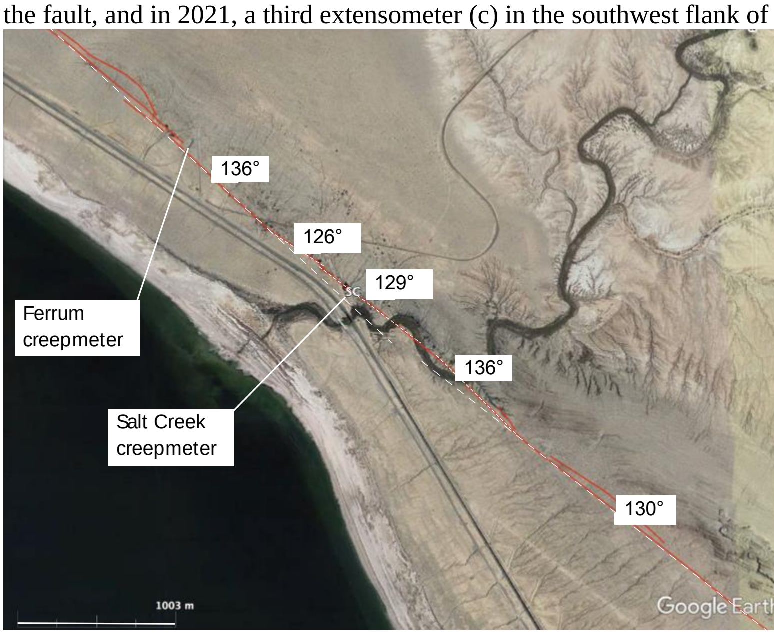
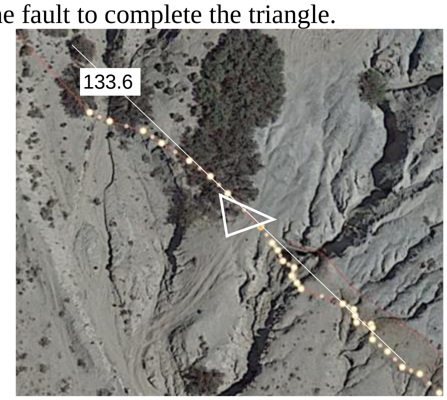
Transpression at Salt Creek - solving for strike, slip and dilation

28 Oct 2023 Friends of the Pleistocene Field trip. Notes from Roger Bilham, University of Colorado.

Typically, extensometers are buried obliquely at 30° to the strike of the fault requiring a correction factor of 1.15 (1/cos30) to convert observed displacement to dextral slip. Inexplicably, c.1970 Caltech installed a wire creepmeter (a) here at 72° to the fault (*McGill et al, 1989*), needing a correction factor of 3.2. Abandoned c.1992, in 2010 we refurbished it, but in 2016, finding its data noisy we installed a conventional carbon rod extensometer (b) at 30° to the fault, and in 2021, a third extensometer (c) in the southwest flank of the fault to complete the triangle.





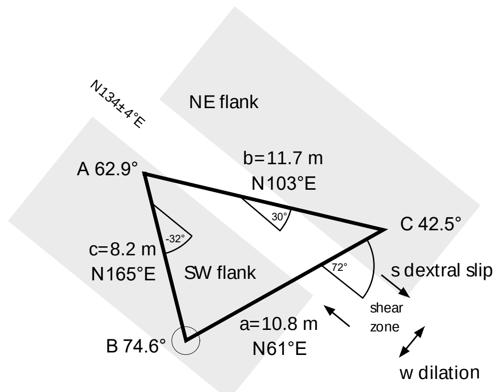
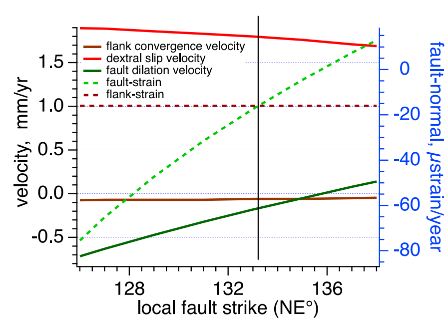


