The influence of time on mechanical weathering rates, modes, and mechanisms

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1. Introduction

Fracture mechanics theory (e.g. Charles 1958) posits that individual crack growth rates increase with time as cracks lengthen and stress intensity at the crack tip increases. This has been rigorously confirmed to occur in rocks in controlled, short-term laboratory settings (e.g. Atkinson & Meredith 1987; Nara et al. 2014). Here, to provide some of the first field documentation of natural, long-term, overall rock cracking evolution in different climates, we present measurements of all visible cracks ≥2 cm long on granitoid, carbonate, and volcanic boulders deposited atop alluvial fan, glacial outwash terrace, and moraine surfaces and within active channels, aged ~0 to ~150 ka. We use these data to estimate rock cracking rates, crack intensity variability, and the impacts of time, climate, and rock type on mechanical weathering.

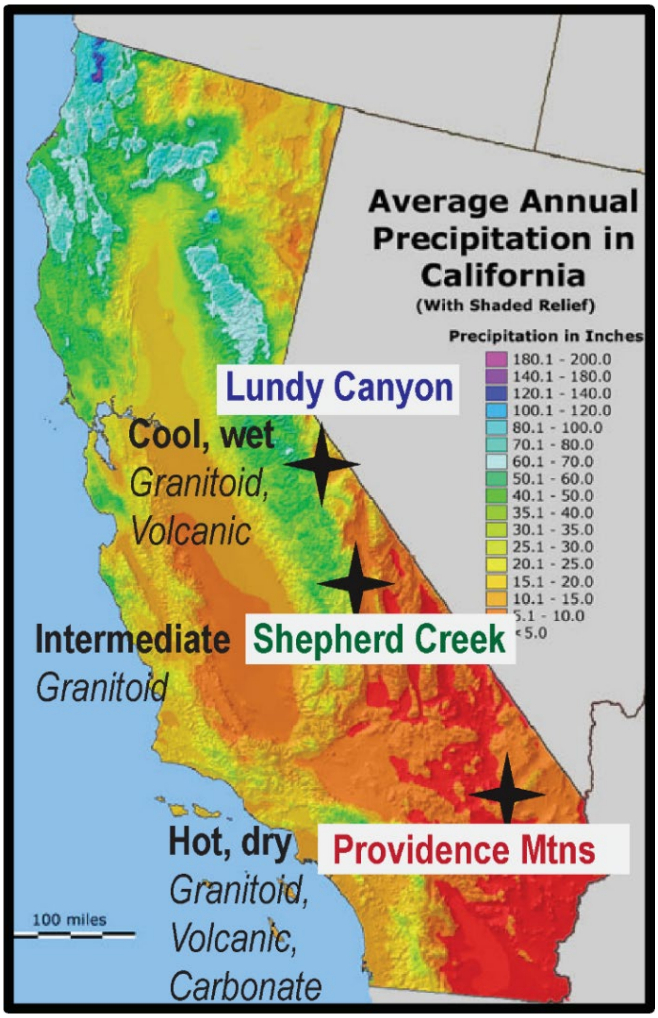

Figure 1. Field site with predominant surficial deposit rock types overlain on current mean annual precipitation, California, USA. Aridity increases from north to south. Mean annual temperature follows this trend, with temperatures increasing from north to south.

2. Methods

We measured all cracks ≥2 cm long exposed on the surface of 15-50 cm diameter boulders on 17 stable, dated depositional surfaces. We collected data for 2163 boulders, totaling 8890 cracks. We avoided sampling bias through random sampling of boulders at regular intervals, or by sampling every boulder within a defined plot.

2.1. Field sites

Data were collected on stable deposits, along transects or within a grid. Sites (Figure 1) in California, USA, were chosen based on (1) availability of granitoid boulders, (2) multiple Quaternary-age depositional surfaces per site, and (3) variability in climate. Lundy Canyon is the northernmost, coolest, wettest site and contains granitoid and metavolcanic boulders. Providence Mountains (Mojave) is the southernmost, hottest, driest site and contains granitoid, volcanic, and carbonate boulders. Shepherd Creek site is intermediate and contains granitoid boulders.

