Rheological implications of post-seismic deformation following the 2019 Ridgecrest Earthquakes

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Abstract

Post-seismic deformation following large earthquakes offers insights into the rheology of the lithosphere and upper asthenosphere. The Mojave, in southern California, is one of the best studied regions on Earth, yet key questions, about fault slip rates and rheological heterogeneity, remain unanswered. Unprecedented geodetic coverage of the 2019 Ridgecrest earthquakes provides an opportunity to test whether rheological models developed for the Mojave, from the Landers, Hector Mine and El Major Cucapah earthquakes, are applicable north of the Garlock fault, and to place bounds on the effects of local rheological heterogeneties associated with the Coso volcanic field. This volcanic field, which is located to the NW of the Mw7.1 rupture trace, is a region of high heat flow and geothermal activity. The locally high temperatures in the Coso volcanic field are likely to be associated with low viscosities compared to the surrounding regions, and high pore pressures due to the hydrothermal activity. The aftershock sequence associated with the Ridgecrest earthquakes shows a notable absence of large magnitude earthquakes in this region. We use variational Bayesian independent component analysis to isolate postseismic deformation in GPS time series around the earthquakes. We present models of the possible poroelastic, afterslip and viscoelastic response driven by coseismic stress changes in the July 2019 Ridgecrest earthquakes and investigate the possible effect of the Coso volcanic field. By modelling a series of different afterslip geometries, and viscoelastic rheologies we identify features of the GPS- and InSAR-derived surface deformation which are diagnostic of different post-seismic mechanisms and rheological heterogeneities.

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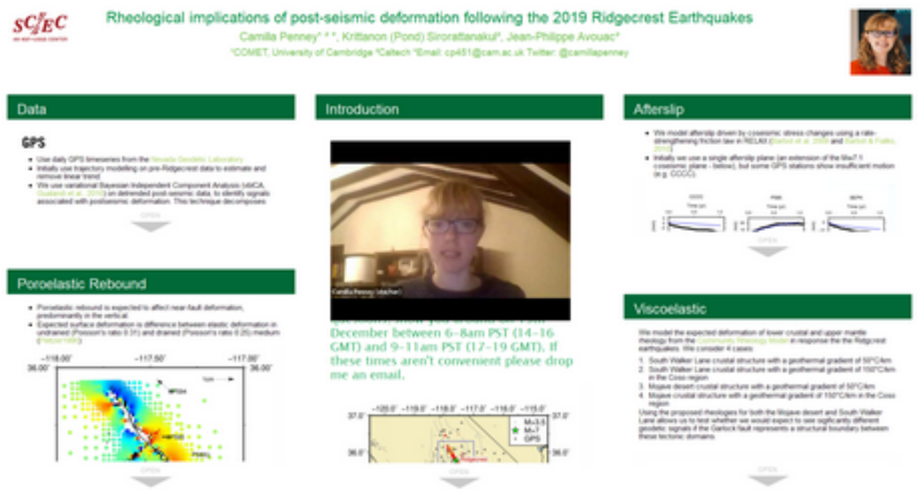

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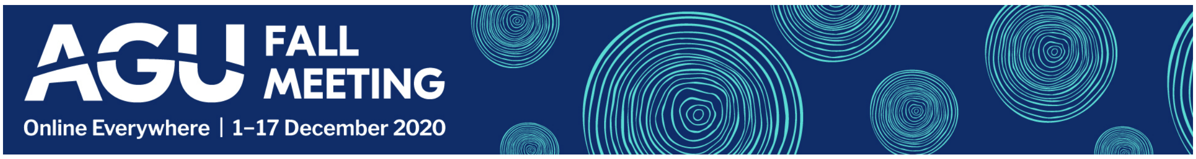
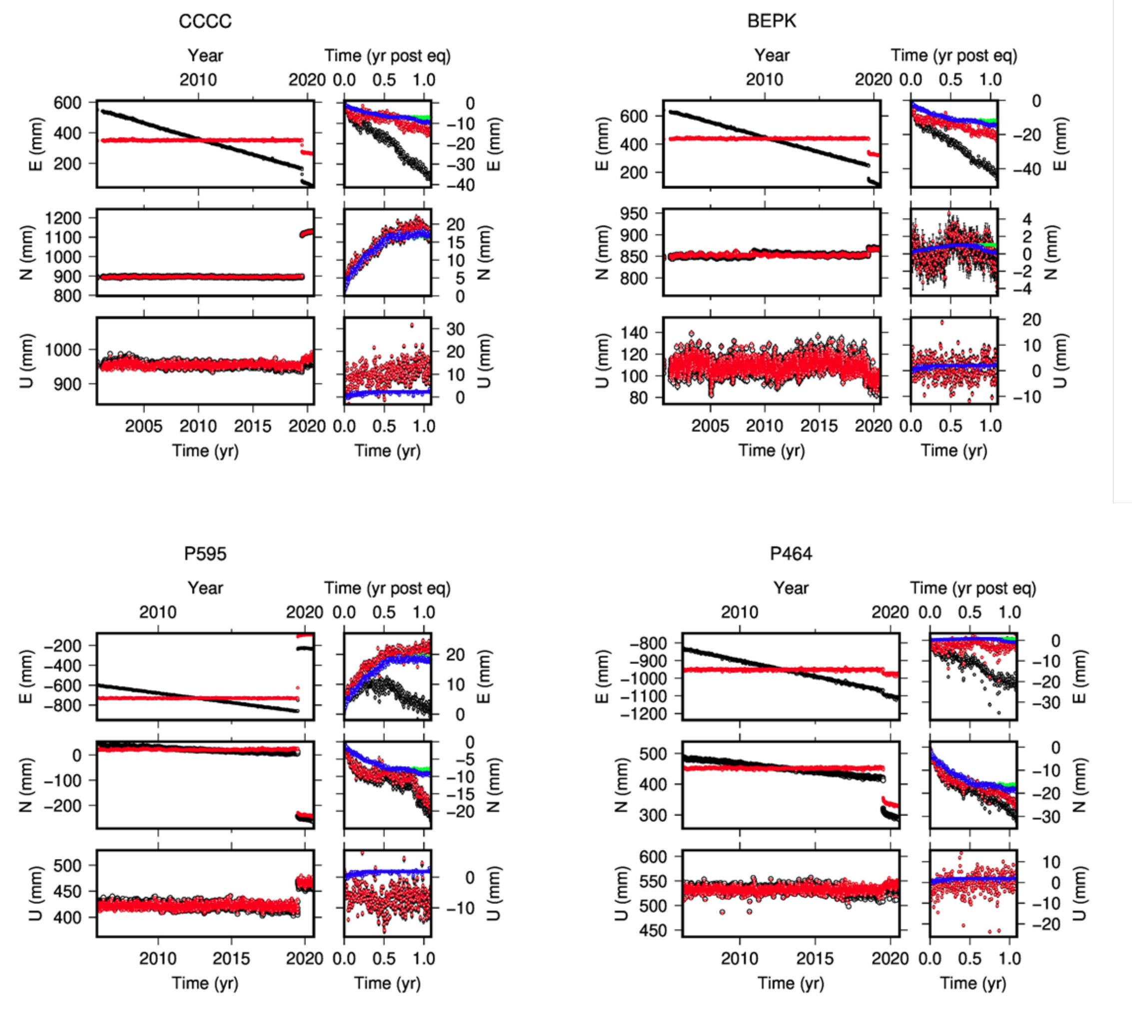


