2024 SCEC Grant Final Report: Fault architecture, geomorphic expression, and mineralogy of the Central Calaveras Fault

SCEC Proposal 25270; Awarded: $30,000

SCEC milestones addressed: A1-3, A2-2, A3-1, A3-4, B1-1, B2-1

Christie Rowe, Nevada Seismological Laboratory
Rich Koehler, Nevada Bureau of Mines and Geology
Hannah Martin, Nevada Seismological Laboratory
Dana Marino, Nevada Seismological Laboratory

Abstract

This project aimed to: (1) compile past paleoseismic studies and mapping on the Calaveras fault, including substantial gray literature; (2) refine and complete the fault trace map using lidar and field mapping; (3) catalog geomorphic features of actively creeping fault strands; (4) sample fault gouge and wall rock from the creeping Calaveras; and (5) provide the orientation of Calaveras fault elements in the SCEC Community Fault Model. We have substantially completed (1-3) which comprise a manuscript led by Ph.D. student Hannah Martin in middle stages of preparation. Field mapping (2) and sampling (4) were completed in November 2025, and we completed a small-scale augering campaign near an alignment array measured since 1972 and an active creepmeter to establish the basis for a trenching proposal. Updated fault traces will be sent to Judy Zachariasen (CGS) for updating in the Quaternary Faults and Folds database for California after publication of the map in a journal article. The dip estimates will be shared with the curators of the SCEC CFM for the next updates. The samples collected under (4) will be characterized (composition (XRF), rough mineralogy (XRD), and microstructure by electron microscope). We have approached Shisharan Shreedharan at Utah State University to plan low-confining stress friction characterization experiments for wet and dry samples of fault gouges and Hannah Martin has submitted a Geological Society of America Student Research Grant proposal for funding to characterize the mineralogy of serpentinite and related weathering products using Raman spectroscopy.

1 Introduction

The San Andreas plate boundary in the San Francisco Bay Area shares slip across a set of subparallel dextral faults, some of which creep either at constant rates or episodically. The Calaveras Fault is the continuation of the creeping section of the San Andreas Fault which moves steadily at approximately the farfield plate rate south of Hollister. North of Hollister, the San Andreas fault is apparently locked, and slip continues on the Calaveras Fault, the slip rate decaying northward until becoming undetectable north of Danville, 115 km along strike. The central Calaveras fault has hosted several recent M6 earthquakes, but our compilation of publically available and grey literature revealed that there is no geologic slip rate reported and there is no clear record of the last surface-rupturing earthquake in spite of active surface deformation and recent seismicity. The central Calaveras is an ideal place to investigate the landscape effects of creep, since it transects farm land, rural areas and wilderness areas with no major urban development. Most of the rocks to the west of the central Calaveras are associated with Franciscan Complex: greenstones, metasediments, and serpentinites, with minor Tertiary volcanics. Bedrock contacts are poorly exposed. Well-stratified Great Valley Group sediments lie east of the Calaveras fault, with well-exposed bedding (Dibblee, 1979).

This is an excellent natural laboratory for answering two questions with broad implications: first, can the field characteristics or geomorphic expression of creeping faults be distinguished from those who only slip seismically? Second, are there any geologic factors (fault structure, fault rock mineralogy, or wall rock characteristics) that can help explain the rapid decay in current creep rate along strike? To answer these questions, we proposed a multi-pronged study to synthesize existing literature including consultant reports, detailed mapping of geomorphic features in Lidar DEM followed by field mapping.

