Fault-zone fluids and aseismic slip: ventilation or lubrication?

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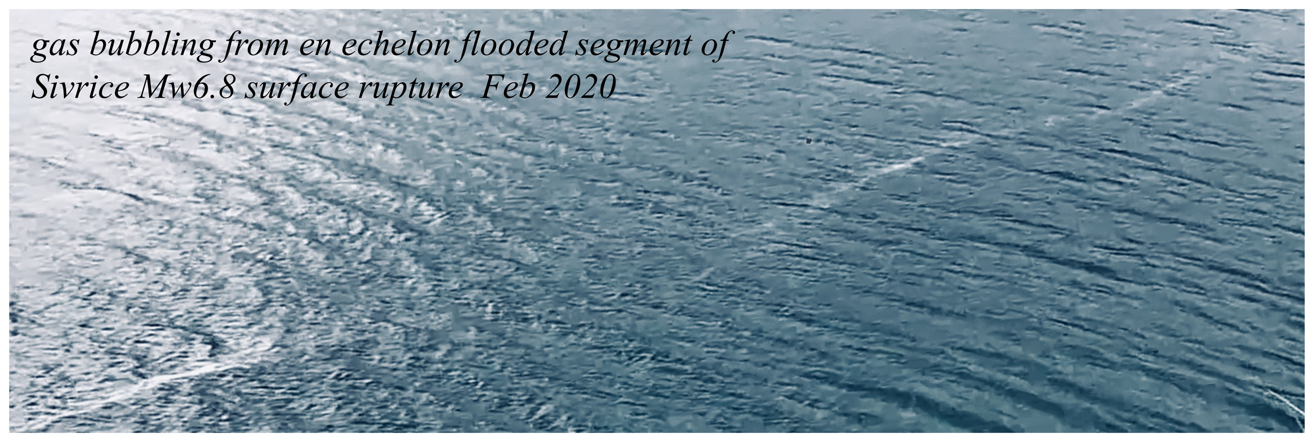
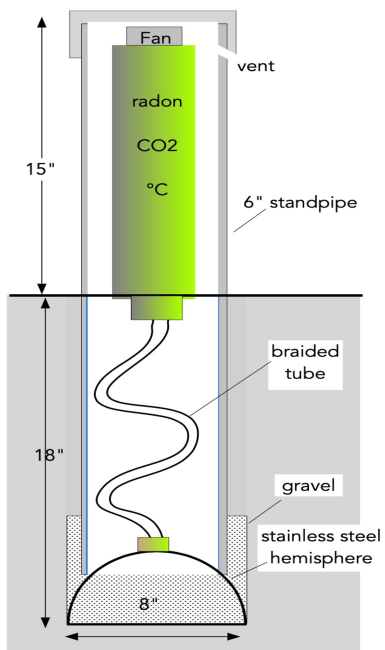
Motivation

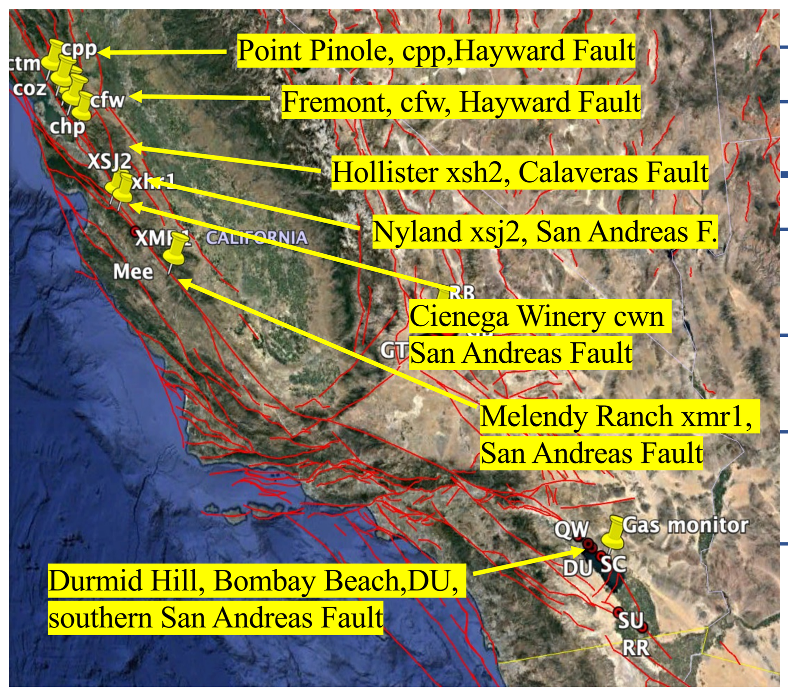
In the days following the 24 Jan 2020 Mw 6.7 Sivrice earthquake, a 2-km-length of the East Anatolian fault beneath the Euphrates River was observed to vent gasses that formed distinct en-echelon lines of bubbles above the surface rupture. One interpretation of this gas venting is that fluid conduits were formed during coseismic slip on the fault, facilitating the escape of subsurface gasses. An alternative explanation is that deep-seated fluids within the fault zone lowered friction on the fault facilitating both coseismic slip and afterslip*.