DATA

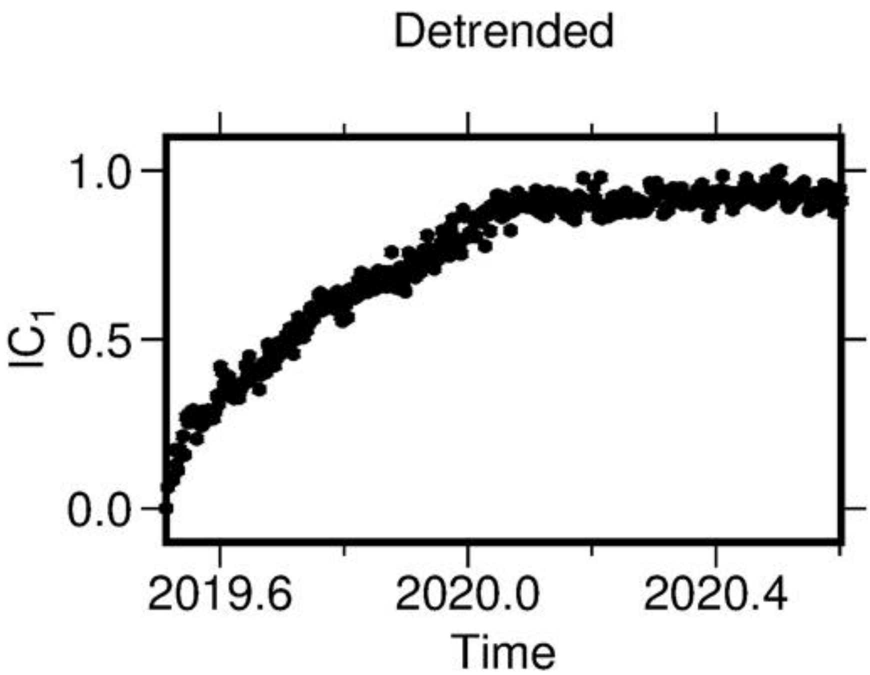
GPS

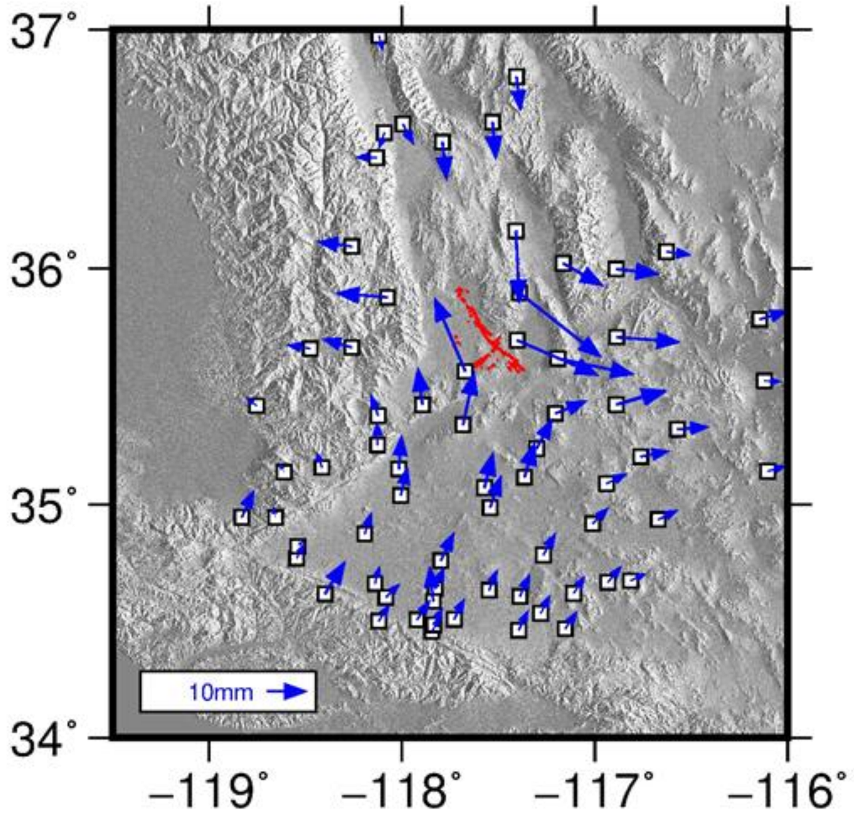
- Use daily GPS timeseries from the Nevada Geodetic Laboratory (http://geodesy.unr.edu/NGLStationPages/GlobalStationList)
- Initially use trajectory modelling on pre-Ridgecrest data to estimate and remove linear trend.
- We use variational Bayesian Independent Component Analysis (vbICA, Gualandi et al., 2016 (https://doi.org/10.1007/s00190-015-0875-4)) on detrended post-seismic data, to identify signals associated with postseismic deformation. This technique decomposes timeseries data into statistically independent components.

$$\mathbf{X_{ICA}} = \mathbf{U_{ICA}}\mathbf{\Sigma_{ICA}}\mathbf{V_{ICA}^T} + \mathbf{N}$$