2.2. *Rock and crack measurements*

Each rock's size and visible mineralogical and weathering properties were measured. Detailed crack data were collected on every ≥2 cm crack, and indices were used to estimate the abundance of smaller cracks (Table 1).

Table 1. Rock and crack measurements.

Rock measurements	**Crack measurements for cracks ≥2 cm exposed length**
Exposed boulder size (length/width/height, cm)	Crack length (mm)
Degree of rock exposure (embeddedness index)	Maximum width (mm) and crack plane strike and dip (degrees)
Roundness and angularity index (Krumbein & Sloss 1963)	Degree of crack edge weathering (index)
Rock type/mineralogy	Quadrant of rock on which the crack is located (N, E, S, W)^
Color*	Notable relationships (crack is parallel to the rock surface or fabric; the crack fully splits the rock apart)
Grain size (mm)	
Fabric type and orientation	Sheet height (mm, for surface-parallel cracks)
Evidence of active granular disaggregation	Density of short cracks (<2 cm long)
Presence of pitting	
Abundance of lichen and varnish coverage	*Only collected at Mojave site
Abundance of pedogenic carbonate*	^Only collected at Mojave and Shepherd Creek sites
Abundance and type^ of crack infilling	

2.3. *Clast size analysis*

At each site, pebble counts (modeled after Wolman 1954) were executed on the surfaces and, where available, on subsurface exposures. Clast length, width, and height were measured for every clast encountered every 25 cm along transects or within plots. Typically 100 clasts were measured, and where clasts were sparse, data were collected for at least 30 clasts. At the Mojave site, data were collected for each rock type. Where subsurface data were available as either erosional cutbanks or within pits, subsurface clast sizes were collected.

3. Results

In laboratory experiments (e.g. Atkinson & Meredith 1987), *individual cracks* grow at an increasing rate as their length increases. However, *mechanical weathering* encompasses the full suite of cracks within any given rock. Therefore, we use our data to consider both the growth of individual cracks (cracking rates) and the growth of the assemblage of cracks (crack intensity variation) over time.

3.1. *Cracking rates decrease over time*

Cracking rates were calculated as the growth rate required for the average initial crack length (mean of crack length for modern wash deposits) to reach the average fourth quartile (75-100% longest) crack length per surface, after the time that has passed since deposition. This approach assumes that 1) the initial crack state of all rocks resembles the current crack state of freshly deposited rocks, and 2) the longest cracks have been growing continuously over the depositional tenure of the rock. Cracking could have initiated after deposition, so these rates represent a reasonable minimum estimate.

For all sites and all rock types, cracking rates decelerate over time, ranging from at least 35 mm/ka in the first ~1ka after deposition, to <0.4 mm/ka beyond 100 ka (Figure 2). Granitoid rocks all have similar cracking rate functions, best fit by a negative power law (Figure 2a). When comparing rock types at the Mojave site (Figure 2b), carbonate rock cracking rates decrease more quickly than granitoid rocks, and volcanic rocks have the most gradual cracking rate decrease; that is, cracking rates are lowest for volcanic rocks in the first ~1 ka (~20 mm/ka) but are higher than other rock types at 5 ka and 10 ka. The fastest individual crack growth is estimated for granitoid rocks in the coolest, wettest site in Lundy Canyon.

For all rock types in three climates, cracking rates begin to converge beyond ~30 ka.

3.2. *Climate and rock type impact crack intensity*

Cracking on the entire exposed rock, or the crack intensity, increases rapidly in the first 5-10 ka then reaches a relatively steady state around 30 ka for all rock types at all sites (Figure 3). In the Mojave, carbonate rocks have the lowest initial crack intensity but increase during the first ~10ka to reach the highest crack intensity (Figure 3a). Granitoid and volcanic rocks increase in crack intensity more gently. In granitoid rocks, the hot/dry rocks in the Mojave have higher crack intensities than those in the intermediate Shepherd Creek site (Figure 3b). The cool/wet Lundy Canyon rocks have the lowest crack intensities.