gas bubbling from en echelon flooded segment of Sivrice Mw6.8 surface rupture Feb 2020

Fluid and gas venting from the San Andreas Fault system has been reported by numerous authors, but an association with fault slip remains elusive.

In the past year, CO2 (≤4000 ppm) and Radon (<100 pC/L) concentrations were measured at 1-minute intervals at 7 USGS creepmeters on the Hayward (2), Calaveras (1) and San Andreas (4) faults. At each site, gases are sensed at ≈50 cm depth and vented to the atmosphere or a subsurface vault via a small extractor fan.





Our results reveal that gas concentrations are not perturbed during the passage of 4 hr duration creep events, a result that argues against slip-induced, subsurface conduit formation.

In contrast, gas concentrations increase several days before large creep events, and remain high during and following them. On the Calaveras fault 15 km NW of Hollister, Radon and CO2 levels exceeded full-scale for about two weeks starting 4 days before 16 mm of slip in late August 2021, and before 13 mm creep in October 2020. (dextral slip=observed displacements/cos40)

Microearthquakes (1.3<Mw<3.1) below 5 km depth on the Calaveras fault migrated SE preceding the second of these slip events, with minor increases in gas concentrations accompanying accelerations in displacement rate June-July. We consider that these anomalously large gas concentrations may be related to fluid migration to the surface, bracketing aseismic slip on the ≈20-km-long segment of the fault outlined by micro-seismicity. The precursory appearance of gasses prior to surface creep is presumably a manifestation of venting perhaps lowering friction on contiguous segments of the shallow fault. However, it is probable that if fluids are associated with earthquakes at or below 5 km depths, the upward migration of these fluids (and associated propagating creep) to the surface may take weeks (hence gas has no utility as a precursor to seismicity). The long duration of anomalous surface gas venting (days) provides a window of opportunity to sample isotope ratios and the composition of gas constituents, a search that has been difficult in past fault zone studies.

*We recorded ≈15 cm of afterslip on the East Anatolian fault at Sivrice in the following year

