables bioturbation of soils associated with well developed, Pleistocene pavements (McAuliffe and McDonald, 2006). The lack of tight clustering of crack orientations in the *Boulder* transects on the older Mojave Qf1 surface likely reflects the impacts of such processes.

The more east–west mean resultant directions of the Qf5 and Qf1 *all rock* transects may reflect the higher variance of these datasets, or they may reflect crack formation of smaller rocks during different diurnal or annual conditions. To create significant side-to-side gradients in smaller rocks, sun angles would need to be significantly lower on the horizon, because as the sun rises, the entire rock surface would quickly be heated. It is possible, therefore, that late-morning winter conditions favor cracking in these smaller rocks and that is

reflected in the observed crack orientations. Another explanation for the more east–west orientation of these *all-rock* datasets compared to the *boulder* data sets would be differential shading of cracks of different depths. Modeling (e.g. Moores et al., 2008) suggests that deeper cracks preferentially retain water when they are oriented east–west whereas shallower cracks preferentially retain water when they are oriented north–south. If rocks at a particular site exhibit primarily deep microfractures when they are deposited, then their crack orientations are expected to be relatively east–west. If a differential shading model were applied to our field observations, then it would suggest that small rocks on surfaces of all ages began with deeper micro cracks, which according to modeling are preferentially propagated in more east–west orientations. It seems unlikely, however, that small rocks would contain larger overall fractures than boulders that result in the observed orientations.

6. Conclusions

The data presented herein from a range of desert environments show that statistically significant number of surface rock cracks exhibit preferential orientations, thereby providing additional evidence of the importance of directional solar heating in fracturing rocks. Ultimately, evaluation of this data, as well as data from previous studies strongly indicate that rock size, surface age and latitude play important roles with respect to their influence on rock fracture. For example, the data from new localities worldwide associated with desert pavements strongly suggest that thermal conditions arising during morning hours are most influential in causing cracking. The Gobi dataset (acquired at 44° N) also suggests that latitude and related seasonal temperature variation play a key role, as indicated by (1) tightly clustered mean resultant orientation that differs as predicted in the McFadden et al. (2005) study from nearly all other datasets (collected at approximately 35° N), and (2) very cold wintertime temperatures may favor crack development in winter given the likelihood for strong clast heating during early morning hours. We cannot rule out, however, the possibility that wintertime solar paths may also play a more important role in crack formation than was recognized in previous studies in American deserts, given evidence from the Silver Lake datasets that exhibit mean resultant ENE–WSW orientations.

Studies of cracks in the Silver Lake area of the Mojave Desert show that rock size and surface age exert at least some influence on development of rock cracks. The average clast size of mature pavements examined in this study and others may be attributable to the size below which thermal cracking does not occur, although simple observations of cracks in these small rocks are sufficiently complicated by inheritance and disturbance so that definite conclusions regarding a limiting size threshold and cracking cannot be drawn at this time. Nevertheless, the Silver Lake studies do strongly suggest that differences in mean resultant orientations and the degree of clustering between very young surfaces and much older pavements are most likely attributable to changes in average rock size and accretionary soil development, the latter of which actually enables the aforementioned disturbance.

More data will be necessary to fully address the temporal evolution of thermal cracking, including additional numerical modeling that can evaluate, for example, the relative roles of pre-stressing or thermal stresses vs. preferential preservation of crack tip water in physical weathering in deserts. The results of this study, however, demonstrate the critical importance of continuing field studies in testing the predictions and conclusions based on model results. For example, although pre-stressing may indeed be an important factor in physical weathering in many deserts, the consistent evidence for *meridional* cracks in surfaces of diverse age and desert environments, climate, vegetation, and distance of clast transport indicate that directional insolation may play *the* key role in initially generating and

propagating fractures, rather than a secondary role as is implied in several recent studies. Our data indicate that seasonal temperature gradients strongly influence crack orientations and suggests that thermal stresses do play an important role, not solely shading and water retention in cracks on an average annual basis as is recently argued by Moores et al. (2008). Although the Moores et al. modeling study does present intriguing results consistent with preferential shading, water retention and possible evolution of preferentially oriented cracks, it cannot rule out the important, if not essential, role that thermal stresses play in producing similar crack orientations, as their model does not explicitly consider actual crack-generating processes. Furthermore, our data lend support to the hypothesis that other non-*meridional* cracks might also be due to thermal stresses that arise due to temperature gradients in the rock. Other models explaining preferred orientations of cracks do not address the origins of these other, commonly observed crack types.

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