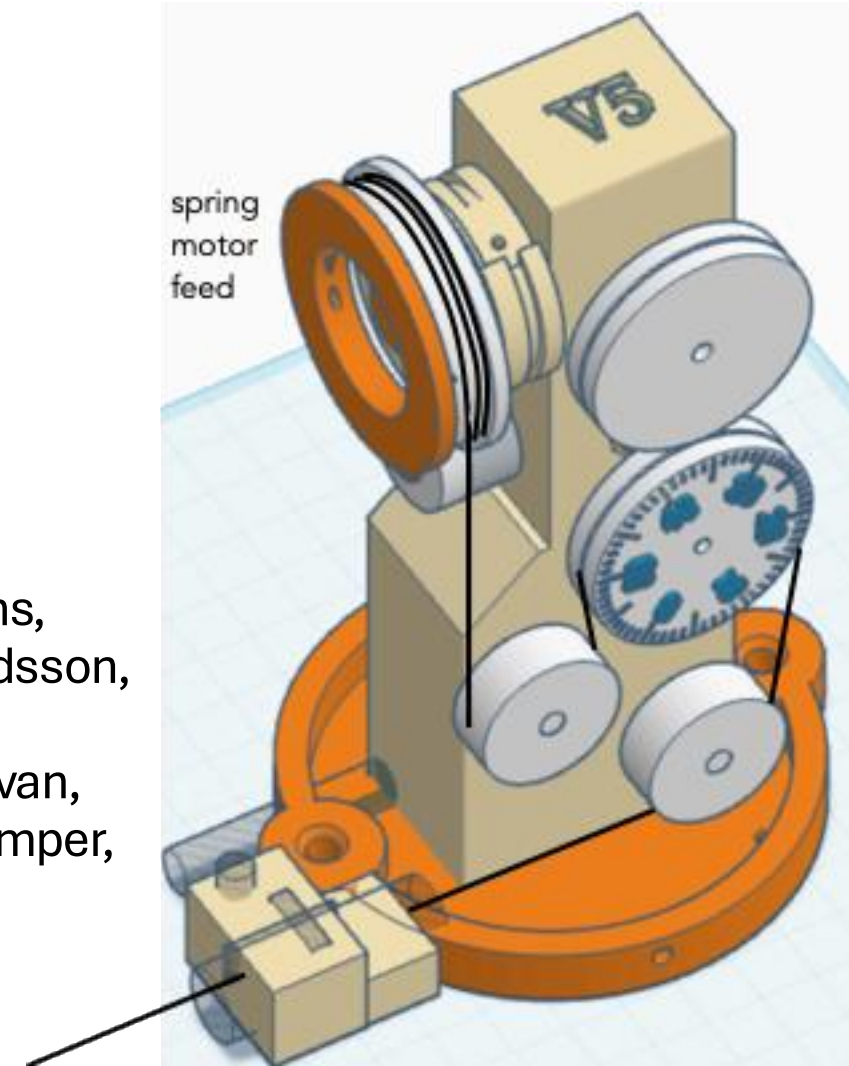


overview of continuous measurements of fault creep

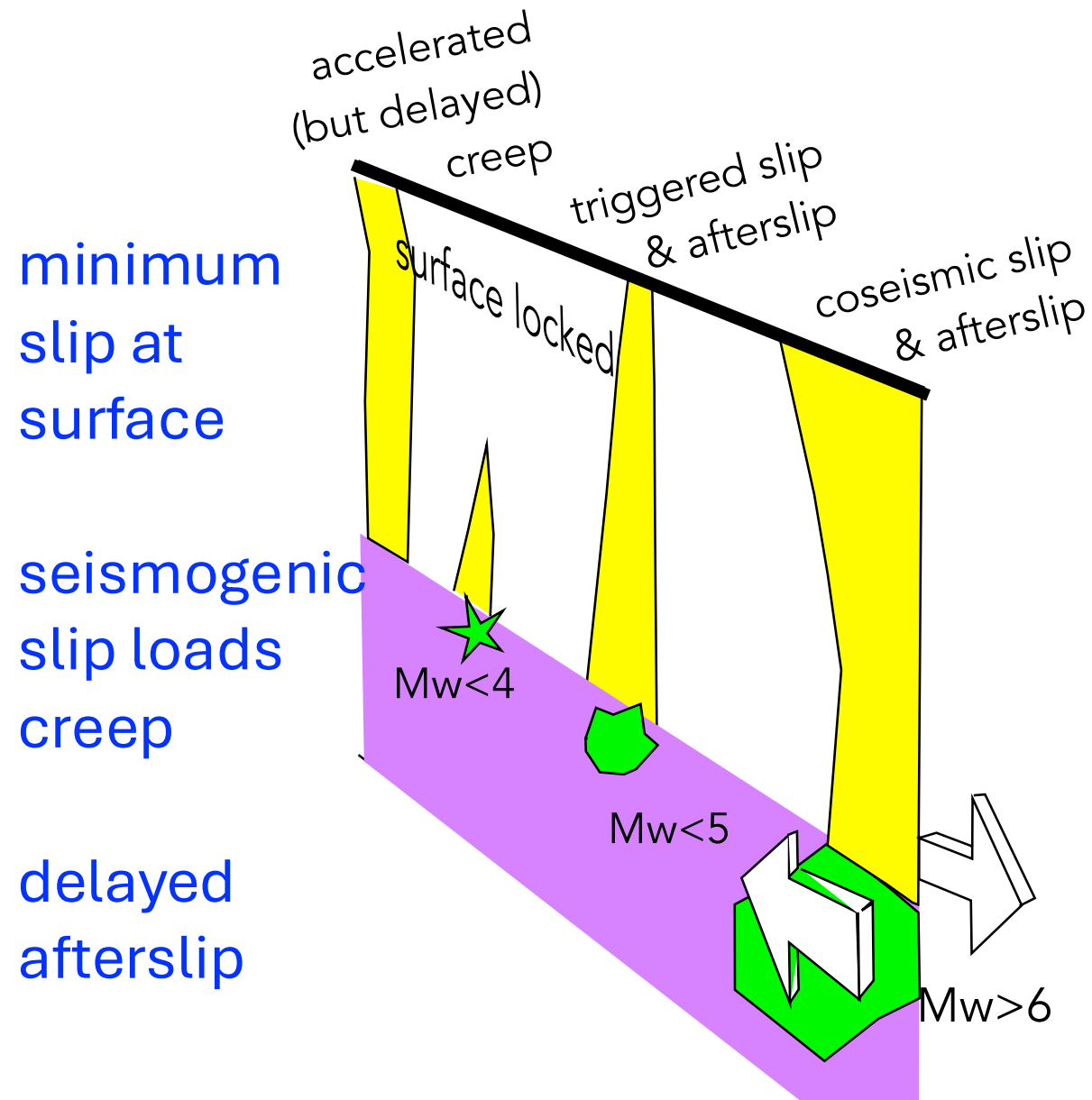
(and 3D-printed .stl creepmeter projects for students in the Bay Area)

Roger Bilham,
University of Colorado,
Boulder CO 80309

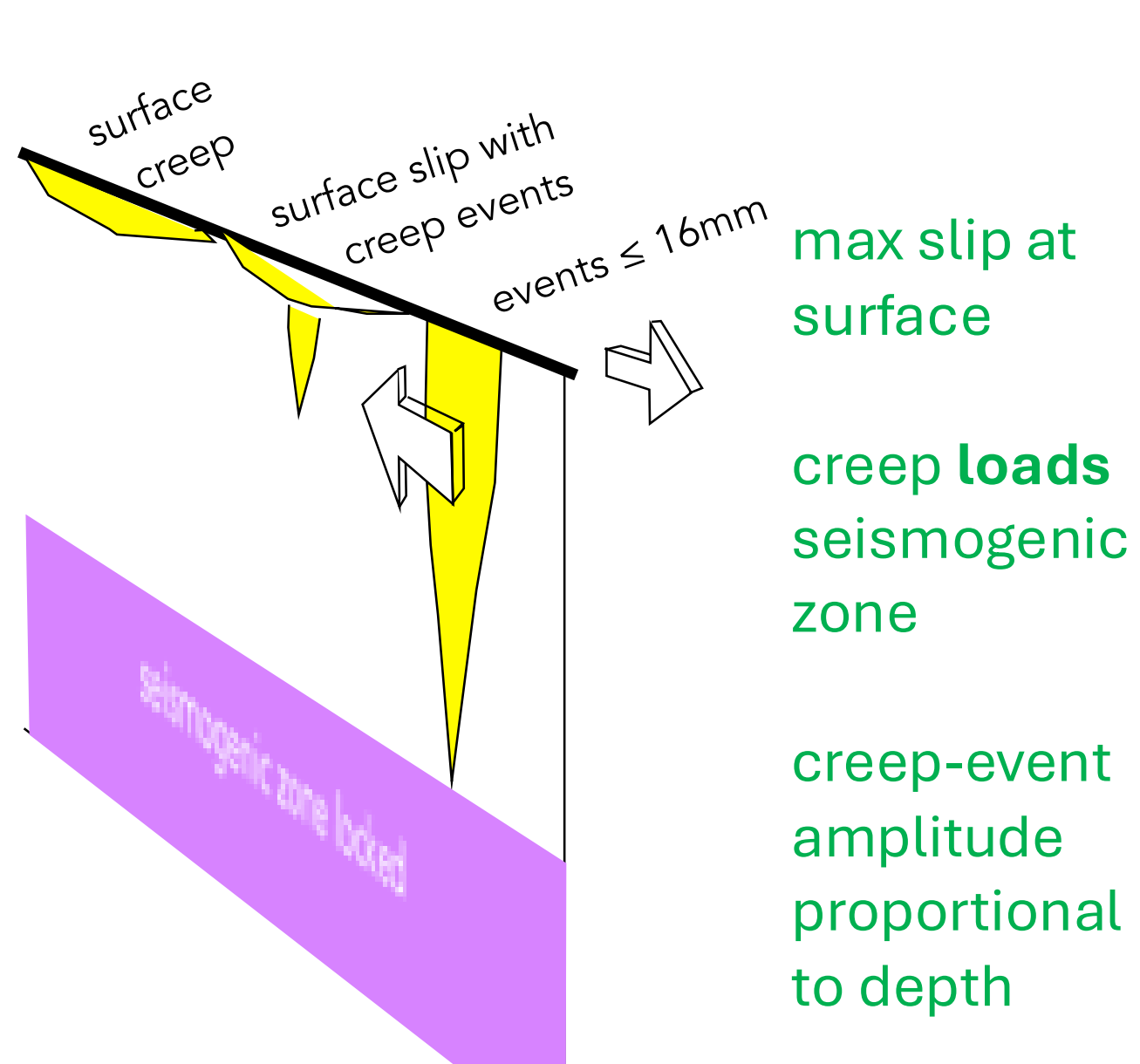
based on divagations and pavaues with Todd Ericksen, John Langbein, Josie Nevitt, Heather Crume, Kathryn Materna, Roland Bürgmann, Dan Gittins, Ricky Garza-Giron, Paul Bodin, Joan Gomberg, Jeff Behr, Freysteinn Sigmundsson, Bob Nason, Eveyin Roelhoffs, Wayne Thatcher, Ben Brooks, Tom Rockwell, Bob Burford, Chi-Yu King, Malcolm Johnson, Niel Goult, Geof King, John Beavan, Keith Evans, Duncan Agnew, Bob Simpson, Kate Breckenridge, Jim Lienkaemper, Scott Whitehead, James Nelson, Ken Smith and many others.



end-member #1 **sleeping** fault:
SLIP at depth drives shallow slip



end-member #2 **creeping** fault: plate
boundary SHEAR drives surface creep

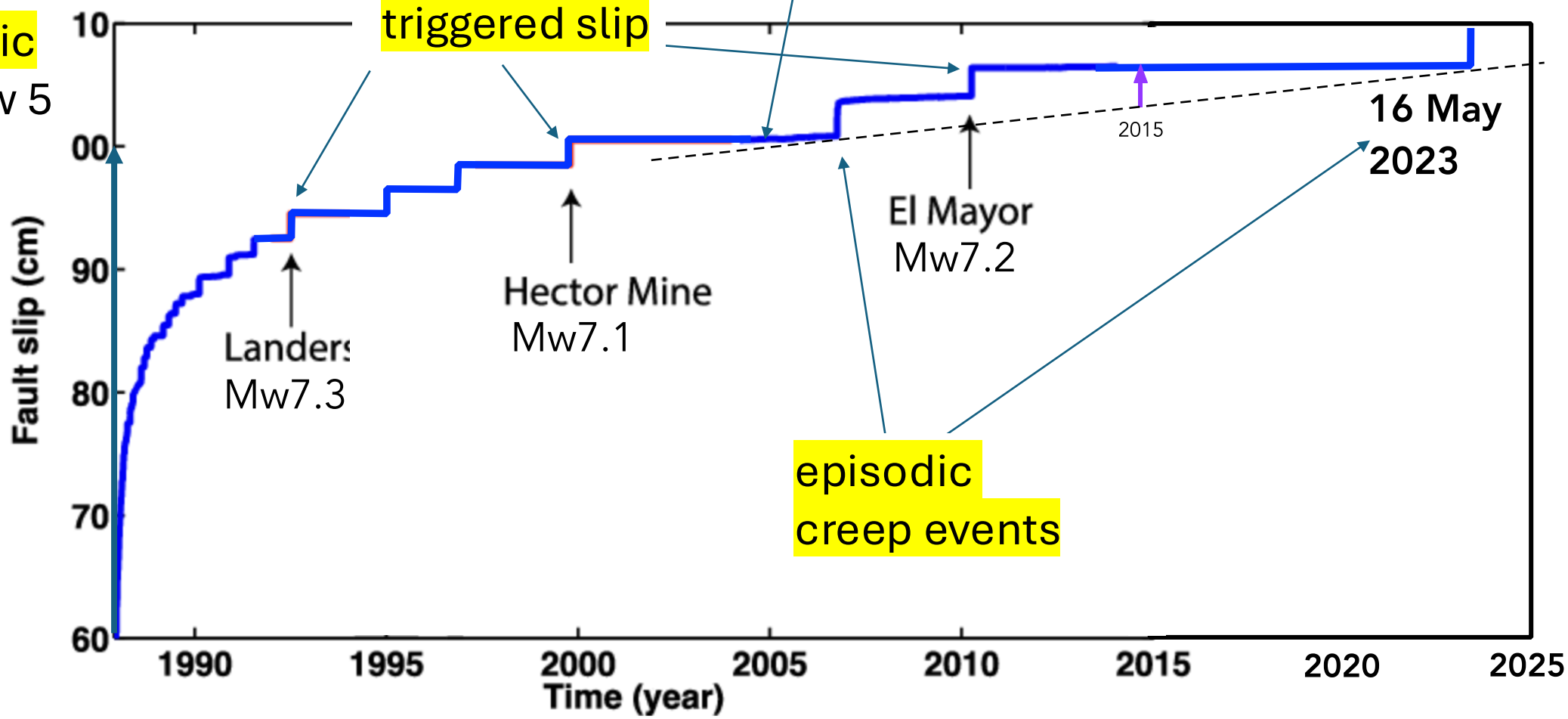


After-slip (surface slip catches up with coseismic slip at depth)

instantaneous creep rate
0.5 mm/yr

(decadal **creep rate** 7 mm/yr)

