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Title: Quantifying Holocene Cliff Retreat Rates at Technical Area 54, a Low- and Mixed-Level Radioactive Waste Disposal Site, Los Alamos National Laboratory, Los Alamos, New Mexico

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Quantifying Holocene Cliff Retreat Rates at Technical Area 54, a Low- and Mixed-Level Radioactive Waste Disposal Site, Los Alamos National Laboratory, Los Alamos, New Mexico

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NNSA National Nuclear Security Administration

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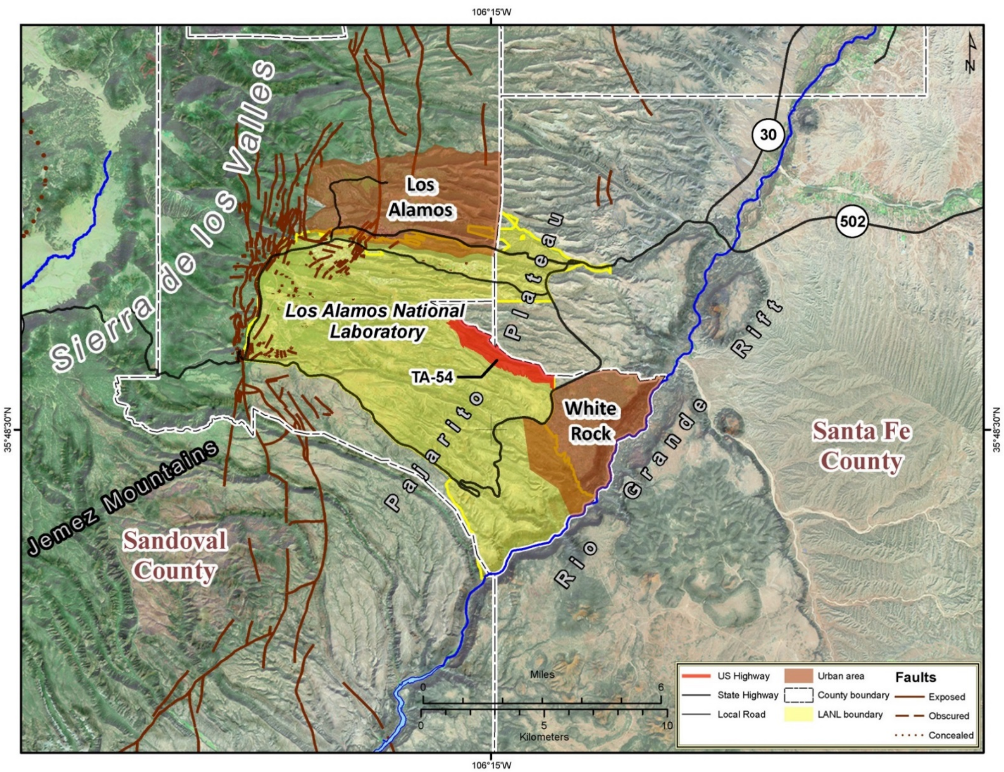
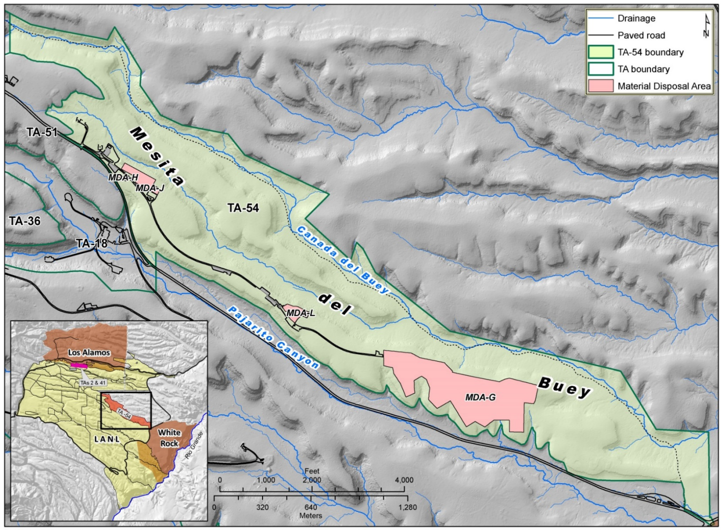
Technical Area 54, Los Alamos National Laboratory

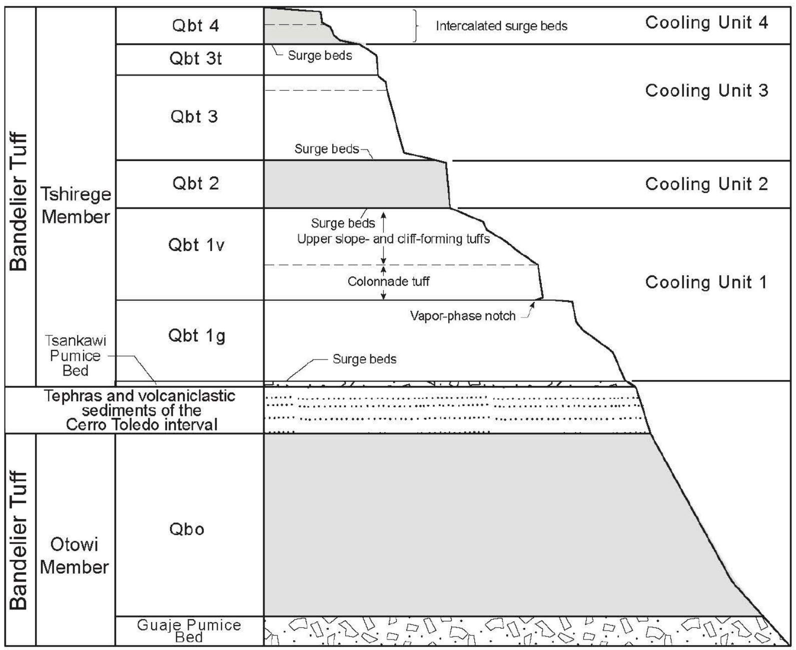




Low-level rad waste disposal facility requires safe, long-term storage.

