17 years of hydrology-driven geodetic deformation in California's Sacramento Valley

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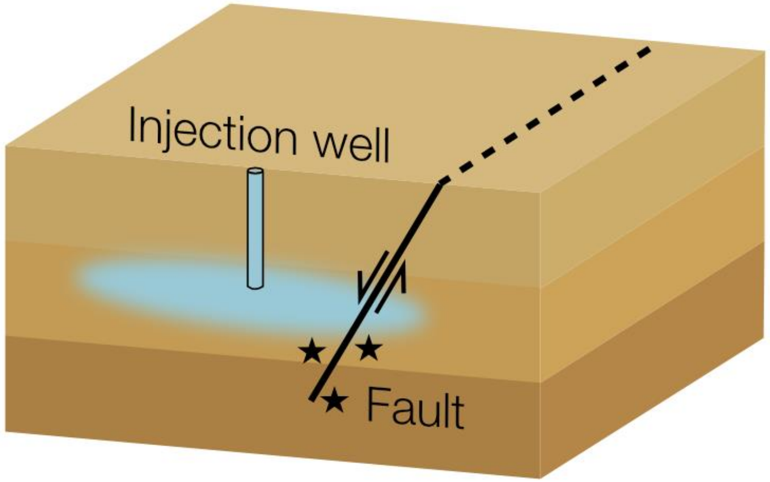
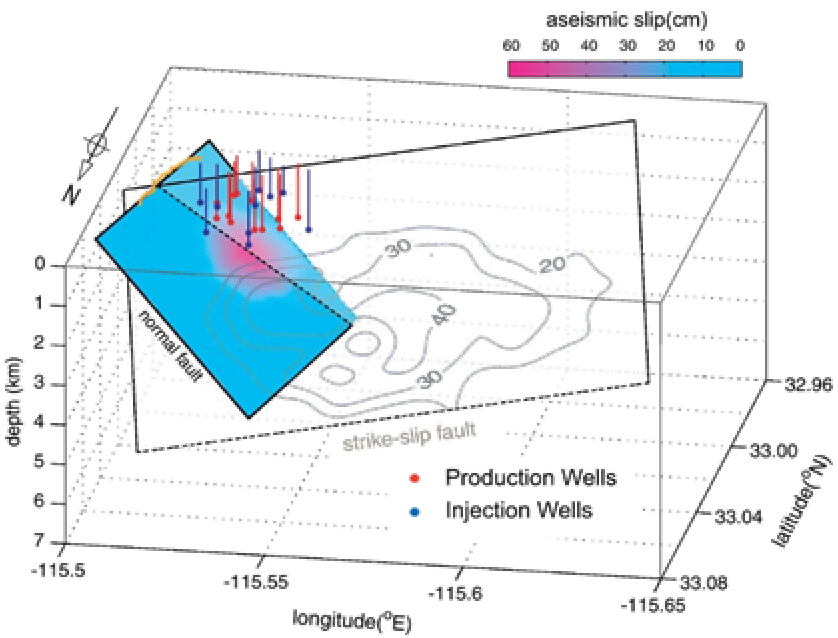
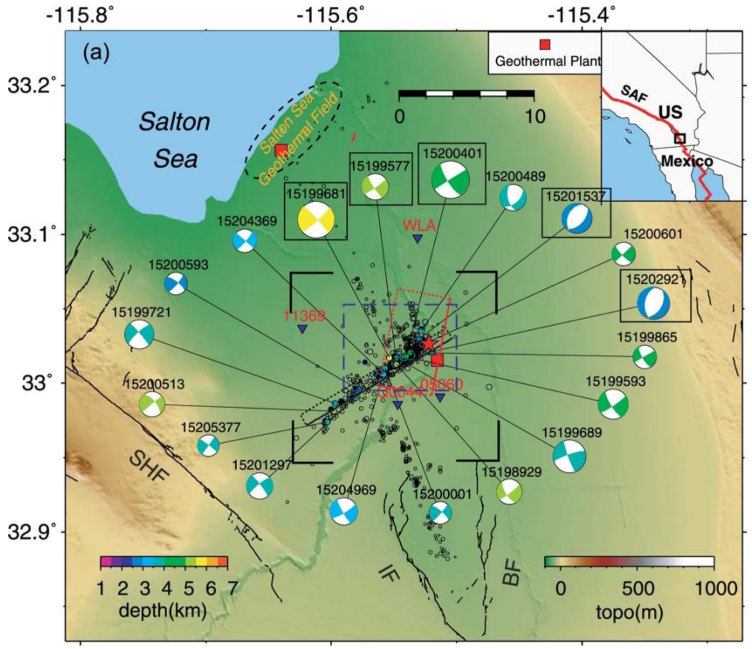
In collaboration with Kristel Chanard, Jean-Philippe Avouac, Manon Dalaison, Jérôme Fortin, Laurent Longuevergne, Luce Fleitout, Donald Argus, Louis-Marie Gauer & Romain Jolivet

How does water deform the solid Earth?



