# Thermal influences on macroscale rock damage


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# Abstract

Fracture processes in rock have widespread implications in the geohazard, geomorphologic, and civil and mining engineering communities. Propagation of fractures reduces overall rock mass strength, can lead to large-scale gravitational instabilities, and can cause significant hazard and damage to infrastructure. The potential for critical fracture in the form of rock falls and rock bursts are often the primary driver for scientific investigations, civil work project planning, and mining investment outlays. However, slower subcritical fracture from long-term monotonic and/or cyclic stress perturbations often control the eventual more rapid (and more catastrophic) response of rock. These slower damage mechanisms may result from existing or perturbed tectonic stresses, stress relief from exhumation or excavation, or long-term environmental stressors such as thermal cycling and frost cracking.

Here we investigate the role of thermal cycling in generating subcritical stresses to which virtually all rock cliffs worldwide are exposed. Our hypothesis – that diurnal and seasonal cycles of temperature can lead to substantial subcritical fracture propagation and eventual critical fracture – has led us to design several field and laboratory experiments to measure both the deformations and the stresses associated with environmental thermal forcing in rock. Our studies focus on granitic exfoliation environments, common in many mountainous regions of the world, where relatively thin (centimeters to decimeters) exfoliation sheets are able to undergo a full thickness thermal response, and where exfoliation-related rock falls are common and in some places, well-documented.

In cliff environments located in Yosemite National Park (California, USA), our field studies using in-situ measurements (i.e., crackmeters and temperature sensors) have shown that diurnal and seasonal thermal cycles lead to cyclic stresses in the subcritical range, with resultant cumulative and seemingly permanent rock deformation outwards from the main cliff surface. Additional field studies using thermal IRT (InfraRed Thermography) imaging identify the locations of rock bridges that likely serve as focal points for these thermally-induced stress concentrations. Although we did not measure the critical fracture conditions that would result in a rock fall, we did, fortuitously, capture the deformation signals leading up to explosive fracture of a nearby granitic 100-m-diameter exfoliation dome during peak temperatures at the site (located ~60 km northwest from Yosemite), thereby proving the efficacy of thermal stresses in driving both long term – and catastrophic – rock damage. These field studies are substantiated by analytical fracture mechanics solutions which show how rock may eventually fail under these conditions. These studies therefore serve as proxies for understanding how some rock falls eventually occur under subcritical thermally-induced cyclic stress conditions, but also more generally for how thermal-stress conditions may affect rock damage in a multitude of environments.

# Motivation

We seek to explain how outcrop-scale rock damage occurs in conjunction with temperature variations, and to learn how landscapes respond to thermal stressors.