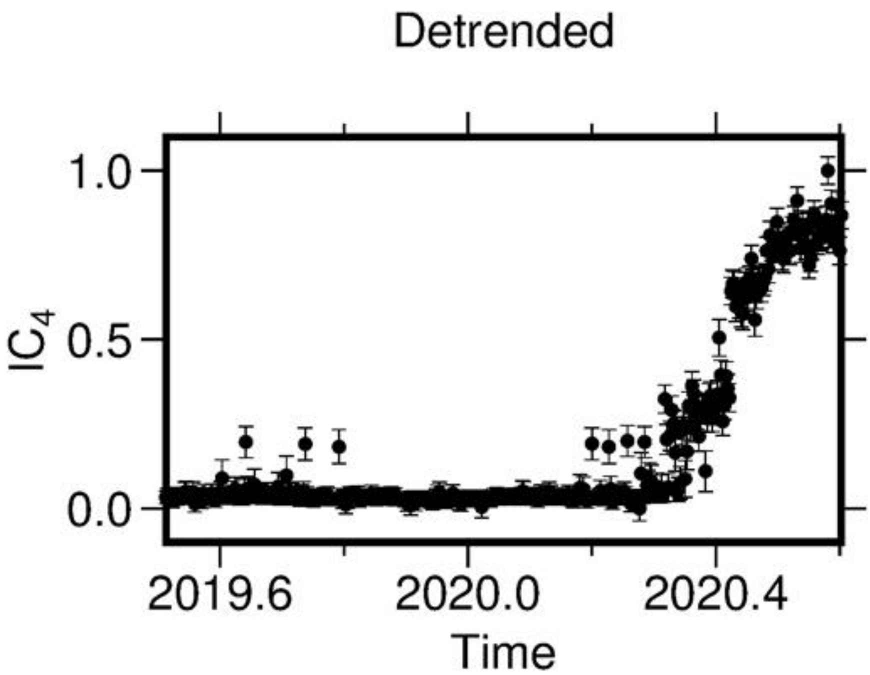


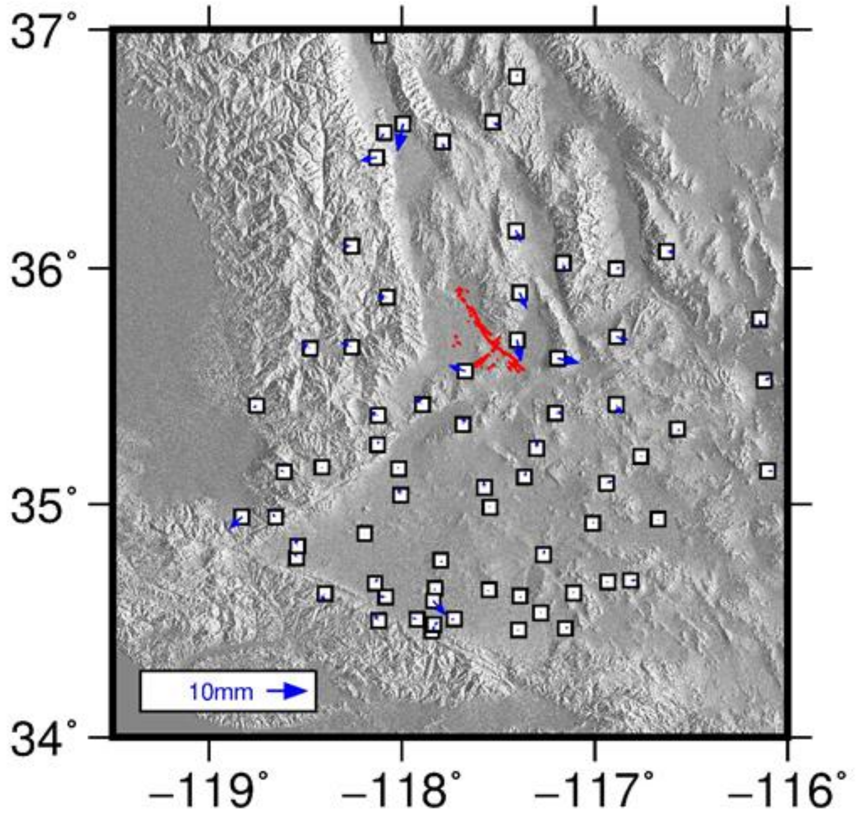
Above: steps in GPS processing. Left panels show timeseries from 2007 - July 2020, right panels zoom in on postseismic data with displacements set to 0 on 7th July. Black - original daily timeseries, red- detrended, green - horizontal timeseries reconstructed using only 1st independent component (IC1 below), blue - reconstruction using 2 horizontal components, one for vertical.





Top panel: temporal part of first independent component, bottom panel: spatial component. Red lines show mapped USGS surface ruptures.



