Geomorphic Characterization of Fault Creep in the San Francisco Bay Area

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1.Why Study Creep?

- Aseismic creep influences fault loading, stress transfer, and earthquake hazard, but is difficult to differentiate from earthquakes in the geologic record.
- The northern Calaveras Fault creeps and generates earthquakes, so its surface expression should record both processes and offers a natural laboratory for determining if landscape or geologic signals can be differentiated.
- We begin with highly detailed geomorphic and geologic mapping to differentiate the landscape and lithologic evidence for displacement and test for correlation of mineralogy with geomorphic expression and slip behavior of different strands.

2. Study Area

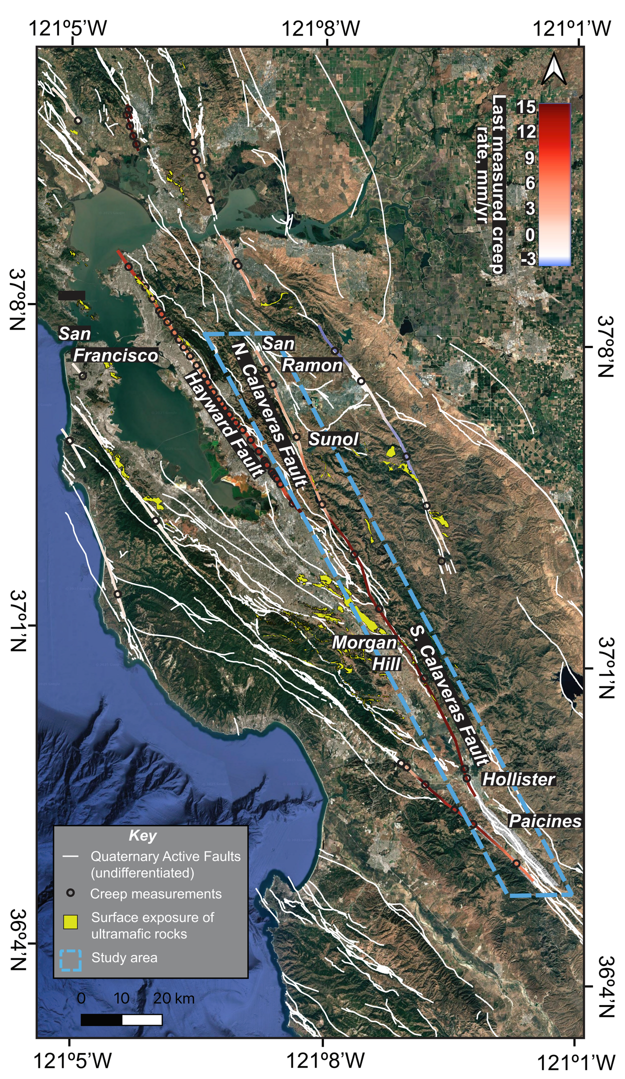


Figure 1: Map of the San Francisco Bay Area highlighting the exposure of ultramafic rocks (yellow polygons from 12 county maps, Graymer et al., 2006) compared to recent observations of fault creep (McFarland et al., 2023).

- Creep is particularly common in the San Francisco Bay Area where the San Andreas Fault System distributes slip across several sub-parallel fault strands (Fig. 1).
- Increasing slip deficit observed in the northern Bay Area (Fig 2).
- We focus on the Calaveras Fault which is both rapidly creeping (Fig. 1) and known to produce large (≥M6) earthquakes in the last century.