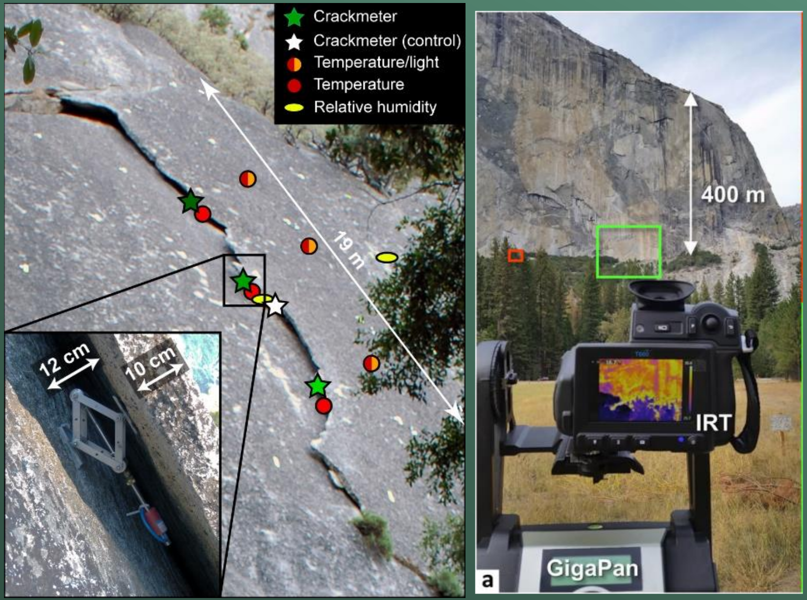

Rock fall from Half Dome, Yosemite, California, USA


Charlotte Dome, California, USA

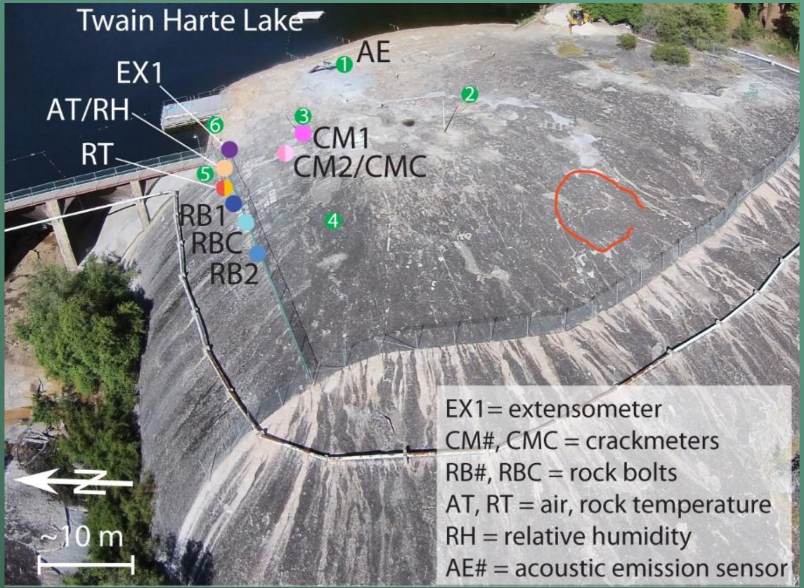
Stock and Collins, 2014, Eos

# Our experiments

We conducted field experiments to measure how granitic exfoliation sheets respond to temperature fluctuations.




Yosemite Valley, California, USA



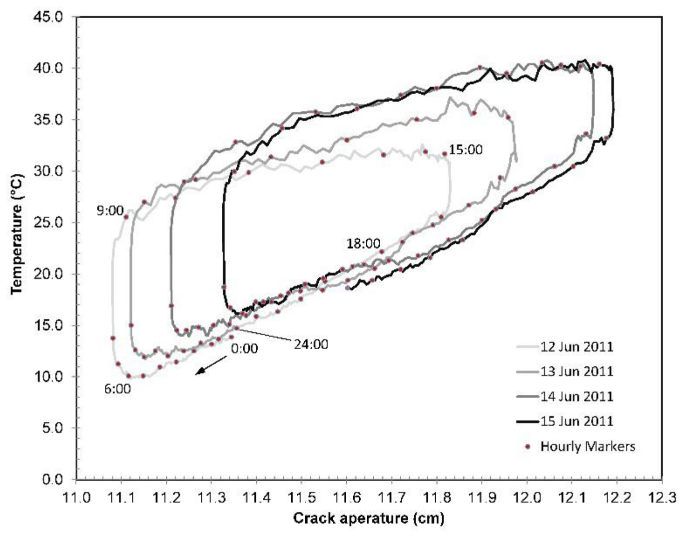

Twain Harte Dome, California, USA



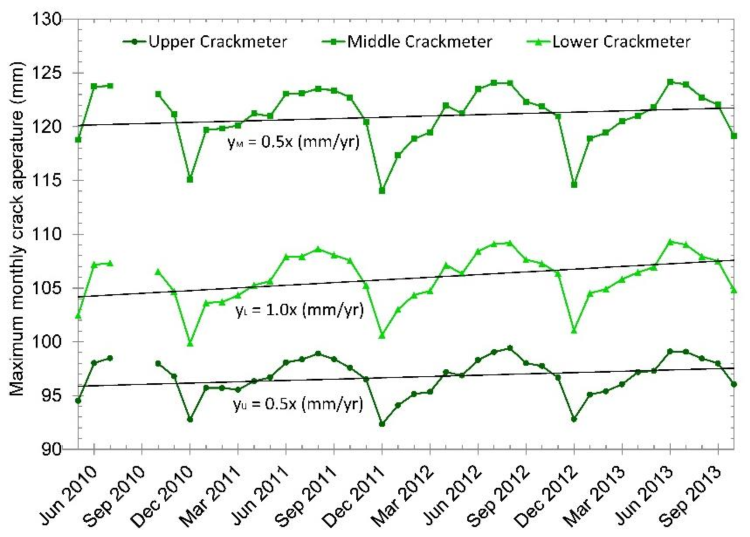
Collins and Stock, 2016; Guerin et al., 2019; Collins et al., 2018

# Measuring thermal deformation

Crack aperture measurements behind a 19-m-tall, 4-m-wide, 10-cm-thick partially-detached granitic exfoliation sheet show clear trends with temperature cycles.




Hysteretic loops show opening and closing of an exfoliation sheet with diurnal temperatures cycles. Cumulative deformation increases over four days of increasing temperatures.



