

Fault creep rates in the San Francisco Bay Area: A Statewide California Earthquake Center Workshop

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OVERVIEW

The San Francisco Bay Area is cut by a network of faults, many of which are creeping. Creep has been measured since the 1970s by survey measurements of 89 alignment arrays. This extraordinary dataset provides evidence for creep transients, some triggered by regional earthquakes, which propagate along strike over days to years. There is no plan for continuing alignment array measurements, a time-consuming task that may be best shared across the research community. Considering these data with other methods for observing creep is critical to advance understanding of the loading conditions and stress transfer in space and time that underlie fault mechanics, seismic cycling and earthquake rupture dynamics. Limited understanding of how creep influences seismic hazard further underscores the need to focus collaborative research in this area and proactively plan for the long term monitoring of creep.

These data are yet to be utilized to their full potential for answering fundamental questions. For example, what does creep reveal about fault loading through the seismic cycle? What does creep mean for seismic hazard, and how should creep rates be used in hazard models? Does the depth of the creep matter? What is the role of bulk deformation in creep behavior? What gaps in spatial or temporal coverage must be filled to answer these questions? The workshop highlighted the promise of long-term creep measurements for answering critical questions, underscoring the importance of continuing to collect these data in a collaborative manner. We also focused on options for organizing and updating data collection and storage moving into the future through the SCEC Community Earth Models. We compared approaches including creepmeters (Langbein et al., 2024), structure-from-motion (Scott et al., 2020; Swiatlowski et al., 2022), remote sensing (Funning et al., 2007), and coda wave interferometry (Luckie and Choens, 2025).

From March 3-6, 53 scientists met at San José State University to evaluate the future of alignment array measurements alongside alternative methods for measuring creep. After field trips to alignment array and strain gauge sites, long format and lightning talks, and breakout sessions to motivate discussion, we launched a white paper reviewing the current methods of monitoring creep and weighing the relative performance of alternative methods. The white paper includes a spreadsheet detailing the monitoring methods and measurement details of 31 different approaches to recording creep data. We also discussed the possibility of including the alignment array and potentially other creep data in the SCEC Community Geodetic Model and/or the SCEC Community Fault Model and/or Fault Slip Rate Database.

WORKSHOP CONTRIBUTIONS

The workshop was opened midday March 3rd by Ahmed Elbana (USC) on behalf of SCEC, and Christie Rowe on behalf of the conveners. We began with introductory, 20 min talks from experts on creep monitoring and the history of alignment arrays in the San Francisco Bay Area, to bring all participants up to speed. Forest McFarland (SF State and SFSU Creep Project) and Dylan Cardiff (SFSU Creep Project) introduced the arrays, showing key field indicators of creep that helped establish where they were installed, and some of the updates to the built environment and wildlife activity that have damaged sites. The motivation in the early days of expanding the number of stations was the possibility of catching a precursory creep event before a significant earthquake - a possibility that remains untested to this day. They recounted how John Galehouse (SF State) and Jim Lienkaemper (USGS) had set up their own arrays and densified the monitoring of the Hayward Fault to a spacing of ~2 km, capturing a 1995 rapid transient which broke a water main in Hayward. Later, John Caskey (SFSU) and Karen Grove (SFSU) contributed to regular measurements. Critically, the researchers documented the location of monuments in detail in field sheets that are either in digital format, or in binders in Forest's office! Plans to transfer these binders to the Steve DeLong at the USGS were made at the Workshop.

Steve DeLong (USGS) updated the group on the specifics of taking creep measurements, starting with peak-to-peak geodolite methods and extending to the finicky theodolite measurements of the last few decades. He gave a somewhat sobering assessment of the state of the array, which had as many as 90 stations but only 60 of which now are considered “active”. Higher precision is possible with theodolite than Global Positioning System (GPS), but achieving this precision is a labor of skill and dedication that may be hard to replicate with a broader team. He explained the pros and cons of the new USGS robotic total station, the conventional total station, RTK GNSS, lidar (terrestrial, mobile and airborne), Synthetic Aperture Radar (SAR), and creepmeters. With excitement, Steve announced the ScienceBase publication of an updated alignment array data release just in time for this workshop!