2 Creeping faults

Creep has been documented on many major seismogenic faults, but is particularly common in the San Francisco Bay Area where the San Andreas plate boundary distributes slip across several sub-parallel fault strands (Fig. 1). The two major East Bay strands, the Hayward and the Calaveras Faults, are fast creeping and considered to have the potential to generate at least M7 earthquakes (Lienkaemper & Galehouse, 1998; Chaussard *et al.*, 2015). At the latitude of San José, most of the other Bay Area faults do not appear to be creeping, although evidence of creep was only recently reported for the Sargent fault (Mongovin & Philibosian, 2021), emphasizing that some creeping faults may not have been detected. The 'main strand' of the San Andreas branches westward and is believed to have remained locked since the 1906 M8.3 earthquake (Gilbert *et al.*, 1907; Nason, 1979; Lienkaemper *et al.*, 2014; McFarland *et al.*, 2023). The San Gregorio fault shows no confirmed movement in the last century, although some offshore earthquakes may have occurred on it (Maier *et al.*, 2017); no active creep has been confirmed (Koehler *et al.*, 2005; McFarland *et al.*, 2023). The Greenville fault shows negligible dextral creep (McFarland *et al.*, 2023). Other WNW-trending faults such as the Silver Creek fault have poorly known history and may be dormant (Langenheim *et al.*, 2015).

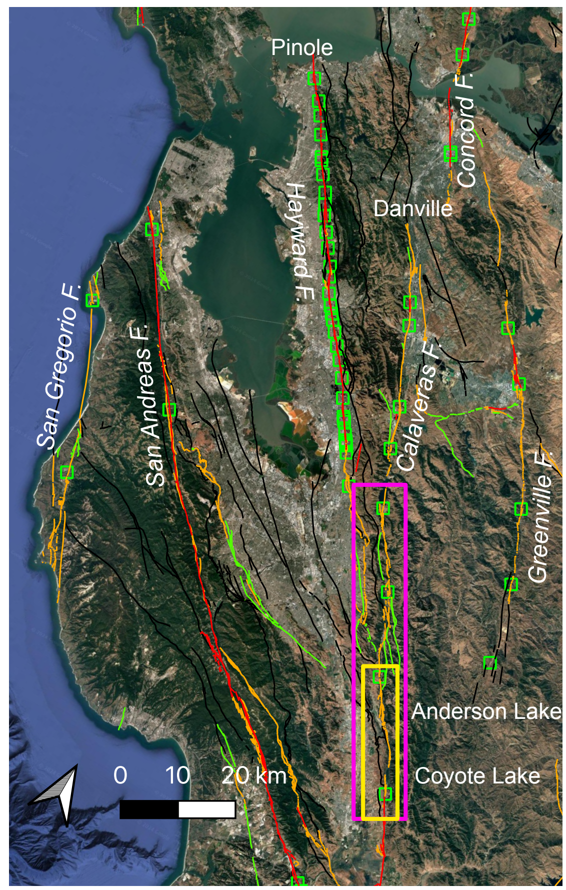

Figure 1: *Bay Area Faults from Bryant & Cluett (1999); red = historic, orange = <15 ka, green = <130 ka, black = undifferentiated Quaternary. Green squares are slip rate measurement sites from McFarland* et al. *(2023). Fuchsia box indicates area of 2025 remote mapping and field reconnaissance, yellow box indicates area of detailed field work and sampling.*

There is no consensus on why some of the faults creep and others don't – it could be due to local geologic conditions, such as mineralogy of fault rocks, wall rocks, and their likely alteration products (Reinen *et al.*, 1991; Moore & Lockner, 2007; Moore & Rymer, 2012), in which case the creepy behavior should persist over geologic time. Creep on shorter timescales has been observed post-seismically (e.g. Freed, 2007), driven by changing stress conditions during a period of aftershocks and fault recovery. Some faults, including the Calaveras and the Hayward, also display occasional creep transients (e.g. Kanu & Johnson, 2011;

McFarland *et al.*, 2023; Li *et al.*, 2023; Huang *et al.*, 2024).

In addition, there is no consensus on how to assign displacements measured in paleoseismic studies to creep vs. seismic slip. This distinction does not matter for determination of geologic slip rates, but is critical for estimating recurrence interval and the size of past earthquakes. Evidence of episodic slip and sediment deposition in a paleoseismic trench may represent a combination of seismic slip and afterslip, for example, and some recent afterslip events have reached similar surface displacements to the mainshock (e.g. Morelan *et al.*, 2015).