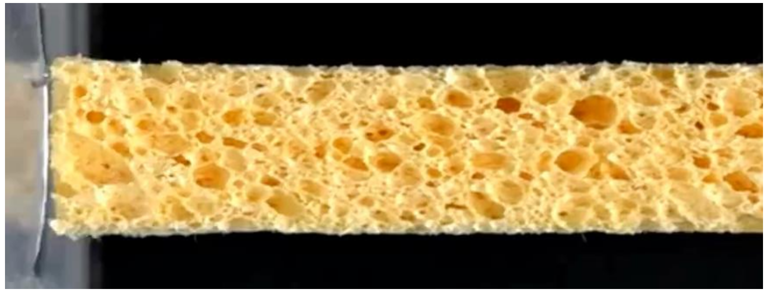
Fluid-induced fault slip
Aseismic + seismic





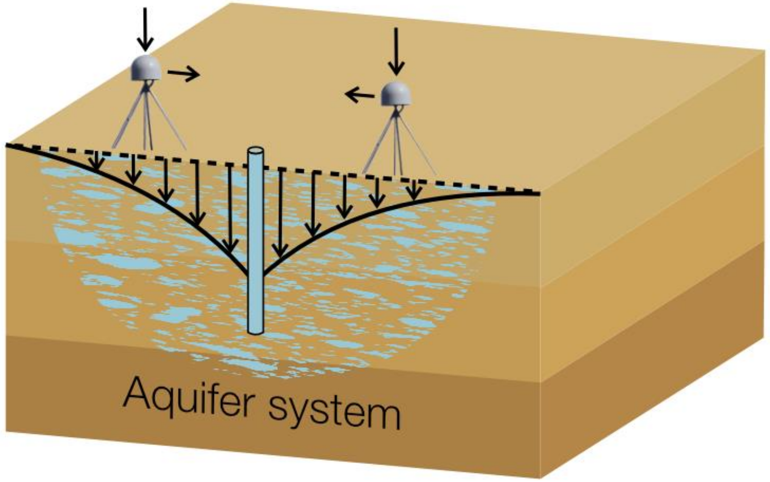
Exploitation at the Brawley geothermal field
linked to both seismic and aseismic slip (*Wei et al., 2015*)

How does water deform the solid Earth?



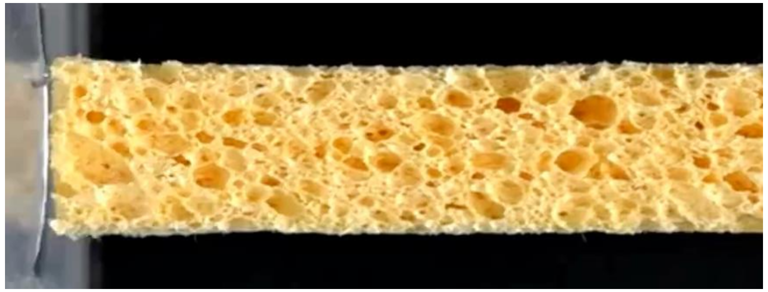
Ha et al. 2018

Fluid-induced fault slip
Aseismic + seismic



Porous response
Poroelastic + inelastic

How does water deform the solid Earth?