Figure 1 The mean strike of southern San Andreas Fault at Salt Creek is 132°, but mapped strands near the creepmeter strike 126°-136° (S. Janecke). The creep rate here is ≈2 mm/yr. The Caltech creepmeter installed c.1970 at 72° the fault recorded 3 mm of triggered slip from the Superstition Hills earthquake (*McGill et al., 1989*). During slip induced by the Chiapas, Ridgecrest the fault experienced transpression. A flank extensometer was installed at -32° to investigate this curious behavior.

It was initially anticipated that the calculate dextral creep rate measured by the two extensometers would be identical. Unexpectedly the creep rates for the interval 2016-2021 (a=1.8 mm/yr and b=0.83 mm) differed by x2.16. We concluded that the fault was both slipping (s) and dilating (w) during slip but that we could solve for each knowing the strike of the fault. Assuming fault-crossing obliquities of ø° and ø °+42° we have:

fault dilation, w=(bcos(ø+42)-acosø)/ (sin(ø+42)cosø -sinqcos(ø+42)) mm

dextral slip, s = (b-wsinø)/cosø mm



However, uncertainty in the appropriate strike of the fault results in a third unknown (*Bryant et al., 2002; Clarke, 1968*). Precise mapping by *Janecke et al., (2018)* shows the fault trace curves concavely to the SW, with a strike at its central section spanned by the creepmeter close to N134°E. We examined a suite of solutions for different strike. The result was inconclusive. In Figure 2 (right) the vertical line at N133.2°E indicates the strike at which fault-normal strain contraction (from c) within and adjoining the fault are identical at 16 μstrain/year. With this resolved strike we used the above equations to calculate slip and dilation 2017-2022 (Figure 3).

We discovered, unexpectedly, that between 2017 and 2021 the fault *contracted* in width by ≈1 mm. The vector plot of dilation (opening) vs. dextral slip, shows that identical contraction occurs during the three slip events and during the secular creep between creep events, with a closure vector of 6°, similar to transpression on Durmid Hill (*Bilham and Williams, 1986*). This trend changed inexplicably in June 22 when the fault widened by 1 mm.

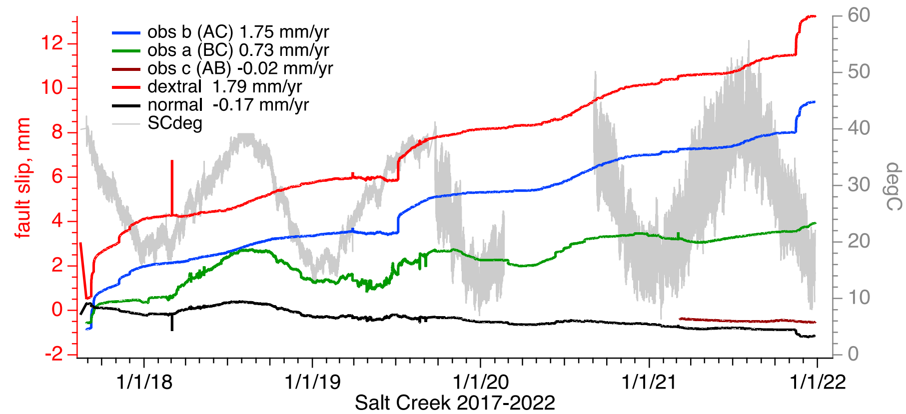


Figure 3 Observed data 2017-2022 on the initial (a) extensometer (green), (b) extensometer (blue) and flank extensometer (c=brown). The red and black traces are the calculated dextral and fault normal displacements. *The fault in this interval is contracting with 6° of transpression*.