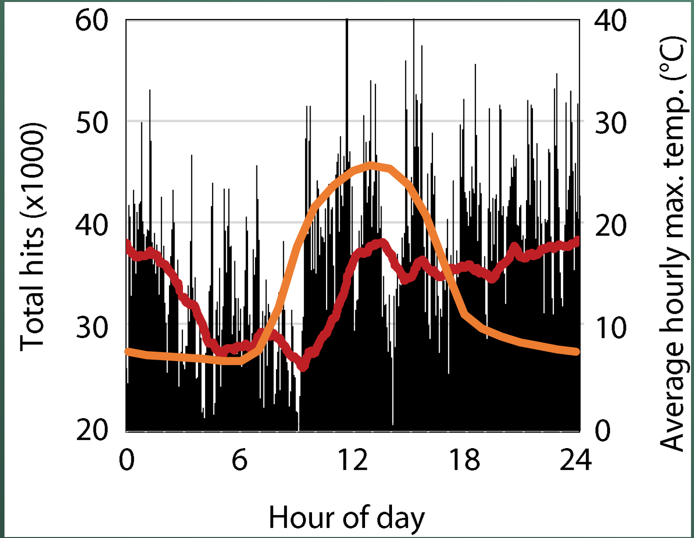

Despite seasonal trends, cumulative annual deformation of the exfoliation sheet increased over three years.



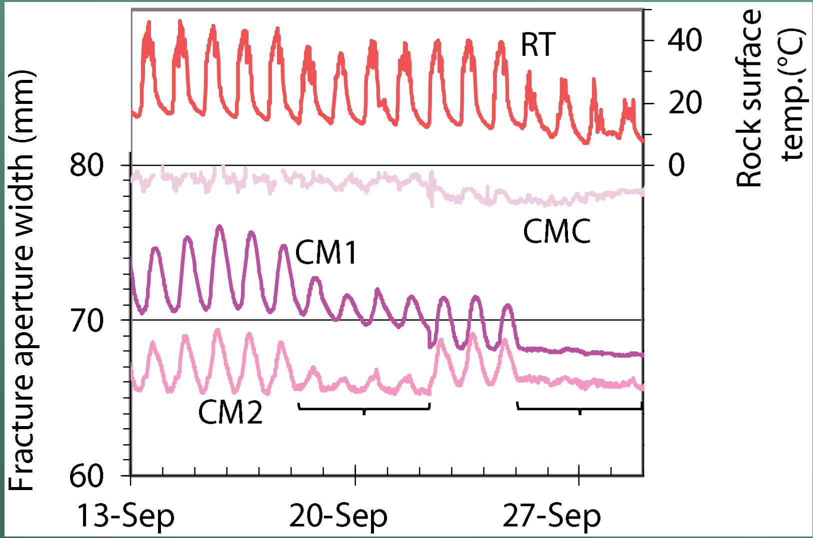
Collins et al., Nature Geoscience, 2016

# Monitoring subcritical fracture

At a granitic exfoliation dome, instrumentation (extensometers, crackmeters, acoustic emissions - AE) show evidence for subcritical fracture with increasing temperatures.




6-month AE data show a sharp increase in the 3-h running average (red line) coinciding with maximum temperatures (orange line)



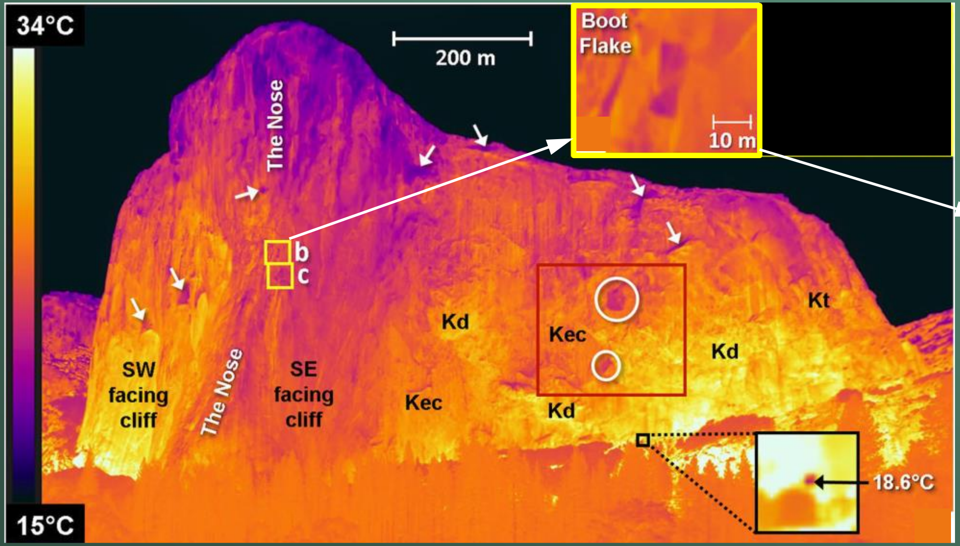

Crackmeter data show diurnal fracture width oscillations followed by collapse (brackets).