3 Aims

This project aimed to:

1. Compile existing data on the traces of the Calaveras fault, including assembling available past earthquake data from paleoseismic study sites (much of this from gray literature)
2. Lidar and Field mapping to correct and complete the fault trace inventory (for contribution to the Quaternary Fault Database managed by California Geological Survey)
3. Systematically search for geomorphological characteristics of actively creeping fault strands
4. Sample fault gouge and wall rock exposed at the surface, characterize mineralogy and microstructures of the fault gouge, and relate these to deformation mechanisms facilitating surface creep
5. Support development of Community Rheology Model and Community Fault Model with geologic and architectural data on the Northern Calaveras fault

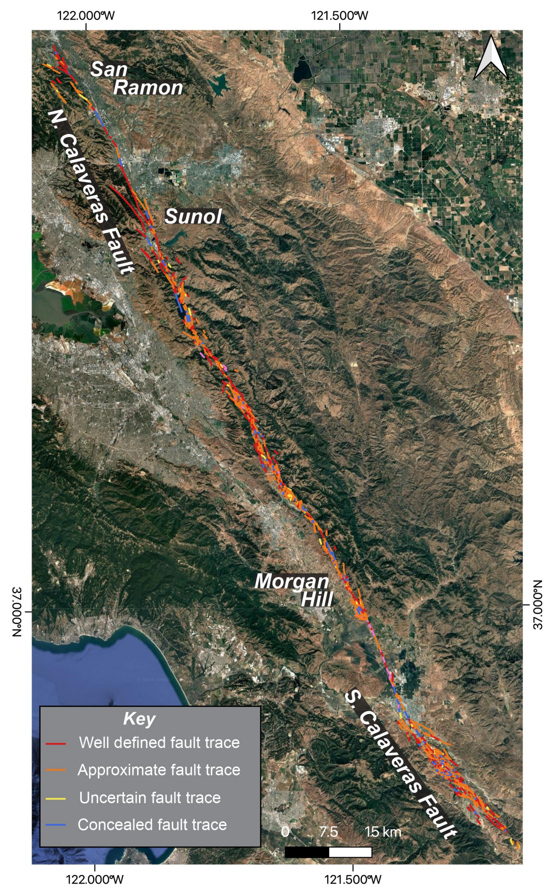

Figure 2: *New map of Calaveras fault zone from geomorphic indicators of faulting.*

4 Results

After one year, aims 1, 2 and 4 are complete, aims 3 and 5 are in progress with significant milestones accomplished. The remaining tasks are completion of the geospatial analysis for item 3, and dissemination including specific data deliveries to the Quaternary Faults and Folds Database (now managed by Judy Zachariasen for the California Geological Survey), estimation of fault dip from outcrop patterns, and a systematic comparison to simplified fault elements in the SCEC CFM. In addition, we continue to leverage these early results for additional work, including the fault gouge study and paleoseismic trencing on the central Calaveras to fill a major data gap revealed by the literature compilation.

4.1 Compilation and literature review

We have compiled a collection of observations from published and grey literature acquired through the generosity of municipalities and professional geologists comprising field work spanning several decades and produced a .shp file of these observation points including relevant metadata. These observations helped locate and identify geomorphic indicators of faulting for our updated map. As we densify our study in the other sections of the Calaveras, these recent observations are essential for characterizing the pre-development fault morphology in less accessible urbanized areas. Our compilation confirms the existence of a significant knowledge gap on the central Calaveras, where high M5- low M6 earthquakes have been frequent in historic times, but there is no confirmed evidence of recent surface rupture. Paleoseismic trenches could help elucidate whether the central Calaveras does rupture to the surface, and whether earthquakes greater than the historic largest M6.2 1984 Morgan Hill are possible. We are applying for permit and funding to excavate one or more paleoseismic trenches close to the creepmeter and alignment array at Coyote Ranch to confirm whether earthquakes rupture the creeping strand or other strands, whether and how creep and earthquakes can be clearly differentiated in the trench logs, and whether there is evidence for larger pre-historic earthquakes.