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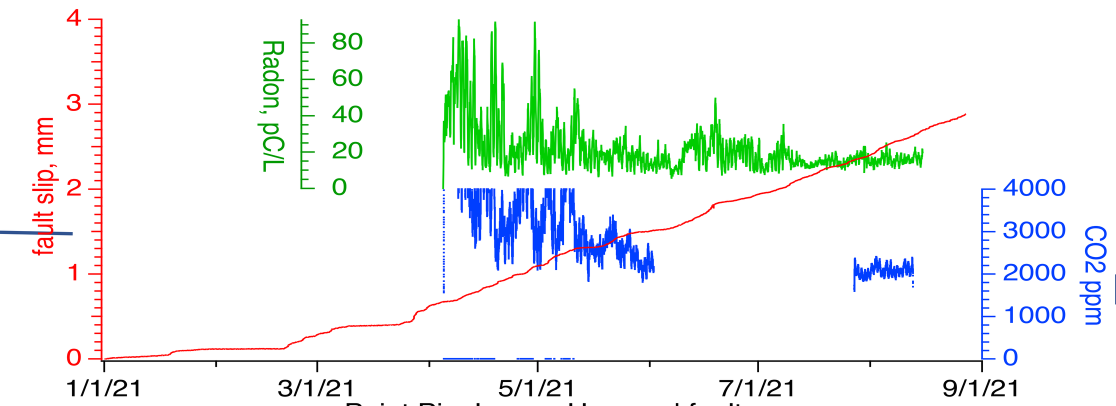
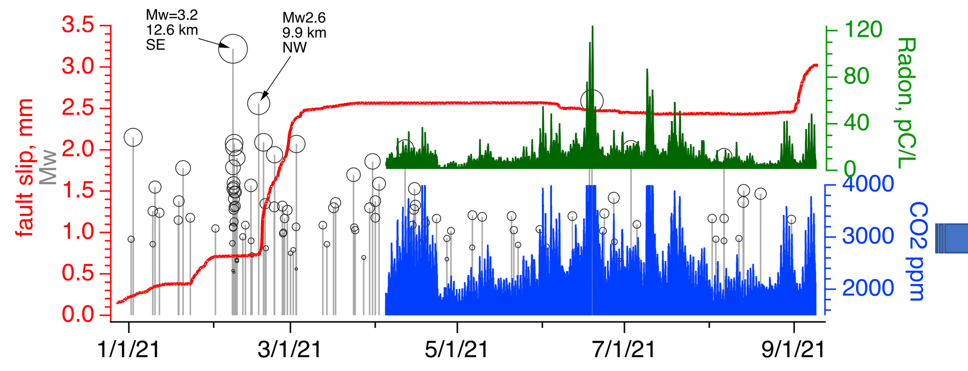
Observations

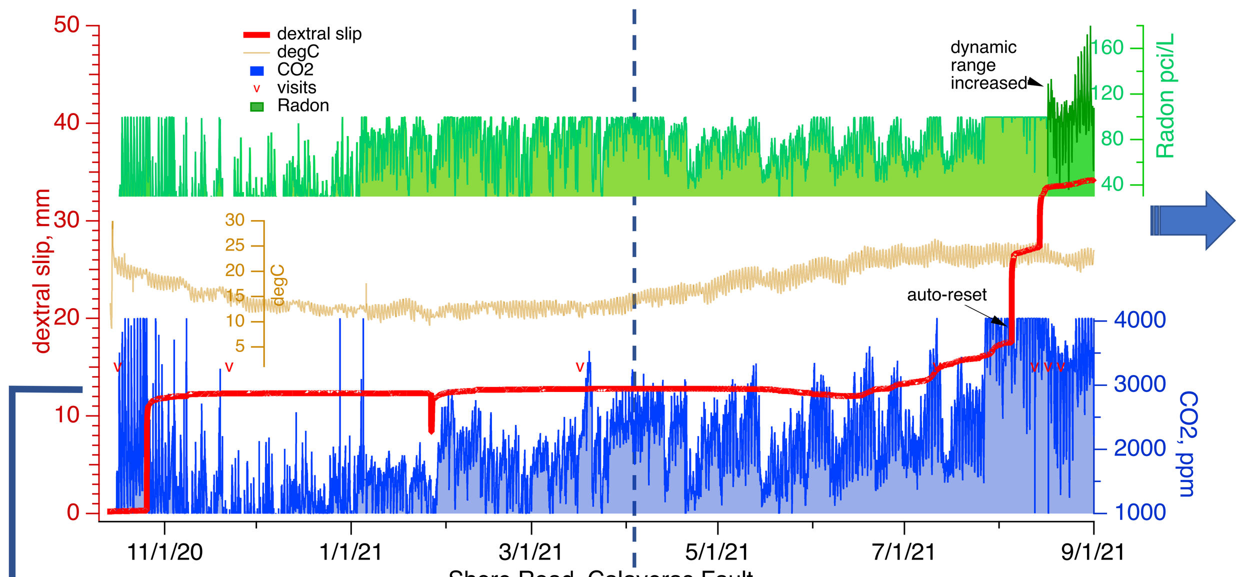
(our CO2 monitors saturate at 4000 ppm, & Rn at 100 pC/L)
(60-s samples at 7 sites : yellow panels summarize observations)