Todd Erickson (USGS) gave a detailed overview of the 20 creepmeter sites the USGS maintains in northern California. Technology advances so quickly that almost no two are alike! The length standard materials could be Invar (Fe-Ni alloy with low thermal expansion), wire or rod, glass rod, “pulltruded” glass fibre/epoxy rod, or carbon rod, measured by sensors of three main types: LVDT, Rotary Hall, and potentiometer. Some sites have sensors for temperature, radon, CO₂, and pore pressure, and different geometries allow fault-orthogonal measurements at some sites that have yielded insight on the relationships between creep and dilation. The meters are telemetered through GOES or cellular, with dedicated solar power. Todd summarized some of the extraordinary observations collected by the creepmeters over the years, with additions from Roger Bilham - triggered slip, afterslip, delayed slip, the propagation rate of slip transients (2 km/yr on the Hayward Fault), the complexities of creep translation from depth to surface, and the effects of atmospheric pressure, precipitation, and CO₂ flux in the shallow soils. Todd closed with some recommendations for future monitoring, including using multipoint alignment arrays, the possibility of installing Roger’s new ~\$1k creepmeters within alignment arrays, forecasting buried infrastructure risks from propagating creep events, and positioning alignment arrays for resolving dilation so that fault-parallel displacement rates can be accurately resolved.

Josie Nevitt (USGS) continued to build on the complexity of creep propagation through specific observations of the West Napa Fault after the 2014 M6 earthquake and the multi-instrumental observatory on the Hayward fault at the Gallegos Winery in Fremont. The coseismic principal slip zone in Napa was a 2 cm tabular layer which disappeared above the water table - was slip distributed in the dry layer of soil, or did it only catch up later? There are decades of observations suggesting surface creep correlates with rainfall - is this only representative of the critical zone? How can we see through these temporal patterns to interpret deep slip from surface measurements? Narrow zones (<5 m) of concentrated creep are flanked by broader zones (10s m wide) which take up additional displacement through volumetric deformation. Borehole inclinometer records at Gallegos Winery show that 7% of the deeper (20+ m) slip is not reaching the surface, or is delayed until rain, and the surface data is noisier than creep measured at depth.

Kaj Johnson (Indiana University) rounded out a packed first half-day of the workshop with a pre-recorded talk, from sabbatical at Leeds. He shared the methods used to reduce geodetic estimates of seismic slip rates due to creep in the 2023 National Seismic Hazard Model (NSHM) (Petersen et al., 2023). This correction decreases the moment rate on faults. The creep rates used in these models come from alignment arrays, creepmeters, and Interferometric SAR (InSAR). Kaj shared the fault-based method used for determining the geodetic slip rates using the LOCS (Locked Or Constant Stress) approach, in which, during the interseismic period, creeping fault patches slip in response to constant stress imposed by the locked patches. The creep rate is therefore determined by the locked patches. At depth, all faults are slipping at the slip rate assigned in the NSHM. For a series of models with different creeping patch distributions, the best-fitting solution is found. This approach fits available creep data on many Bay Area faults, but with large local uncertainties, arising partially from the large number of unknowns, including the connectedness or segmentation of faults, creep rates through time, behavior at boundaries between stationary and creeping patches, and physical mechanisms/stress sensitivity.