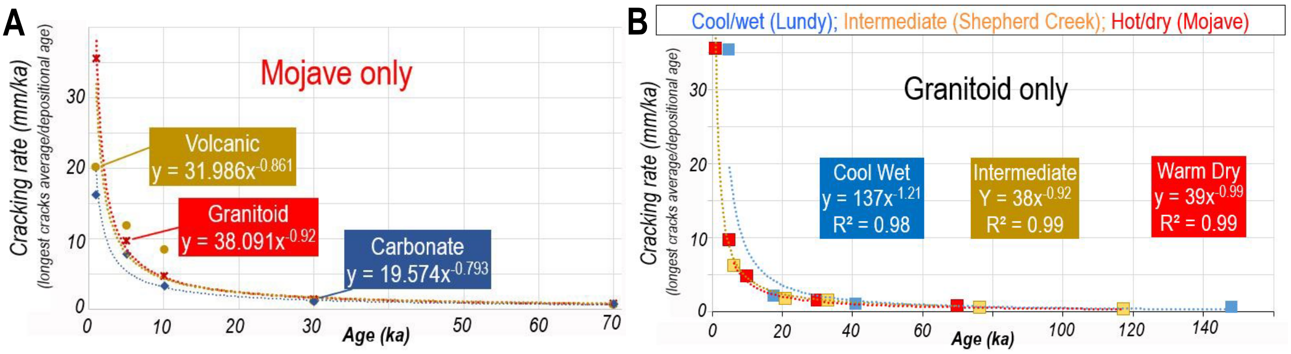

Figure 2. Cracking rate decreases over time in A) all rock types and B) all climates. Automatic power law fits were been calculated for consistency and comparison; however, volcanic rocks are better characterized by a logarithmic fit (R^2 increased from 0.83 to 0.97).

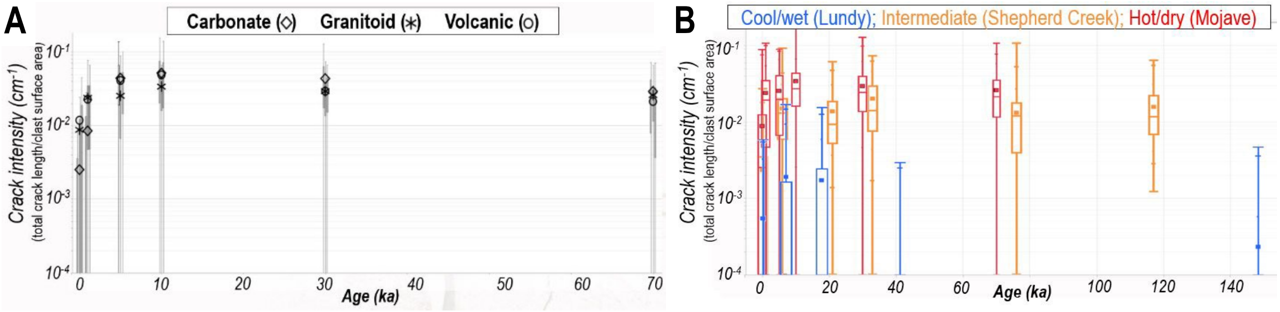

Figure 3. Crack intensity increases over time in A) all rock types at the Mojave site, and B) for granitoid boulders in hot and intermediate climates. Box and whisker ranges were calculated using mean values of crack intensity per rock, per surface. Symbols represent the mean value of all rocks per surface. In B) Lundy Canyon crack intensity is near-zero for older surfaces.