Point Pinole, cpp Hayward fault

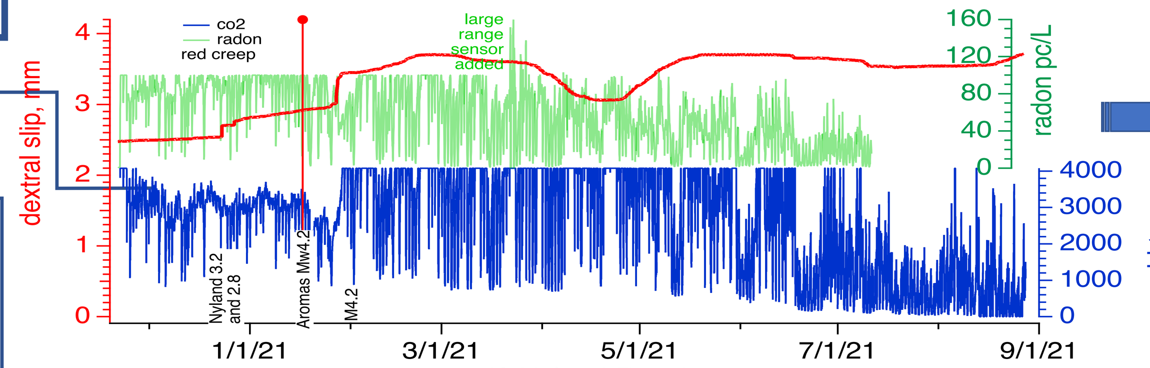
May/June 11-15 day flux Radon. No creep events occurred during gas monitoring


cfw gas, creep & seismicity within 15 km

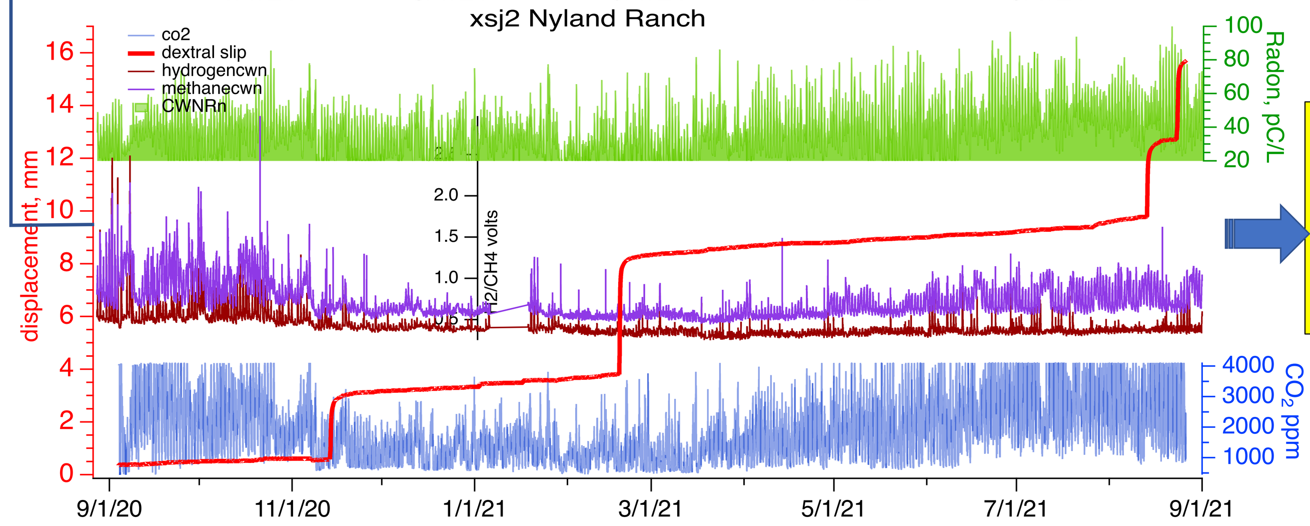
10-20 day fluctuations of CO2 and Radon from 30 m deep borehole through the fault. No synchronous gas venting during creep event