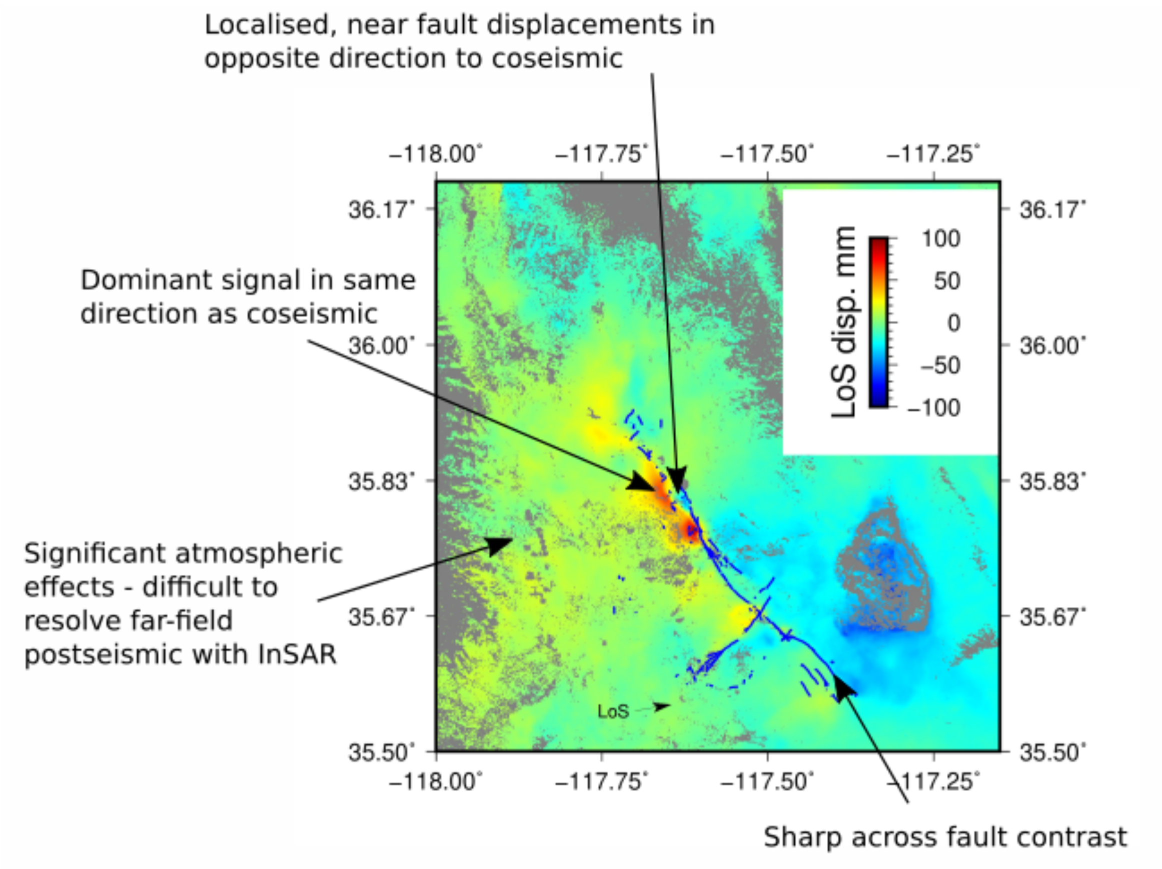


Much lower amplitude IC4 - still shows similar spatial pattern to IC1 so likely to also be associated with post-seismic deformation.

Key Observations

- Postseismic displacements of up to a few cms are observed in the first year after the Ridgecrest earthquakes.
- The pattern of GPS displacements is similar to the coseismic displacement pattern.
- The postseismic displacement requires two independent components, one of which starts about 9 months after the earthquakes.

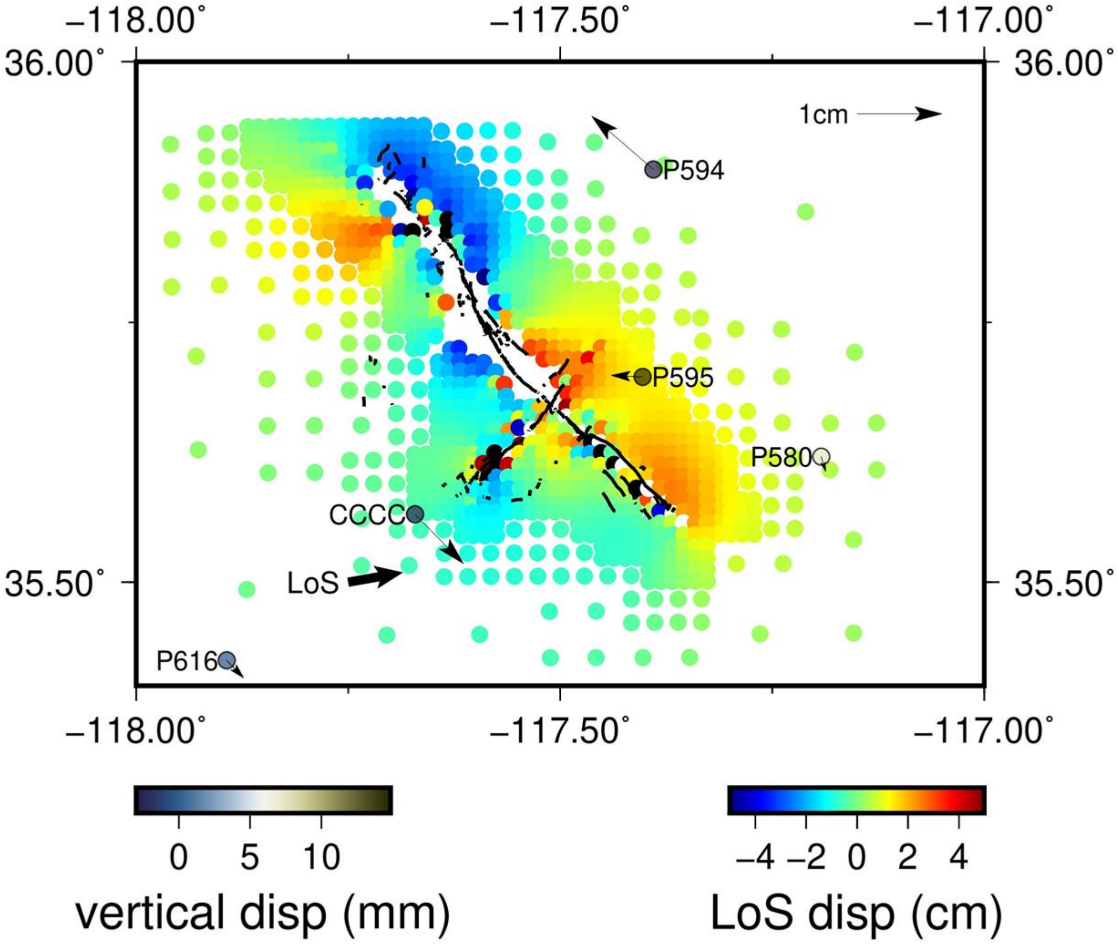
InSAR



Sentinel ascending track 64 - velocities from timeseries to September 2019 (Wang, personal communication, also see Wang & Burgmann, 2020 (https://doi.org/10.1785/0220190299)). Positive velocities are towards satellite.