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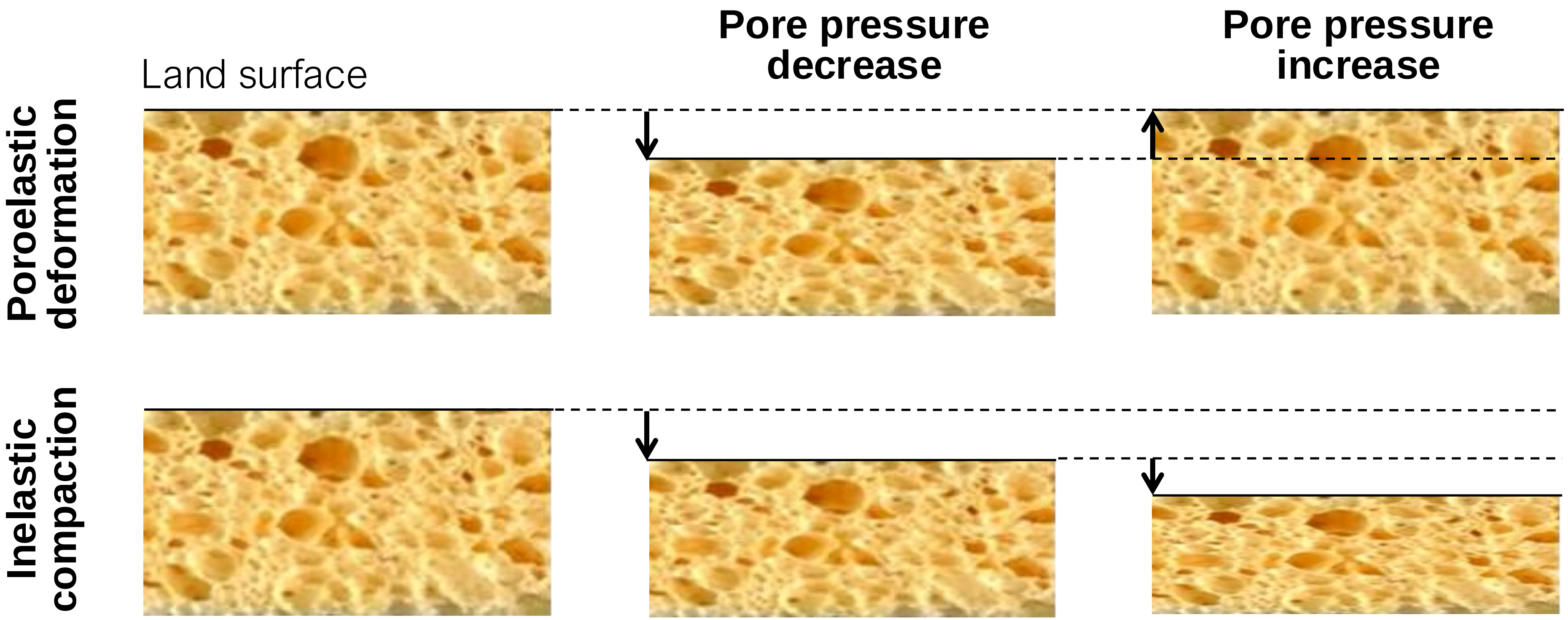
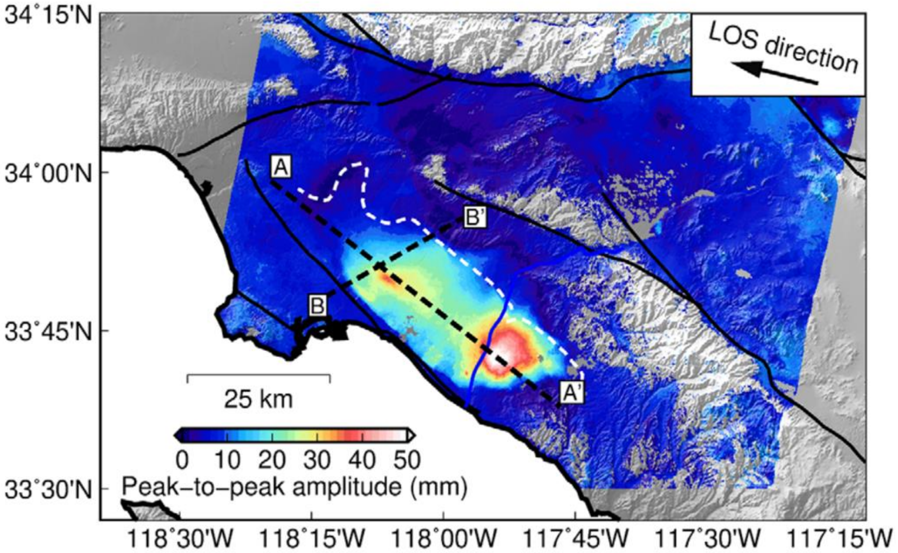
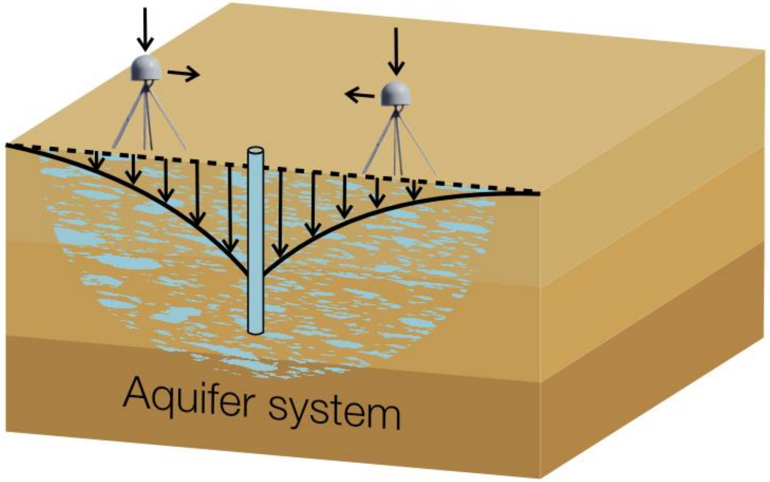