4.2 Mapping

During the one-year study supported by this grant, we have completed the digitization of all paleoseismic study sites we could compile from published and grey literature. We have produced a detailed geomorphic indicator map for the entire Calaveras fault (Fig. 1, magenta box; Fig. 2) and ground-truthed a significant part of the central Calaveras (Fig. 1, yellow box). Our approach was based on the geomorphic indicator framework presented by Adam *et al.* (2025), incorporating an uncertainty toolbox shared by Chelsea Scott (OpenTopography / ASU). The geomorphic indicators in the central Calaveras around Coyote Lake were mapped in detail by Witter *et al.* (2003), capturing several of the key features common in the bedrock styles of the area as well as the narrow fluvial canyons in the East Bay Hills. We have expanded and refined the geomorphic indicator categories to capture the full range of faulting-related features in this area, incorporating the full strike length of the Calaveras Fault so that the indicator statistics can be applied from end-to-end.

We have established a geostatistical approach for comparing the spatial patterns of different geomorphic indicators of faulting to the distribution of different bedrock and sediment types from published maps (Dibblee, 1979; Graymer *et al.*, 2006). Figure 3 demonstrates the approach to mapping on lidar DEMs, adapted from recent methodological advances of Scott *et al.* (2024); Adam *et al.* (2025). The revised fault map (Fig. 3C) based on geomorphic indicators of faulting with recorded uncertainties (Fig. 3B) is complete for the central Calaveras. Further field work over the next 2 years will allow us to ground truth the other fault sections.

The geostatistical analysis is still in process for the complete map area, but preliminary results show that there are specific bedrock associations with some types of geomorphic indicators. Some of these are relatively simple, e.g. triangular facets are common in harder rocks (basalt, sandstone) and absent when the fault transects Quaternary terraces.

In the ground-truthed region of the central Calaveras, the fault often has multiple closely spaced parallel strands (Dibblee, 1979; Bryant & Cluett, 1999; Graymer *et al.*, 2006) but the indications of active creep occur only on one of the strands. This area of the fault transects the East Bay hills and there are fewer offset anthropogenic structures than in urbanized areas, so the location of active creep is constrained mostly from a few points - the creep meter and historic alignment array at Coyote Ranch, the Coyote Lake Dam, and the E. Dunne Ave. bridge. Associated with the creeping strand, we have identified supporting indicators of fault activity such as cold water springs and travertine deposits indicating modern to recent CO_2 seepage.

