The Evolution of Rock Dome Exfoliation Through Time and Space: Comparisons Between Climatic, Geomorphic, and Geologic Settings

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1. Background and Motivation

Exfoliation domes and their associated surface-parallel sheeting joints have been a perplexing geologic feature for over a century, despite their abundant presence worldwide (Figure 1) and significant influence on numerous Earth processes, such as hydrology, mass-wasting, and regolith/soil production.

Figure 1: Examples of exfoliation domes worldwide. A: Diamond Rock and Paarl Rock, South Africa. Photo credit: Dr. John Diemer, UNC Charlotte. B: Half Dome, Yosemite National Park, CA. Photo by David Iliff, License: CC-BY-SA 3.0. C: Corcovado Mountain, Rio de Janeiro, Brazil. Photo by Companhia da Escalada. D: Stone Mountain, GA. Photo by Patricia Ann.

Competing hypotheses exist regarding the formation of sheeting joints and exfoliation. The formation mechanism is traditionally attributed to the removal of overburden (i.e., Leith et al. 2014), where previously-confined rock is exposed via uplift or exhumation, causing pressure to release and the rock to expand. Other hypotheses include the influence of surface morphology and tectonics, where surface-curvature-dependent compressive stresses produce tensional expansion, causing crack propagation (Martel, 2006; 2011). Yet another hypothesis is that exfoliation is insolation-driven (Eppes et al., 2016; Collins and Stock, 2016), under the influence of thermal cycling on both daily and annual scales. Cracking activity peaks have been found in these studies to correlate with temperature peaks, such as sunrise and sunset, or summer and winter. However, as recently review by Martel (2017), any singular existing hypothesis is insufficient in explaining the complicated differential scales of sheeting joint formation. Multiple recommendations are made in his review to improve the understanding of sheeting joints; for example, mapping fresh sheeting joints where the depth of the joints can be quantified. These data would be valuable in modelling sheeting joint formation, but have not been systematically collected before.

The purpose of this study is to further understand these ambiguous features by assembling and evaluating a unique data set addressing the morphology and mechanical weathering characteristics of sheeting joints. These data were collected and analyzed on granitic exfoliation domes in four different geologic, geomorphic, and/or climatic settings, including sites near the Sierra Nevada range in California and the Blue Ridge Mountains in North and South Carolina (Figure 2).

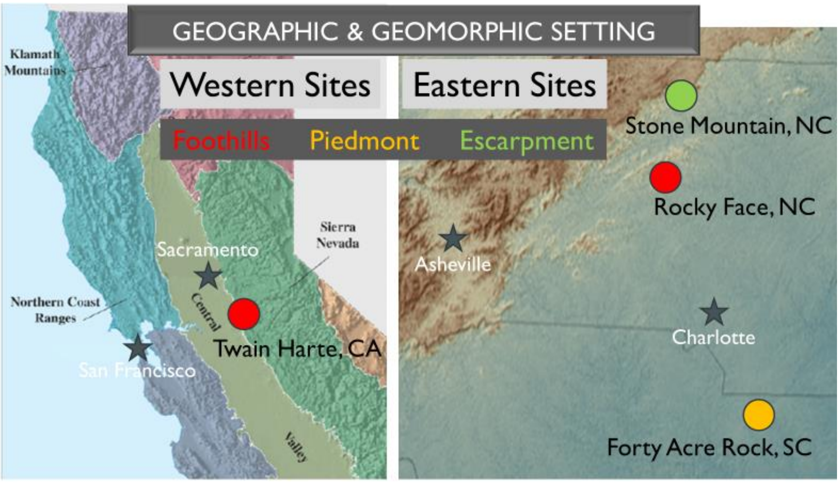


Figure 2: Field areas of data collection.

2. Study Area

The California exfoliation domes are located in and around Twain Harte, which is about 100 mile southeast of Sacramento in the western foothills of the Sierras. The three locations in the Carolinas were geomorphically variable, spanning from the Blue Ridge escarpment, into the foothills, then into the flatter piedmont region. Climatically, all of the field areas in the Carolinas are characterized as humid temperate and, generally, when moving from low to high elevation, temperatures decrease and precipitation increases. In the California field areas, the domes are smaller in size by comparison, and the climate is dryer overall with Mediterranean-like trends. Geologically, erosion rates in the Carolina Piedmont are slower overall as compared to the escarpment or foothills (Sullivan, 2007). Measured erosion rates were not available for the California field areas, but it is important to note that the locations were outside the extent of glacial erosion and downstream incision is minimal.

Exfoliation at these sites could be observed in at least three different scales – micro-, meso-, and macroscale (Figure 3). This suggests a variance in frequency and driving formation influence, meant to be further explored by this systematically-collected data set.

Figure 3: Examples of exfoliation sheeting: microscale (L), mesoscale (C), and macroscale (R).