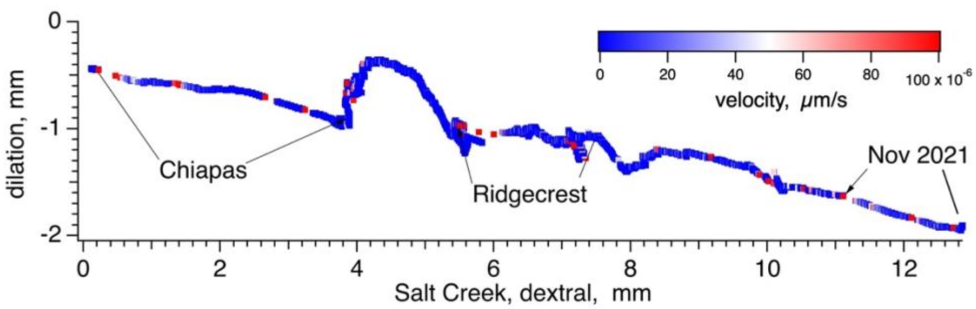


Figure 4. Dilation vs. dextral slip calculated for N133E fault strike indicate 6° transpression of the fault. Creep events shown account for ≈50% of this transpression (Fig.6) . The trace is colored according to dextral slip velocity

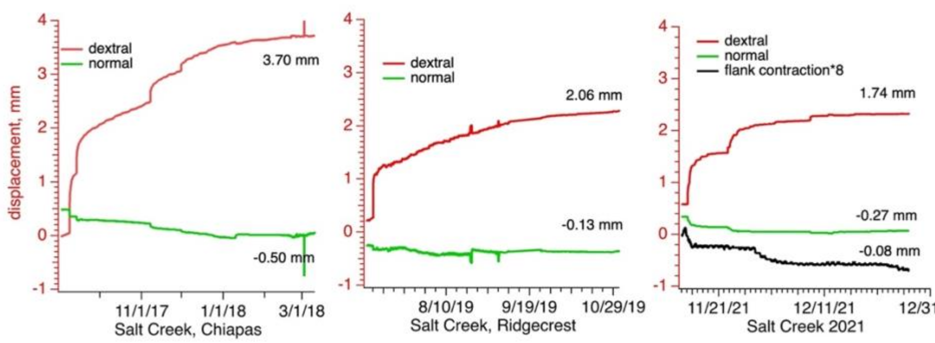


Figure 6 Calculated dextral slip (red) and fault zone contraction (green) at the time of two triggered slip events and the Nov/Dec 2021 spontaneous creep event. Transpression ceased in June 2022!

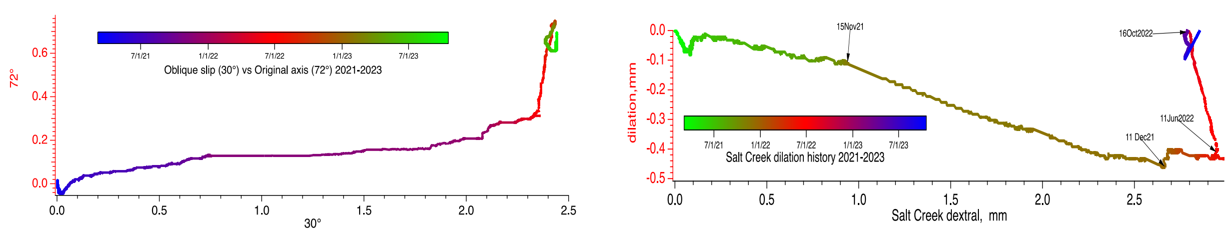
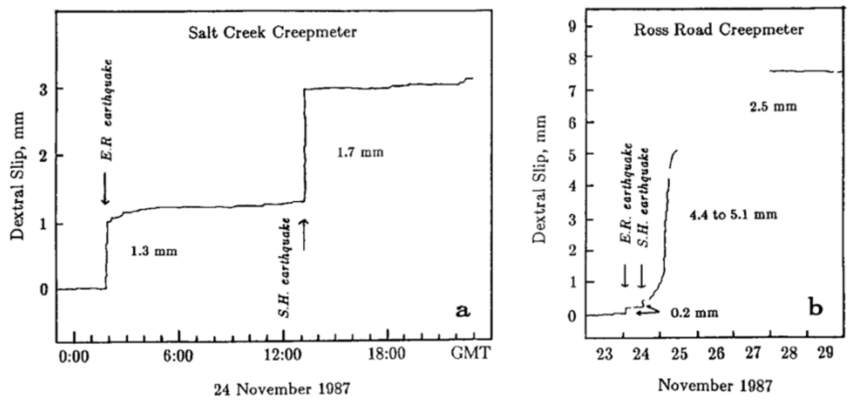