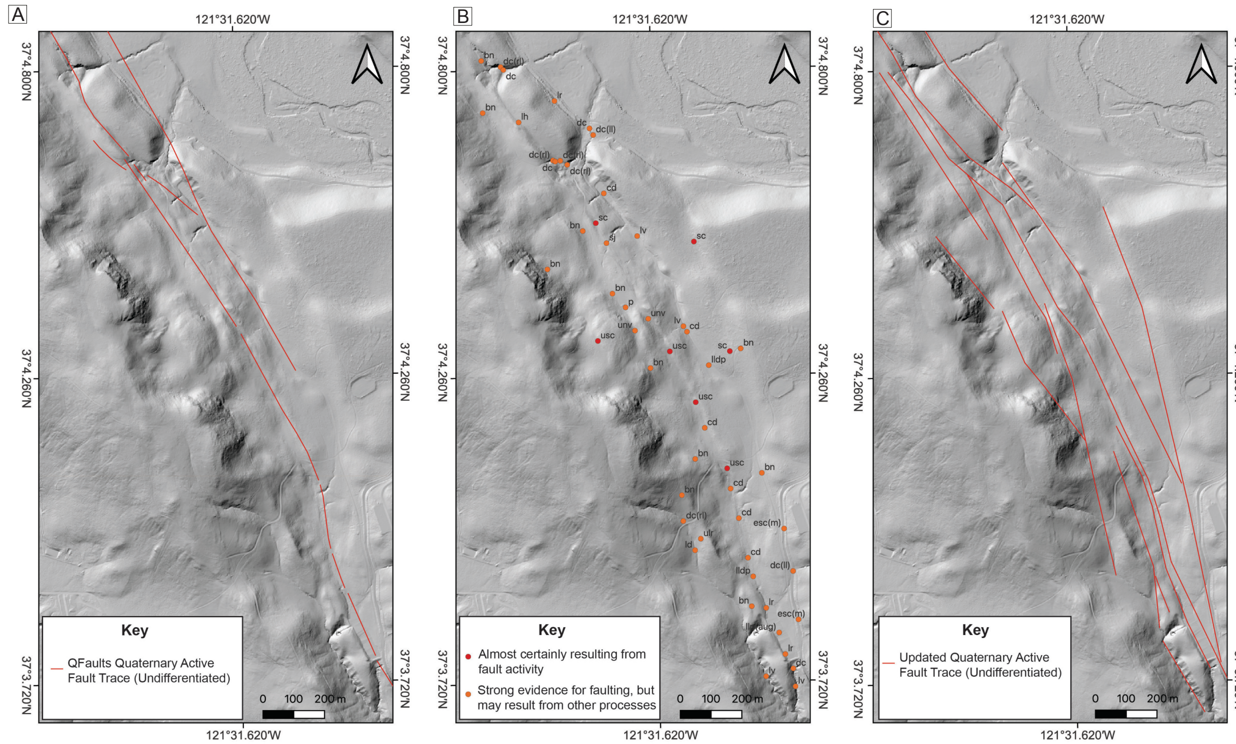

Figure 3: *Hillshade images showing the process of improving the fault trace maps in the Calaveras fault. A: Existing Quaternary Faults and Folds Database (Bryant & Cluett, 1999) fault strands, fault 54a, central Calaveras. B: Identified geomorphic indicators. C: Interpreted fault map.*

4.3 Fault and Wall Rock Sampling

Under permit from the Santa Clara Valley Water Authority ("Valley Water") and Santa Clara County Parks (Coyote Lake) we collected over 40 samples of fault gouge and wallrock for further investigation. Preliminary mineralogy will be estimated by XRD at UNR, and we have applied for additional funding to support travel for Hannah Martin to collaborate with Dr. Matthew Tarling at UBC for Raman spectral identification of serpentinite mineralogy *in situ* on key creeping zone samples. Our field observations indicate that the fault rock in the actively creeping strand varies strongly with the local wallrock, from which it is mostly derived. In the Franciscan sandstones we see brecciated patches of enhanced cementation (Fig. 4A). Where the fault cuts through serpentinite, it transposes and reactivates older pre-existing shear fabrics, often brecciating the pre-existing scaly fabric forming narrow cataclastic zones of thin cleaved flakes (Fig. 4B). When the fault intersects the black shales of the Great Valley group, a wide zone of vertical scaly fabric develops, containing blocks of the brecciated serpentinite and sandstone (Fig. 4C). Where the creeping strand cuts very young fluvial terraces, we noted cracked and rotated pebbles and cobbles forming a narrow (10s cm) band of re-oriented fragments (Fig. 4D). This study is ongoing.

4.4 Community Earth Models

The updated fault trace maps will be used to calculate the dip of the major fault strands from apparent curvature of the fault traces across the landscape. Our estimated dips will also be compared with precisely located microseismicity where available to confirm we have selected the active fault

Figure 4: *Four examples of lithology-specific sub-vertical fabrics in the actively creeping strand of the Calaveras Fault. A: Angular breccias with patchy cementation in Franciscan sandstone at Coyote Lake. B: Splintery scaly fabric in reworked serpentinite, south of E. Dunne Ave. bridge. C: Disaggregated sandstone beds and weakly developed scaly fabric in black shale of the Berryessa Formation, Great Valley Group, near Coyote Lake dam. D: Narrow zone of rotated pebbles in poorly sorted unconsolidated modern fluvial terrace, under the E. Dunne Ave. bridge.*

trace. The implied dips from fault trace intersections with the landscape will be compared to the Calaveras Fault in the SCEC Community Fault Model and we will communicate any suggestions for revision to the CFM leadership team.