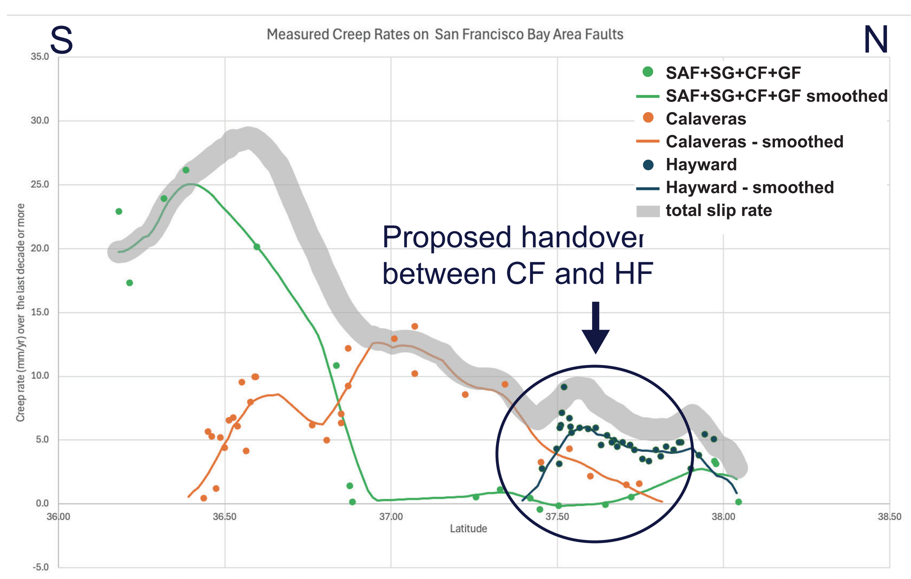
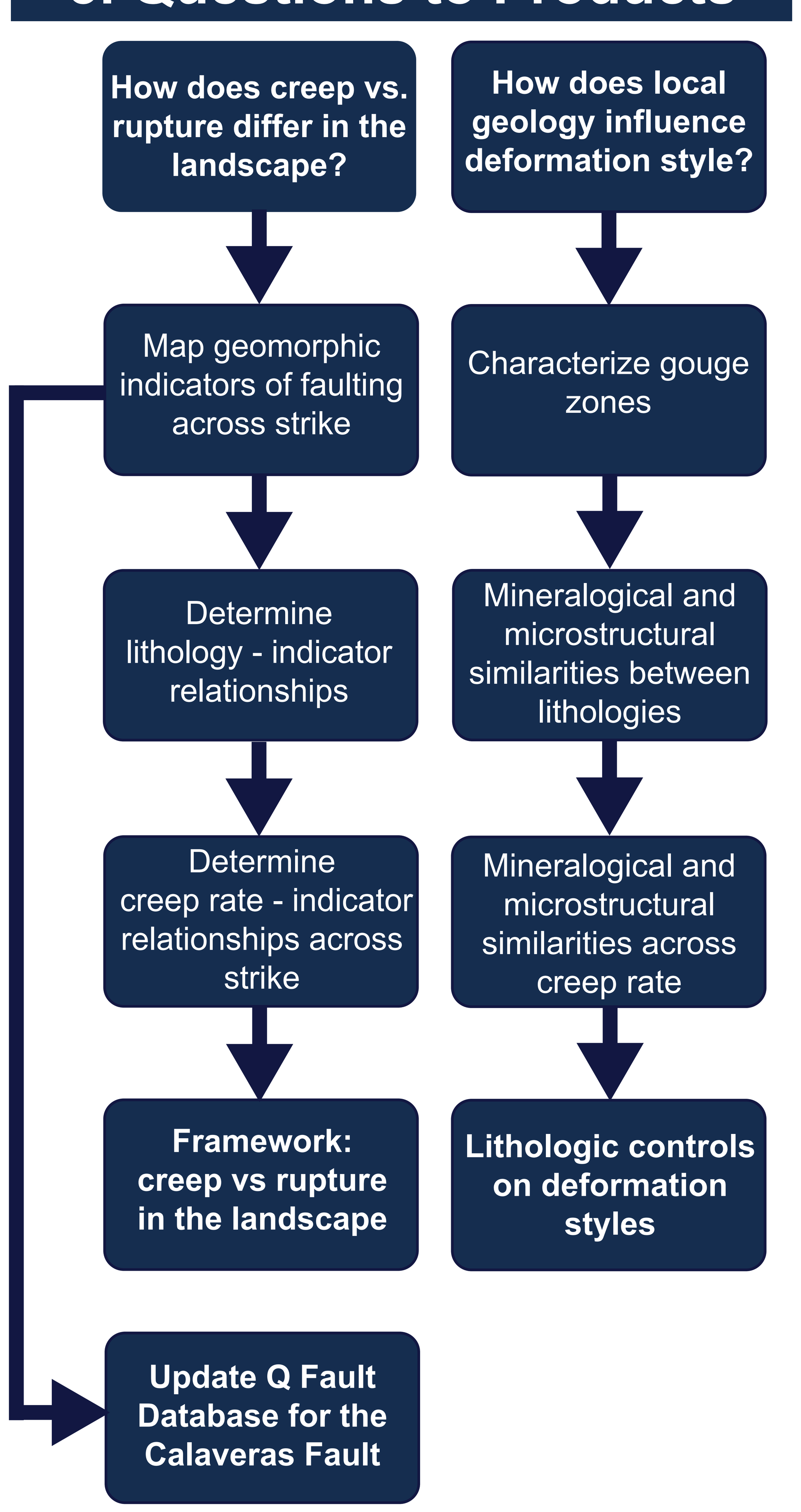