1m
coseismic slip below 5 km

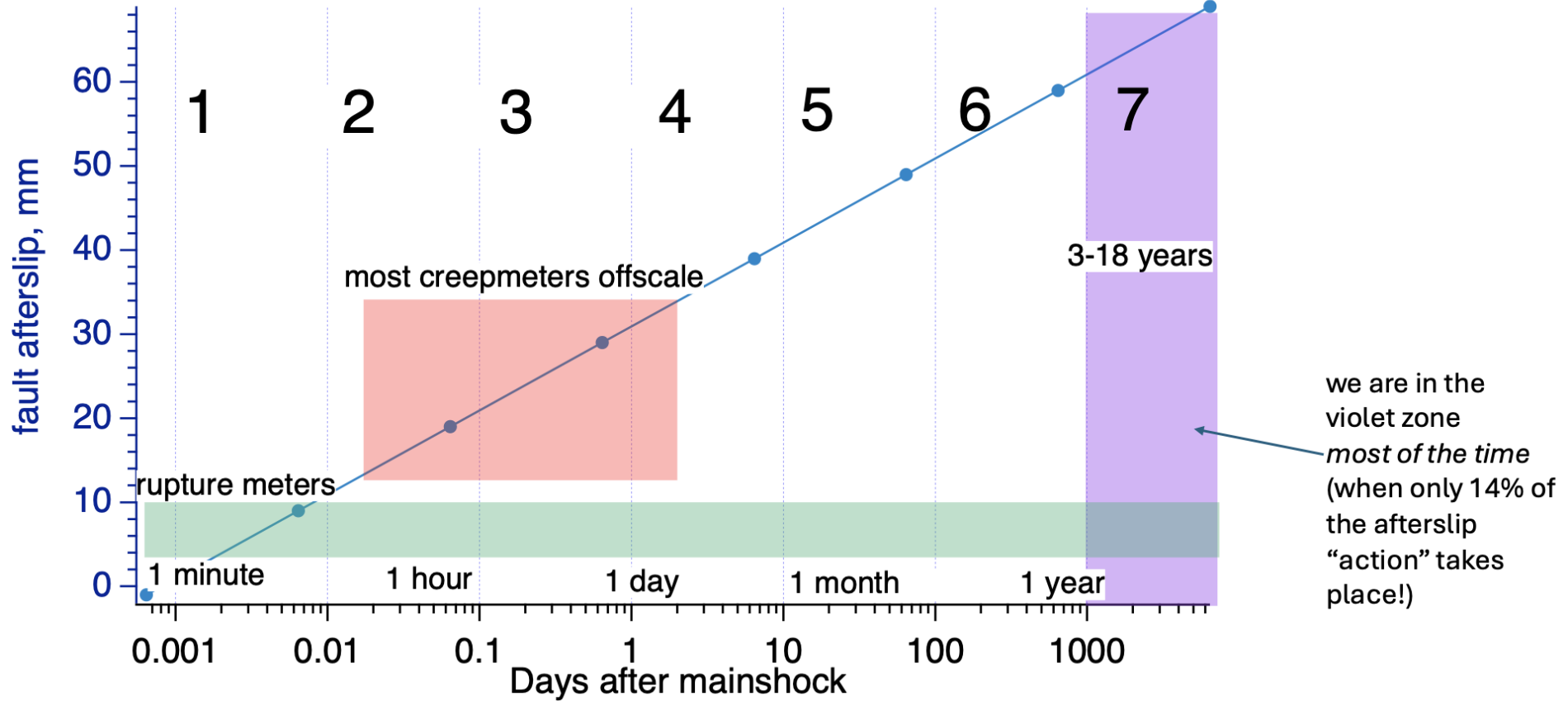


Superstition Hills Fault

37 years of surface creep following the Mw=6.8 Superstition Hills Fault earthquake

afterslip vs log time

“as much slip occurs in the the first hour as in the next ten” etc. example 38 years of Parkfield creep
6 “octaves” of slip between 1 minute and 1 year



This figure depicts afterslip in seven intervals of time, from tens of seconds to 18 years after the mainshock. Exactly 10 cm of slip occurs in each interval.
Half of the afterslip is over within a month of the mainshock!
Early creepmeters lost most of the afterslip signal
Rupture meters can record all 7 time intervals without adjustment.

mathematical models for afterslip

Modified Omori $\frac{A}{1-p} \left[\left(1 + \frac{(t - T_{eq})}{\tau}\right)^{1-p} - 1 \right]$

Double Omori $\left(1 + \frac{(t - T_{eq})}{\tau_1}\right)^{1-p} - 1 - \left(\frac{\tau_2}{\tau_1}\right)^{1-p} \left(\left(1 + \frac{(t - T_{eq})}{\tau_2}\right)^{1-p} - 1\right)$

AFTER $A \left[\frac{(t - T_{eq})/\tau}{(t - T_{eq})/\tau + 1} \right]^p$

Boatwright et al 1989

Stretched Exponential $A(1 - e^{-(t - T_{eq})^p/\tau})$

Migan (2015)

Double exponential $y_0 + A_1 \exp\left\{\frac{-(x - x_0)}{\tau_1}\right\} + A_2 \exp\left\{\frac{-(x - x_0)}{\tau_2}\right\}$
(lazy empirical fit)

Physics based $U_p = \frac{A-B}{k} \ln\left[\left(\frac{kV_c^S}{A-B}\right)t + 1\right] + V_0 t$

Marone et al. 1991

mathematical models for afterslip

Modified Omori $\frac{A}{1-p} \left[(1 + (t - T_{eq})/\tau)^{1-p} - 1 \right]$

Double Omori $(1 + (t - T_{eq})/\tau_1)^{1-p} \left(\frac{t - T_{eq}}{\tau_2} \right)^{1-p} \left(1 + (t - T_{eq})/\tau_2 \right)^{1-p}$

AFTER

Boatwright et al 1989

Stretched Exponential

Mignan (2015)

Double exponential

(roger's empirical method)

Physics based

Marone et al. 1991

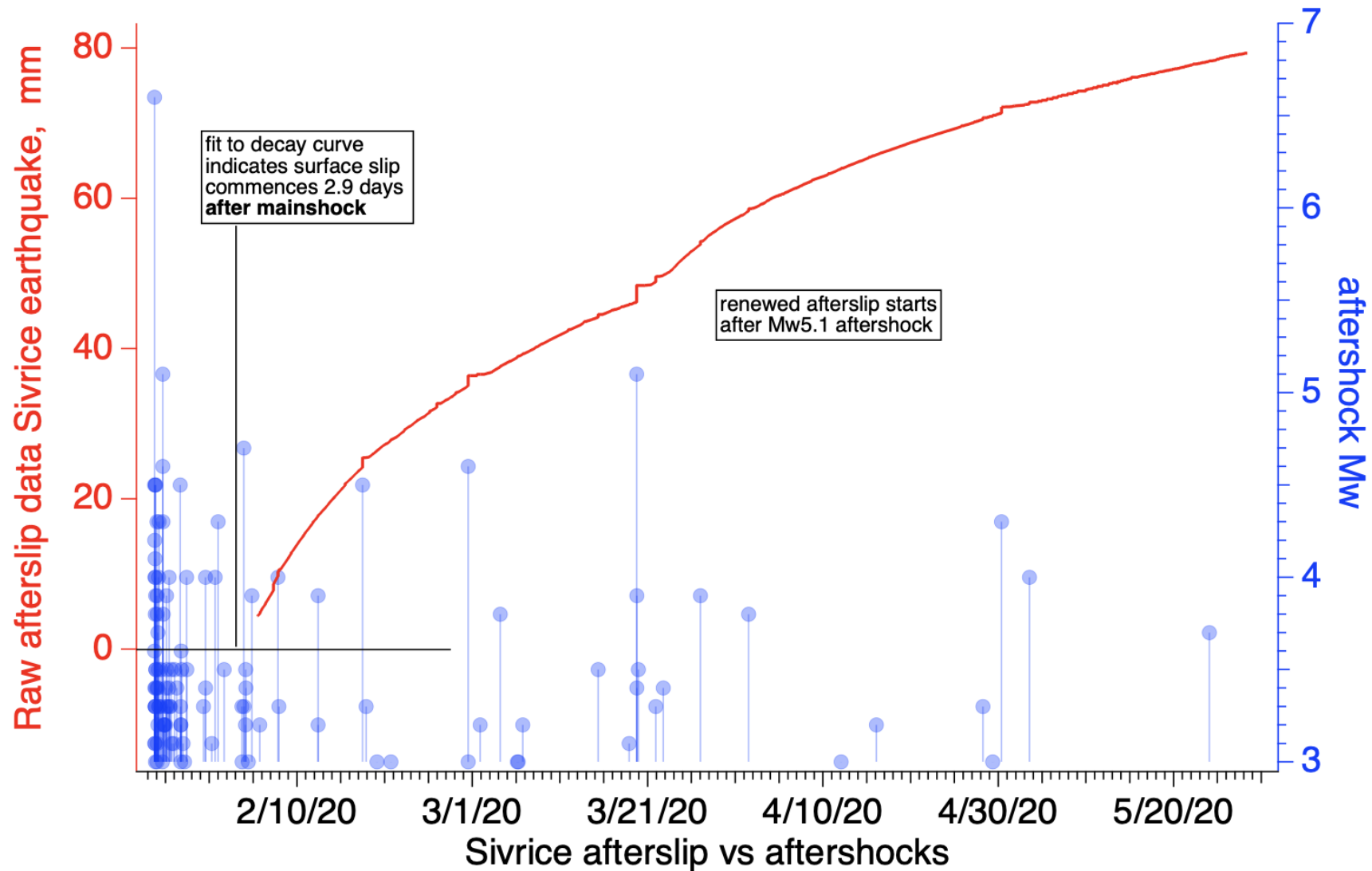
$$A \left(1 - e^{-(t - T_{eq})^p / \tau} \right)$$

$$y_0 + A_1 \exp \left\{ \frac{-(x - x_0)}{\tau_1} \right\} + A_2 \exp \left\{ \frac{-(x - x_0)}{\tau_2} \right\}$$

$$U_p = \frac{A - B}{k} \ln \left[\left(\frac{k V \dot{C} S}{A - B} \right) t + 1 \right] + V_0 t.$$

none applicable to real data because each aftershock adds a new decay curve!
[same criticism applies to aftershock models!]

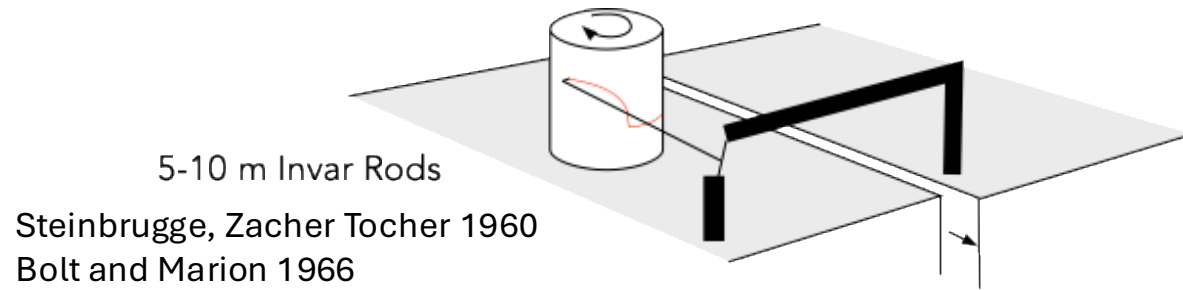
Sivrice 2020 example: afterslip interrupted by afterslip!



Large aftershocks result in locally renewed afterslip. Hence attempts to model afterslip with single time dependent decay model are doomed. Afterslip is the sum of multiple decay curves.