4.5 Dissemination and future work

Results from this work have been presented in Thunder Tralks at the January 2026 USGS virtual Northern California Earthquake Hazards Workshop and the March 2026 SCEC Fault Creep Workshop at San José State University. We are committed to additional presentations at the 2026 Statewide California Earthquake Center Annual Meeting and other professional conferences such as Seismological Society of America (2026 Pasadena) and the American Geophysical Union Annual Meeting (2026 San Francisco). We anticipate one journal article on the geomorphic expression of creeping faults to be submitted in 2026 to BSSA or similar journal. We will also produce data products to support further research, e.g. GIS layers and model inputs, which will be published as supplementary data with peer-reviewed journal articles or as data reports (e.g. in Seismica). Support for meeting travel and publication fees will be provided from Koehler and Rowes' other research funds.

Under the same permits, we have completed a shallow hand-auger investigation of potential trench sites at Coyote Ranch and will pursue funding and permission to excavate a paleoseismic trench near the existing creep meter and alignment array. Fault rock analysis is ongoing.

Acknowledgments

We thank Keith Kelson for expert advice and significant assistance with the literature compilation. Dana Marino did much of the heavy lifting to compile the literature and digitize old maps. We are grateful for field assistance from Maggie Duncan (Desert Research Institute) and Alex Travers (University of Otago) under some seriously damp conditions, and to Mark Stirling (University of Otago) for allowing Alex the time to work with us. We are grateful to Santa Clara Valley Water for permission to traverse Coyote Creek and the upper reaches of Anderson Lake, and sample along the reservoirs. We thank Santa Clara County Parks, particularly the staff at Harvey Bear-Coyote Lake Park and the parks archeologist Ben Curry for their support and interest in our study. We hope that in the future we may collaborate more on interpretive materials to make this extraordinary active fault landscape more accessible for the people of Santa Clara County.

4.6 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., *et al.* (2025). A systematic approach to mapping tectonic faults and documenting supporting geomorphology. *Geosphere*, *21*(2), 227–244.

Bryant, W. A. & Cluett, S. E. (1999). Fault number 54a, Calaveras Fault zone, Northern Calaveras section. Tech. rep., Quaternary fault and fold database of the United States: US Geological Survey website.

Chaussard, E., Bürgmann, R., Fattahi, H., Johnson, C., Nadeau, R., Taira, T., & Johanson, I. (2015). Interseismic coupling and refined earthquake potential on the Hayward-Calaveras fault zone. *Journal of Geophysical Research: Solid Earth*, *120*(12), 8570–8590.

Dibblee, T. W. (1979). Preliminary geologic maps of the Gilroy Hot Springs, Gilroy, Mt. Sizer, Morgan Hill quadrangles, Santa Clara County, and the Mt. Madonna quadrangle, Santa Clara and Santa

Cruz Counties, California. Geologic Map Open-File Report OF-73-59, U.S. Geological Survey. Map scale 1:24,000.

Freed, A. M. (2007). Afterslip (and only afterslip) following the 2004 Parkfield, California, earthquake. *Geophysical Research Letters*, *34*(6).

Gilbert, G. K., Humphfrey, R. L., Sewell, J. S., & Soulé, F. (1907). *The San Francisco Earthquake and Fire of April 18, 1906 and their Effects on Structures and Structural Materials*, vol. 1 of *Series R, Structural Materials*. United States Geological Survey, Washington Government Printing Office.

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. Tech. rep., US Geological Survey.

Huang, L., Schwartz, S., & Brodsky, E. (2024). Microseismicity at the Time of a Large Creep Event on the Calaveras Fault is Unresponsive to Stress Changes. *Seismica*, *3*(2).