3. Field Methodology

Methodology for field data collection was extensive for all sites. Each dome was mapped, and exfoliation characterized using transects across the full exposed surface of the dome. Along these transects, data was collected pertaining to slab morphology via topographic profiling, the overall facing aspect of the slab, and surface slope measurements. This detailed field mapping revealed an average of three "generations" of exfoliation sheeting joints at all study sites, which manifested as stratigraphically stacked slabs with characteristics thicknesses. As a convention, these slabs were assigned numbers observed in the field – "1" being a freshly exposed, bottommost slab and "4" being the oldest and topmost slab. It was clear that these demarcated distinct exfoliation events that had occurred and broken away part of the "shell" of the dome.

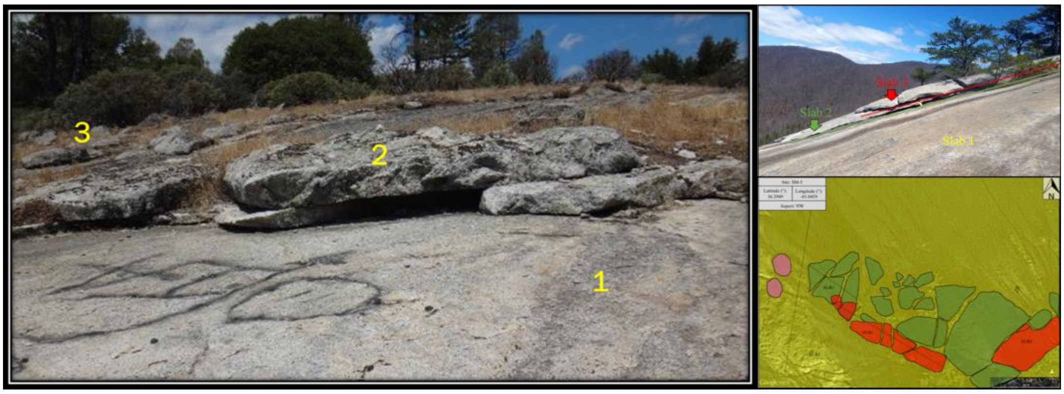


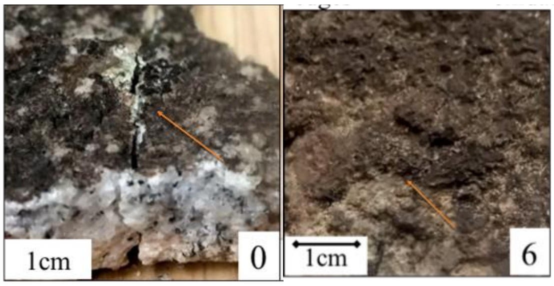
Figure 4: (L) California Foothills dome with three generations of exfoliation. (R) Blue Ridge Escarpment dome with three generations of exfoliation (top) with a digitized map of slab generations (bottom).

These slabs exhibited distinctly different weathering characteristics including crack morphology and slab surface compressive strength – with older slabs generally exhibiting greater degrees of weathering. Many weathering characteristics were compiled into this data set, and these data were used as a proxy for slab age because the degree of rock weathering increases with exposure age. Methodological data collection included:

- Lichen and vegetation coverage (presumably increasing with surface exposure time),
- Granular disintegration percentage (to quantify where grains have become loose from the solid rock surface),
- Mesoscale spalling presence (onion-like sheeting not as large as the slab development),
- Surface dissection (how broken apart each surface was), and
- Surface compressive strength as measure by Schmidt hammer.

In addition to these data collected from the macroscale transects, yet another transect was evaluated for microscale exfoliation – collecting data pertaining to the characteristics of every linear void greater than two centimeters long. For each crack, collected data included:

- Crack geometry in relation to the rock surface,
- Total crack length from end to end until termination,
- Crack height (if present – the difference between the heights of the rock surfaces on either side of the crack),
- Crack orientation (either strike and dip or aspect of the exposed edge),
- The presence of granular disintegration, microspalling, and microcracking in the general area, and
- The assignment of a weathering index range to approximate overall extent of weathering. “0” would be a fresh crack with chips, sharp edges, and no signs of oxidation, up to a “6” which is the most weathered crack – sealed with only an edge remnant present (Figure 5).



Fresh, no signs of weathering or oxidation

Sealed, edge only present

Figure 5: End members of weathering index scale in microcrack characterization.

4. Preliminary Results of Macroscale Sheeting Joint Formation

Over half of all sites had three generations of exfoliation slabs (Figure 6). Twain Harte Rock in California has a fresh slab that was exposed in 2014 during a rapid, large, violent exfoliation event (and multiple subsequent smaller events), and is

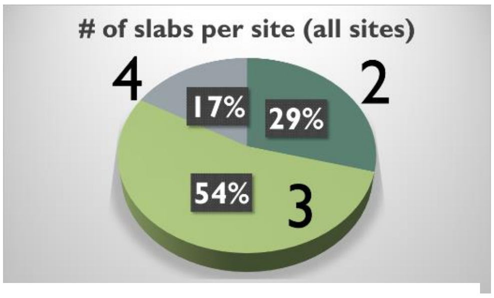


Figure 6: Slab generation disttribution at all sites.

seemingly the only recent cracking event present at any of the field areas, resulting in four slab generations. These generational trends suggest that the periodicity of these exfoliation events are generally temporally consistent, assuming that weathering is roughly constant through time.