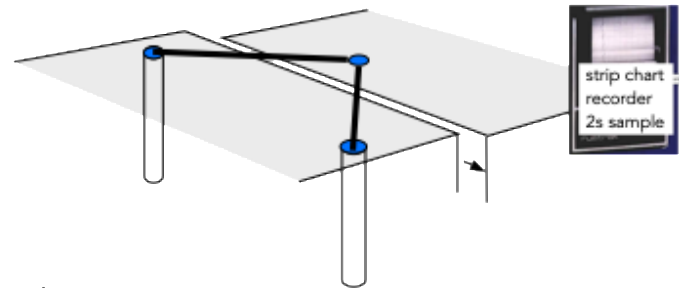
evolution of creepmeters since 1960

1965
Chart recorder



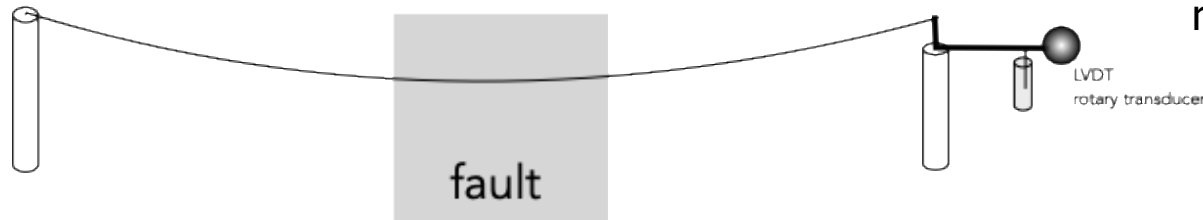
1968-1970
Chart recorders

Bob Nason 5-10 m dual-axis Invar Rods
resistive sensor



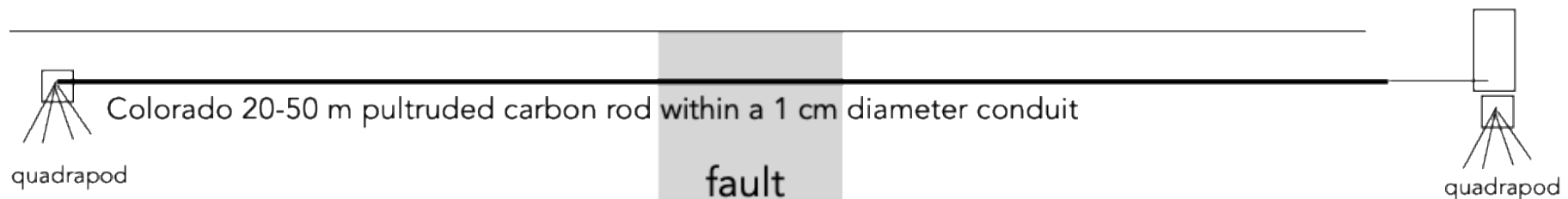
1968-1995 10 minute GOES telemetry

Bob Burford 10-30 m catenary
Goultly and Gilman 10 m catenary within 20 cm diameter pipe



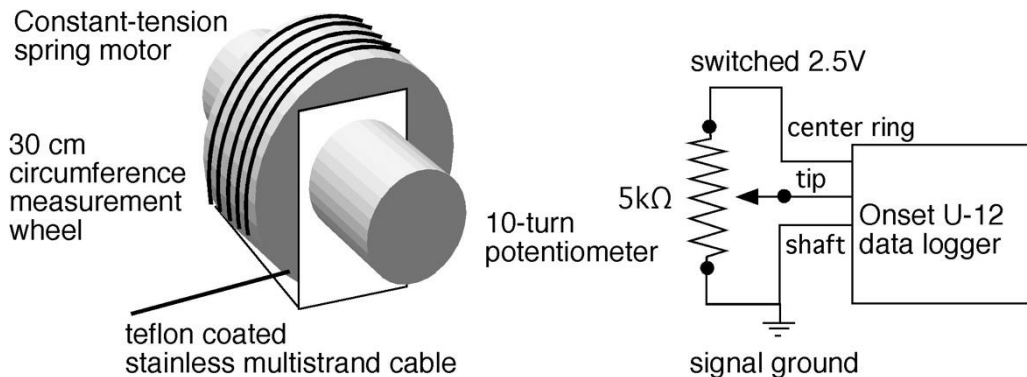
2020 Cell telemetry 1 minute samples
range increased 10 cm to 150 cm

submersible Rotary Hall sensor
resolution 2.6 μm , Range 1.5 m

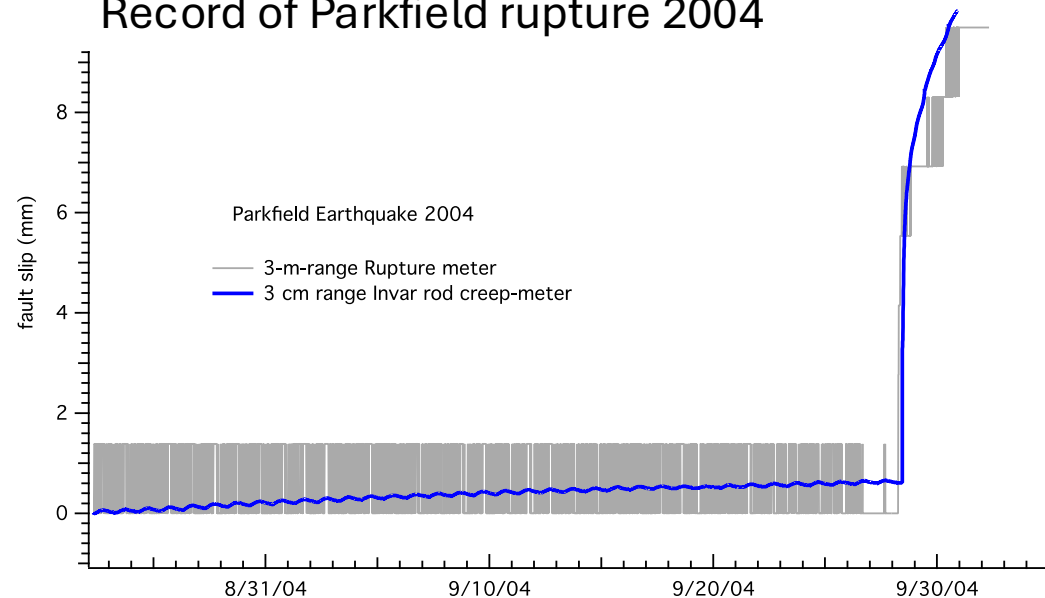


afterslip requires >1 m measurement range!

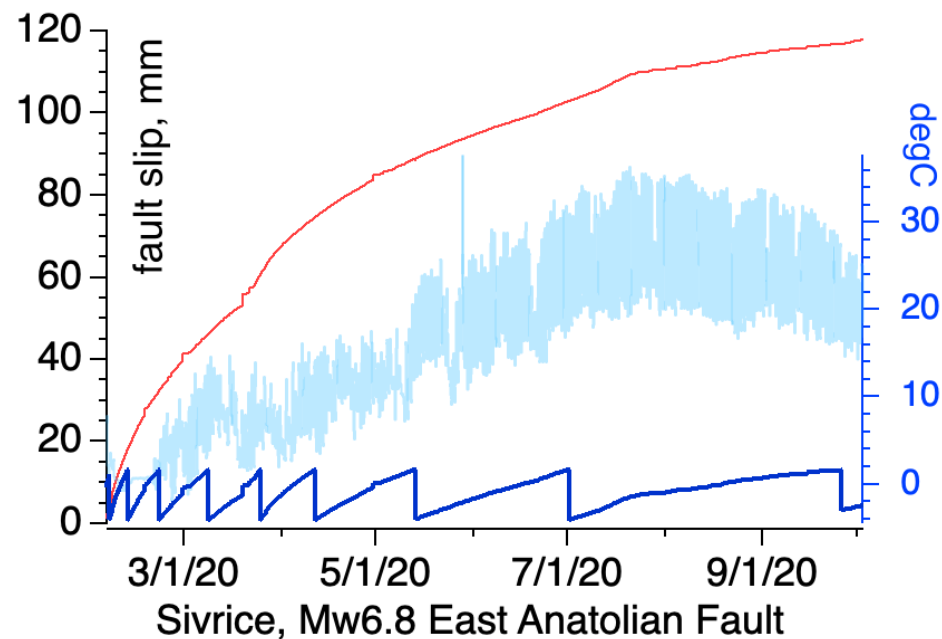
Rupture meter 3.3 m range 1.5 mm resolution



