Testing rheological models for creep events using their temporal evolution

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ENVIRONMENTAL RESEARCH DOCTORAL TRAINING PARTNERSHIP
Natural Environment Research Council

Background

Fault creep is observed along many faults worldwide (Titus et al., 2011) and is known to accumulate in bursts of slip punctuating a steady slip (e.g., Gittins & Hawthorne, 2022; Gladwin et al., 1994)

Despite observations of creep events dating back to the mid-1900s, there is still no consensus about the driving mechanism behind them, with many models proposed (e.g., Bilham & Behr, 1992; Wei et al., 2013; Wesson, 1988).

Here we use the shape of the creep event to understand better the driving rheology of creep events.
We model the shape of creep events using a variety of rheological laws in both the frictional and ductile regime.

Data

We use data from 17 USGS creepmeters, 4 USGS strainmeters and 4 PBO strainmeters installed along the creeping section of the San Andreas Fault (Figure 1).

The creepmeter records are decades-long time-series datasets with slip values recorded every 10 minutes.

The USGS strainmeter records are decades-long time-series datasets with strain values recorded every 18 – 30 minutes.

The PBO strainmeter records begin in 2007 with strain values recorded every 10 minutes

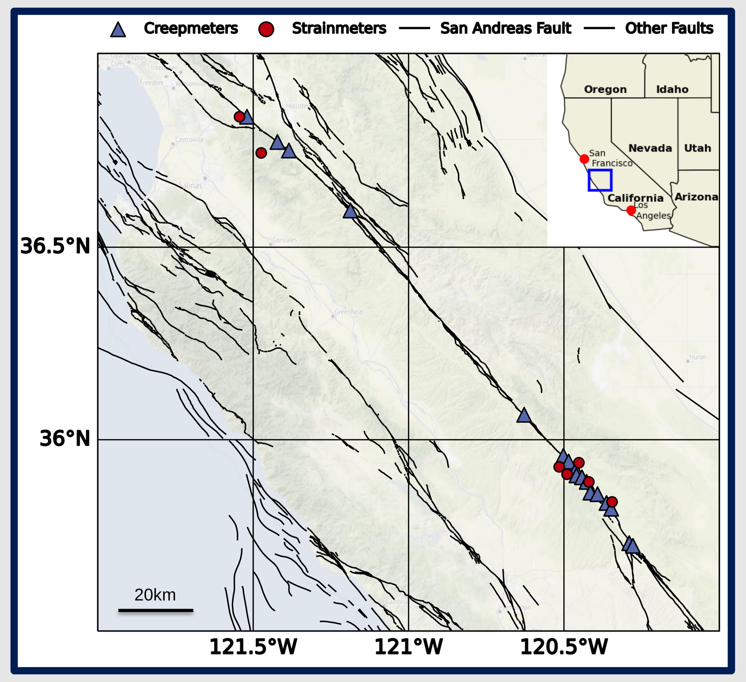

Figure 1: Map creepmeter locations used in this study. Faults in central California are shown in black.

Rheological Models Tested

We test different rheologies to see which best describes the temporal evolution of creep events:

- Linear Viscous Flow – e.g., Montési, 2004.
- Power-Law Viscous Flow – e.g., Wesson, 1988, Montési, 2004.
- Velocity Strengthening Friction - Steady State – e.g., Montési., 2004, Helmstetter & Shaw, 2009.
- Velocity Strengthening Friction - Stress >> Steady State – e.g., Helmstetter & Shaw, 2009.
- Rate Dependant Friction – e.g., Helmstetter & Shaw, 2009.

Phase splitting

Creep events often have more than one phase of slip.

Each of these slip phases needs to be modelled for shape separately, possibly with some influence/residual slip from the first phase existing in the second.

We manually pick the separations in the phases of slip to isolate:

- *Phase 0*: Slip before the event.
- *Phase 1*: Slip in the first phase of the event.
- *Phase 2*: Slip in a second phase of the event if it exists.

Methods and Preliminary Results

Does the creep event have one phase or two?