Shore Road, Calaveras Fault

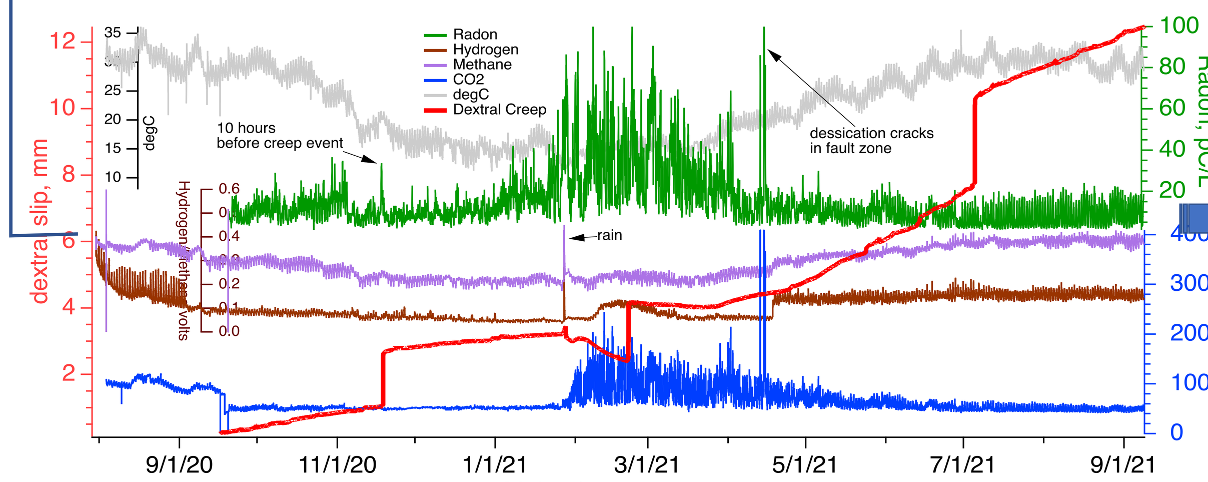
Rn and CO2 flux went off-scale days before large creep events >12 mm (the largest ever recorded at this site.) Microseismicity below ≈5 km migrated from NW to SE March-August


xsj2 Nyland Ranch

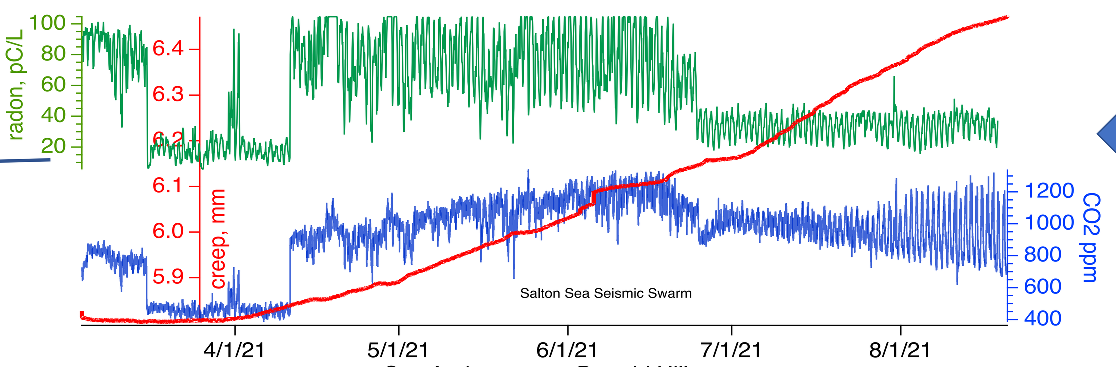
Rn and CO2 flux increased after local Mw=3 earthquakes and triggered slip.


Cienega Winery, cwn

active winery (=high gas noise no synchronous venting of H2, CH4, Rn and CO2 during creep events.


Melendy xmr

H2, CH4, Rn and CO2 monitored but no synchronous venting during creep events. Major gas flux follows rain,. Flux spikes during desiccation-crack formation


San Andreas seep Durmid Hill

No synchronous gas venting during triggered slip. Peak gas flux coincides with microseismic swarm beneath Salton Sea. (But may be a seasonal variation in gas flux).