Technical Area 54, Los Alamos National Laboratory

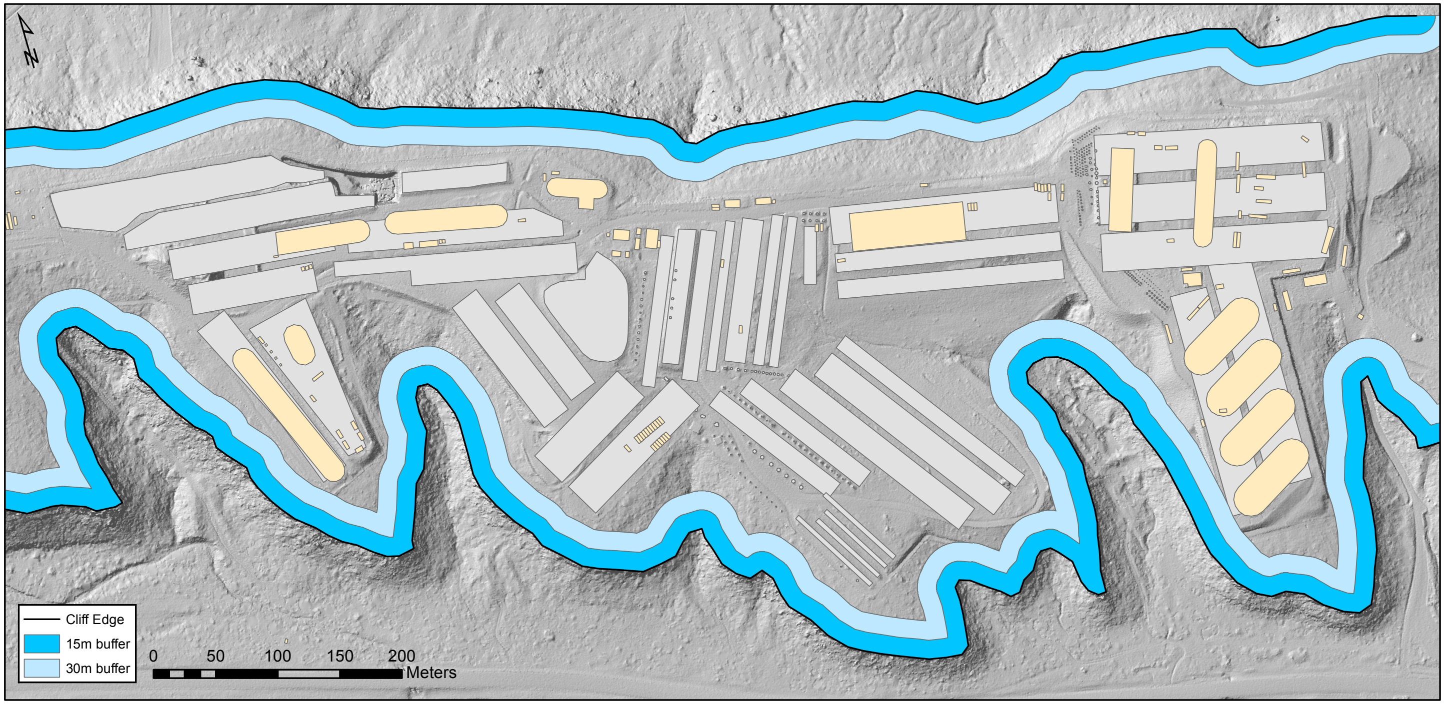
- **Geology (and the resulting topography) introduces cliff retreat hazards**



Steep-walled canyons are high-risk locations for cliff failure and retreat.

TA-54 Design and Project Motivation

- Cliffs will need to retreat 30+ meters to expose pits and shafts



- Buried waste needs to be contained for ~10,000 years (40 CFR §191, 1993)

Continued cliff retreat will eventually expose storage facilities.

Slope Characteristics and Mechanisms of Cliff Retreat

South-facing slopes

North-facing slopes

- **Slope aspect**
- **Vegetation**
- **Fracture characteristics: fill, density, orientation**
- **Seismic toppling?**

South slopes = ⬇️ vegetation, ⬆️ chem. weathering, proximal to structures.

Previous Studies

- **Wohletz (1996):** documented background fracture density
- **Reneau (1995):** "...the south rim seems to be dominated by the infrequent failure of narrow fracture-bounded tuff blocks, with an average block thickness of 1.0 – 1.3 m and a maximum block thickness of 6.1 m"*
  → Average erosion rates are misleading
- **Poths and Goff (1990):** ^{21}Ne cosmogenic dating = 1.8 – 2.8m per 10,000 years
- **Albrecht et al. (1993):** ^{10}Be and ^{26}Al cosmogenic dating = 0.5 – 1.1m per 10,000 years

Cliff retreat studies are minimal and 20-30 years old!

***The north rims typically display large-scale mass movement features in a zone typically 30 – 60 m wide**

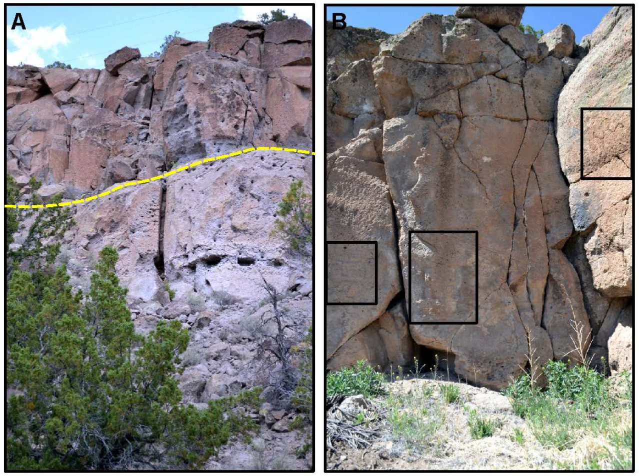
Quantifying Cliff Retreat at TA-54

Discussed in this talk:

- **Fracture mapping and characterization**
- **Slope and factor of safety measurements**
- **Surface exposure dating**
- **Preliminary analysis of ground motion required for cliff failure**

Additional work (refer to Miller et al. 2018):