POROELASTIC REBOUND

- Poroelastic rebound is expected to affect near-fault deformation, predominantly in the vertical.
- Expected surface deformation is difference between elastic deformation in undrained (Poisson's ratio 0.31) and drained (Poisson's ratio 0.25) medium (Peltzer1996 (https://doi.org/10.1126/science.273.5279.1202))

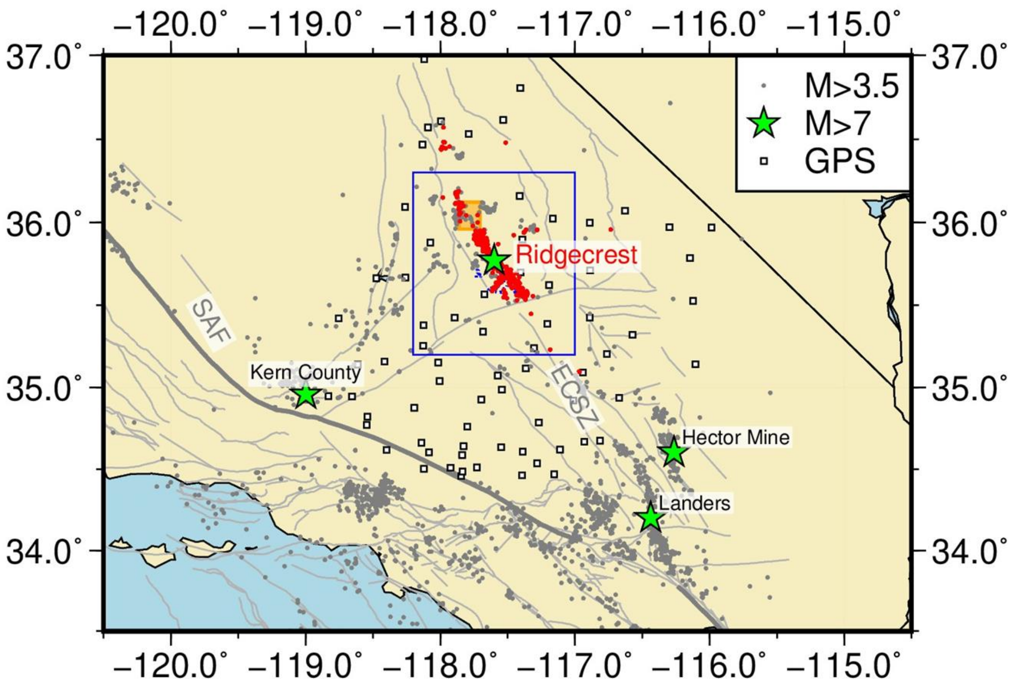


Modelled poroelastic deformation in LoS of Sentinel track A64 (using CSI (https://github.com/jolivetr/csi)). Positive motions are towards satellite. The predicted displacements are generally too large + in the opposite sense to GPS displacements. The exception is the patch of towards-satellite deformation to the NW which is consistent with InSAR observations.

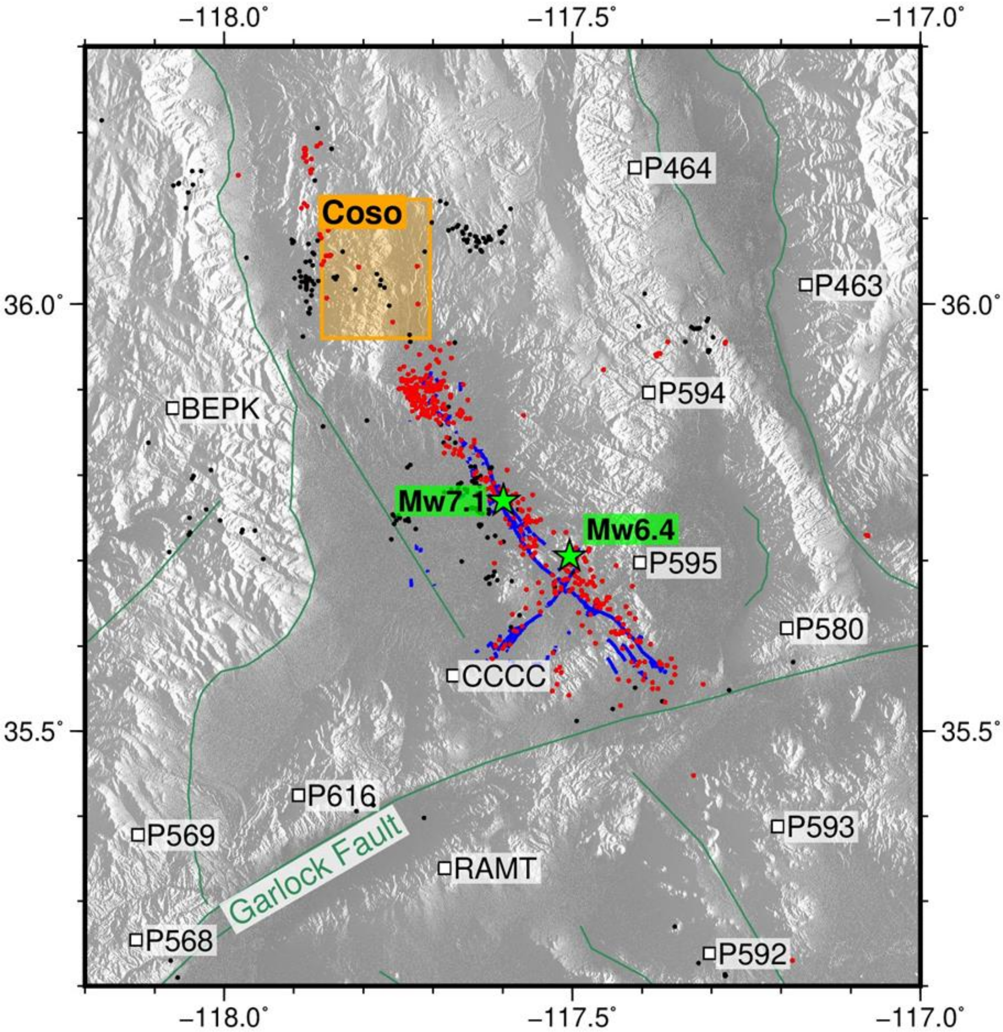
INTRODUCTION

[VIDEO] https://www.youtube.com/embed/nPn2CtJhFOg?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

I will be available to answer questions/show you around on 15th December between 6-8am PST (14-16 GMT) and 9-11am PST (17-19 GMT). If these times aren't convenient please drop me an email.



The 2019 Ridgecrest earthquakes occurred in the East California Shear Zone (ECSZ) above, a region of distributed right-lateral faulting east of the San Andreas Fault (SAF) which has accommodated several recent Mw7+ earthquakes (green stars).