Collins et al., Nature Communications, 2018

# Identifying rock bridges

Thermal imaging measurements over diurnal cycles detected the detached and attached areas (i.e., rock bridges) of exfoliation sheets.




Thermograph of El Capitan, Yosemite, California, USA at 17:45 on 8 October 2015

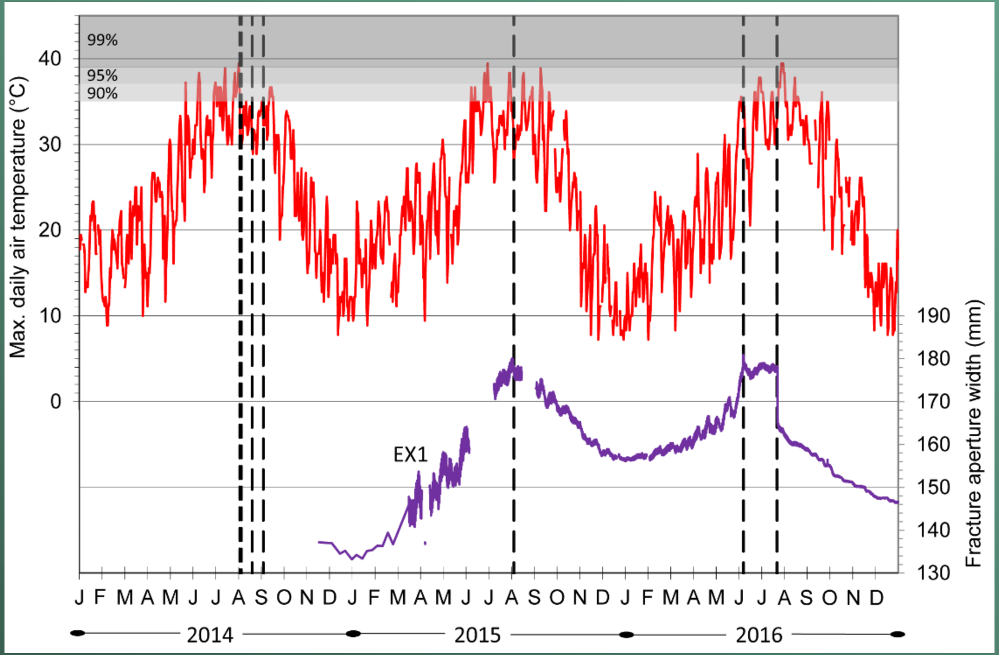




Guerin et al., 2019

# Transition of subcritical to critical fracture

Exfoliation sheet deformation (with subcritical crack growth; e.g., 2015) occurred in tandem with daily and seasonal temperature cycles. We captured several episodes of explosive rupture (critical crack growth; dashed vertical lines in 2014 and 2016)




Collins et al., RMRE, 2019; Collins et al., Nature Communications, 2018

# Observing critical fracture

Explosive (critical) fracture was directly observed in several cases. These occurred during the hottest summer days (within 99$^{th}$ percentile of highest temperature on record).

Explosive fracture of a ~100 $m^2$ area of Twain Harte dome's surface

Effects included fracturing 30-cm-thick granitic rock sheets.



Collins et al., Nature Communications, 2018

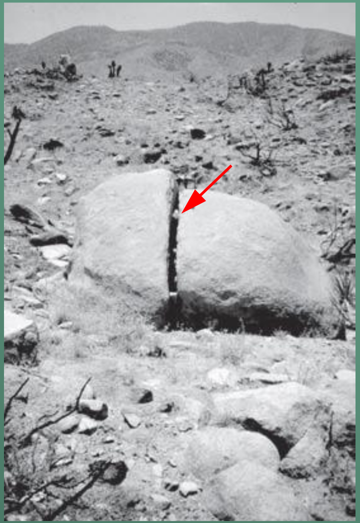
# Explaining thermal-stress-induced rock falls

We quantified the conditions under which cyclic thermal fracture occurs in rock outcrops. This work provide explanations for some types of rock falls, as well as the propagation of fractures (i.e., rock damage) in a variety of geomorphologic environments.