One Phase

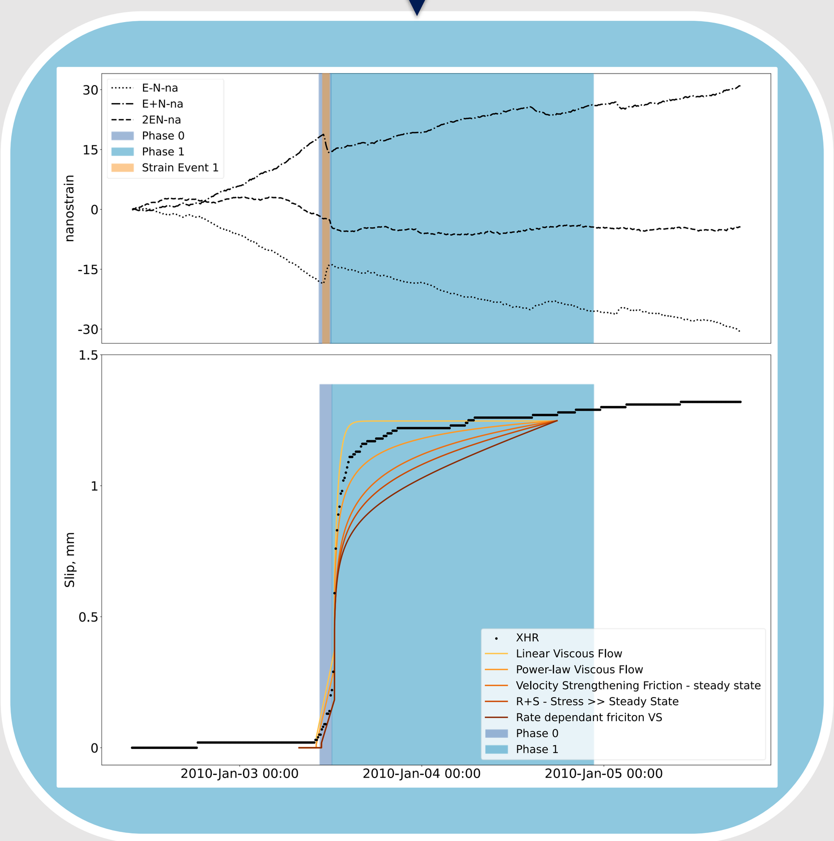

Figure 3: *Top.* Strainmeter record from B065 with a strain event highlighted. *Bottom.* Creep event recorded at Harris Ranch with different rheological models plotted. Vertical highlights on both plots show the different phases of the creep event.

Two Phases

Does the creep event have one strain step or two?