Figure 2: Creep rates along Bay Area faults, smoothed and summed from resampled data. Sources include creep meters, InSAR, and theodolite arrays (e.g., Titus et al., 2005; Li et al., 2023; McFarland et al., 2023).

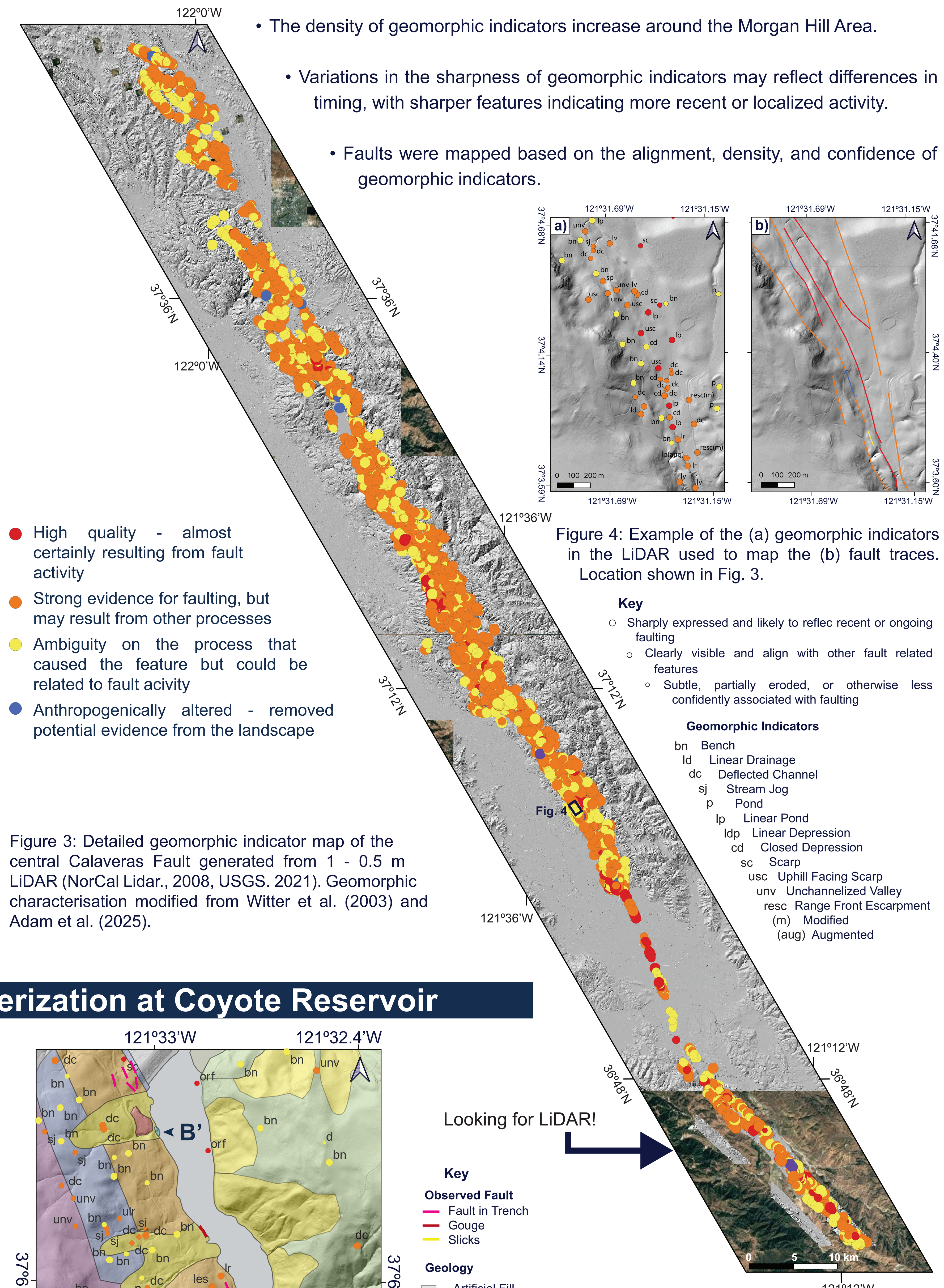
3. Questions to Products



4. Geomorphic Indicators of Faulting

The Calaveras Fault in the Quaternary Fault and Fold Database has not been updated since the widespread availability of LiDAR (Bryant and Cluett, 1999; NorCal Lidar, 2008).

- The density of geomorphic indicators increase around the Morgan Hill Area.
- Variations in the sharpness of geomorphic indicators may reflect differences in timing, with sharper features indicating more recent or localized activity.
- Faults were mapped based on the alignment, density, and confidence of geomorphic indicators.



- High quality - almost certainly resulting from fault activity
- Strong evidence for faulting, but may result from other processes
- Ambiguity on the process that caused the feature but could be related to fault acivity
- Anthropogenically altered - removed potential evidence from the landscape

Figure 3: Detailed geomorphic indicator map of the central Calaveras Fault generated from 1 - 0.5 m LiDAR (NorCal Lidar., 2008, USGS. 2021). Geomorphic characterisation modified from Witter et al. (2003) and Adam et al. (2025).

Figure 4: Example of the (a) geomorphic indicators in the LiDAR used to map the (b) fault traces. Location shown in Fig. 3.

5. Lithology - Indicator Relationships

Chi-squared test of independence indicates a signficant association between geomorphic indicator type and geology mechanical group ($\chi^2 = 550.31$, df = 196, p = 0.00).

- Plutonic Rocks account for 2% of the total study area and only host linear valleys and deflected channels.
- Lithified Sediments account for 60 % of the total study area and host a wide variety of geomorphic indicators.
- Long linear ponds (where pond length is 3x larger than the pond width) are over-represented in the serpentine and under-represented in the Sedimentary Rock (Fig. 9).
  - Abundant in the south and south central area of the Calaveras Fault where the creep rate is higher.