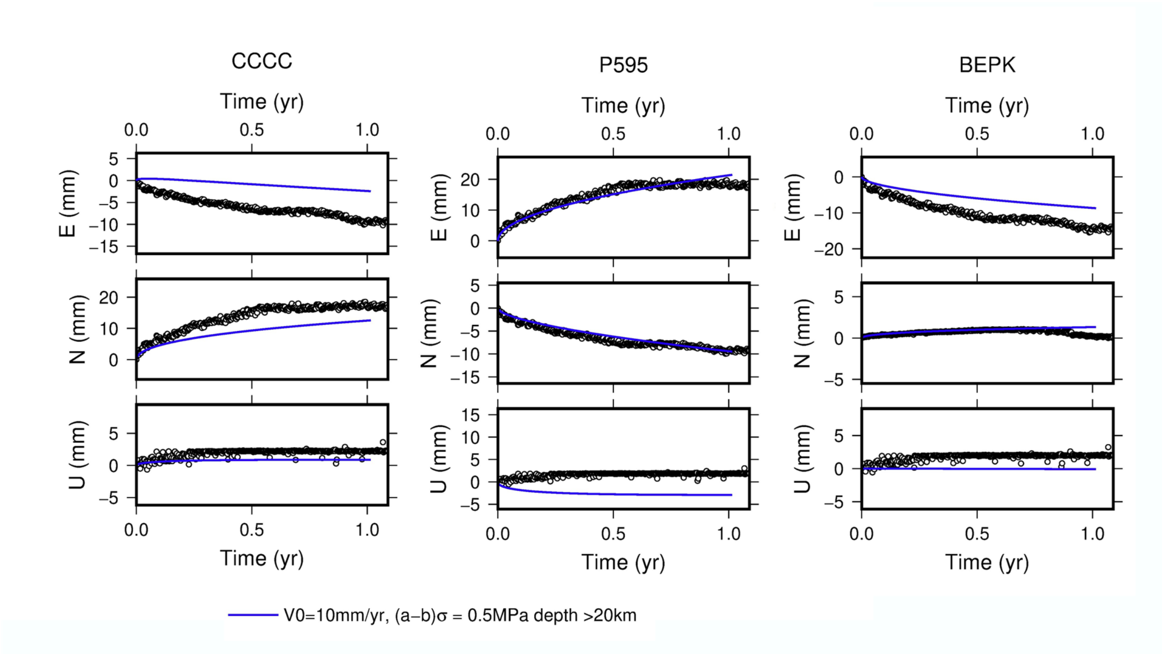


Postseismic deformation from large earthquakes such as the Ridgecrest earthquakes allow us to probe the rheology of the lower crust and upper mantle. In particular, this study explores:

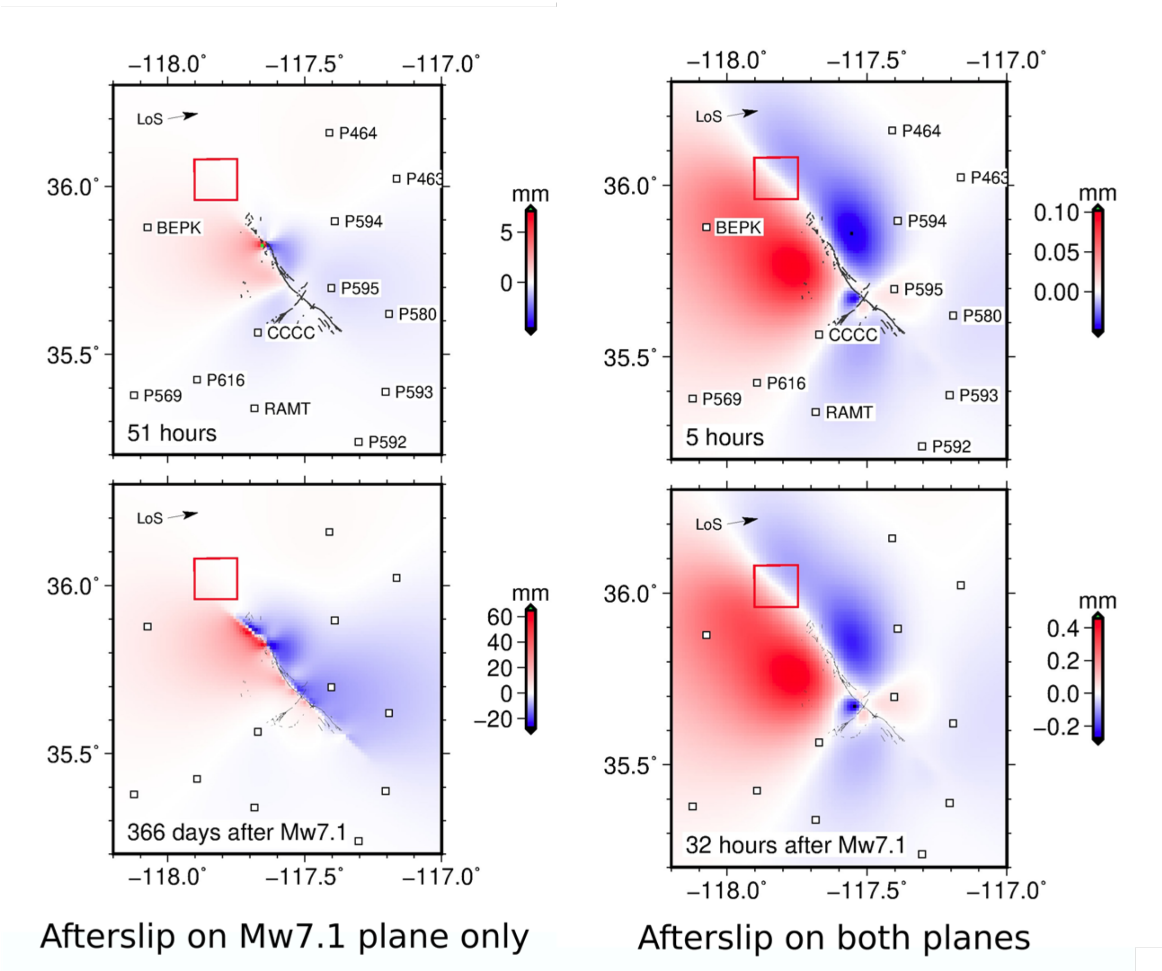
1. Whether the postseismic deformation from the Ridgecrest earthquakes is consistent with previous rheological models of this region
2. What the anticipated effect of local rheological variations, such as those associated with high geothermal gradients (Monastero et al., 2005 (https://doi.org/10.1130/B25600.1)) in the Coso geothermal region, is on post-seismic deformation, and what scales of rheological variation (both spatial and material) are required for rheological heterogeneity to be geodetically observable.