Yosemite, 2017

California (Matthes, 1930)

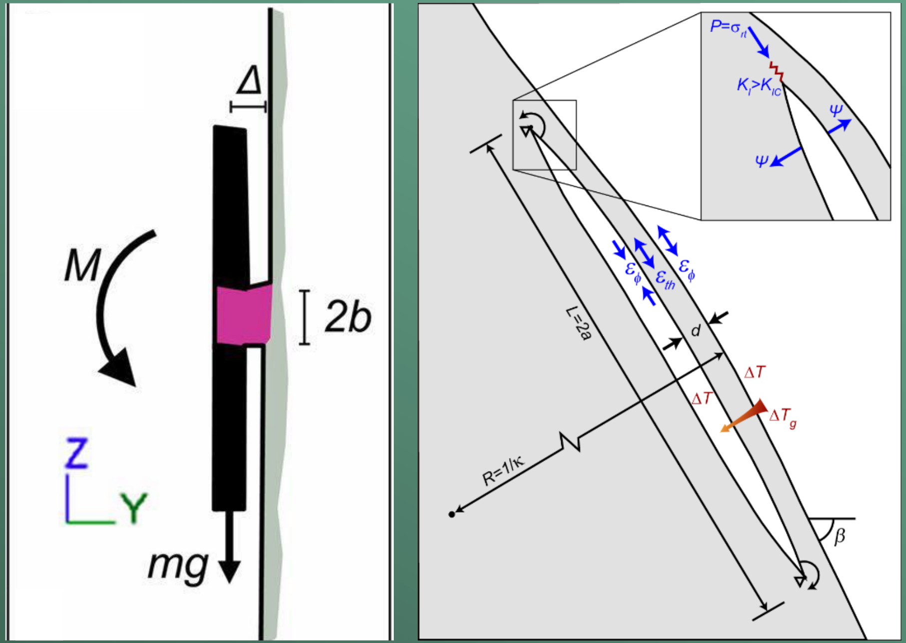
Australia (Twidale, 2012)



California (McFadden et al., 2005)

# Conclusions

- Thermal cyclic forcing can cause both subcritical and critical rock fracture;
- In situ and remote sensing tools offer insight into rock behavior from environmental stressors;
- Links between fracture mechanics and macroscale rock outcrop response are key to development of predictive models for rock damage and fracture




Fracture mechanics models provide the ability to understand rock bridge evolution and exfoliation processes.



Collins and Stock, 2016; Guerin et al., 2019

# References


- Collins, B.D. & Stock, G.M. (2016) Rockfall triggering by cyclic thermal stressing of exfoliation fractures, Nature Geoscience, 9, 395-401, doi:10.1038/ngeo2686.
- Collins, B.D., Stock, G.M., Eppes, M.C., Lewis, S.W., Corbett, S.C., & Smith, J.B., 2018, Thermal influences on spontaneous rock dome exfoliation, Nature Communications, 9(762), doi:10.1038/s41467-017-02728-1.
- Collins, B.D., Stock, G.M., Eppes, M.C. (2019) Relaxation response of critically-stressed macroscale surficial rock sheets, Rock Mechanics and Rock Engineering, 52(12), 5013-5023, doi:10.1007/s00603-019-01832-6.
- Guerin, A. Jaboyedoff, M., Collins, B.D., Derron, M-H, Stock, G.M., Matasci, B., Boesiger, M., Lefeuvre, C., Podladchikov, Y.Y. (2019) Detection of rock bridges by infrared thermal imaging and modeling, Nature Scientific Reports, 9:13138, doi:10.1038/s41598-019-49336-1.
- Guerin, A., Stock, G.M., Radue, M.J., Jaboyedoff, M., Collins, B.D., Matasci, B., Avdievitch, N., Derron, M-H, 2020, Quantifying 40 years of rockfall activity in Yosemite Valley with historical structure-from-motion photogrammetry and terrestrial laser scanning, Geomorphology, 356(107069), doi:10.1016/j.geomorph.2020.107069.
- McFadden, L. D., Eppes, M. C., Gillespie, A. R. & Hallet, B. (2005) Physical weathering in arid landscapes due to diurnal variation in the direction of solar heating, GSA Bulletin, 117, 161-173, doi:10.1130/B25508.1.
- Matthes, F. E. (1930) Geologic History of the Yosemite Valley, US Geological Survey Professional Paper 160, US Geological Survey.
- Stock, G.M. & Collins, B.D. (2014) Reducing rockfall risk in Yosemite National Park, Eos, American Geophysical Union, 95(29), 261-263.
- Twidale, C.R. (2012) Landscape analysis: derivation and rediscovery of ideas, Geomorphologie, 18(3), 259-277, doi:10.4000/geomorphologie.9900.