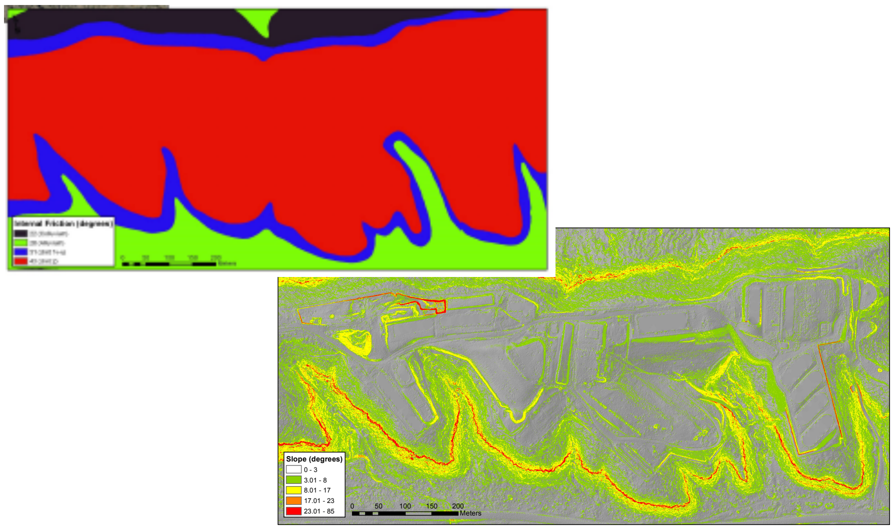
- Block fall mapping
- Rock surface hardness
- Photodocumentation
- Cliff face dating using rock art
- Canyon width measurements

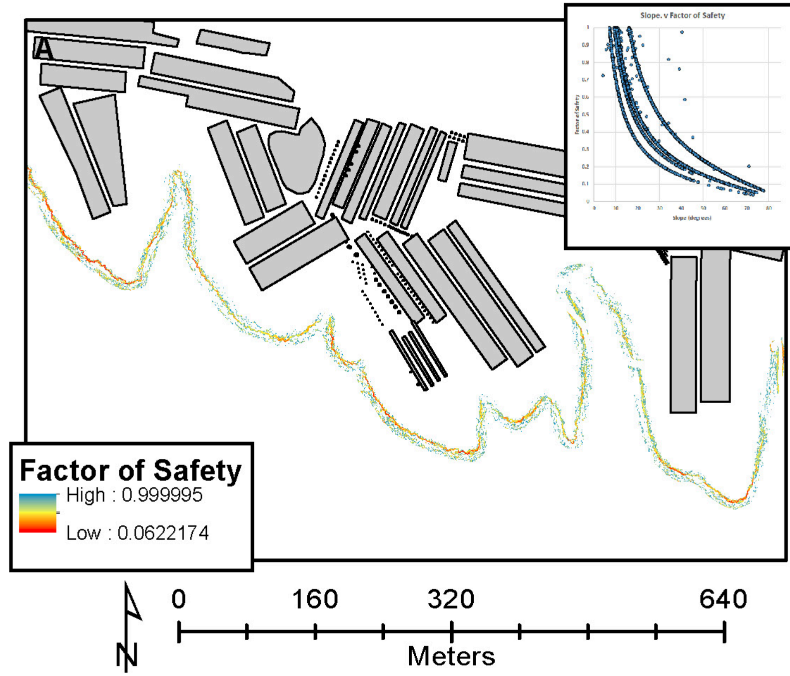


Quantification of retreat rates requires integration of numerous datasets.

Factor of Safety Calculations

- **Factor of Safety calculations use rock mechanical properties and slope to identify the probability of a failure along the cliff walls**





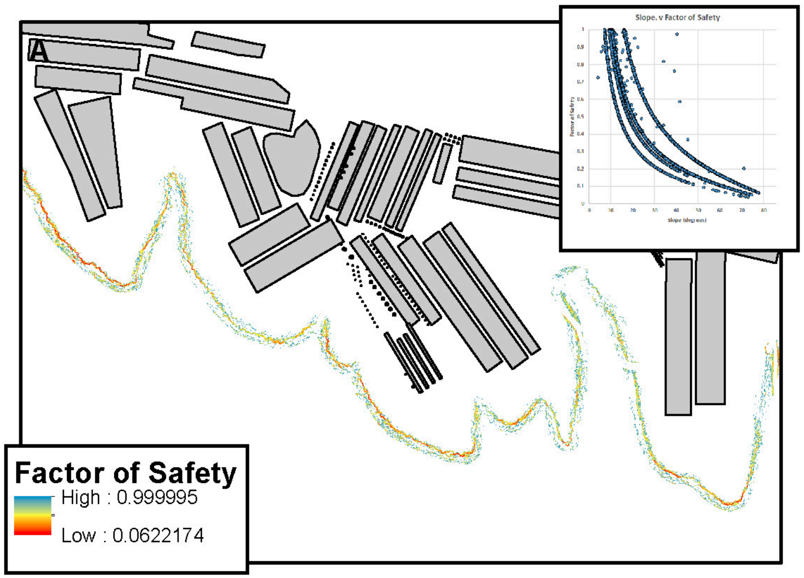
Factor of Safety = tan(ϕ)/tan(α)
ϕ = angle of internal friction
α = slope (degrees)

Factor of Safety <1

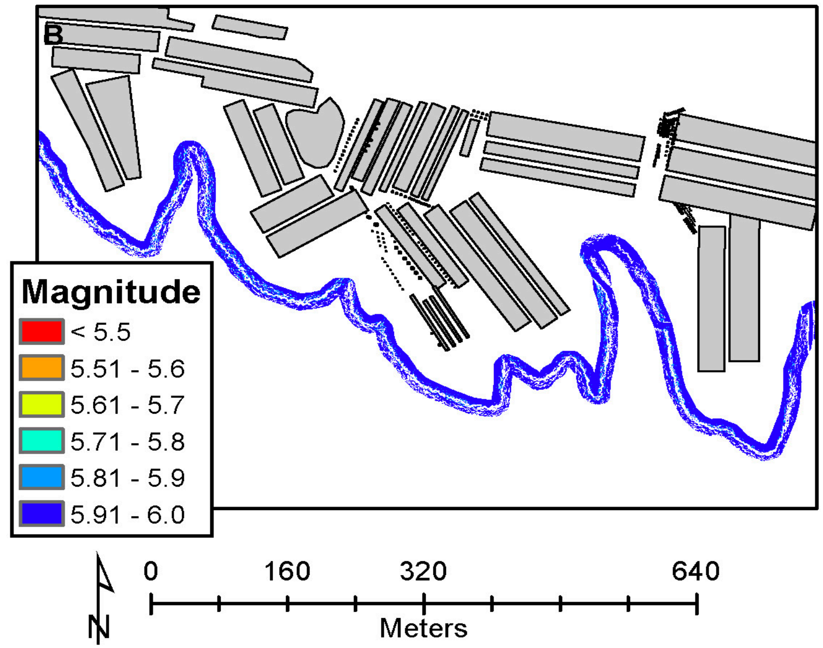
FoS calculations highlight inherent instability along the south cliffs.