Figure 7(left) Raw vector 72° vs 30°. (right) Dextral/ dilation vector for the period 2020-Oct 2023.

In June 2022 the calculated relationship between dextral slip and dilation changed, presumably due to a different fault strand becoming active. Inconstancy in the active strand hosting slip implies that the correction factor for early data from the Caltech extensometer (2004-2020) must be considered unreliable.

Implications

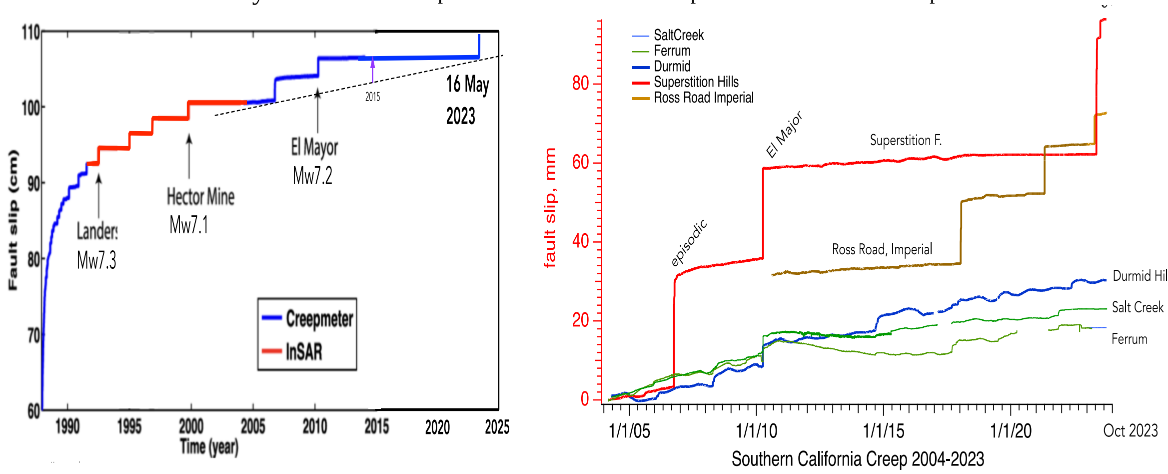
The original calibration factor for the Caltech creepmeter (a) was x3.23. The above calculations reveal that its assumed obliquity provides an erroneous measure of dextral slip because the ratio of convergence to dextral slip varies with time and was not known prior to 2016 The amplitude of slip triggered by the Superstition Hills earthquake is thus questionable.



The observed convergence rate 0.17 mm/yr prior to 2021 is consistent with reported transpression of Durmid Hill at 7.1° (*Bilham and Williams, 1985*), but it is surprising that it can be observed at the scale of a single fault segment. In particular the strain contraction rate over the ≈10 m width of the fault zone spanned by the creepmeters (Figure 2) was large (-16 µstrain/year) and would approach strains typical of failure in rock (10^{-4}) within 6 years. Between June and Oct 2022, however, contraction ceased, and dilation of the fault zone annulled the contraction that had occurred in the previous two years. In the past year October 2022-2023 net dilation *and* dextral slip at Salt Creek has been zero, indicating a creep slip deficit of ≈2.4 mm. This deficit will be either released spontaneously or will be triggered by surface waves from a nearby earthquake.