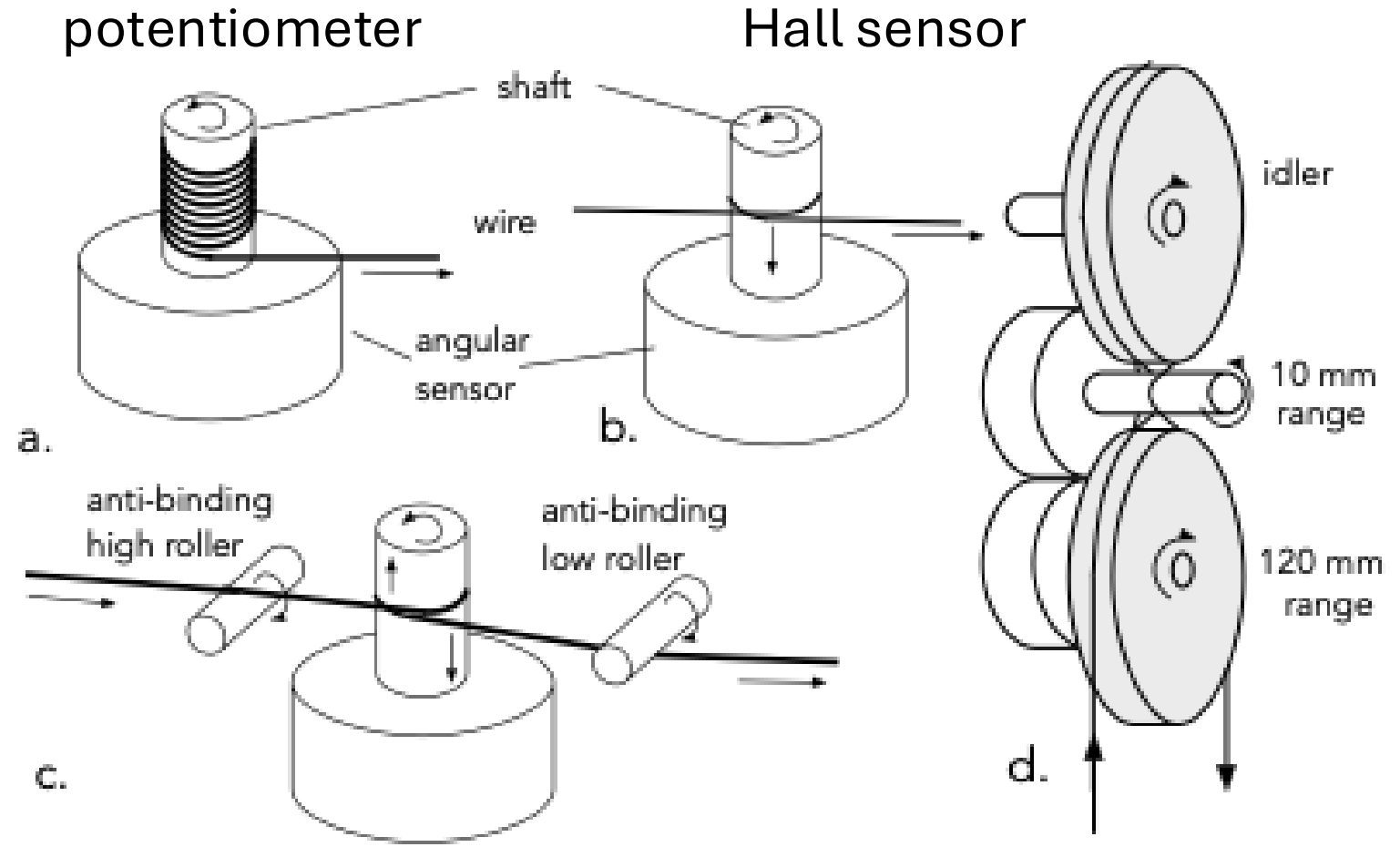
Record of Parkfield rupture 2004



Rupture meter 1.5 m range 2.6 μ m resolution

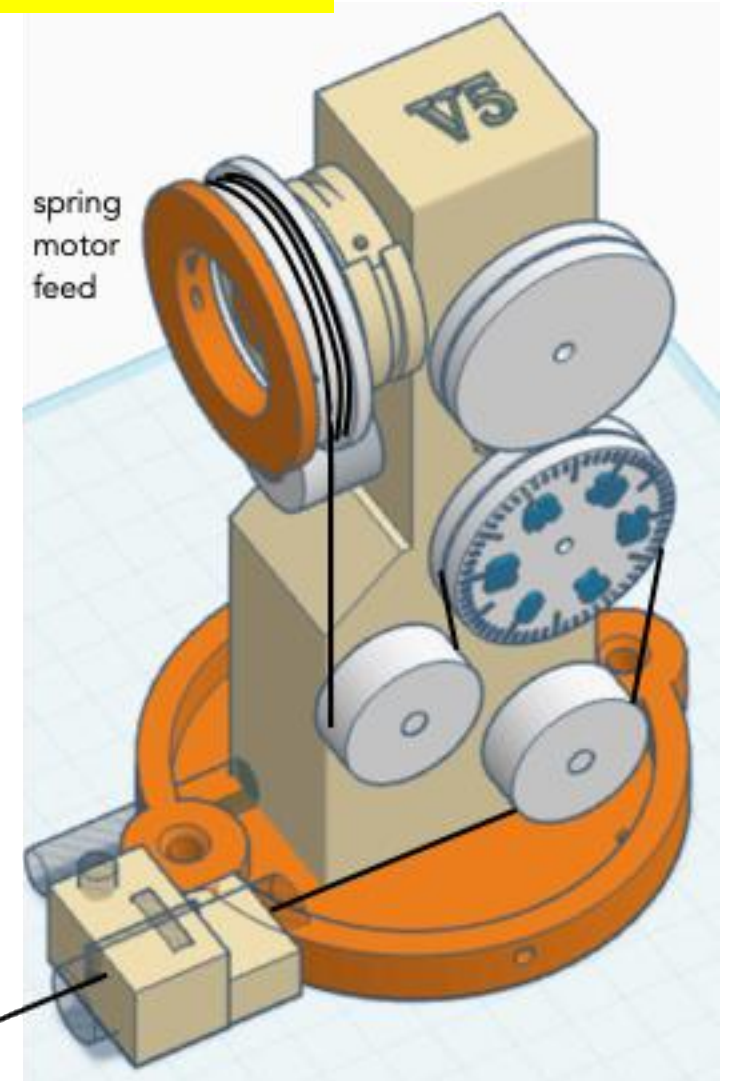


wire tensioning geometry evolution in past two decades



hysteresis
horizontal dry

no-hysteresis
vertical submersible

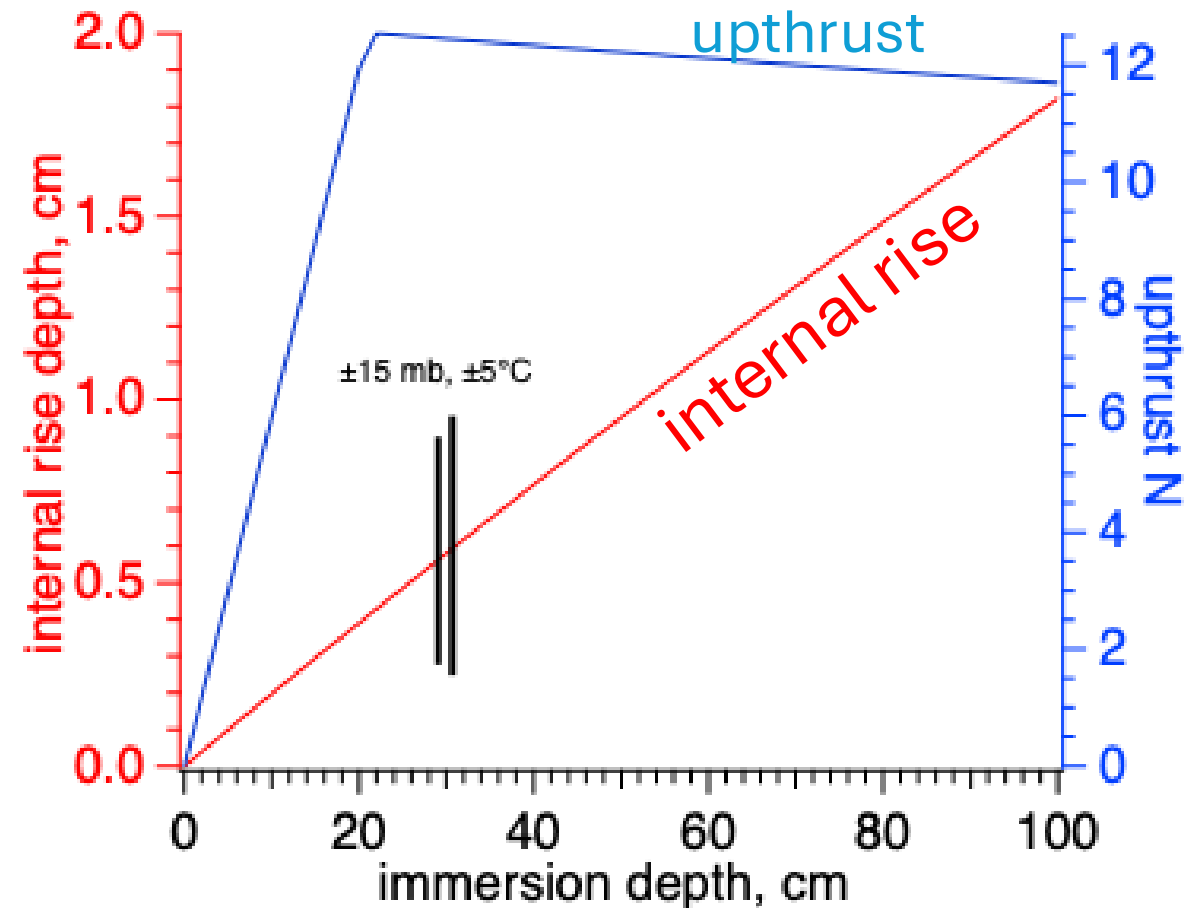
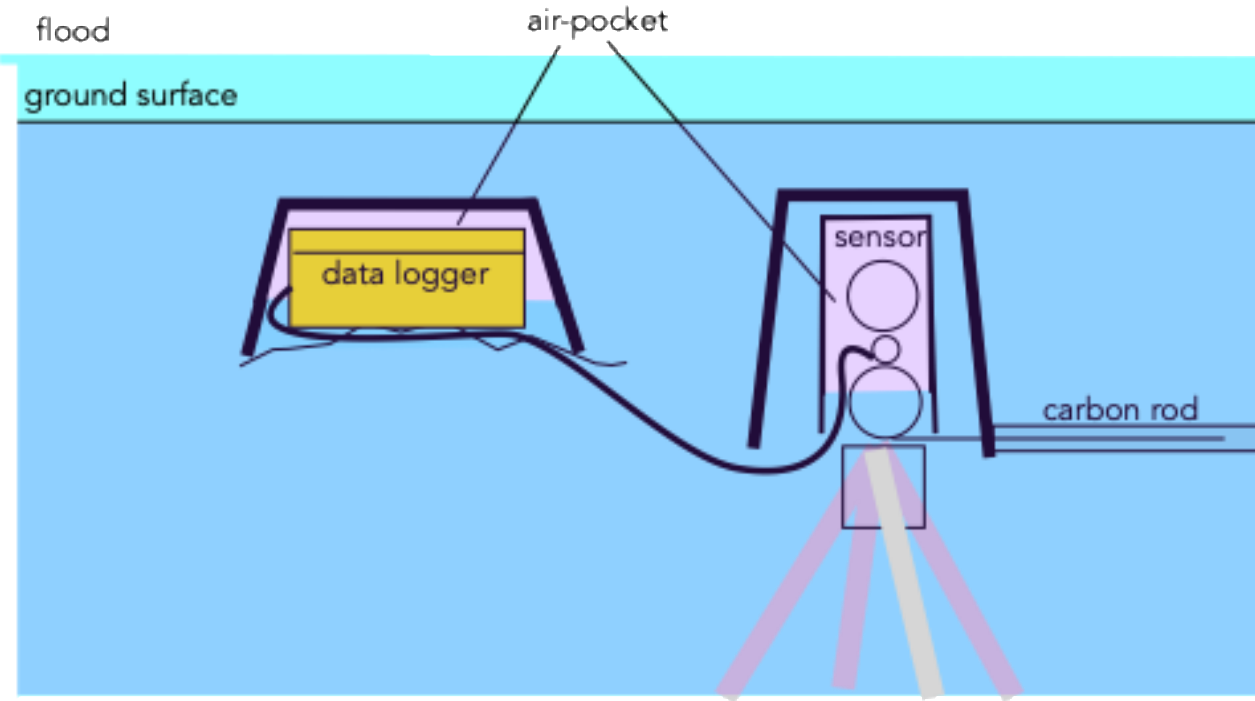


3d printed .stl file takes 6 hours
bearings & springs from Amazon
Hall sensor from Mexico

submersible operation during atmospheric rivers

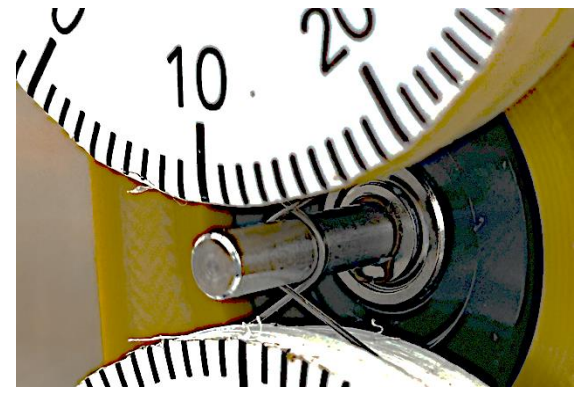
internal water level rise \approx flood depth/48 \approx 2 cm/m

upthrust \leq 12N peaks at 20 cm immersion



sealed stainless or glass bearings
atmos. pressure and temperature changes immersion depth \pm 5 mm

Hall sensor non-linearity and hysteresis (now) below 20 μm

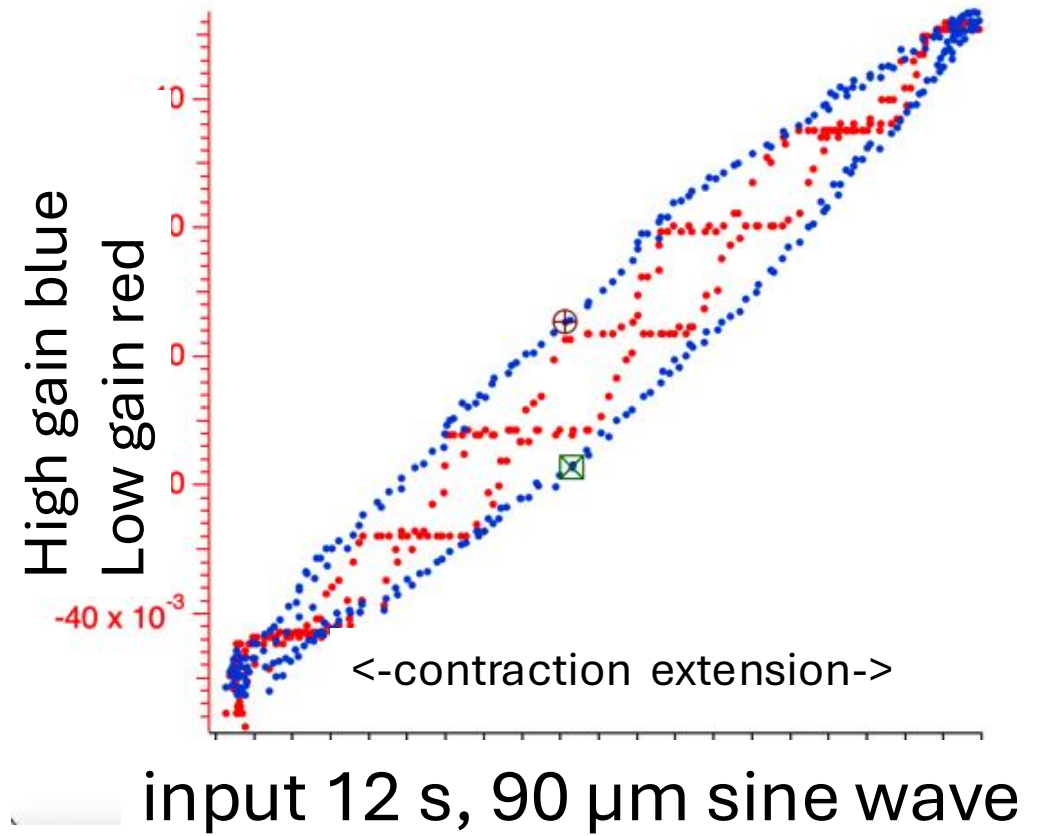
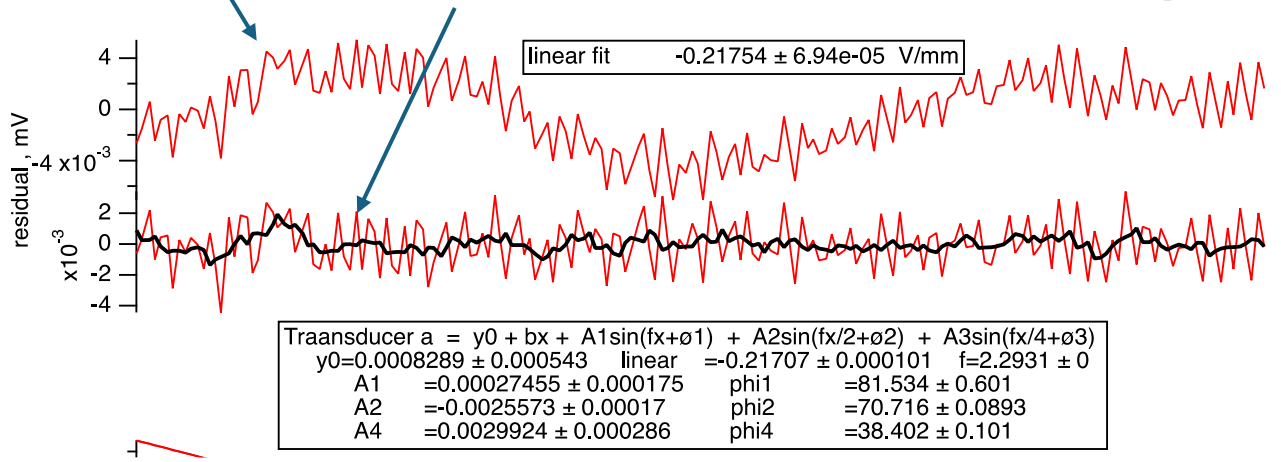