Seismic Toppling

- **What EQ magnitude is required to initiate cliff failure in locations where FoS>1?**



Factor of Safety <1

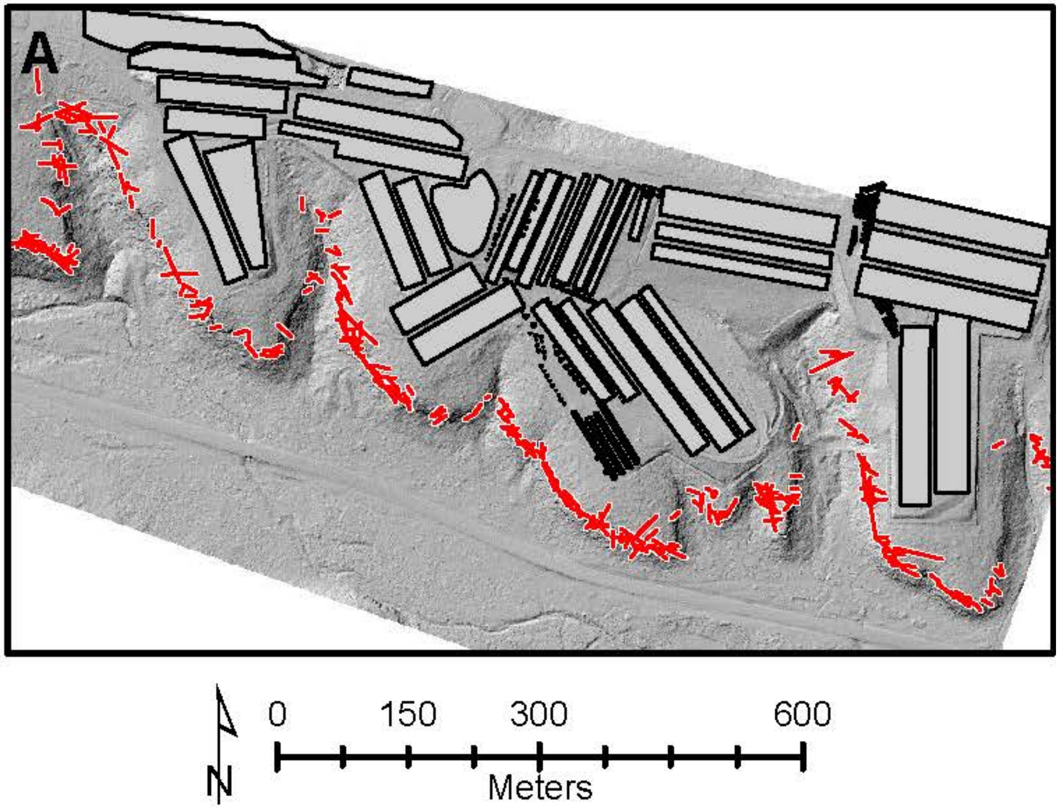


EQ magnitude where FOS >1

EQ magnitudes of ~5.5+ will initiate cliff failure at TA-54.

Calculations modeled after Newmark (1965); Arias (1970); Jibson and Keefer (1993)

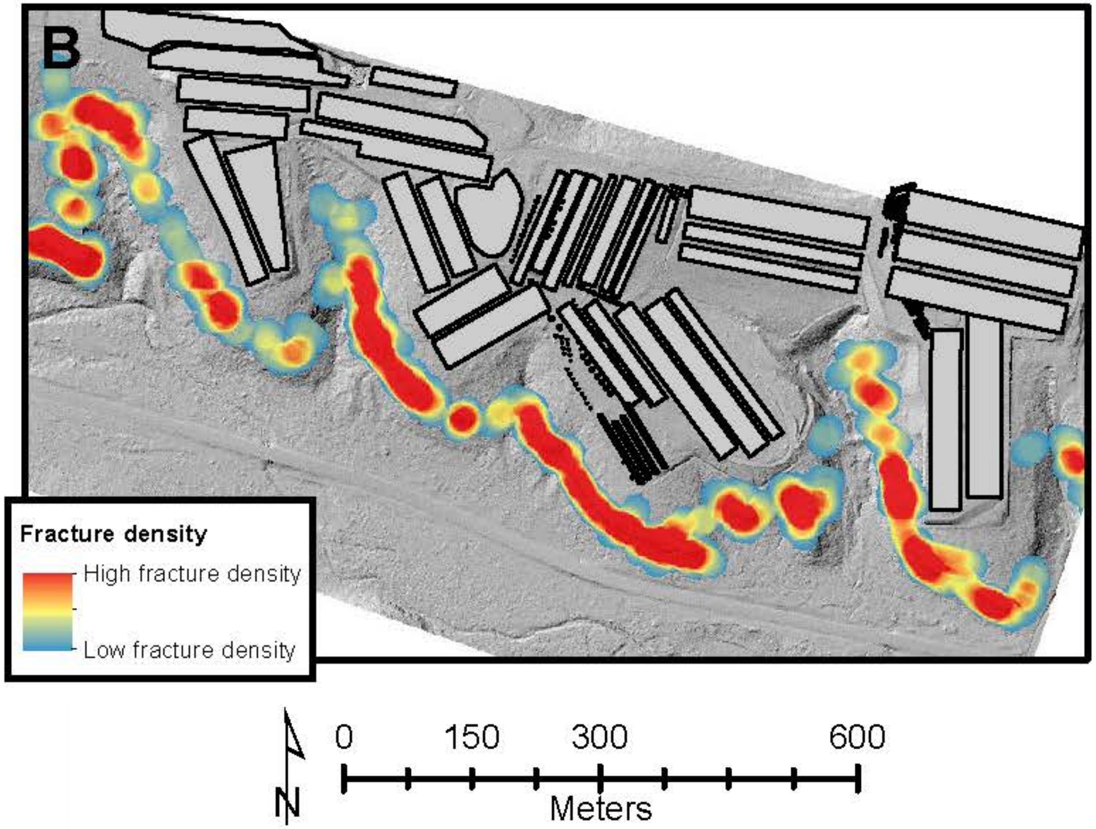
Fracture Mapping



- **Fracture mapping completed via field and aerial photo reconnaissance**

Frx mapping and characterization is essential for predictive analyses.