3.3. *Modes of cracking explain clast production*

We analyzed the clast size and aspect ratio evolution over time using the pebble count data collected on each surface. These data help us estimate when the “missing” cracks propagated through, successfully dividing the original rock in two. Variations of clast sizes and shapes over time correlate with the abundance of different modes of cracking, with e.g. peaks in surface-parallel cracking followed by an increase in the abundance of small, elongated rocks.

4. Discussion

Our field dataset shows that cracking on surficial boulders proceeds in similar patterns in arid to semi-arid climates, and in different rock types. Non-linear cracking rates and crack intensity functions may be unintuitive at first glance, but these data are supported by physical phenomena, well established in fracture mechanics.

4.1. *Fracture mechanics supports long-term rates*

Fracture mechanics theory supports decreasing cracking rate trends where 1) stress relaxation on individual cracks occurs due to increasing crack intensity across the entire boulder; 2) cracking-enhanced porosity alters the elastic properties, and thus strain, distributed within the rock; and 3) a transition from Felicity effect to Kaiser effect can occur over geologic time as the material reaches its “fatigue limit”. We expect that the timing of this transition is dependent on imposed stress magnitude over time.

Crack spacing influences stress field distributions, where e.g. Olson (2004) modeled that the growth of a suite of cracks depends on individual crack growth as well as stress field interactions among the cracks, and the crack spacing is related to the subcritical crack growth index *n*. As *n* changes with environmental and rock parameters (e.g. Atkinson & Meredith 1987), the weathering process coupled with the growth of the assemblage of cracks can logically lead to a decrease in cracking rates over time. The increase in bulk rock porosity due to added cracks can decrease the rock’s Young’s modulus, perhaps explaining why materials reach a steady state of cracking when the rock reaches its fatigue limit. Unless the stress is increased, cracking may stabilize or cease.

4.2. Implications

The time-dependent mechanical weathering rates that we observe have important implications for understanding rock's evolving susceptibility to chemical weathering and erosion. These results can be applied across the geosciences, including but not limited to landslide and rockfall hazard assessment, landscape evolution, erosion predictions, sedimentology, and geological dating. These findings can also be beneficial for construction and engineering, or archaeological preservation.

4.3. Study design limitations

Inherent biases cannot be avoided when using a space-for-time approach to understand mechanical weathering: 1) cracks observed on the boulder surface do not represent all cracks within the boulder; 2) once a crack propagates through the boulder, the crack is no longer measurable and rock division occurs; and 3) as the size of boulders on the surface changes through rock division, the selection of equally-sized boulders can bias the individual boulders being measured (i.e. a "survivor's bias" where only the strongest rocks remain for sampling). We find that clast size and shape data are consistent with "missing" cracks converting larger rocks to smaller rocks and are consistent with the trends seen in our measured cracking data.

We will address rock type variability over time and between sites through mineralogical, bulk chemical, and mechanical property analysis. This work is underway. The sites all underwent climate variability throughout the Quaternary; however, their location in the western Basin and Range and east of the Sierra Nevada suggests that all sites were subjected to similar climatic events and experienced relatively similar paleoclimate trends over time.

A multitude of biases exist which may explain or modify our results, e.g. sampling biases of the cracks, sampling biases of the boulders, variable environmental stresses over time, chemical processes concurrently changing the mineralogy and physical properties of the rocks, and differences between rock "types" at different sites. However, fracture mechanics theory can be used to explain our results with equally compelling veracity.

5. Conclusions

Overall, rock cracking rate estimates from this dataset suggest that rates are variable and dependent on rock type and climate. After accounting for inherent biases, we explore multiple internal and external phenomena that could explain the results of our crack measurement field data. Factors which may be influencing observed rates include the interplay between chemical and mechanical weathering, and the dependency of strain/deformation of a rock on its elastic properties, which will change not only with increasing porosity as individual cracks grow in abundance and length, but also with changing climates. In the future, modeling will be used to elucidate the dependence on rock type vs. climatic variables, and hopefully allow a better integration of clast size data with crack data to explain the sediment distributions geoscientists observe in different climates.

6. Acknowledgments

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