Slumgullion 3.3 m range
2.6 μm resolution

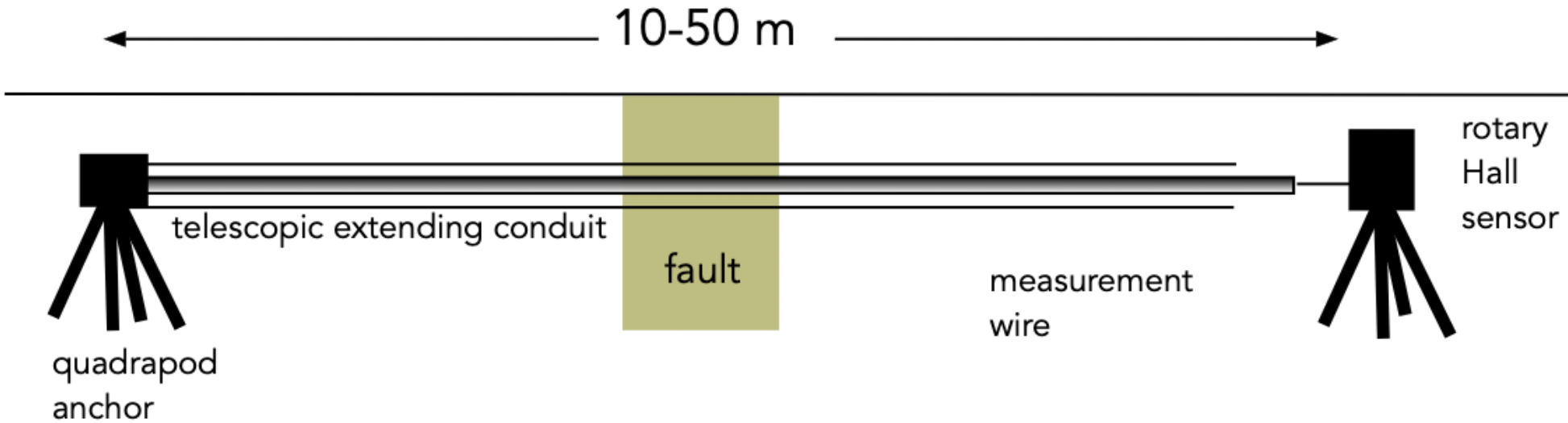
antisymmetric wire wrap

hysteresis largely eliminated
pre 2026 >3 mm, now <20 μm

nominal non-linearity <0.5%
quadrature fit <0.1% (11 μm)



length standard of choice – pultruded carbon



Composition	corrosion	ppm/°C	cost /m
Stainless steel	good	11	\$10
Invar (36% Nickel 63% Iron)	rusts	1.5	\$20
Glass fiber (Si)	good	5	\$10
Quartz Fiber (Si)	good	1.5	\$50
Pultruded carbon rod (C)	good	-0.1	\$7

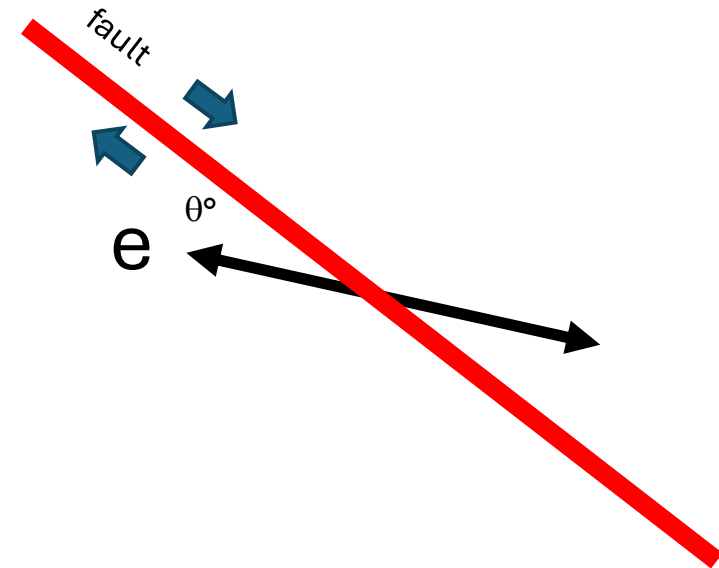
the \$600 30-m-creepmeter!
 1 minute samples for 1 year
 from C-cell batteries
 \$200 carbon rod
 \$100 3d printed sensor
 \$250 data logger
 \$50 for anchors etc

fault zone dilation & surface rotation

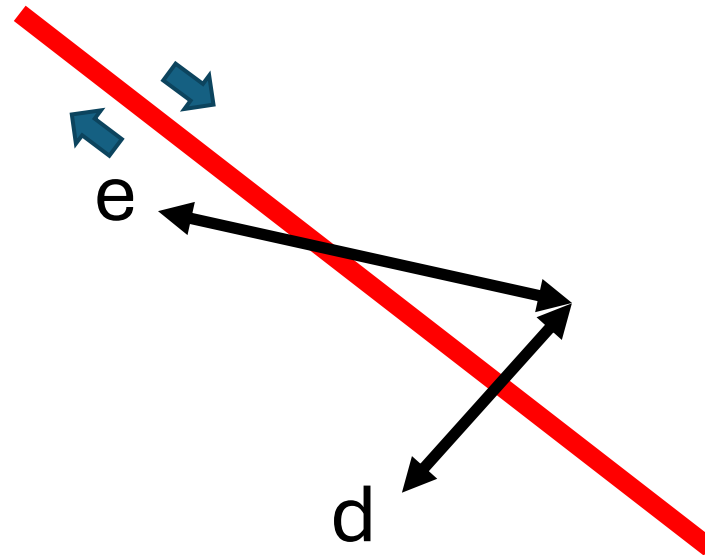
(scalar geometry has caused us to miss much of interest in the past half century!)

20 m surface node spacing needed to capture Fremont slip below 25 m. (Josie Nevitt next talk.)

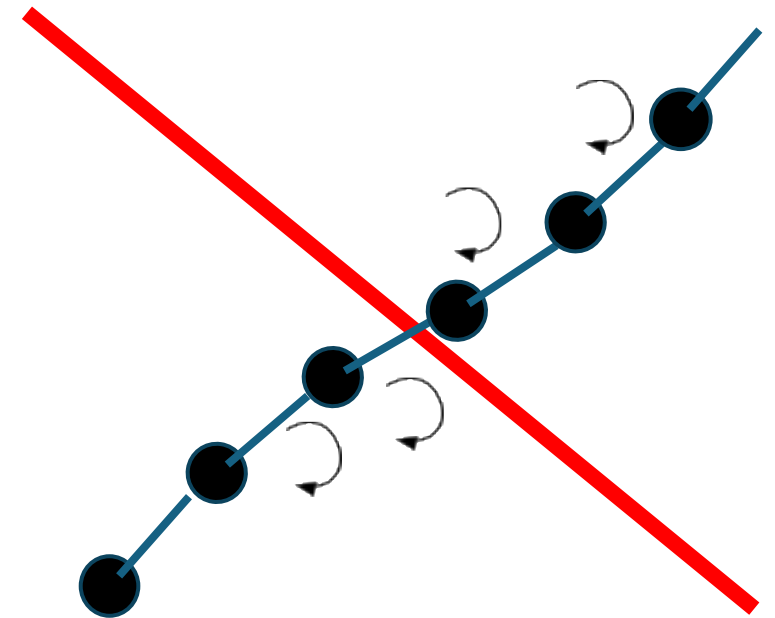
second axis reveals influence of rain, temperature and fault dilation



$\theta=30^\circ$ **scalar**
creep = $e/\cos\theta$



slip vector
dextral slip = $(e-d/\sin\theta)/\cos\theta$



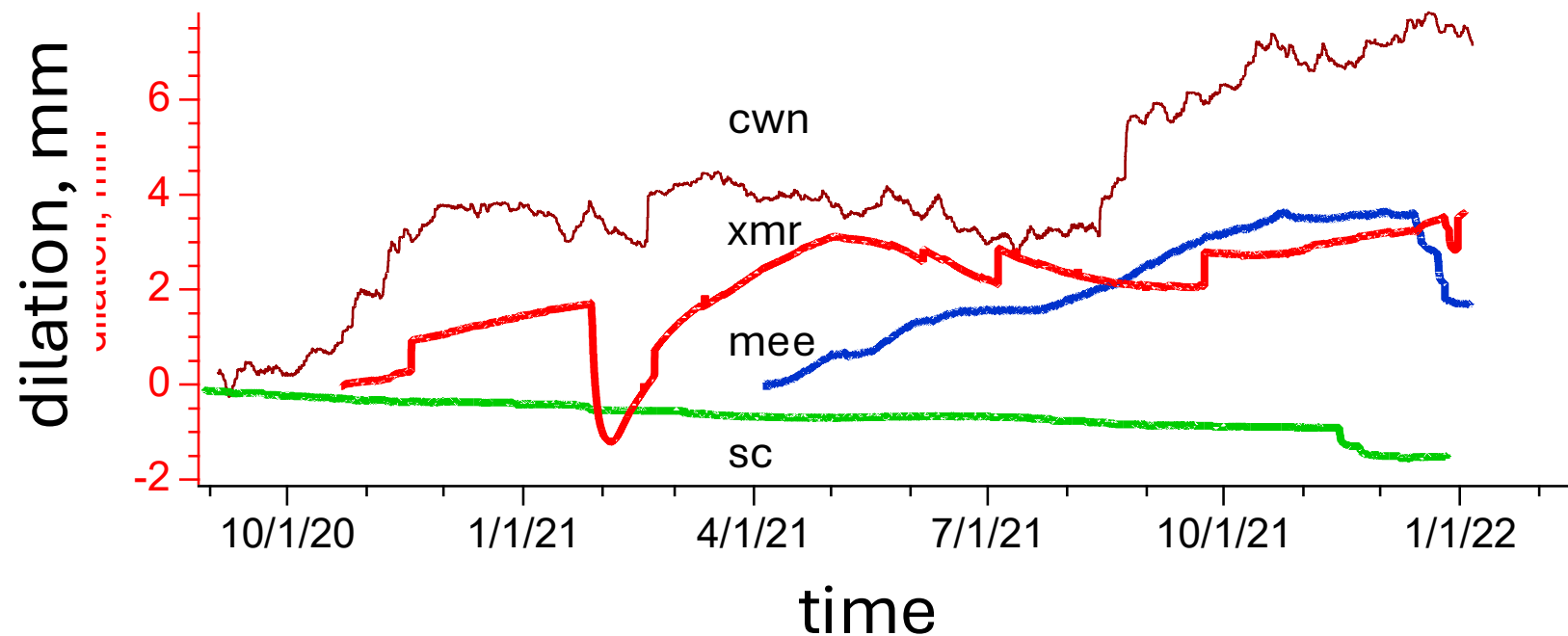
tensor strain-rate field:
subsurface slip results in
arc-tan rotation.