March 4 was an all-day field trip. At Camellia Drive, the HCAM alignment array site, USGS geologists Steve DeLong, Todd Ericksen, Chad Trexler, Jessie Vermeer, Cassie Hanagan and Rezagene Milani guided participants in using the alignment array equipment with the new total station, in contrast to the theodolites used for much of the duration of the SFSU Creep Project. A 3D laser scanner with low grade GPS also was available for participants to practice data collection. Participants were able to observe offset curves, cracking in the asphalt and damage to property. After lunch at Fremont Central Park, we toured the geomorphic evidence of creep in the southeast part of the park, as well as pipe infrastructure used to transport water from the Hetch-Hetchy reservoir to the Bay Area that crosses the Hayward fault at this location. At Gallegos Winery, Josie Nevitt, Todd Ericksen and Roger Bilham described the borehole strainmeter, first installed in the 1980s and surprisingly crossing what is likely a secondary strand of the fault branching off the main structure toward the surface. Now updated with a sophisticated inclinometer, the site has revealed transient creep events. Todd Ericksen also provided an overview of the USGS Riegl Vz 1000 laser scanner. The day closed with a fantastic dinner at The Farmer's Union in San José.

March 5 included a series of slightly shorter (15 min) talks. We started with Steve DeLong (USGS) sharing the data collected the previous day - an updated measurement at HCAM was on trend with the previously measured creep rate of 7 mm/yr. Jessie Vermeer processed the point clouds from the terrestrial laser scanner revealing continued offset on the curbs of Camelia Dr. Data downloaded from the shallow creepmeter at Gallegos Winery indicated a slight uptick in creep rate to 0.5 mm/day, a higher than average rate indicating a creep transient is being recorded at that site.

Roland Bürgman covered decades of creep rate variations on the Hayward fault, noting that surface creep averages about 5 mm/yr, equivalent to about an M6.8 every century. Most of the Hayward fault has been creeping slightly faster since 2010 than before, while there has been a decrease in creep rate in the central Calaveras and slight increase in the northern Calaveras. Roland linked the temporal and spatial variations in creep rates to asperity erosion as creeping patches grow on decadal scales, which might be a ubiquitous feature of partially coupled faults.

Chelsea Scott (ASU) described spatial differencing methods used to resolve deformation fields at two localities on the San Andreas fault, which also show spatially and temporally variable creep rates, with the fastest creeping section stable near Pinnacles National Monument. Differencing lidar elevation data back to 2005 revealed distribution of strain over Mustang Ridge, a partially active transpressional duplex.

Heather Crume (Moody's) presented her creepmeter observations from Fox Creek on the San Andreas fault south of Hollister. They confirmed dilation associated with creep pulses (which would appear like sinistral slip if measured only with a perpendicular meter!), with creep occurring in pulses of a few mm in one day, with variable rates in between. Two creepmeters separated by 130 m recorded southward propagation of creep events (130 m/20 min) much faster than the 2 km /yr Roger had mentioned for the Calaveras! The total creep and the shape of the event are different at the two creepmeters.

Thomas Luckie (Sandia National Lab) showed the development of a method using coda wave interferometry to detect small translations of rock volume along the Hayward fault, and thereby measure creep. This is a modification of the method used to detect velocity changes by assuming no change in distance, and using two creepmeters as a baseline. Temperature changes must be accounted for, but the method is able to coarsely recover the changes in creep patterns.

Belle Philibosian (USGS) delivered a two-part talk on field observations of creeping faults. First, she shared the finding that the Sargent Fault is creeping on two strands, which had to be rediscovered, as the multi-monument alignment array was not measured between 1975-2019. Second, she showed trench logs from Topo Creek on the fastest-creeping section of the San Andreas. Folded but unbroken soil layers, subtle vertical fabric, absence of shaking-related features like broken blocks, fissures, or upward

termination, are all consistent with creep without earthquakes for the last 1000 years or possibly 2200 years. These “creepy” soil features also have been found in trenches on faults that both rupture and creep.

Andrew Barbour (USGS) gave an overview of the USGS’s Crustal Deformation Center, which has a mandate to measure crustal deformation with InSAR, mobile laser scanning, semi-permanent and continuous GPS networks, creepmeters, strain meters and surveys. They are working on data handling and processing, and resurveying around Parkfield in readiness for anticipated work ramping up there.