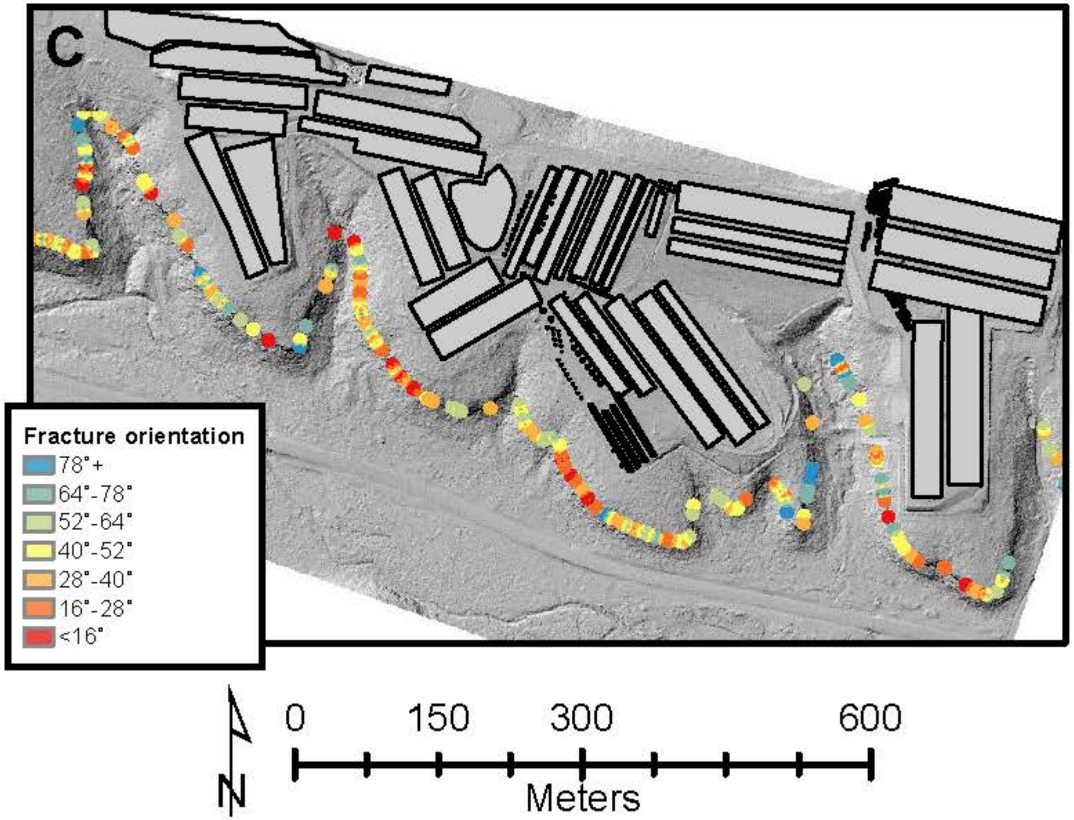
Fracture Density



- **Fracture density calculated in ArcGIS to highlight areas of high density.**

High fracture density introduces greater risk of cliff failure.

Fracture Orientation



- **Fracture orientations calculated in ArcGIS**

Subparallel = higher risk of failure. Orthogonal = lower risk of failure.

Fracture Fill

- **Fracture fill was documented in the field**

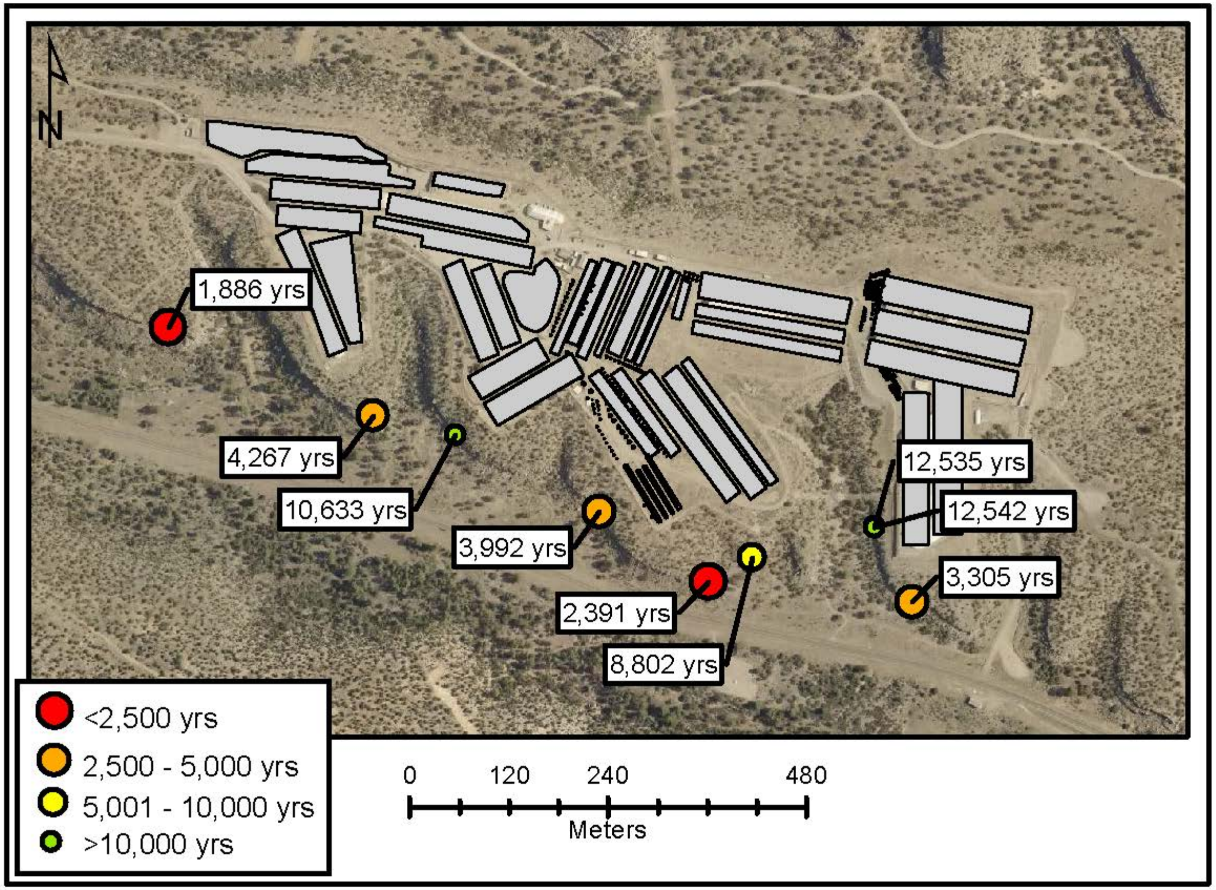
Frx fill introduces higher risk of failure, but only in the presence of water.