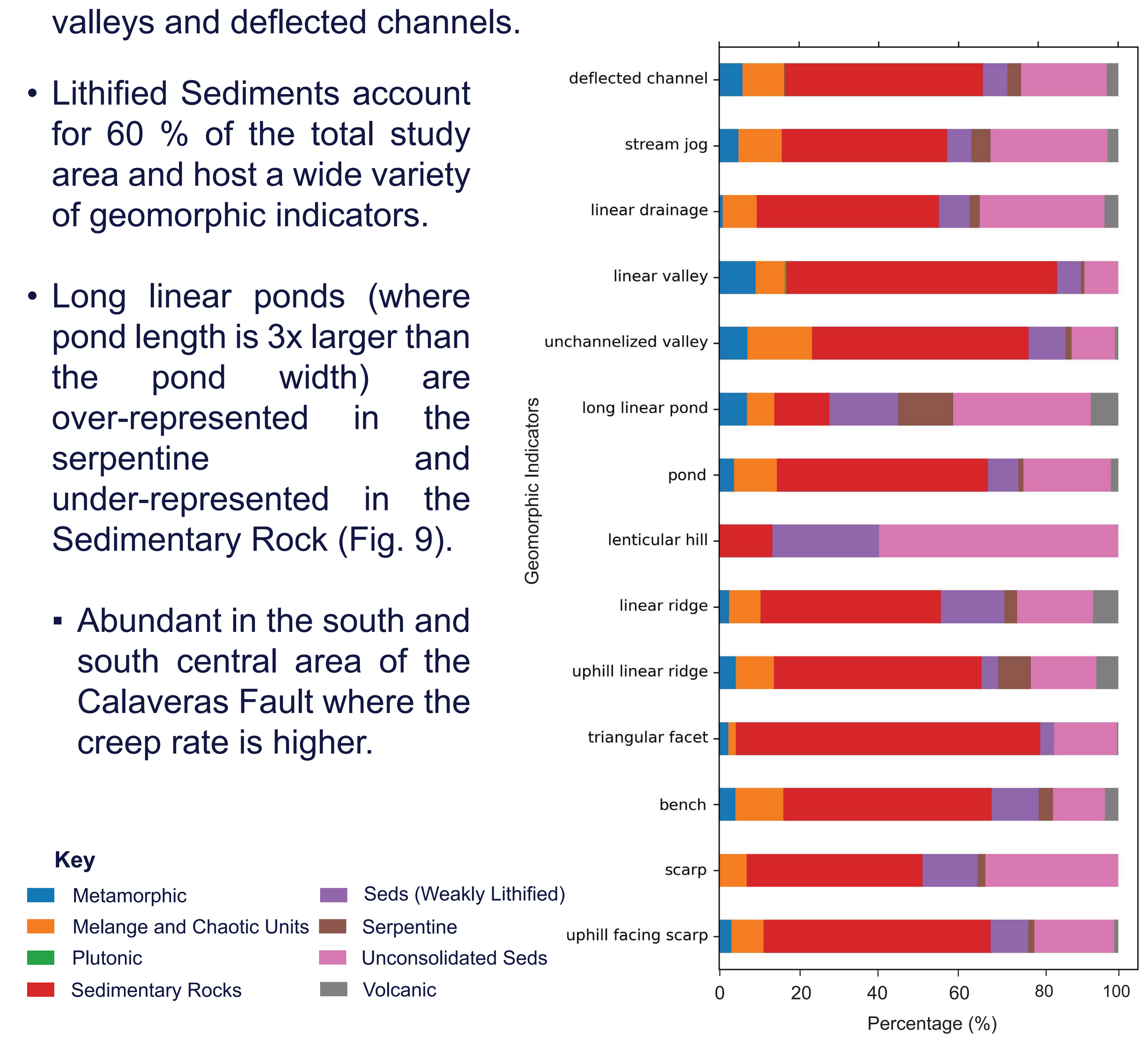


Figure 8: Distribution of the geology types across a subset of geomorphic indicator types, illustrating that the occurrence of indicators varies with underlying geology.

