Advances in understanding and mitigating rockfalls in Yosemite National Park

Greg M. Stock, PhD, PG

National Park Service, Yosemite National Park
Historical rockfalls in Yosemite Valley

- More than 1,000 rockfalls documented since 1857
- Average of 1 rockfall every 5 days
- 16 fatalities from rockfalls, more than 92 injuries

Stock et al. (2013) USGS Data Series
Cosmogenic 10Be exposure age dating + field
and LiDAR mapping identifies at least 10 rock avalanches

Exposure dating useful for refined mapping

Deposit ages range from 1.0 to 11.6 ka

Remarkable consistency of cosmogenic 10Be exposure ages within each deposit

Large (M>7) paleoearthquakes along eastern Sierra Nevada faults may be primary triggers

Photo by Stuart Kapicka
Quantifying rockfalls with remote sensing techniques
Gigapixel panoramic photography

October 2008 rockfall
Terrestrial laser scanning (lidar)
Repeat terrestrial laser scanning

Volume 5,663 ± 36 m³
37 rockfalls detected between October 2010 and October 2013, only 5 of which were reported; 12 rockfalls were >1 m³ in volume
27-28 September 2017 El Capitan rockfalls
27-28 September 2017 El Capitan rockfalls
27-28 September 2017 El Capitan rockfalls

Climbers

27 September 2017 rockfalls

28 September 2017 rockfall
Measuring rockfall volumes with SfM and LiDAR

Volume of 27 September rockfalls 450 m$^3$; volume of 28 September rockfall 10,250 m$^3$
Measuring rockfall volumes with SfM and LiDAR

46 distinct areas of volume loss detected on cliff

Volume range: 0.04 m³ – 10,265 m³

Volume gain at base of cliff due to talus deposition
Using old photographs for Structure from Motion

21 black & white photographs of the Middle Brother cliff taken from a helicopter by Park Search & Rescue circa 1976
Circa 1976 Structure from Motion point cloud for Middle Brother (5.9 million points)
Rockfalls detected between 1976 and 2016

116 rockfalls detected during this period

Only 62 rockfalls documented in the database

Timing of rockfalls

- 1976-2010
- 2010-2012
- 2012-2013
- 2013-2015
- 2015-2016
Eadweard Muybridge, “Tutokunula, Valley of the Yosemite” (1872)
Investigating potential rockfall triggers
Rockfalls by time of year

- More rock falls in winter and spring, fewer in summer
- No strong overall seasonality to rock-fall activity, likely because there are many rockfall triggers
Probable rockfall triggers

- Triggers based on temporal coincidence with environmental conditions
- Precipitation dominates known rockfall triggers, but ~50% are either unknown or unrecognized
Rockfalls with “unrecognized” triggers

27 July 2006 Half Dome rockfall

11 October 2010 El Capitan rockfall
Monitoring deformation of an exfoliation sheet

Collins & Stock (2016) Nature Geoscience
Monitoring deformation of an exfoliation sheet

- Crack aperture measured with vibrating wire crack meters (+ control) at 3 locations along rock sheet at 5 minute intervals
- Measured near-surface air temperature, solar radiation, and relative humidity across and within sheet at 5 minute intervals
- Data collected for 3.5 years

Collins & Stock (2016) Nature Geoscience
Daily cycles of deformation

- Rock sheet deforms daily by up to 1.5 cm, with the greatest deformation in the middle of the sheet.
- Deformation occurs primarily in response to temperature variations.
- In the summer, daily deformations progressively move the sheet outward.

Collins & Stock (2016) Nature Geoscience
Seasonal and annual cycles of deformation

Deformation is seasonal, with maximum deformation in the late July and August. Deformation is annually cumulative, with up to 1 mm/yr crack aperture widening.
2009-2010 Rhombus Wall rock falls

Progressive failure along sheeting joints

Stock et al. (2012) *Earth Surface Processes and Landforms*
2009-2010 Rhombus Wall rock falls

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Stock et al. (2012) Earth Surface Processes and Landforms
Understanding rockfalls over geologic timescales
Rock avalanches in Yosemite Valley

Investigating the trigger(s) for Yosemite’s largest rockfalls
$^{10}$Be exposure dating of rock avalanches

Rock avalanches in Yosemite are ideal targets for $^{10}$Be exposure dating because they:

- Are essentially instantaneous events
- Excavate deep-seated rocks previously shielded from cosmic rays (no inheritance)
- Experience little/no modification or erosion after deposition
- Contain abundant quartz
Sample $^{10}$Be exposure age (years)

- OYV-1: 2,385 ± 236 (107)
- OYV-2: 2,275 ± 246 (143)
- OYV-3: 2,384 ± 222 (73)
- OYV-4: 2,390 ± 226 (83)

Mean age = 2,360 years

Reduced $\chi^2 = 0.22$, $P = 0.88$
Old Yosemite Village rock avalanche

$n = 4$

Modeled $^{10}$Be Exposure Age (yrs)
Earthquake triggering of rock falls

26 March 1872 rupture on Owens Valley fault (200 km distant) triggered many large rock falls in Yosemite Valley

“At half past two o’clock of a moonlit morning in March, I was awakened by a tremendous earthquake… The Eagle Rock on the south wall gave way and I saw it falling in thousands of great boulders …”

- John Muir, 1912, *The Yosemite*
Earthquake triggering of rock avalanches

Melody et al., 2012; Le et al., 2011; Sarmiento et al., 2011; Brothers et al., 2009; Bacon et al., 2007; Bacon et al., 2005; Lee et al., 2001; Ramelli et al., 2002, 1999; Seitz & Kent, 2004; Bell et al., 1984; Stock and Uhrhammer, 2010; Cordes et al., 2013
Assessing rockfall hazard and risk
Mapping rockfall susceptibility

Matasci et al. (2017) Landslides
Runout modeling of potential future rock falls

STONE model simulations from areas of mapped high susceptibility
Rock avalanches in Yosemite Valley
Runout modeling of potential future rock falls

Regional STONE simulations from all slopes ≥ 60°

Number of rock-fall trajectories

- 1-2
- 2-10
- 10-50
- 50-100
- 100-250
- 250-500
- >500

Stock et al. (2014) USGS
Quantitative rockfall hazard assessment

Hazard line (blue) represents a 1/500 annualized probability of exceedance
Quantitative rockfall risk assessment

Structures ranked according to their risk (exposure * position within hazard zone)
Frequency-based rock-fall risk assessment

Structures with risk metrics >6 closed, relocated, or repurposed, *reducing risk by 95%*

Yosemite Valley structures within the hazard zone

Stock et al. (2014) USGS
Summary

- Exfoliation-type rockfalls are dominant in Yosemite.
- Remote sensing tools offer vast improvements in our ability to document rockfalls and quantify their hazard.
- Many rockfalls have “unrecognized” triggers, likely resulting from subtle processes like cyclical temperature changes.
- Cosmogenic exposure dating suggests that earthquakes are the likely triggers of the largest rockfalls in Yosemite.
- The National Park uses rockfall science to reduce risk in hazardous areas, though that risk will never be eliminated.