One Event

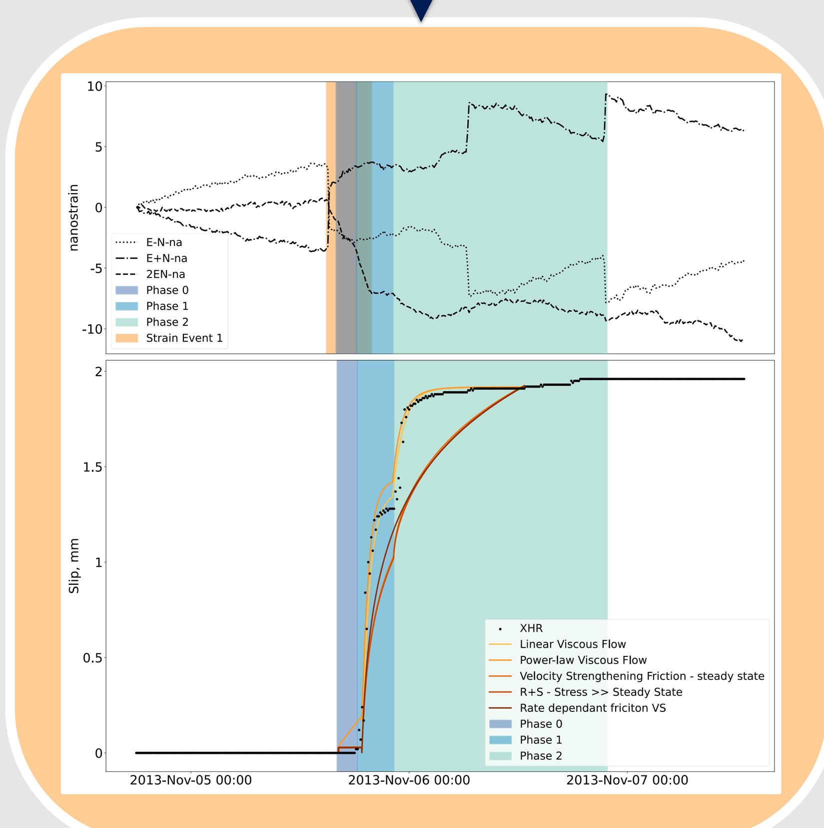

Figure 4: *Top.* Strainmeter record from B065 with a strain event highlighted. *Bottom.* Creep event recorded at Harris Ranch with different rheological models plotted with both phases fitted together. Vertical highlights on both plots show the different phases of the creep event.

Two Events

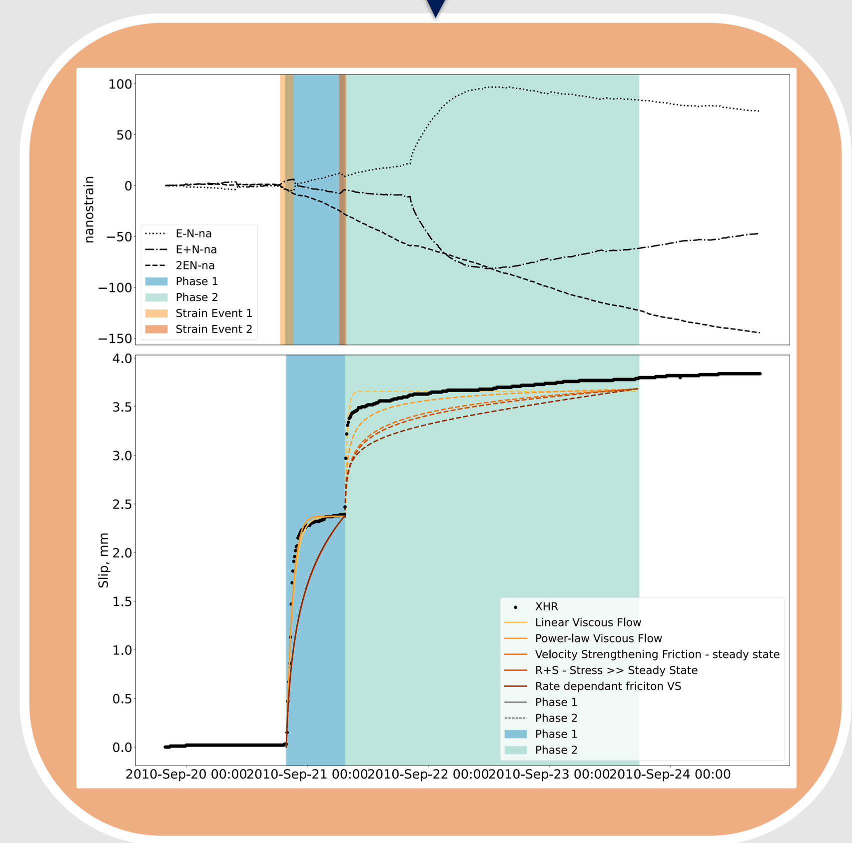

Figure 5: *Top.* Strainmeter record from B065 with two strain events highlighted. *Bottom.* Creep event recorded at Harris Ranch with different rheological models plotted with both phases fitted separately. Vertical highlights on both plots show the different phases of the creep event