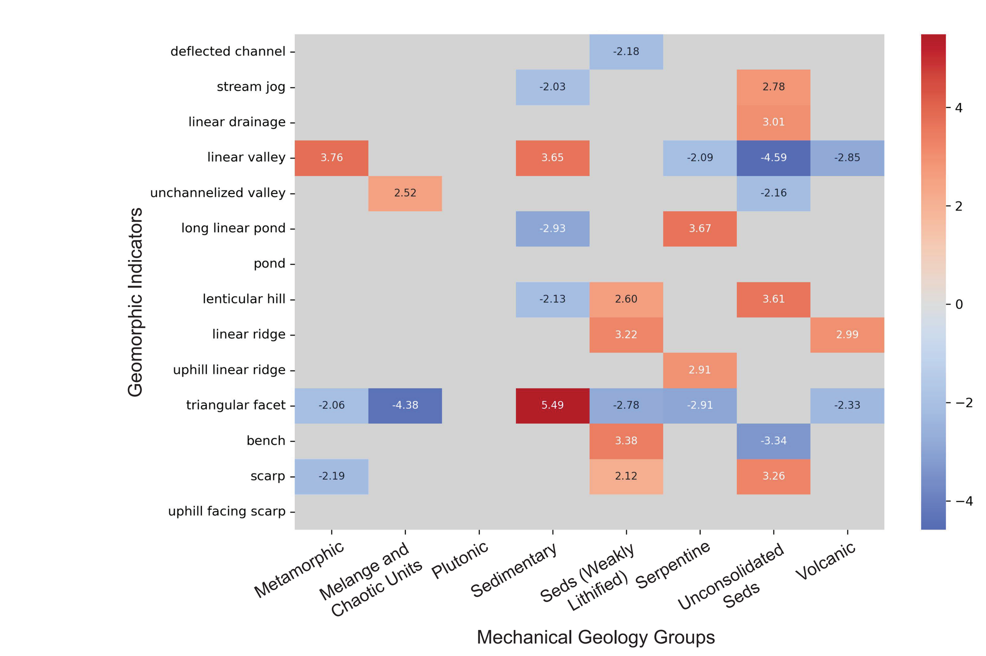


Figure 9: Standardized residuals from the chi-squared test of independence showing which geomorphic indicators from the subset shown in Fig.8 are over- or under-represented within each mechanical geology group.

6. Gouge Characterization at Coyote Reservoir

- A and B are shutter ridges
  - A has ~ 1.4 - 1.6 km apparent offset (A-A')
  - B has ~ 0.8 - 1.4 km apparent offset (B-B')
- Fault gouge appears to manifest differently between the serpentinite (Fig. 6) and sandstone (Fig. 7)

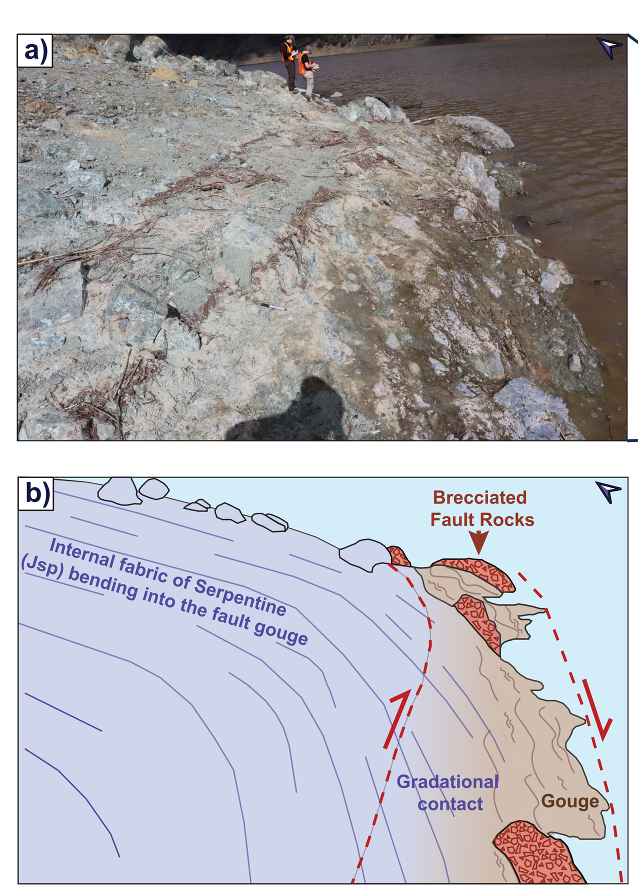


Figure 6: (a) Field photo of a serpentine outcrop with fault gouge exposed at the waterline. (b) Schematic illustration showing how the internal fabric of the serpentine bends into the gouge zone, highlighting localized deformation.