The same spatial and temporal trend can be observed in macroscale slab thickness measurements (Figure 7). It can be seen that thicknesses were consistent across all sites and slab generations in both the Carolinas and California.

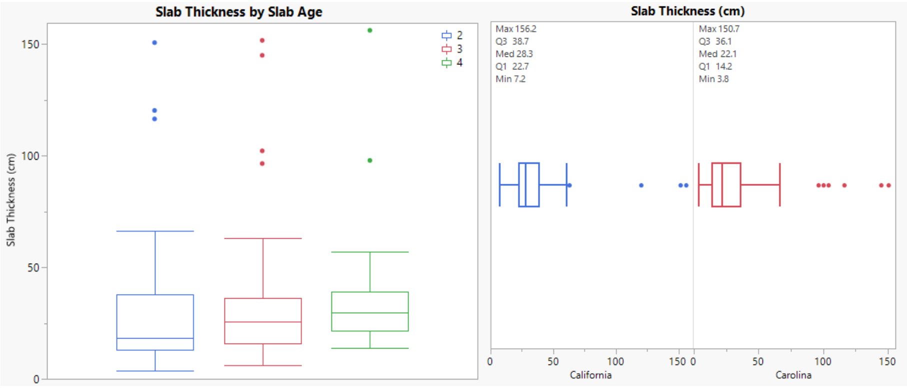


Figure 7: Box-and-whisker data distribution off all slab thickness data at all sites. It can be seen that overall mean slab thickness is consistent temporally (L) and spatially (R) consistent.

Based on the consistency of thickness at this scale and Student's t-test statistical analysis of these data, it is suggested that exfoliation formation is spatially and temporally consistent. At minimum, this mechanism that is influencing the development of shallow (<2 m) major (~20 – 30 cm) exfoliation, based on the existence of the slab generations and their characteristic thickness trends. Preliminary results from observed chronofunctions of weathering features provide evidence of a recurrence interval of slab formations that may be continuous through time and space, despite their different geomorphic settings and presumed exhumation history.

To quantify and understand the degree of weathering on these slabs, a Schmidt rebound hammer was used along the macrotransects. The Schmidt hammer is a non-intrusive tool that measures the compressive strength of a hard surface by quantifying the rebound of a spring-loaded hammer off of that surface. This method has been used in other studies as a relative age-dating technique because rock strength decreases as weathering increases. In **Error! Reference source not found.**, a strong negative correlation between rock strength and slab age can be observed. Lower R-values indicate a lower rock strength and, therefore, a higher degree of weathering. This result confirms that each exfoliation slab was exposed at a distinctly different interval from its over- or underlying neighbor. The Carolina Piedmont site is not as strong, but it is of note that this site has the slowest erosion rate of the eastern sites. It is possible that this slow erosion rate is inhibiting the exfoliation because of increased weathering.

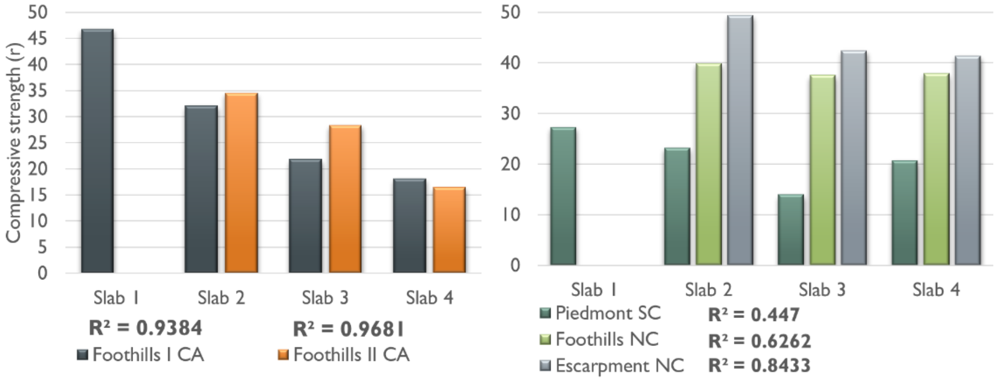


Figure 8: Rock surface compressive strength and correlation with slab generation.

5. Future Work

This comprehensive data set and preliminary analysis can further be used to test existing hypotheses of sheeting joint and exfoliation slab formation mechanisms. However, there is a great deal of additional analysis to be done by this study, including (but not limited to) an exploration and calculation of thermal penetration depth with respect to testing the hypothesis of thermally-driven cracking events. Further, evaluation of mesoscale and microscale cracking data will be executed in a similar method to the analysis described above to understand cracking behavior at these different scales. This extensive data set still has enormous potential even beyond what has been described herein, and hopefully will continue to be utilized in the understanding exfoliation dome mechanics and sheeting joint formation.

6. Acknowledgments

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