Non-tectonic gas signals 2020-2021

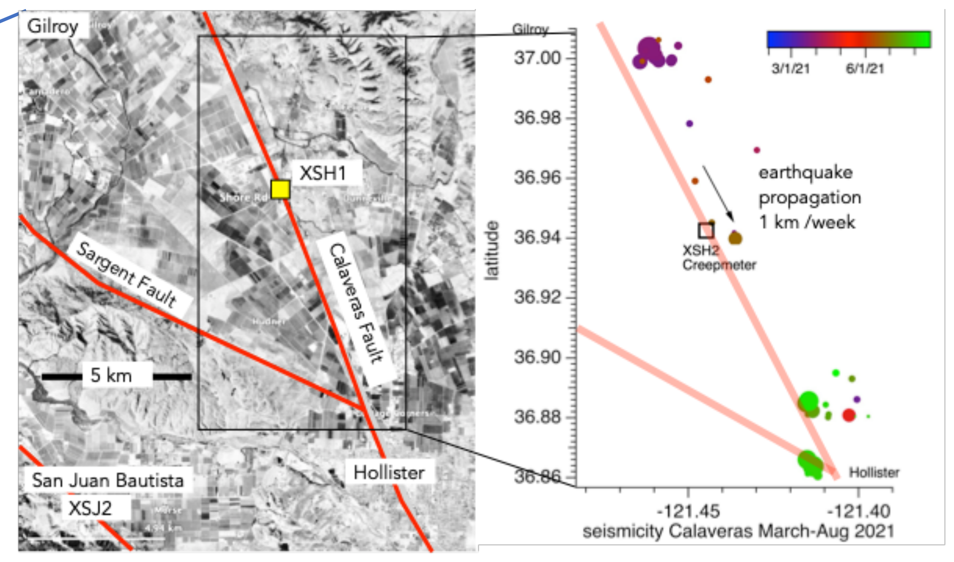
1. Diurnal fluctuations of 500 ppm in CO2 arise from biological processes
2. Rainfall stimulates growth of micro-organisms in soils followed by major CO2 flux.
3. Radon and CO2 tend to track each other suggesting common carrier gas.
4. Absolute levels of H2 are high at Calaveras site (courtesy Sara Peek USGS)
5. No significant "noise" from atmospheric pressure or temperature
6. Observed gas fluctuations probably caused by *flux rate* changes (3 above) as opposed to constant flux rate with variable gas proportions.

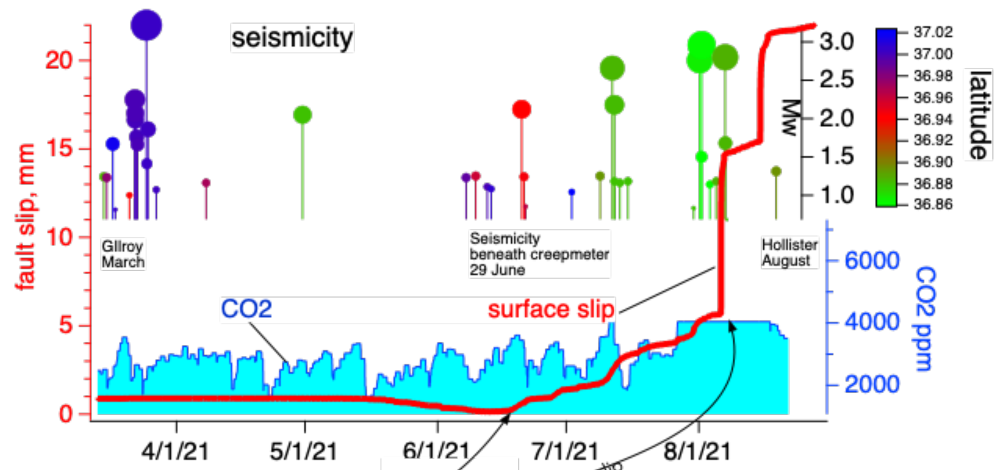
A recognized weakness in our pilot experiment is that we have not simultaneously monitored gasses in "off-fault" settings.