Kanu, C. & Johnson, K. (2011). Arrest and recovery of frictional creep on the southern Hayward fault triggered by the 1989 Loma Prieta, California, earthquake and implications for future earthquakes. *Journal of Geophysical Research: Solid Earth*, *116*(B4).

Koehler, R. D., Witter, R. C., Simpson, G. D., Hemphill-Haley, E., Lettis, W. R., Pearce, J. T., Sundermann, S., & Streig, A. (2005). Paleoseismic investigation of the northern San Gregorio Fault, Half Moon Bay, California. Final Technical Report Award No. 04HQGR0045, U.S. Geological Survey National Earthquake Hazards Reduction Program. 70 pages.

Langenheim, V. E., Jachens, R. C., Wentworth, C. M., Graymer, R. W., Stanley, R. G., McLaughlin, R. J., Simpson, R. W., Williams, R. A., Andersen, D. W., & Ponce, D. A. (2015). A summary of the late Cenozoic stratigraphic and tectonic history of the Santa Clara Valley, California. *Geosphere*, *11*(1), 52–60.

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. *Journal of Geophysical Research: Solid Earth*, *128*(1), e2022JB025363.

Lienkaemper, J. J. & Galehouse, J. S. (1998). New evidence doubles the seismic potential of the Hayward fault. *Seismological Research Letters*, *69*(6), 519–523.

Lienkaemper, J. J., McFarland, F. S., Simpson, R. W., & Caskey, S. J. (2014). Using surface creep rate to infer fraction locked for sections of the San Andreas Fault System in Northern California from alignment array and GPS data. *Bulletin of the Seismological Society of America*, *104*(6), 3094–3114.

Maier, K. L., Paull, C. K., Brothers, D. S., Caress, D. W., McGann, M., Lundsten, E. M., Anderson, K., & Gwiazda, R. (2017). Investigation of late Pleistocene and Holocene activity in the San Gregorio Fault Zone on the continental slope north of Monterey Canyon, offshore central California. *Bulletin of the Seismological Society of America*, *107*(3), 1094–1106.

McFarland, F., Lienkaemper, J., Caskey, S., & Elliot, A. (2023). Data from theodolite measurements of creep rates on San Francisco Bay Region Faults, California (ver. 2.2, July 2023). Data release, U.S. Geological Survey. Https://doi.org/10.5066/F76W9896.

Mongovin, D. D. & Philibosian, B. (2021). Creep on the Sargent Fault over the past 50 yr from alignment arrays with implications for slip transfer between the Calaveras and San Andreas Faults, California. *Bulletin of the Seismological Society of America*, *111*(6), 3189–3203.

Moore, D. E. & Lockner, D. A. (2007). Friction of the smectite clay montmorillonite: A review and interpretation of data. *The seismogenic zone of subduction thrust faults*, 317–345.

Moore, D. E. & Rymer, M. J. (2012). Correlation of clayey gouge in a surface exposure of serpentinite in the San Andreas Fault with gouge from the San Andreas Fault Observatory at Depth (SAFOD). *Journal of Structural Geology*, *38*, 51–60.

Morelan, A. E., Trexler, C. C., & Oskin, M. E. (2015). Surface-rupture and slip observations on the day of the 24 August 2014 South Napa earthquake. *Seismological Research Letters*, *86*(4), 1119–1127.

Nason, R. (1979). Earthquakes and fault creep on the northern San Andreas Fault. *Tectonophysics*, *52*.

Reinen, L. A., Weeks, J. D., & Tullis, T. E. (1991). The frictional behavior of serpentinite: Implications for aseismic creep on shallow crustal faults. *Geophysical Research Letters*, *18*(10), 1921–1924.

Scott, C., Kottke, A., Madugo, C., Arrowsmith, J. R., Adam, R., & Zuckerman, M. (2024). Tectonic landform and lithologic age impact uncertainties in fault displacement hazard models. *Geophysical Research Letters*, *51*(16), e2024GL109145.

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. Final Technical Report Award No. 01HQGR0212, U.S. Geological Survey National Earthquake Hazards Reduction Program. 42 pages.