Creep Southern California 2004-2023

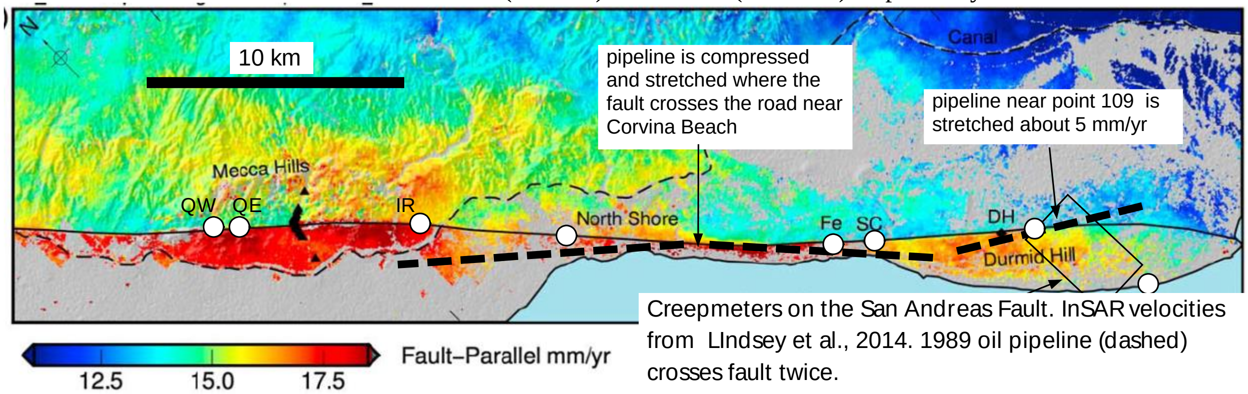
data in the last month may be viewed at https://dashboard.hobolink.com/public/4563/SoCal%20Creep-04-04-2020%2012:49:12



(Left) Thirty-seven years of afterslip on the Superstition Hills fault following the 1989 Mw6.8 earthquake. No creepmeters operated in California 1992-2004. (Right) 2004-23 creep on the Superstition Hills (≈4.2 mm/yr), Imperial (≈3 mm/yr) & San Andreas faults (2.4 mm/yr). It is probable that a large triggered event occurred on the Imperial fault a few days before the start of recording in 2010. [NEHRP funding 1989-1992 & 2004-2011].

No surface slip accompanied the Superstition Mw6.8 mainshock. All surface slip occurred in the form of afterslip. Triggered slip on many of the southern California's faults occurs in response to earthquakes on other faults in the Coachella/Imperial valley and elsewhere. It was first noticed by Max Wyss during the 1968 Mw6.6 Borrego Mtn earthquake post seismic investigation. Triggered slip occurs during the passage of surface waves and typically releases an accumulated slip deficit (*Bodin et al. 1994, Bilham and Castillo, 2020*). Notably, 3 months of triggered slip followed the Mw8.1 Chiapas Mexico earthquake (*Tymofyeyeva et al, 2019*).

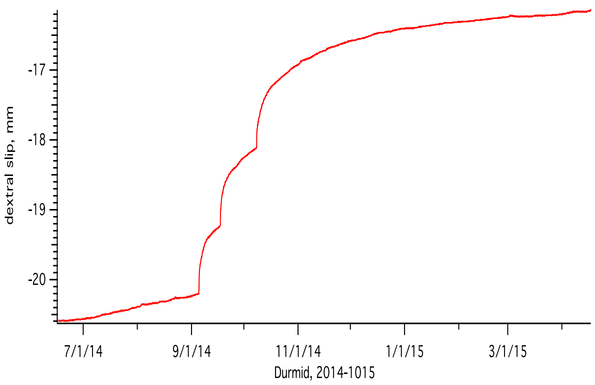
Large (1 cm) creep events are many years apart on the Superstition and Imperial faults following earthquakes in 1989 and 1979, but occur at 2-3 year intervals on the San Andreas fault. These 1-3 mm amplitude events propagate between creepmeters at rates of ≈2 km/hr. Following the Ridgecrest Mw7 event creep events propagated both NW and SE in the northern Mecca Hills at 55 cm/s (2 km/hr) and 5 cm/s (200 m/hr) respectively.