Surface Exposure Dating

- Carbon-14 surface exposure dates were obtained for 9 cliff face locations

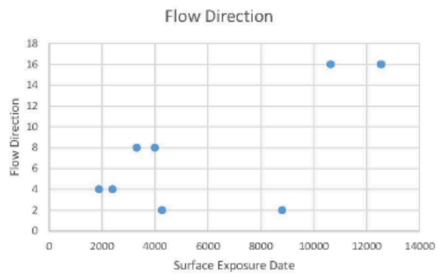
Constrains the timing of recent failures by providing failure event age.

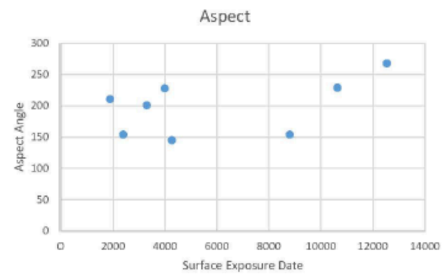
Surface Exposure Dating Results

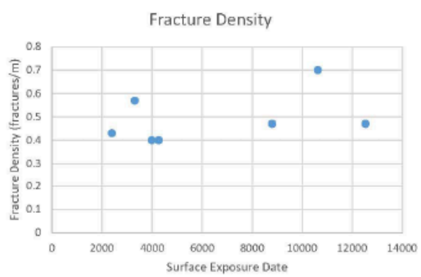


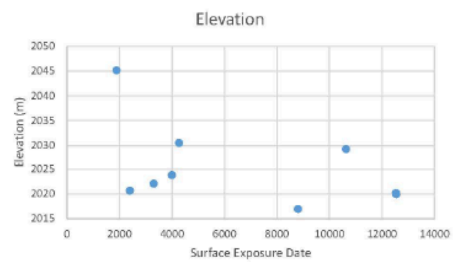
Exposure dates of 1,886-12,542 yrs; erosion rates of 0.2-3m/10,000 yrs.

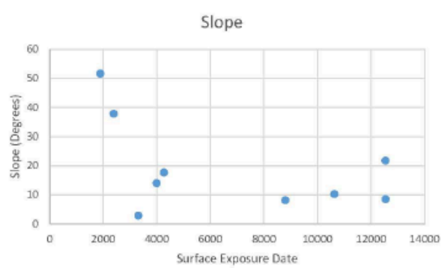
Cosmogenic Age Correlations





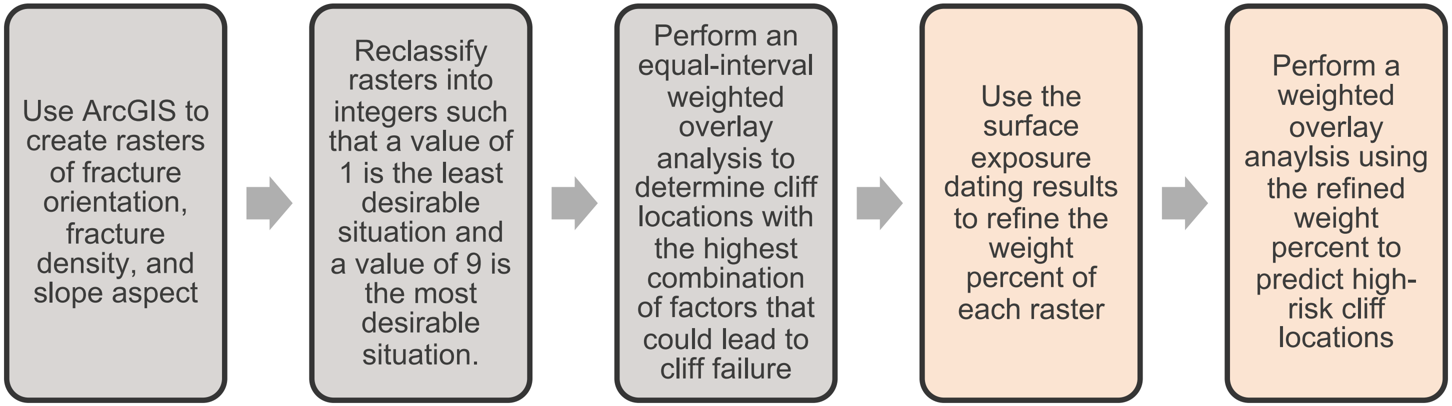






No obvious correlation between cosmo ages and single cliff feature.