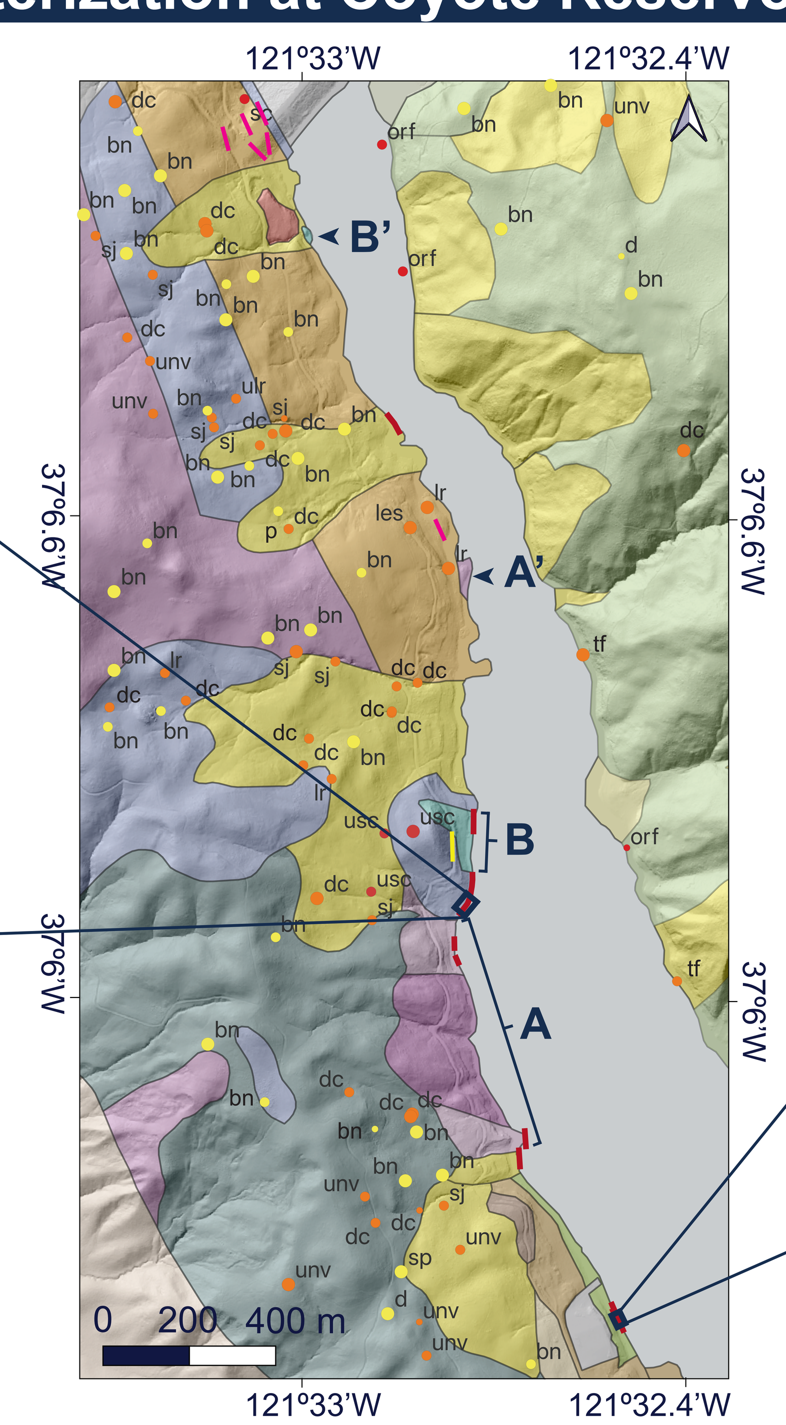


Figure 5: Geologic map of Coyote Lake modified from Witter et al. (2003) and Graymer et al. (2006).