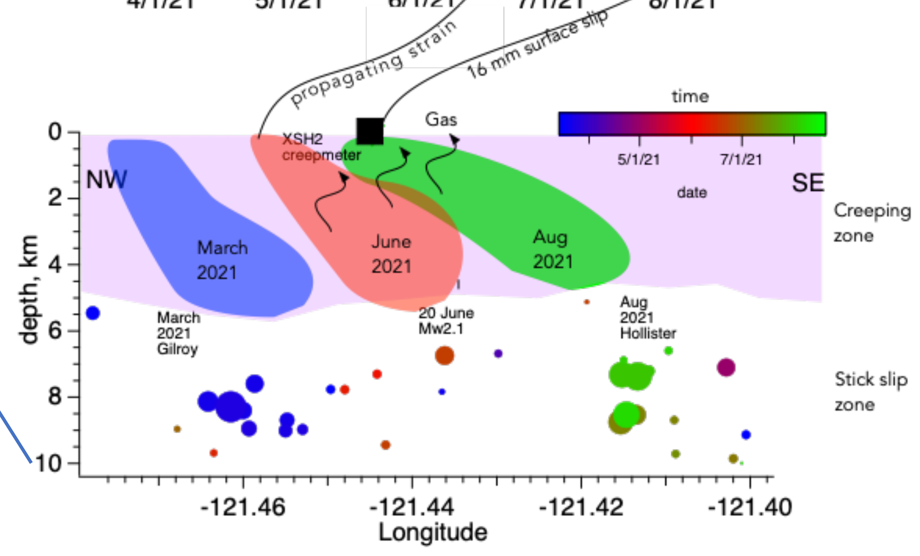
Results

Gas fluctuations and fault slip

1. "off-scale" gas flux preceded large creep events at *xsh* on the Calaveras fault (12 mm in Oct 2020 & 16 mm Aug 2021). The second of these was a double event preceded by minor gas venting during four <1.5 mm events starting in June (see panel below)
2. Although surface gas venting leads surface slip by ≈4 days, it lags behind seismicity 5 km below the sensor by 5-6 weeks.
3. The Hayward fault emits pulses of gas, twice background levels, at 10-20 day intervals (*cpp* and *cfw*). (No creep events occurred in our sample window)
4. No synchronous gas venting accompanied 1-3 mm amplitude creep events at *cfw* and *xmr*. Pulses of gas accompanied development of en-echelon desiccation cracks in fault zone.
5. Peak gas flux accompanied a microseismic swarm in the Salton Sea, but this may be a seasonal effect.


seismicity Calaveras March-Aug 2021





Provisional interpretation of Calaveras propagating slip episode March-September 2021

1. Seismicity occurred in patches below 5 km depth apparently migrating from Gilroy to Hollister between March and Sept 2021 (≈1 km/week). We interpret this as a propagating pulse of slip below ≈5 km depth.
2. Fault creep (and/or strain) started in late June at roughly the time of a Mw=2.4 earthquake 6 km beneath the creepmeter. During June and July, pulses of CO2 and Radon at 1-3 week intervals increase in peak amplitude and loosely correspond to episodes of minor fault slip. Four days before a 16 mm creep doublet, both gas monitors went off-scale.
3. If we equate microseismicity at depth with the nucleation of upward propagating creep, surface slip lags about 6-7 weeks behind slip at depth. Clearly surface gas and creep is of no use as a precursor for forecasting seismicity.
4. We speculate that aseismic slip is initiated at the base of a 5-km-deep creeping zone and propagates slowly toward the surface (≈30 m/day), accompanied by fault zone fluids (CO2, H2 etc)

Conclusions

The title to this poster poses an (as yet) unanswered question. However......

(a) It appears probable that surface gas venting lags weeks behind seismicity at depth.

(b) A burst of gasses 4 days before large creep events on the Calaveras fault suggests that rising fault zone fluids may facilitate fault creep. Here (and elsewhere) no synchronous burst of gas is observed during a 4-hour-duration creep event. i.e. local slip does not result in the creation of significant fluid pathways.

(c) Fault zone gasses appear to vent at 1-3 week intervals (Hayward and Calaveras Faults) but these are not associated with creep events.

Caveat - we have not operated sensors simultaneously both on, and near, a fault.