AFTERSLIP

- We model afterslip driven by coseismic stress changes using a rate-strengthening friction law in RELAX (Barbot et al. 2009 (https://doi.org/10.1029/2008JB005748) and Barbot & Fialko, 2010 (https://doi.org/10.1111/j.1365-246X.2010.04678.x))
- Initially we use a single afterslip plane (an extension of the Mw7.1 coseismic plane - below), but some GPS stations show insufficient motion (e.g. CCCC).



- Preliminary modelling (below) suggests that including the Mw6.4 plane will help to fit the sign of displacements at GPS stations such as CCCC.



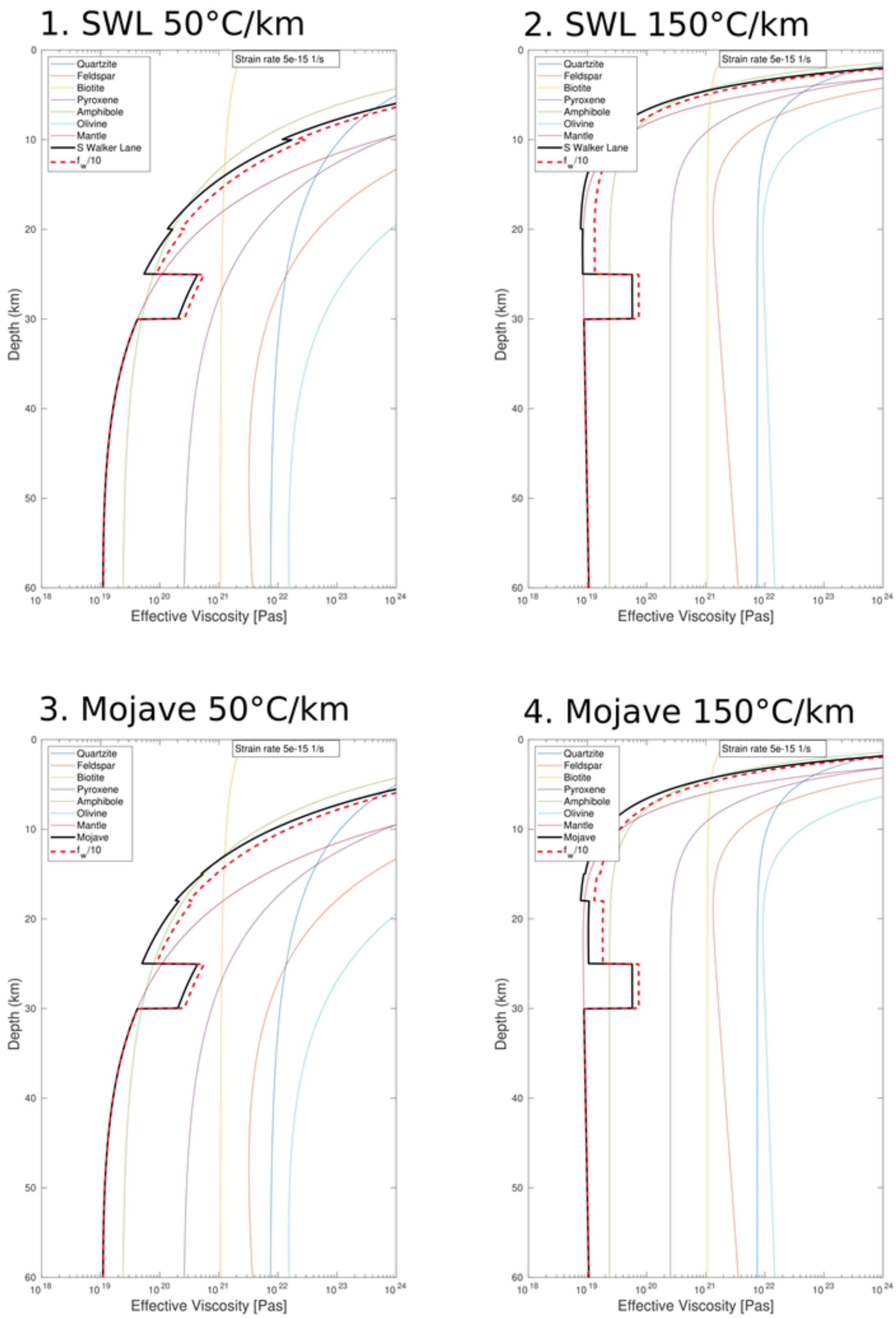
In the models above (a-b)σ=0.5MPa at depths >20km, with a layered structure above. Note the different time and displacement scales. Displacements are shown in the Sentinel 1A ascending track 64 line of sight, with positive motion towards the satellite.