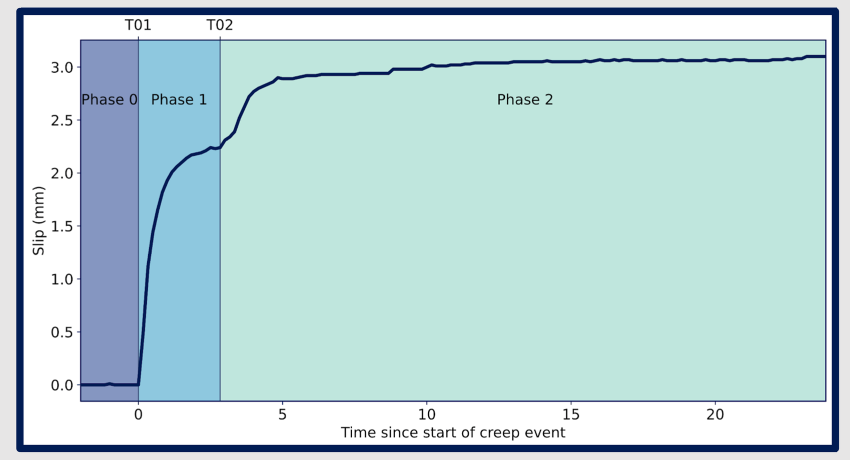

Figure 2: Example creep event from the Harris Ranch creepmeter in January 1992. Here the different *Phase 0*, *Phase 1*, and *Phase 2* are shaded to indicate their durations.

We fit the two different phases of the creep event both together and separately, allowing for us to account for the association of some creep events with single or double strain steps prior to the onset of the different phases.

Together	Separate
$\delta = \begin{cases} V_s t + K, & t < T_{01} \\ V_s t + Rheology_1, & t > T_{01} \\ V_s t + Rheology_1 + Rheology_2 & t > T_{02} \end{cases}$	$\delta = \begin{cases} V_s t + K, & t < T_{01} \\ Rheology_1, & t > T_{01} \\ Rheology_2 & t > T_{02} \end{cases}$

Where δ is the slip, V_s is the background slip velocity prior to the event, t is time, K is the starting offset, T_{0X} is the start time of each new slip phase (Figure 2), and $Rheology_X$ is the rheological model used to model each slip phase. Here we focus on using the same rheology for both phases.

Fitting

To assess the fit of all these different rheologies we use a misfit function based upon the covariance matrix of the creepmeter data:

$$misfit = \frac{(\delta_{obs} - \delta_{pred})^T \cdot C^{-1} \cdot (\delta_{obs} - \delta_{pred})}{(\delta_{obs})^T \cdot C^{-1} \cdot (\delta_{obs})}$$

Where δ_{obs} is the observed slip, δ_{pred} is the predicted slip, and C is the covariance matrix.

We then perform a minimisation using the Nelder-Mead algorithm, within a basin hopping algorithm to find the best fit for each rheology.

Summary and Further Work

- We have tested different rheologies to try and explain the temporal evolution of creep events and find that a large proportion of creep events are fitted well by rheological laws in the ductile regime.
- Possible explanations for this observation include: a potentially weak fault, temporal evolution of creep events recorded at creepmeters is dominated by the properties of the material they are installed in (i.e., soil properties), or modelling the shape of creep events is not the best way to answer this question?
- We continue to work on this issue and hope to have more robust results from other creepmeters soon.
- Further work will involve using strainmeter data to try and constrain the along-depth extent of creep events.

References

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Acknowledgements

This work was supported by the UKRI Natural Environment Research Council grant number: NE/S007474/1. Creep data are provided by the United States Geological Survey and are available at https://earthquake.usgs.gov/monitoring/deformation/data/download.php. Strain data is available from two sources. Strain data is provided by the United States Geological Survey and the UNAVCO Plate Boundary Observatory and are available at https://earthquake.usgs.gov/monitoring/deformation/data/download.php and https://www.unavco.org/data/strain-seismic/bsm-data/bsm-data.html. The plotted fault traces are taken from the Quaternary fault and fold database for the United States, provided by the USGS and the California Geological Survey and accessed from the USGS website https://www.usgs.gov/natural-hazards/earthquake-hazards/faults.

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