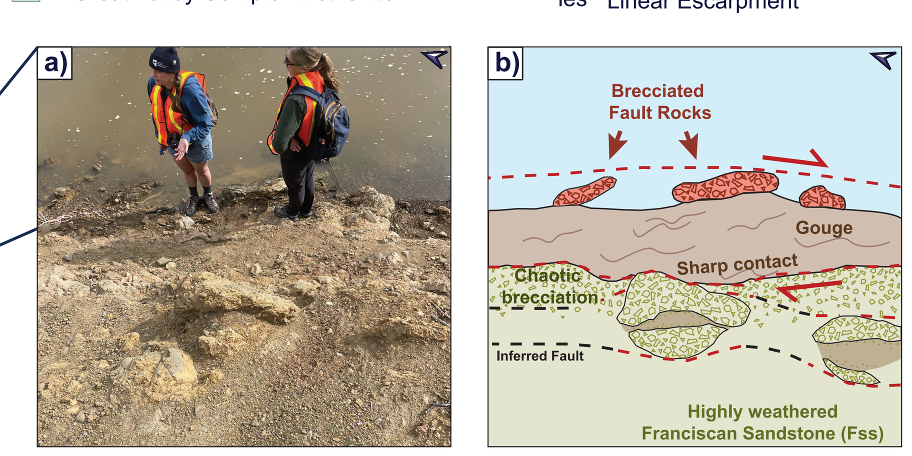


Figure 7: (a) Field photo of highly weathered Franciscan Sandstone with fault gouge exposed at the waterline. (b) Schematic illustration showing the relatively sharp boundary between the Franciscan Sandstone and gouge zone.

7. Future Work

- Update Quaternary Fault and Fold Database for the Calaveras Fault.
- Remove geomorphic indicators that aren't correlated with a fault strand and re-test the correlation between geomorphic indicators and lithology - does the geology ability to create clay influence certain indicators?
- Test the correlation between geomorphic indicators and creep rate along strike.
- XRD and Raman spectroscopy on gouge samples to determine how mineralogy and micrtostructures change with local lithology and across strike.

References

Adam, R.N., Scott, C., Arrowsmith, J.R., Reano, D., Madugo, C., Koehler, R.D., Zuckerman, M.G., Gray, B., Kozaci, O., González, T., AbramsonWard, H., Rockwell, T.K., Gath, E., Kottke, A.R., Leuchter, E., 2025. A systematic approach to mapping tectonic faults and documenting supporting geomorphology. Geosphere. https://doi.org/10.1130/GES02767.1

Bryant, W.A., Cluett, S.E., 1999. Fault number 54a, Calaveras Fault zone, Northern Calaveras section. (Technical Report), Quaternary fault and fold database of the United States: US Geologic Survey Website.

Graymer, R.W., Moring, B.C., Saucedo, G.J., Wentworth, C.M., Brabb, E.E., Knudsen, K.L., 2006. Geologic map of the San Francisco Bay Region, counties: Alameda, Contra Costa, Marin, Monterey, Napa, San Benito, San Francisco, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma. (Technical Report No. Map 2918), Scientific Investigations. U.S. Geologic Survey.

Li, Y., Bürgmann, R., Taira, T., 2023. Spatiotemporal Variations of Surface Deformation, Shallow Creep Rate, and Slip Partitioning Between the San Andreas and Southern Calaveras Fault. JGR Solid Earth 128, e2022JB025363.

McFarland, F., Lienkaemper, J., Caskey, S., Elliot, A., 2023. Data from theodolite measurements of creep rates on San Francisco Bay Region Faults, California. https://doi.org/Https://doi.org/10.5066/F76W9896.

NorCal Lidar, 2008. EarthScope Northern California LiDAR Project. https://doi.org/10.5069/G9057CV2.

Titus, S.J., DeMets, C., Tikoff, B., 2005. New slip rate estimates for the creeping segment of the San Andreas fault, California. Geol 33, 205.

USGS, 2021. United States Geological Survey 3D Elevation Program 1 meter Digital Elevation Model.

Witter, R.C., Kelson, K.I., Barron, A.D., Sundermann, S.T., 2003. MAP OF ACTIVE FAULT TRACES, GEOMORPHIC FEATURES AND QUATERNARY SURFICIAL DEPOSITS ALONG THE CENTRAL CALAVERAS FAULT, SANTA CLARA COUNTY, CALIFORNIA (Technical Report).

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