VISCOELASTIC

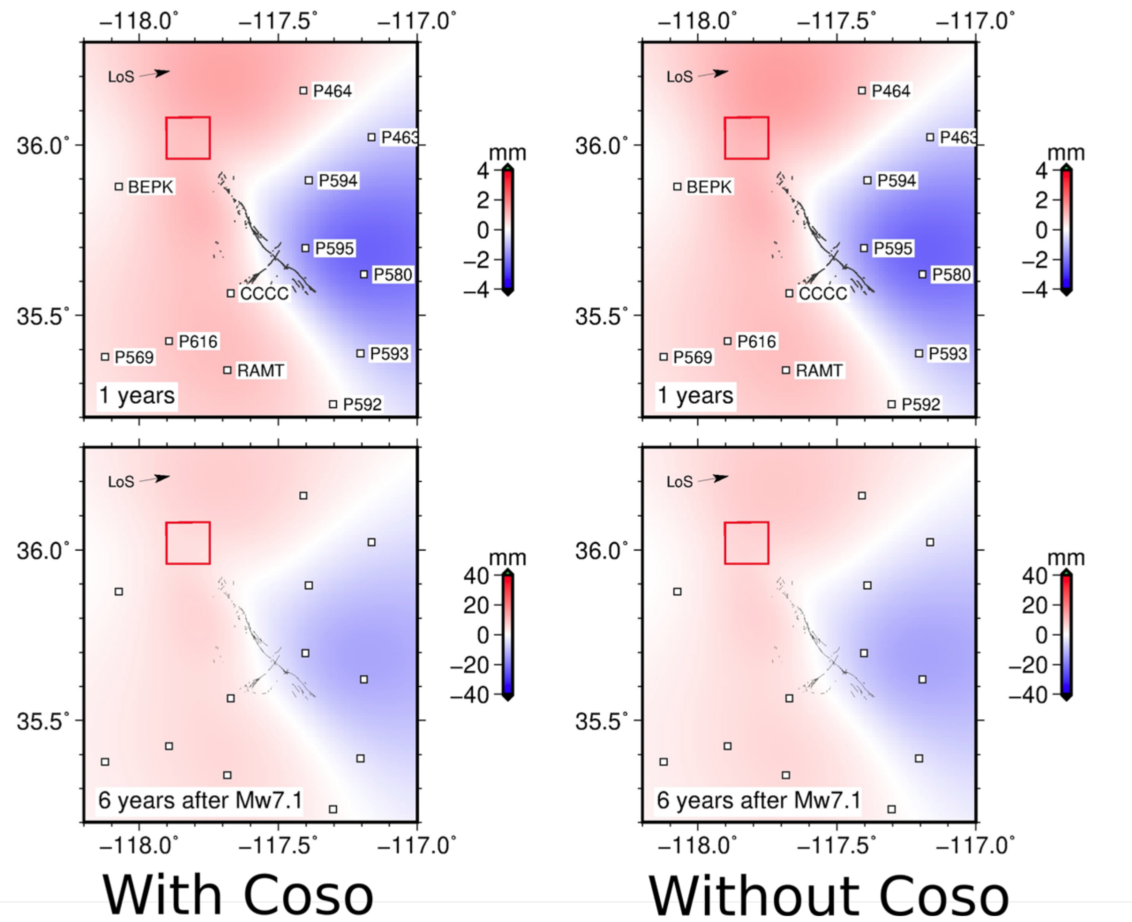
We model the expected deformation of lower crustal and upper mantle rheology from the Community Rheology Model (https://www.scec.org/research/crm) in response the the Ridgcrest earthquakes. We consider 4 cases:

1. South Walker Lane crustal structure with a geothermal gradient of 50°C/km
2. South Walker Lane crustal structure with a geothermal gradient of 150°C/km in the Coso region
3. Mojave desert crustal structure with a geothermal gradient of 50°C/km
4. Mojave crustal structure with a geothermal gradient of 150°C/km in the Coso region

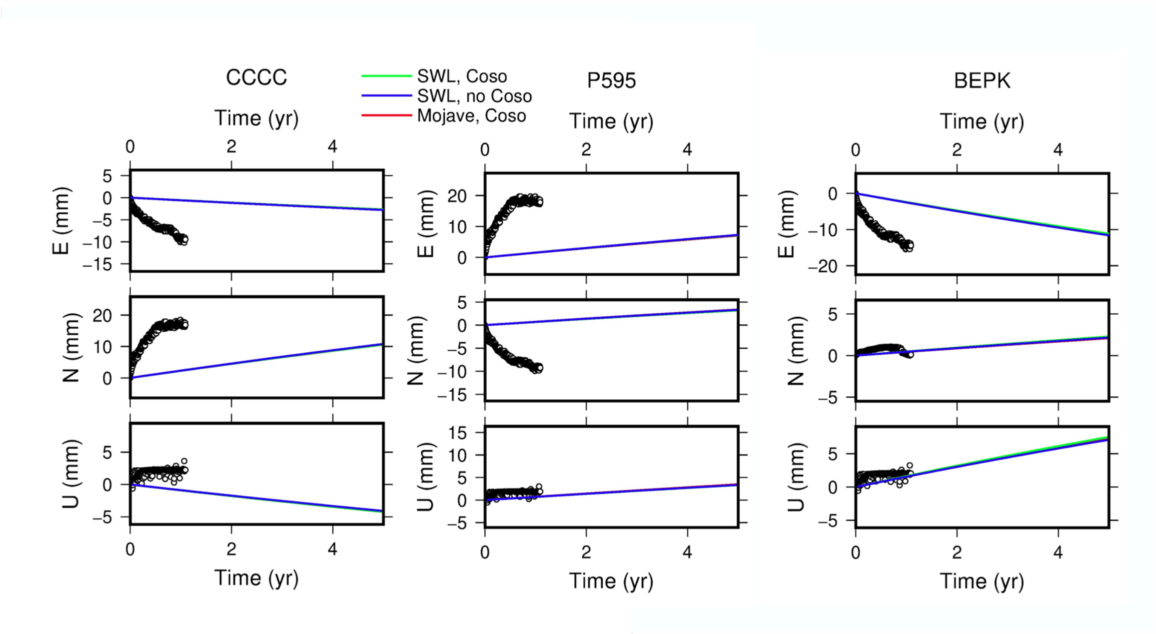
Using the proposed rheologies for both the Mojave desert and South Walker Lane allows us to test whether we would expect to see sigificantly different geodetic signals if the Garlock fault represents a structural boundary between these tectonic domains.



There is little difference in effective viscosity between the Mojave and South Walker Lane rheologies, but the higher geothermal gradients are expected to alter the viscosity structure substantially (note that we have not considered compositional variations associated with the Coso geothermal field which might also have an effect).



Above - modelled surface displacements resulting from the Mw7.1 earthquake in the CRM South Walker Lane rheology after 1 year and 6 years - left with a region of high geothermal gradients in the red box (Coso geothermal region), right- with uniform geothermal gradients. Displacements are projected into the line of sight corresponding to Sentinel 1A ascending track 64, with positive motion towards the satellite. The presence of the Coso geothermal field has very little impact on the predicted surface displacements.



Above - modelled GPS displacements due to viscoelastic deformation and observed GPS displacements. There is no observable difference in displacements between models with and without Coso, or between the Mojave and South Walker Lane rheologies (all model lines appear blue because they plot on top of each other). The relaxation times associated with these rheologies are too long to explain initial postseismic transients, but these models use the effective viscosity at a given strain rate as the Maxwell viscosity, using a Burgers rheology/allowing strain-rate dependence would lead to more rapid deformation at earlier times.

AUTHOR INFORMATION

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