time series view

dilation



contraction

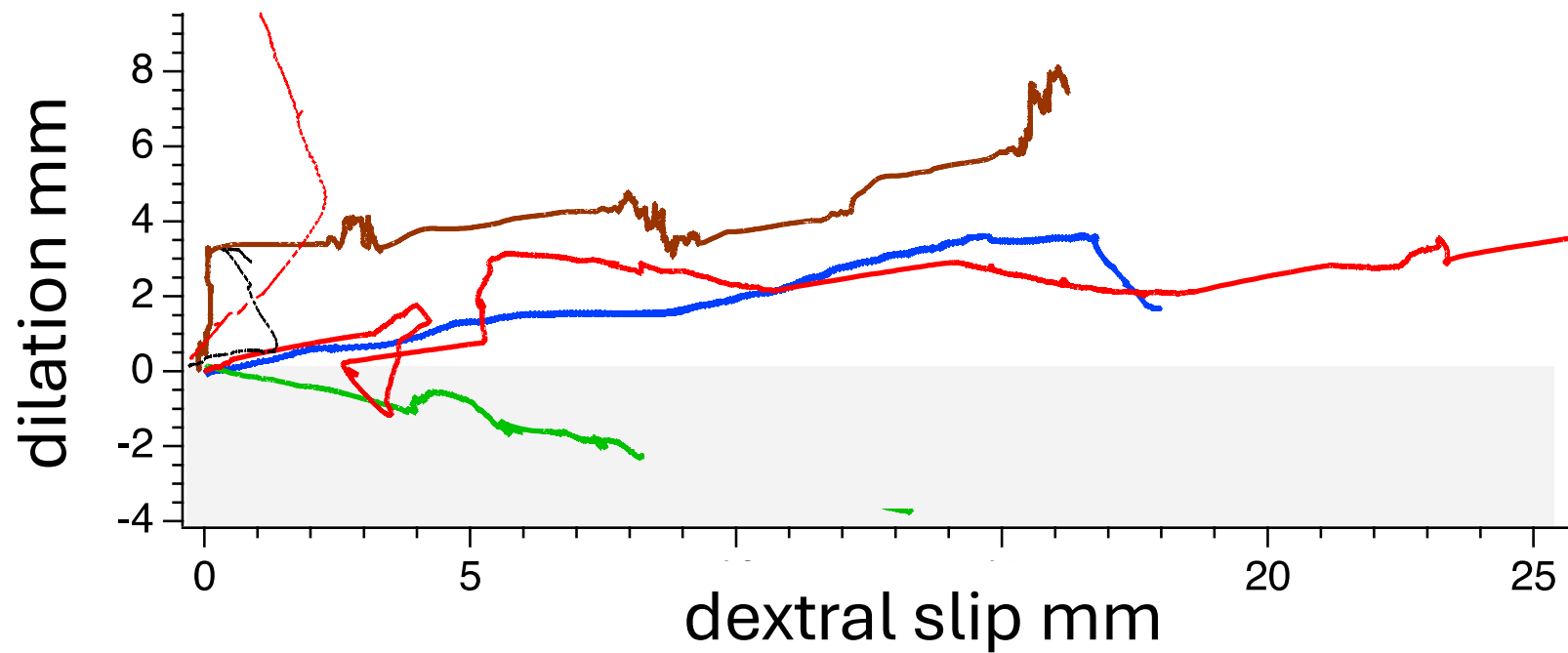


slip vector view

transtension



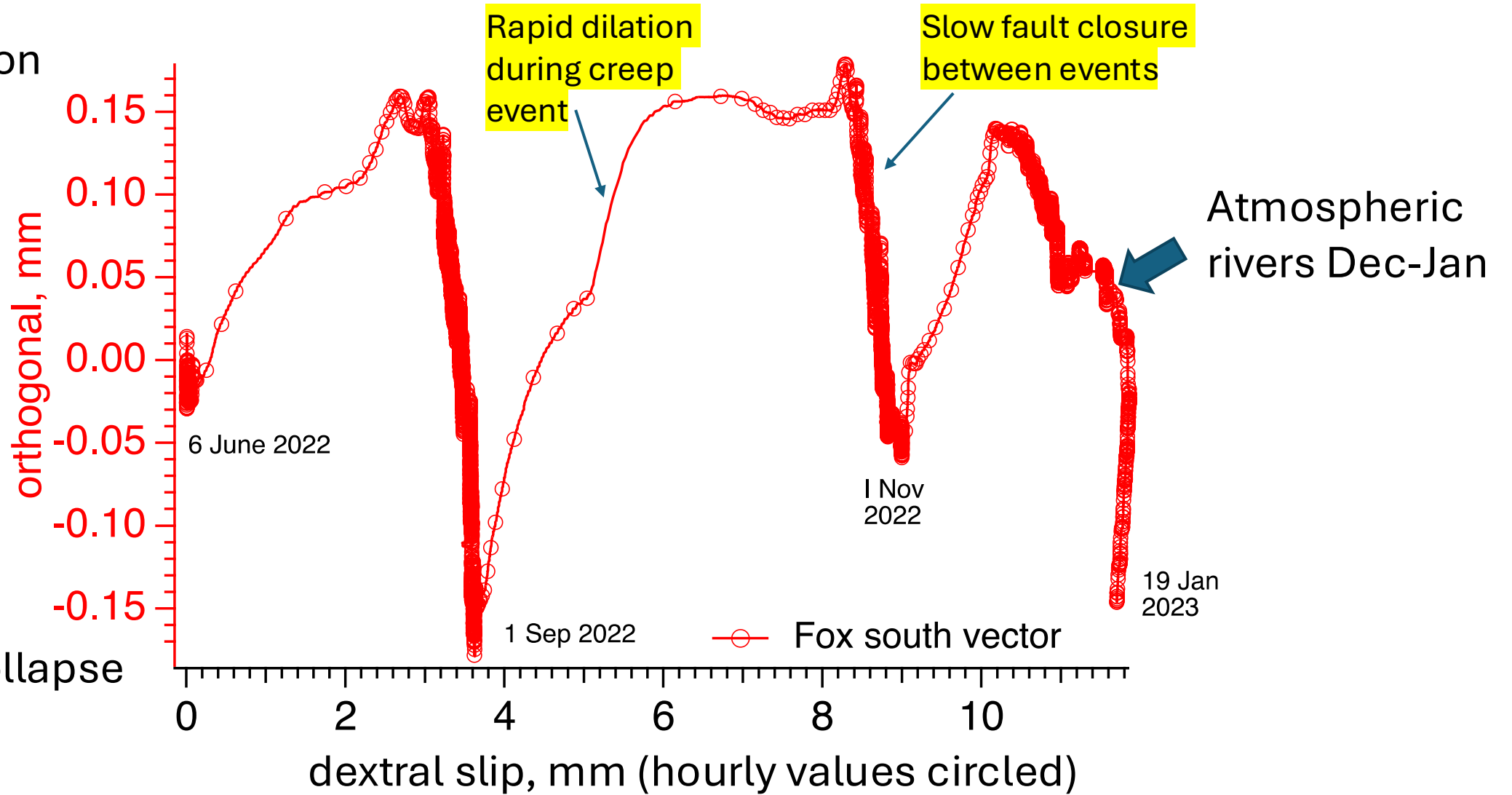
transpression



Fox Creek June 2022-Jan 2023 biaxial vector plot (data points once per hour)

Heather Crume will present Thursday

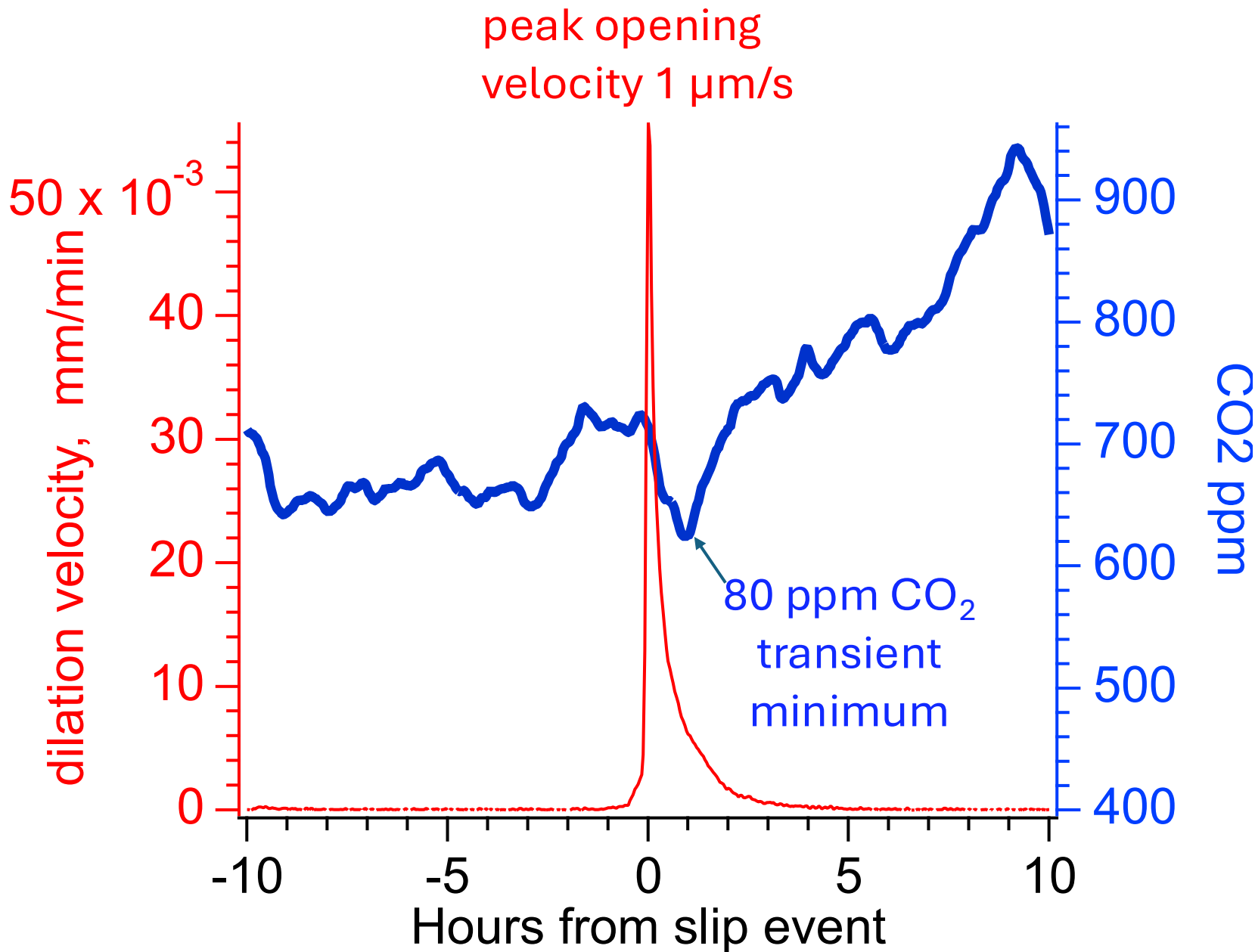
fault expansion



fault zone collapse

fault dilation during creep events sucks atmospheric CO₂ *into* fault zone

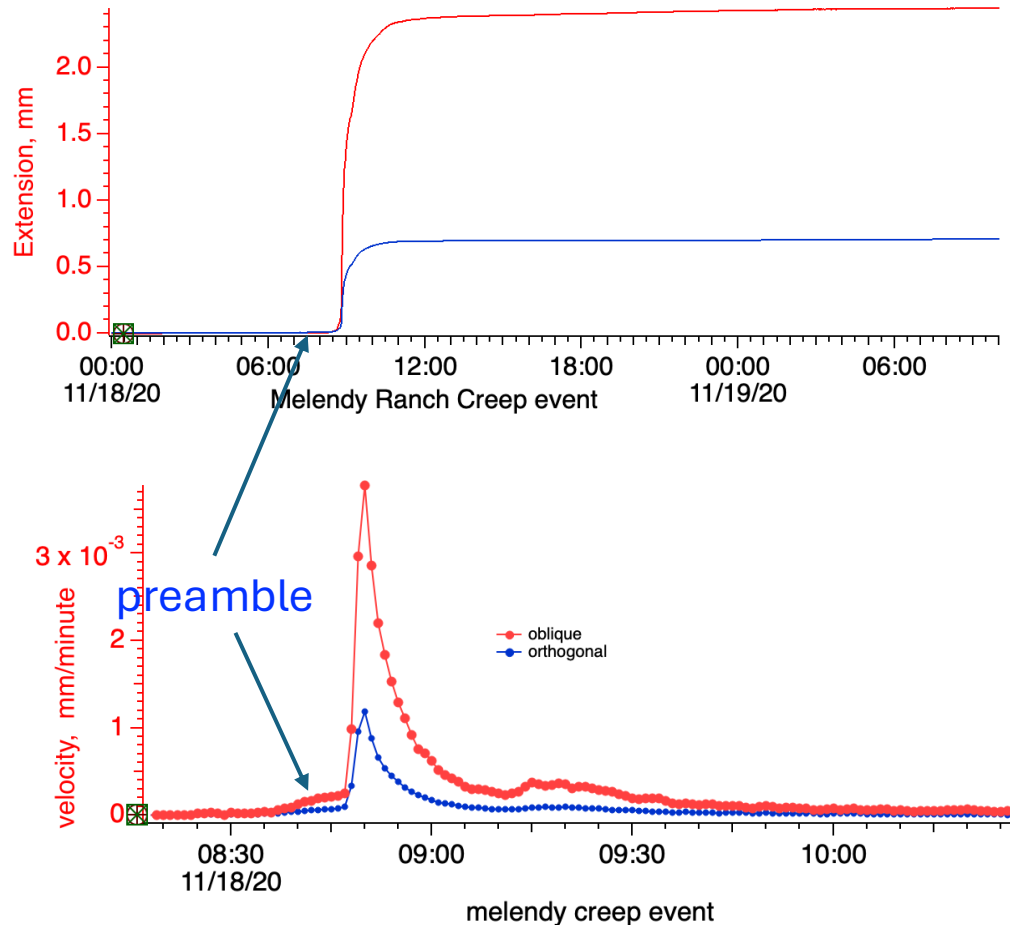
Radon (50-100 pc/L) and CO₂ (50-4000 ppm) levels in fault zone are typically lethal!



stack of 5 events
1 minute samples

Creep events – what do they tell us?