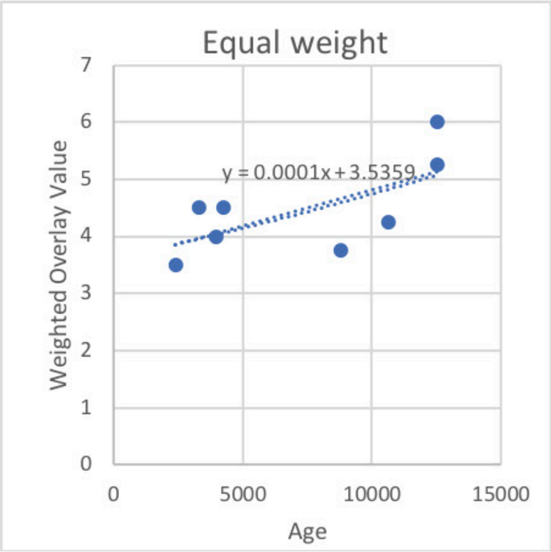
Fracture Characteristic Thresholds

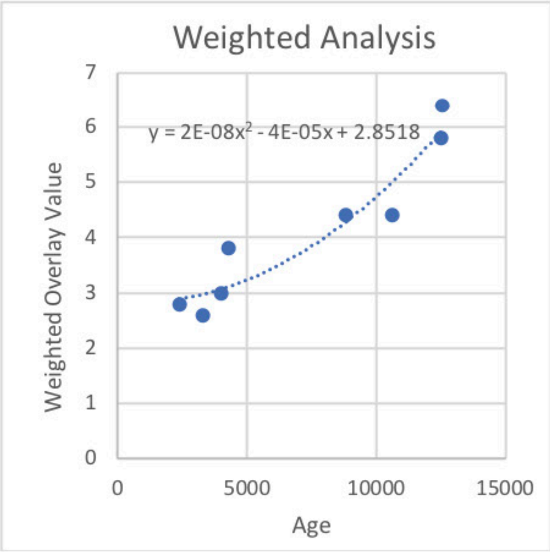


Raster	Condition = 1 (least desirable)	Condition = 9 (most desirable)
Fracture fill	Fill present	Fill not present
Fracture orientation	Fractures sub-parallel to cliff face	Fractures orthogonal to cliff face
Fracture density	High fracture density	Low fracture density
Slope aspect	South 45° East to South 45° West	North 45° East and North 45° West

Geospatial analyses allow for integration of frx features.

Fracture Characteristic Integration



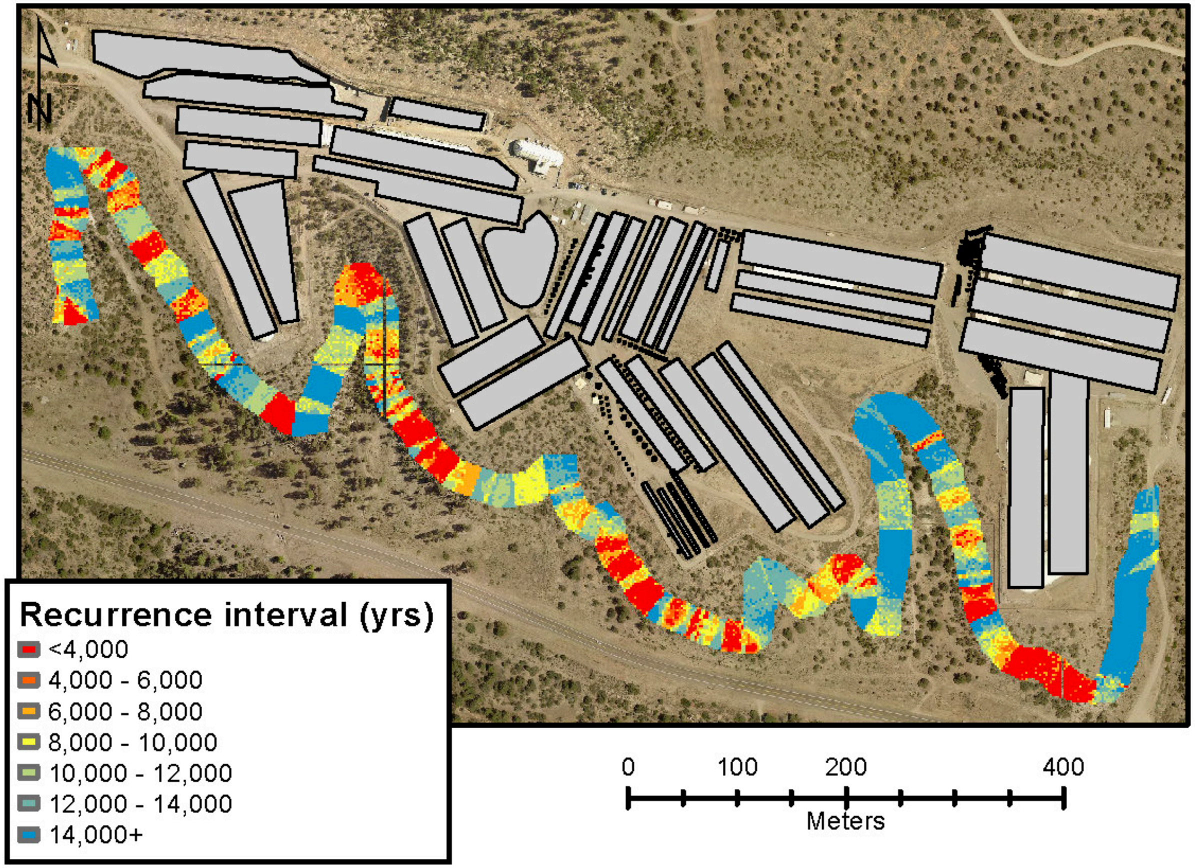


Raster	Wt %
Frx fill	0%
Frx density	20%
Frx orientation	60%
Slope aspect	20%

- **Equal weight analysis = poor correlation between age and condition**
- **Weighted analyses = better correlation between age and condition**

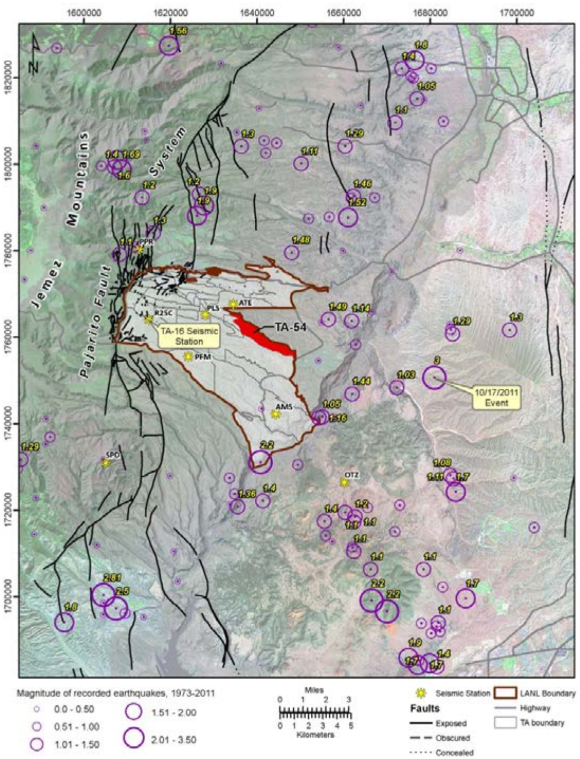
Aspect + frx density and orientation are the most important cliff parameters.