Eric Fielding (NASA/JPL) showed gaps in Sentinel-1 InSAR in forested areas, but good resolution in urban areas. Flight lines over the Bay Area pick up creep across Hayward and Calaveras faults, showing slightly more slip than what is picked up with the alignment arrays and creepmeters (up to 10 mm/yr at Gallegos Winery over a zone about 100 m wide; up to 200 m-wide zone at HCAM). The newly launched NISAR will provide great Bay Area data products (pity about the radar block in Mill Valley!).

Jessica Murray (USGS) gave a great overview of crustal deformation monitoring by GNSS, where there is good network coverage on most Bay Area faults, and farther north on the Maacama and Bartlett Springs faults, sometimes co-located with creepmeters and alignment arrays. The GNSS data is complimentary to InSAR for resolving slower creep and 3D velocity fields. There are trade-offs in modeling locking depth that are underconstrained.

Gareth Funning (UCR) is working on a California-wide velocity dataset based on InSAR data, including velocity measurements on 50 faults, and 3D strain. The creeping central San Andreas is shortening across the fault at ~1 cm/yr. The modeling approach incorporates locked spots with freely sliding dislocation at depth and iterate locking geometry to resolve the best match to surface data. This approach on the Hayward fault shows locking concentrated in Oakland, with deeper partial locking south to Fremont.

Katherine Guns (USGS) gave an insightful summary of the pros and cons of air- and space-based remote sensing to measure creeping faults. Validation from other datasets (alignment arrays, creepmeters, etc) is important due to the sensitivity of these methods to noise, as demonstrated at Mee Ranch, where C-band radar, UAVSAR, Lidar, alignment array and creepmeter are all in good agreement. The Maacama fault in densely vegetated norcal is the opposite, risk of convolving the topographic effects with the fault-related deformation. The satellite passes over the Bay Area are oriented for low sensitivity to N-S motion.

During the Thunder Talks session, Kim Blisniuk (SJSU) showed recent discoveries of additional fault strands outside the alignment array, cutting 11ka terrace sand, suggesting creep on the San Gregorio Fault. Ashley Walsh (SJSU) showed repeat terrestrial lidar scans on the new San Gregorio fault strands and associated rotational slumps that will document the deformation. Karen Castaneda (SJSU) compared mobile, terrestrial, and airborne lidar data sets in Hall’s Valley on the central Calaveras Fault to test which best revealed fault geometry. Hannah Martin (UNR) showed her detailed geomorphic indicator mapping of the Calaveras fault and the results of a shallow augering investigation as part of citing a paleoseismic trench for this section, where the last surface rupturing earthquake is unknown. Danielle Madugo (CGS) presented the Alquist-Priolo Zone (A-P) updates motivated by InSAR and field mapping, including offset curb measurements, in Concord which revealed an actively creeping fault strand outside of the previous A-P limits. Evan Agbayani (UCB) used campaign GPS to survey alignment arrays on the Hayward Fault, and will use the data to assess the utility of this method and model the slip patterns. Chris Madugo (PG&E) presented PG&E’s efforts to monitor fault creep as a hazard to buried infrastructure, increasing importance due to undergrounding for fire protection across the state. They are interested in locations of creeping zones, distribution of creep between fault strands, and creep variations with depth in the shallow subsurface. Cassie Hanagan (USGS) used repeat terrestrial lidar to show the Mee Ridge duplex is only partially active, on a part of the fault which may have been creeping for 2 my, accumulating as much as 6 km of slip with no earthquakes. Rezagene Milani (SJSU) demonstrated the use of multiple photogrammetry and lidar campaigns mapping the creeping section of the Bartlett Springs fault through