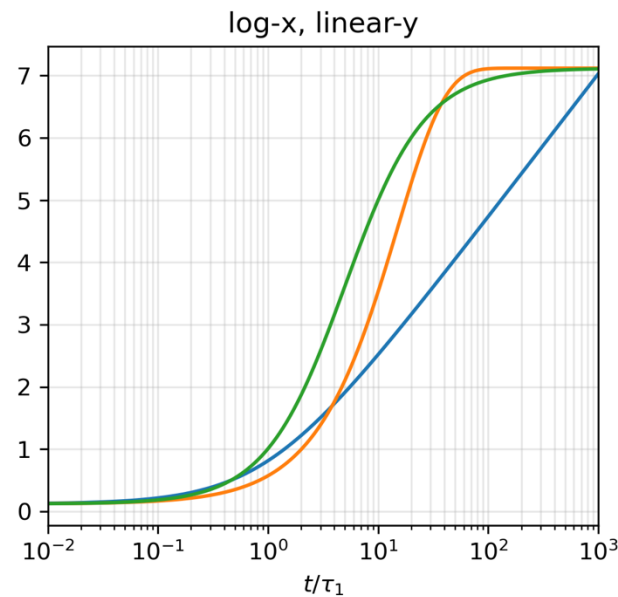
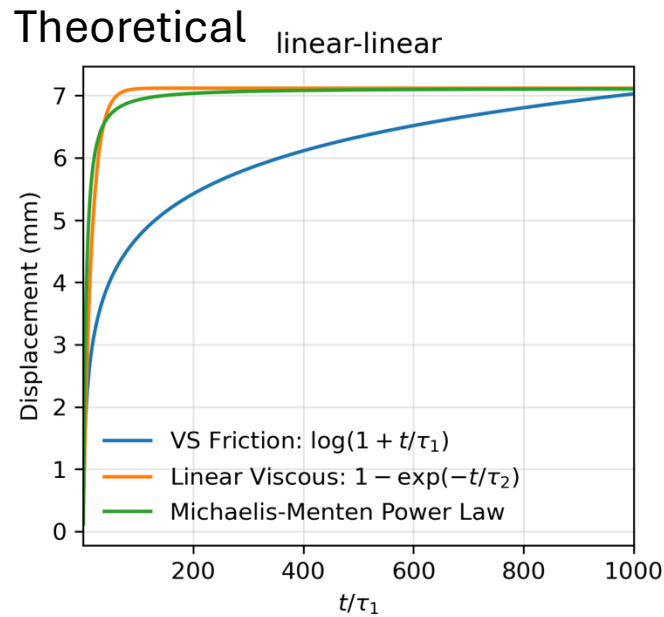
- Displacements 0.1-26 mm in minutes or days
- slip velocities $\sim 10^{-8}$ to $>10^{-5}$ m/s
- propagate at rates of >10 km/day



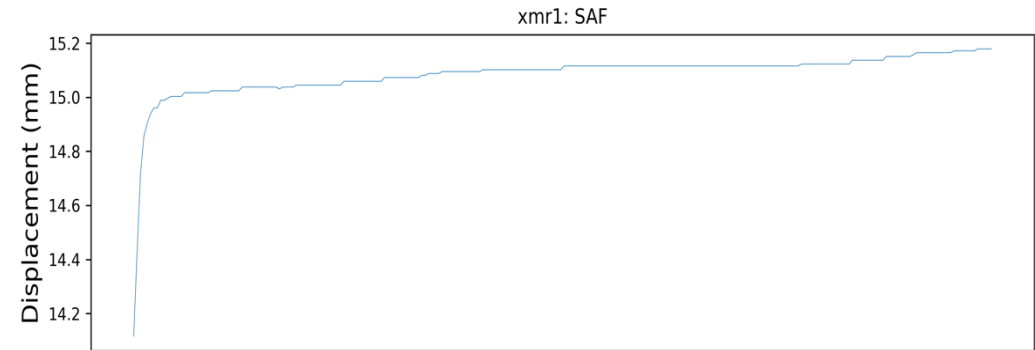
- Creep events release fraction of a fault's slip deficit
- quantitative constraint of shallow rheology
- preamble may be *strain* from creep event propagating from below surface carapace!

are creep events slow earthquakes or dull viscous slip?

- are their time-histories shaped like “log” functions, which would indicate rate-strengthening friction?
 - Answer: No, they are sharper than a typical “log” function; more similar to an exponential, the relaxation curve for a linear viscous material.

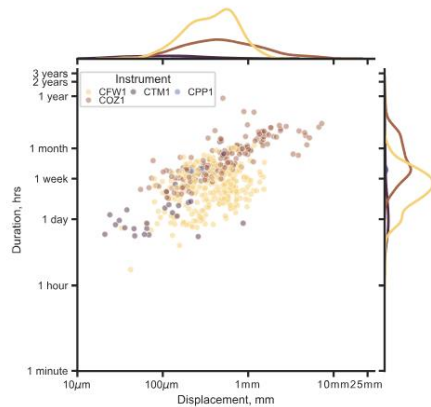


Example at Melendy Ranch from Kathryn Materna

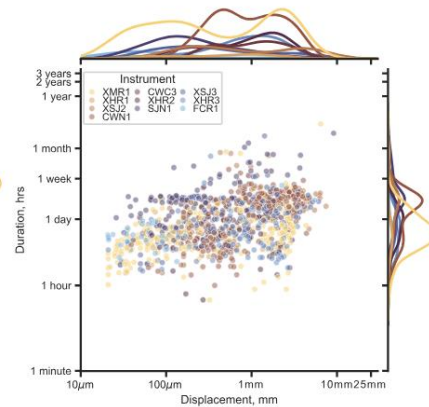


scaling creep event statistics from the new 5k Gittins catalog?

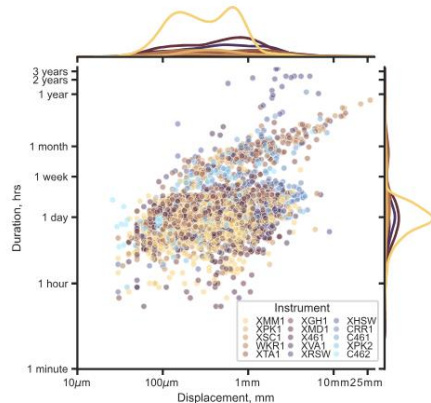
a) Hayward, California



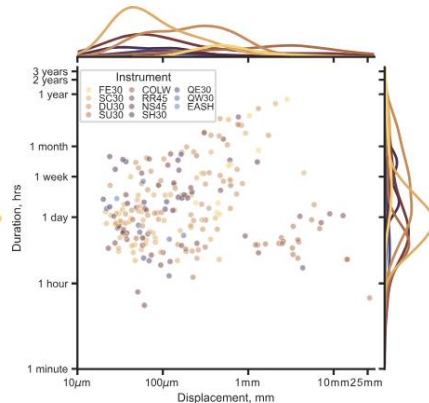
b) Hollister, California



c) Parkfield, California



d) Salton Trough, California



a catalog of >5,000 “manual picks” of creep events

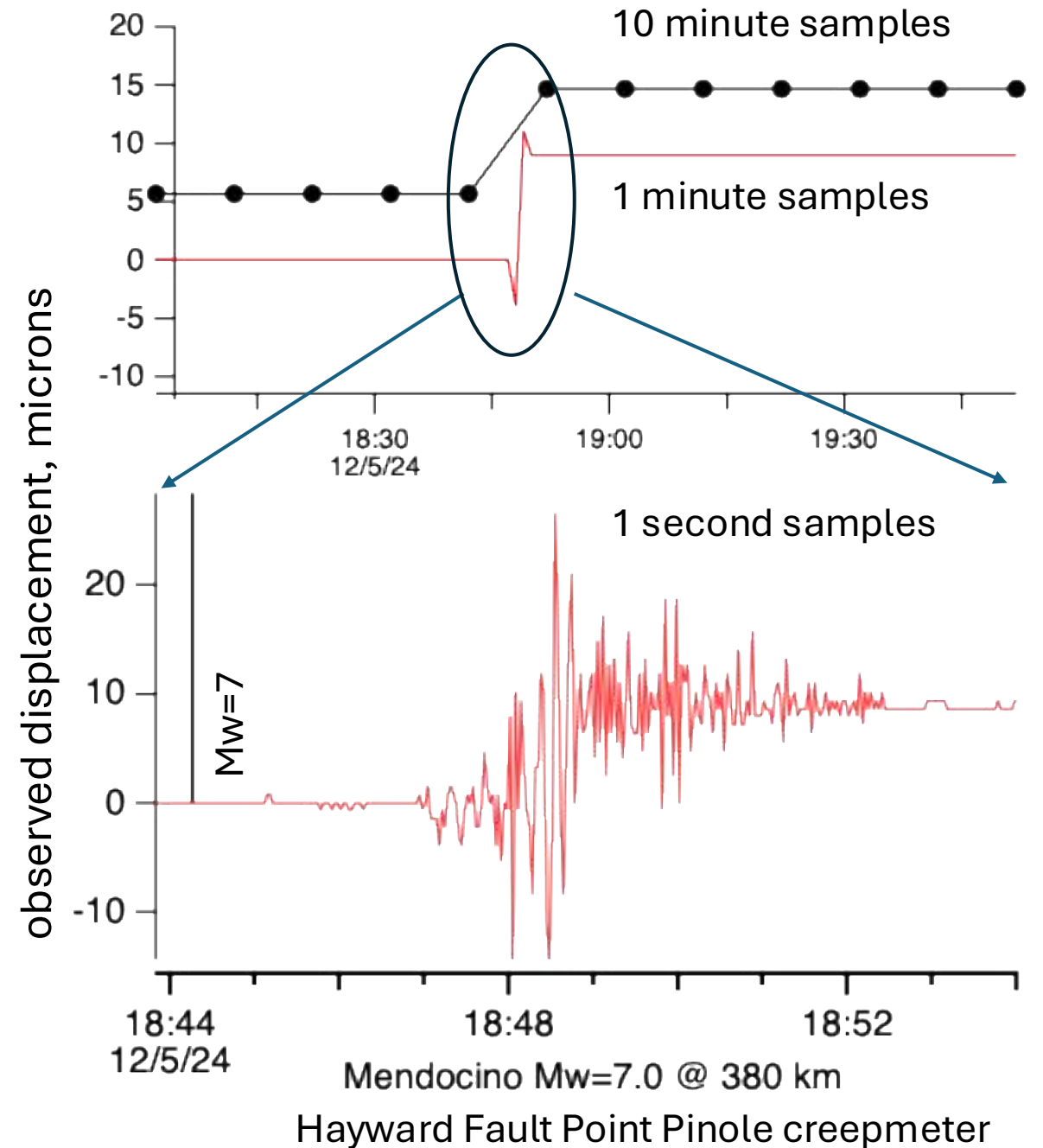
This allows us to investigate the scaling of displacement with respect to other fault parameters and stack the time series together for the first time.

from Kathryn Materna

triggered slip appears to be a continuous spectrum, 1s -1y

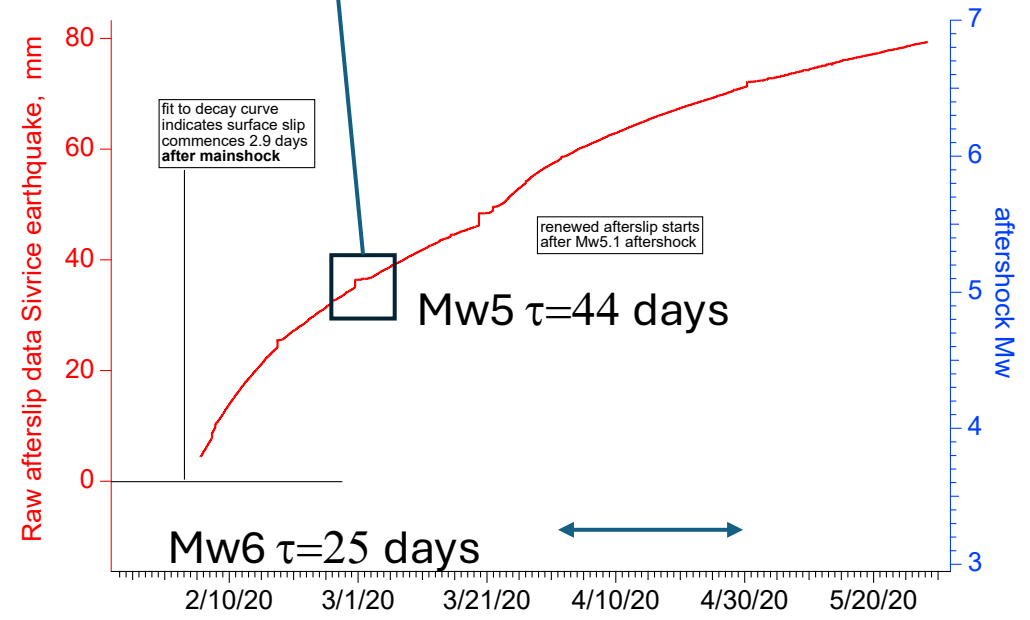
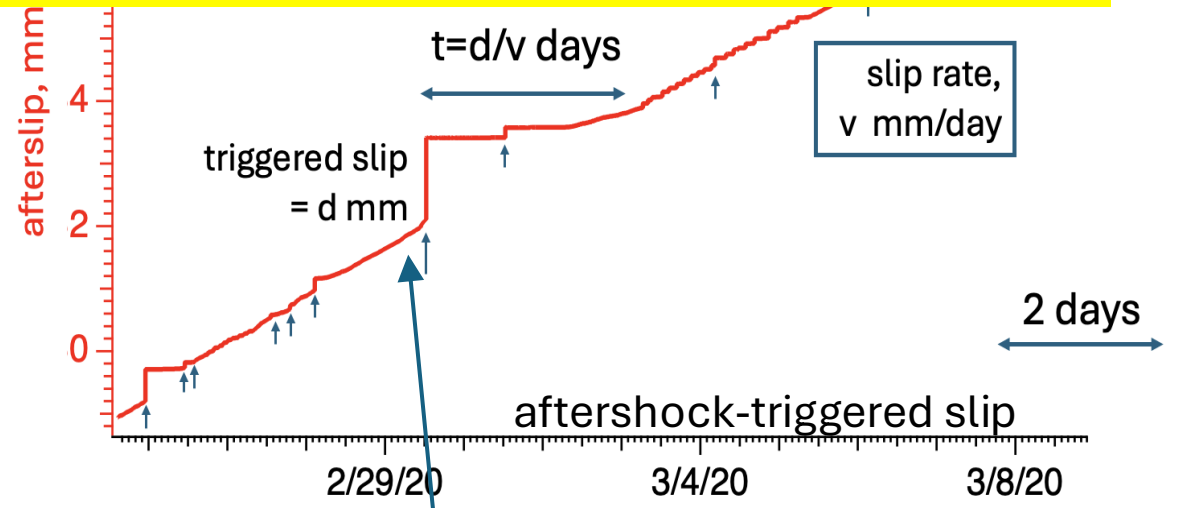
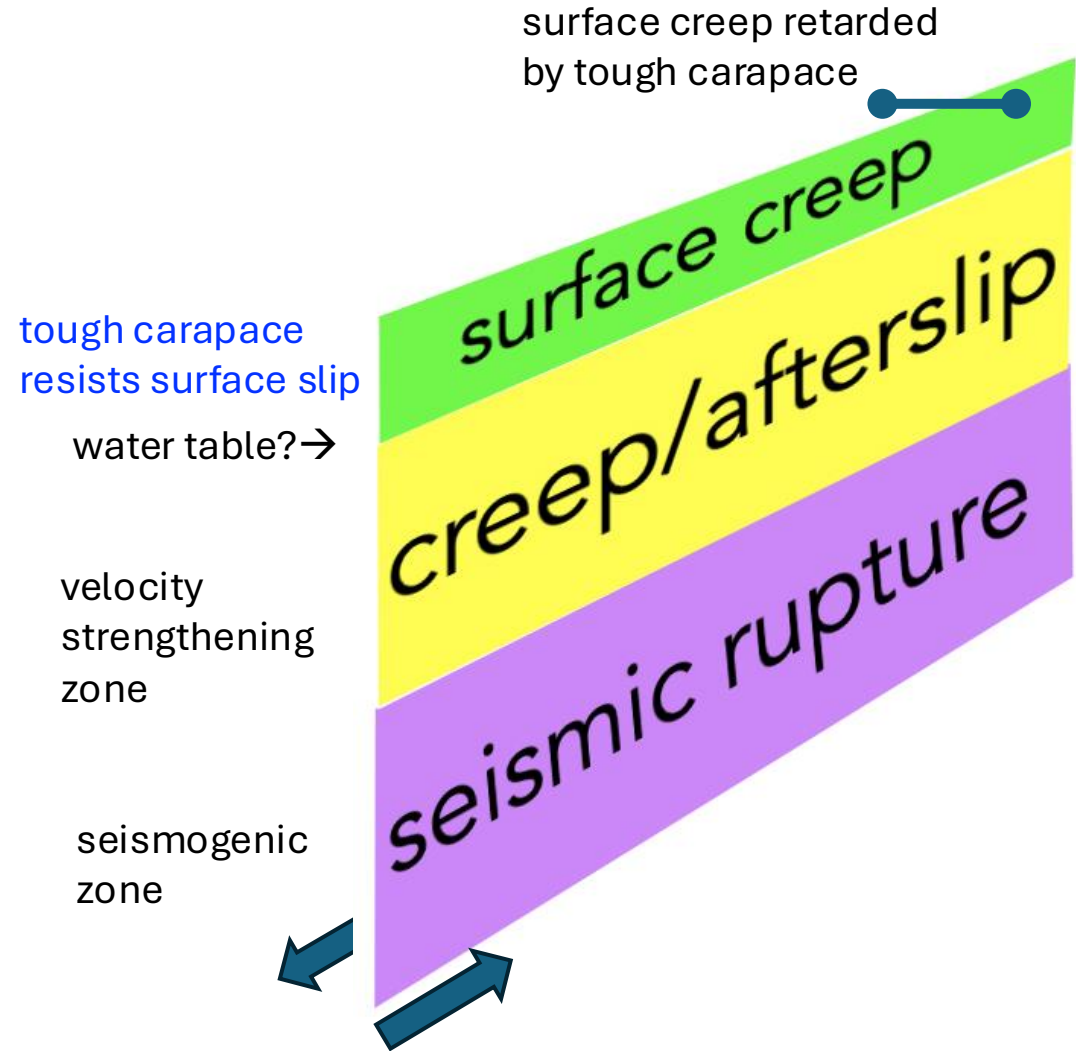
slip induced by Coulomb failure of stiff surface carapace (recall afterslip)