Creepmeters on the San Andreas Fault. InSAR velocities from LIndsey et al., 2014. 1989 oil pipeline (dashed) crosses fault twice.

Ferrum Apparent slip reversal 2010-2014 recorded by the Ferrum creepmeter was caused by slip on an unmonitored western strand of the fault in the Ferrum cutting. It was destroyed in 2022 by railtrack removal operations and its planned re-installation will measure both strands.

Caltech's refurbished **North Shore** creepmeter records negligible creep, and its future is questionable due to developments on the land. It is located at a releasing offset between the Durmid Hills and Mecca Hills (*Bilham and Williams,1985; Lindsey et al., 2014*) and recorded minor slip during the Ridgecrest earthquake



A 20-inch diameter petroleum pipeline crosses the San Andreas fault in tension at the **Durmid Hill** creepmeter. We measure a slip rate here of ≈2.4 mm/yr, about half the InSAR velocity (*Lindsey et al., 2014*) which samples a wider footprint. We calculate the pipeline has been stretched about 13 cm since its installation in 1989. Distributed over 1 km this represents ≈130 µstrain, about 10% of the elastic limit of steel. Creep here is partly steady but occasionally occurs as multiple slip events with up to 4 mm of slip (Figure left). In the next earthquake it will rupture here in tension, and possibly at the Salton Sea State Park campsite in compression.

Bilham, R. and P. Williams, Sawtooth segmentation and deformation processes on the San Andreas Fault, California, Geophys. Res. Lett., 12, 557-560, 1985.

Bilham, R., and B. Castillo, (2020) The July 2019 Ridgecrest, California, earthquake sequence recorded by creepmeters: negligible epicentral afterslip and prolonged triggered slip at teleseismic distances, *Seismological Research Letters*, 91 (2A): 707–720 doi: 10.1785/0220190293.

Bodin. P., R. Bilham, J. Behr, J. Gomberg, and K Hudnut, Slip Triggered on Southern California Faults by the Landers, Earthquake Sequence. *Bull. Seism. Soc. Amer.* 84(3), 806-816, 1994.

Bryant, W.A., and Lundberg, M., compilers, 2002, Fault number 1j, San Andreas fault zone, Coachella section, in Quaternary fault and fold database of the United States: U.S. Geological Survey website, https://earthquakes.usgs.gov/hazards/qfaults,

Jänecke, Susanne U. , Daniel K. Markowski, James P. Evans, Patricia Persaud, Miles Kenney, 2018, Durmid ladder structure and its implications for the nucleation sites of the next M >7.5 earthquake on the San Andreas fault or Brawley seismic zone in southern California, Lithosphere doi: https://doi.org/10.1130/L629.1

Lindsey, E. O., Y. Fialko, Y. Bock, D.T. Sandwell and R. Bilham, Localized and distributed creep along the southern San Andreas Fault, *J. Geophys Res.*, 119(10), 7909-7922, 2014, DOI: 10.1002/2014JB011275

Louie, J. N., Clarence R. Allen, David C. Johnson, Paul C. Haase, Stephen N. Cohn; Fault slip in southern California. *Bulletin of the Seismological Society of America* 1985;; 75 (3): 811–833. doi: https://doi.org/10.1785/BSSA0750030811

McGill, S.F.,C.R Allen, K W.Hudnut, 1989 Slip on the Superstition Hills fault and on nearby faults associated with the 24 November 1987 Elmore ranch and Superstition Hills earthquakes, Southern California Bull. Seism. Soc. America, 79(2), pp. 362-375

Tymofyeyeva, E. Yuri Fialko, Junle Jiang, Xiaohua Xu, David Sandwell, Roger Bilham, Thomas K. Rockwell, Chelsea Blanton, Faith Burkett, Allen Gontz, and Shahram Moapoor. **(2019)** Slow slip event on the southern San Andreas fault triggered by the 2017 Mw8.2 Chiapas (Mexico) earthquake *J. Geophys. Res*. 124, 9956– 9975. DOI: 10.1029/2018JB016765