complicated geology. Jaeseok Lee (Brown) characterized fault complexity via surface trace orientation, focal mechanism heterogeneity, relocated earthquake catalogs and seismic anisotropy, and showed that complex faults creep more slowly than simple faults. Taka'aki Taira (UCB) presented an updated catalog of repeating earthquakes for the Hayward and Rodgers Creek faults which may show the linkage across the Napa-Sonoma marshes, and also showed that the Calaveras creep has been slowing since 2010 while the Hayward fault has been creeping faster since 2010. Cate Sloat (SJSU) is using MODSTRAIN by Fred Pollitz (USGS) to fit geodetic strain across the Bay Area in order to quantify the proportion of on- to off-fault deformation as additional faults are added to the model. Solène Antoine (Caltech) showed optical image correlation which resolves on- and off-fault deformation patterns that can be modeled to constrain inelastic deformation, requiring accurate mechanical properties for faults and wall rocks to close the shallow fault strain budget. Hiroki Sone (UW) performed creep tests on San Andreas fault gouge from the Lake Elizabeth geotech cores to confirm that the strain is well fit by viscoplastic models, which can describe localized and distributed strain. Junle Jiang (UO) showed the history of triggered and spontaneous creep transients on the Superstition Hills fault, showing that spontaneous creep events may be time-predictable, while triggered events may be slip predictable. Travis Alongi (USGS) has a novel approach for quantifying fault complexity, using the variation in fault trace orientation and dip variability from relocated seismicity, finding more variation at depth than suggested from surface traces alone. Brittany Botell (Univ.Memphis) showed the impact of using different fault models (e.g. SCEC CFM and the USGS Bay Area Geologic Block Model) on dynamic rupture propagation in the Calaveras-Hayward-Rodgers Creek fault system.

Continuing the longer talks, Mike Floyd (MIT) presented an overview of the SCEC Community Velocity Model, which hosts GNSS and InSAR time series and velocity products, posing the question of whether we can transform creepmeter and alignment array measurements into similar formats. The CGM explorer has a clickable station map, which makes it easy to see the data. The CGM is expanding for horizontal strain rate fields, but extrapolating across discontinuities like creeping faults presents a challenge.

Curtis Baden (USGS) elaborated on the challenges of migrating USGS creepmeter data into a real-time archive, including 15 active and 14 retired sites. The raw data is voltage change, and there is a lot of metadata with instrument changes, calibrations and resets. Earthscope is working on the metadata management scheme. Download is available at earthquake.usgs.gov/monitoring/deformation/data/

Ruth Harris (USGS) wrapped up the talks for the workshop with a broad overview of earthquake history in the East Bay across the partially creeping fault network of the Calaveras, Hayward and Rodgers Creek faults totalling 200 km of fault length. Her rupture models incorporate the geologic model for the East Bay hills, abstracted to blobs of different frictional properties for serpentinite, gabbro and Franciscan sediments. Adding cohesion to the faults prevents unrealistic ground motion predictions. Simulated Rodgers Creek earthquakes can propagate along the whole Hayward to the Calaveras, but earthquakes nucleating on the Hayward close to major creeping patches do not propagate as far.

We wrapped up the meeting by launching a manuscript summarizing the current state of, and state-of-the-art, creep monitoring and measuring methods, as well as avenues of successful research and future pathways. Through this manuscript, we aim to demonstrate the importance of ongoing commitment to maintenance and expansion of fault creep monitoring. We document the direct and immediate utility of fault creep studies to address direct displacement hazards and for identifying fault zones for regulatory applications. We elucidate the potential insights arising from new approaches, analytical advances, and integration of laboratory measurements of deformation behavior into mechanical and dynamic models of earthquake cycles. In the future, creep datasets may be incorporated for training machine learning models which will more fully explore the effects of creep on seismic cycles. We will conclude with broad recommendations that will serve as a touchstone for future proposals, including a SCEC TAG proposal to develop a detailed community workplan.

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