triggered slip can be induced by transient reduction in shallow friction *at any time scale*



1: seismic triggered slip

surface waves reduce friction and release **carapace** slip deficit



East Anatolian fault: Sivrice afterslip

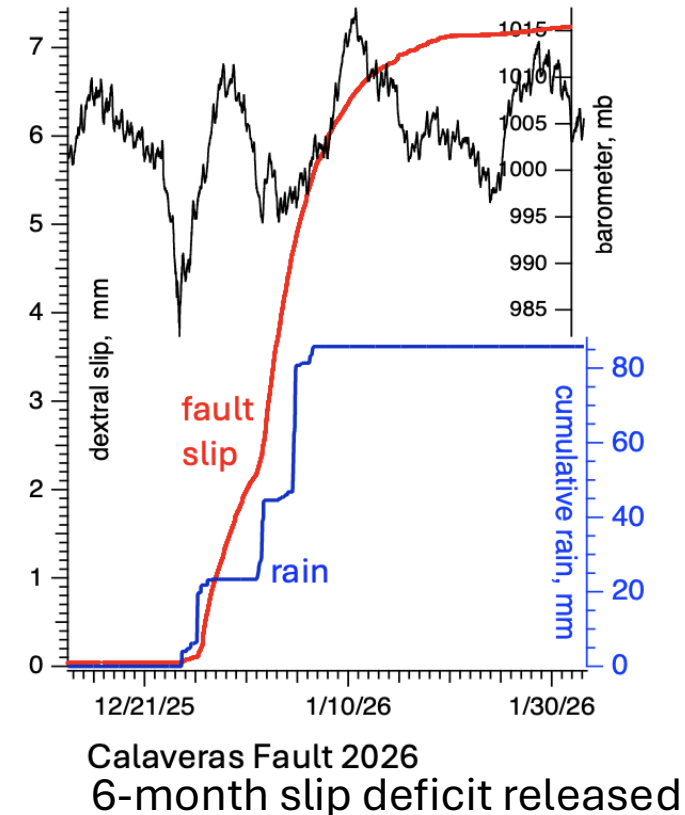
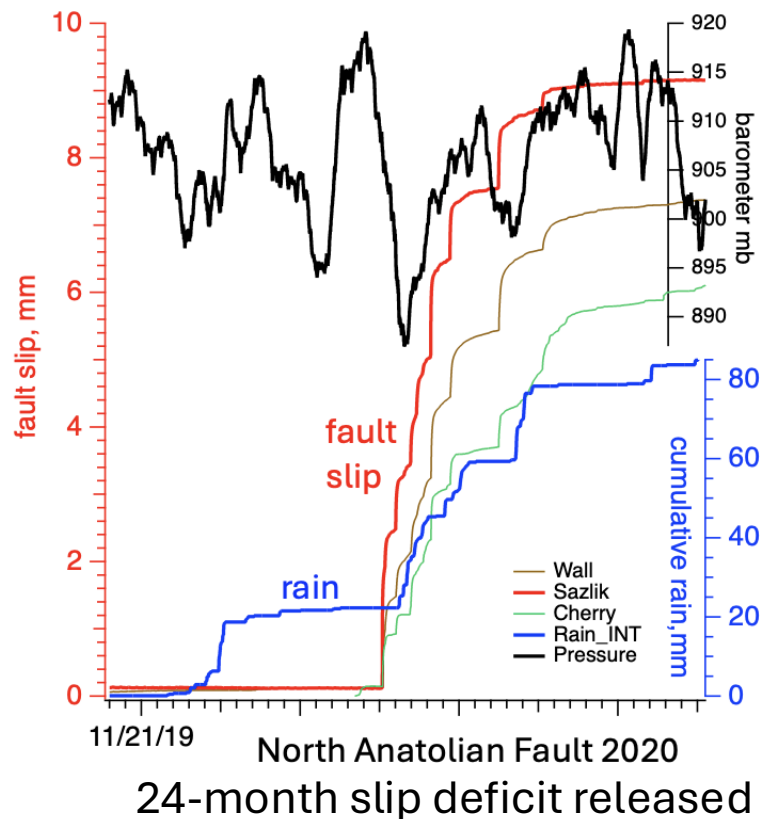
2. aseismic triggered slip

weakened surface fault releases carapace slip deficit

surface flooding increases subsurface pore-pressure ($h\rho g$)

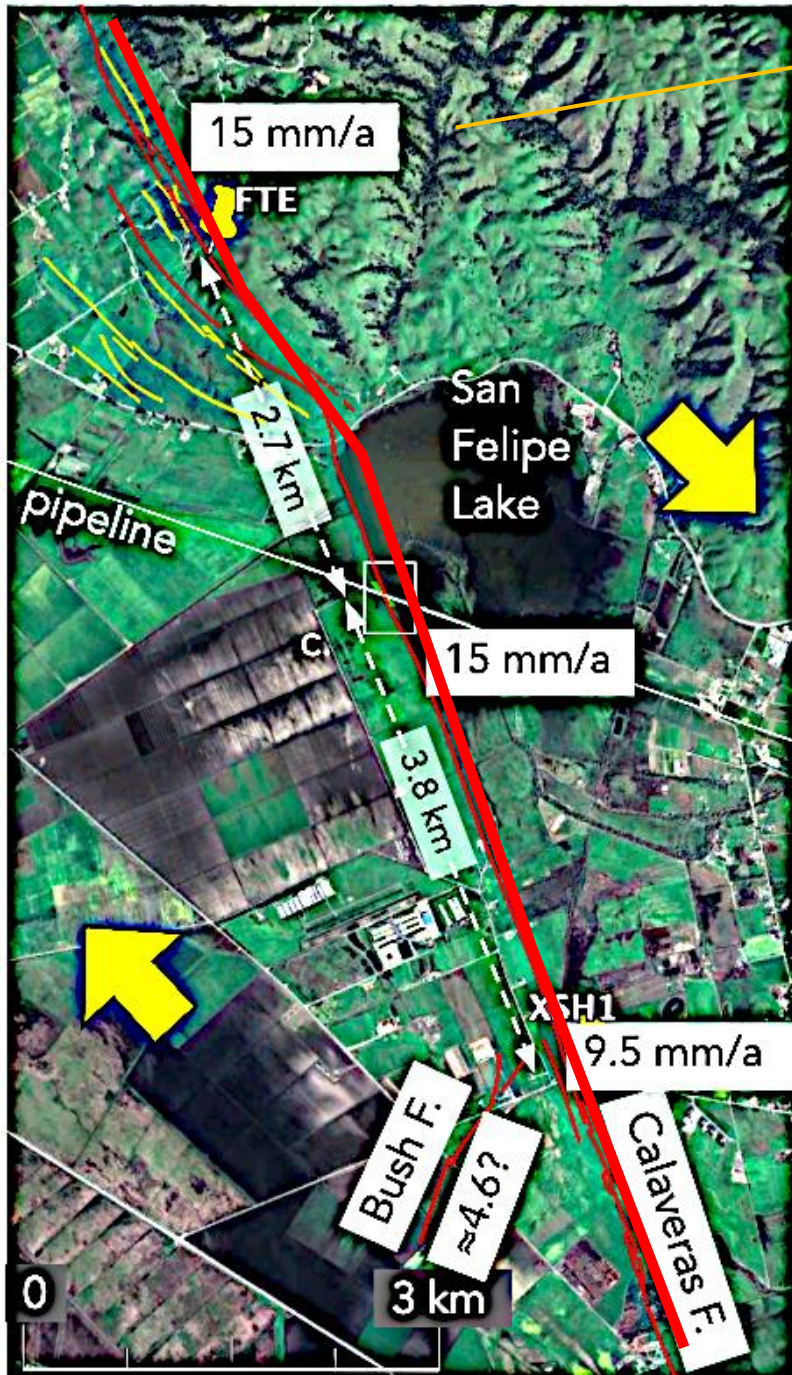
clamping stress reduces 3 mbar per 10 mbar barometric low

wet clay saturation reduces strength of surface carapace

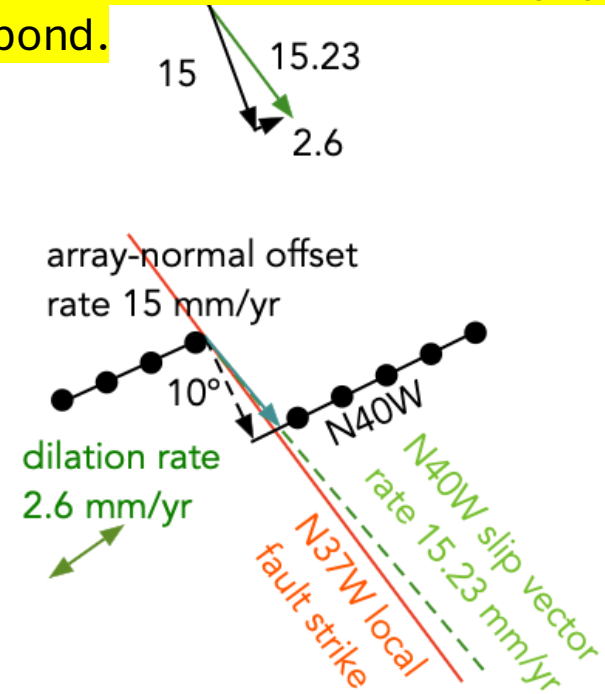


Alignment Array thoughts for the meeting

- Two types of alignment array: multipoint and angle change.
Angle change measurements lose fault depth and position info.
Plea for more multipoint arrays! Refurbish old ones?
- Some alignment arrays quantify dilation due to misalignment from slip vector.
Why don't we measure dilation as well as shear?
- Encourage students to install \$1k biaxial creepmeters at center of existing alignment arrays (where possible). **Creepmeters can provide heads-up on timely array remeasurement after creep events.**
- Events occur every one or two years on the Calaveras. Much more frequently than damaging earthquakes. **The ≈ 2 km/hr propagation velocity of creep events, in principle, permits early warning of pending pipeline vulnerability. Potential for citizen science.**



- Using the regional slip vector (N40W yellow arrows) for the northern Hollister Valley, the Furtado Ranch alignment array (Kelson et al., 2023) yields a slip rate of 15.23 mm/yr (not 15 mm/yr) with a dilation rate of 2.6 mm/yr presumably responsible for the sag pond.



- In principle, creepmeters north and south of the Santa Clara Valley pipeline (two 2-m-diameter pipes) can be used to provide early warning of approaching creep events (sometimes these exceed 15 mm)