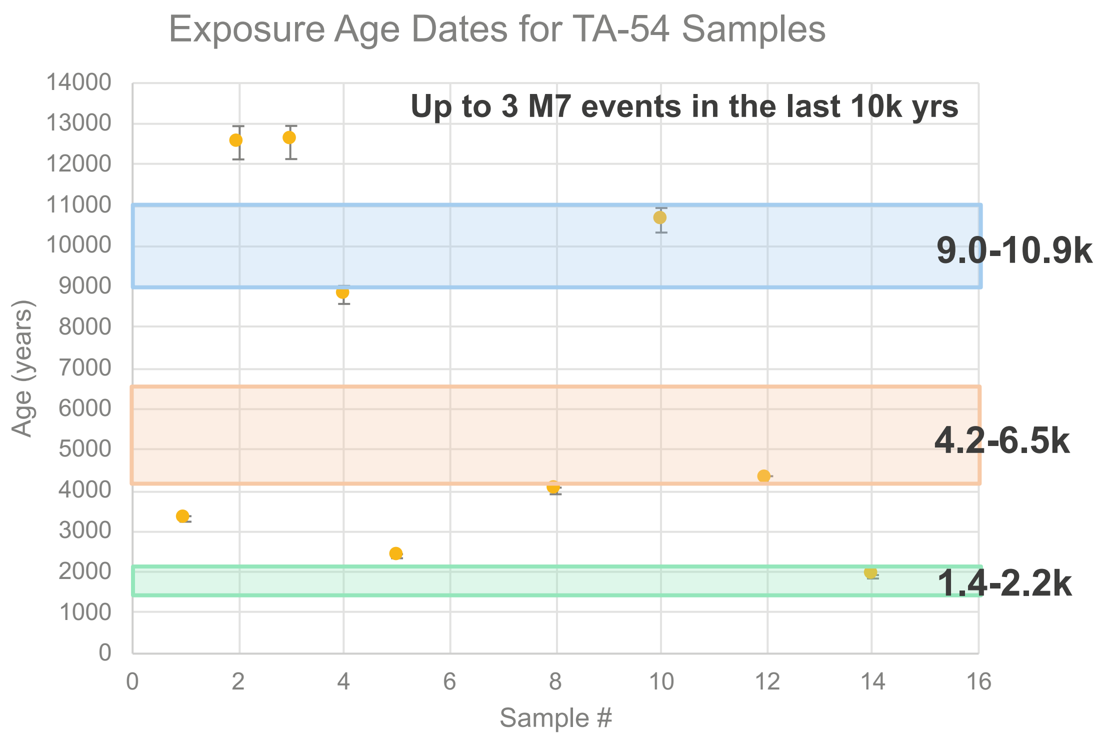
Predicting Future Failures



Data fusion highlights at-risk locations.

Cliff Retreat during Seismic Events





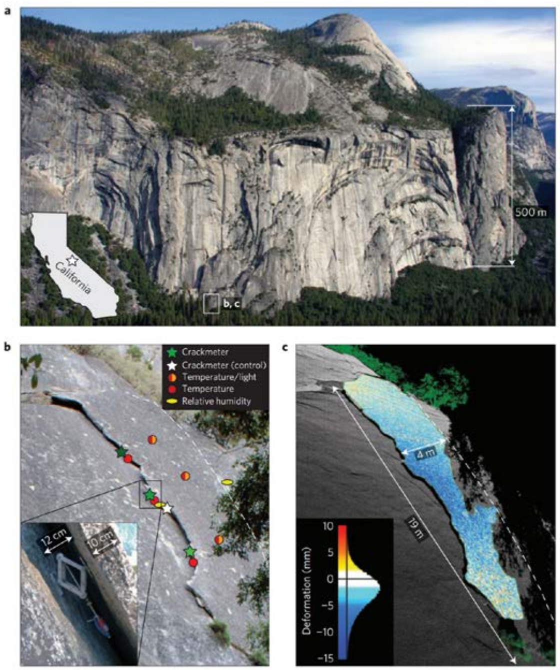
- **Initial analyses estimate that ~M5.5+ will produce enough ground motion for block failure to occur**

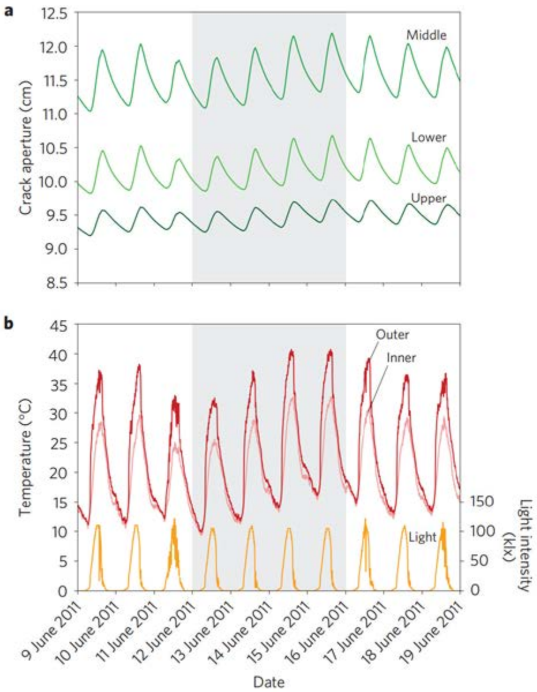
Relationship between EQs and cliff retreat is unclear.

Left: Los Alamos Seismic Network (Contact: Peter Roberts), Right: Seismic data from Lewis et al. 2009; Wong et al. 2007

Moving Towards Further Retreat Quantification

- **Fracture monitoring via crack meters collects temperature, moisture, and light datasets to study cyclic thermal forcing and diurnal temperature swings – both have been shown to trigger rock fall events**





Installation of crack meters can help further quantify retreat events.

Images and plots from Collins and Stock (2016)

Conclusions

- Cliff failure is occurring and threatens to expose pits and shafts
- Steep slope angles = FoS < 1 = high probability of failure and retreat
- EQ magnitude > 5.5 could initiate failure where FoS > 1
- Fracture characterization (location, orientation, etc.) essential for predictive analysis of at-risk cliff failure locations
- Additional surface exposure dating would be helpful and further constrain the effect of fracture characteristics
- Continued monitoring is essential for change detection and identification of areas with higher cliff retreat rates.
- Preparing manuscript for submission to ESPL – end of FY19

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