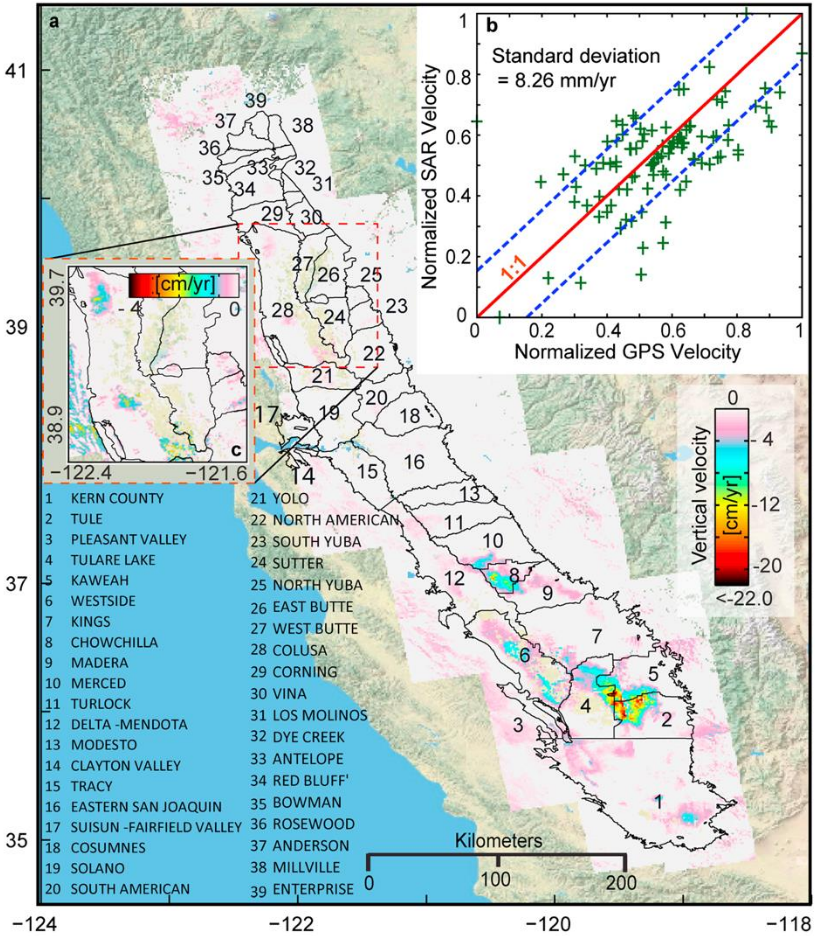
How does water deform the solid Earth?

Seasonal deformation of the
Los Angeles Basin
(*Riel et al., 2018*)





Porous response
Poroelastic + inelastic



Vertical velocities in the
Central Valley (*Ojha et al., 2018*)

How does water deform the solid Earth?

Fluid-induced fault slip
Aseismic + seismic

Porous response
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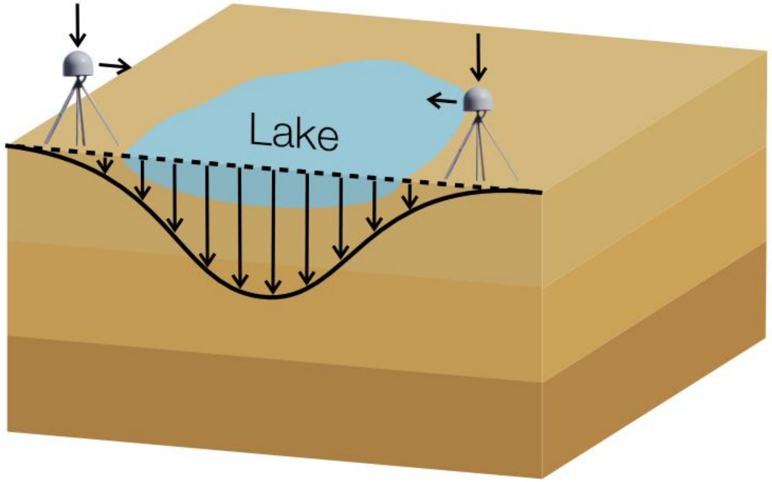
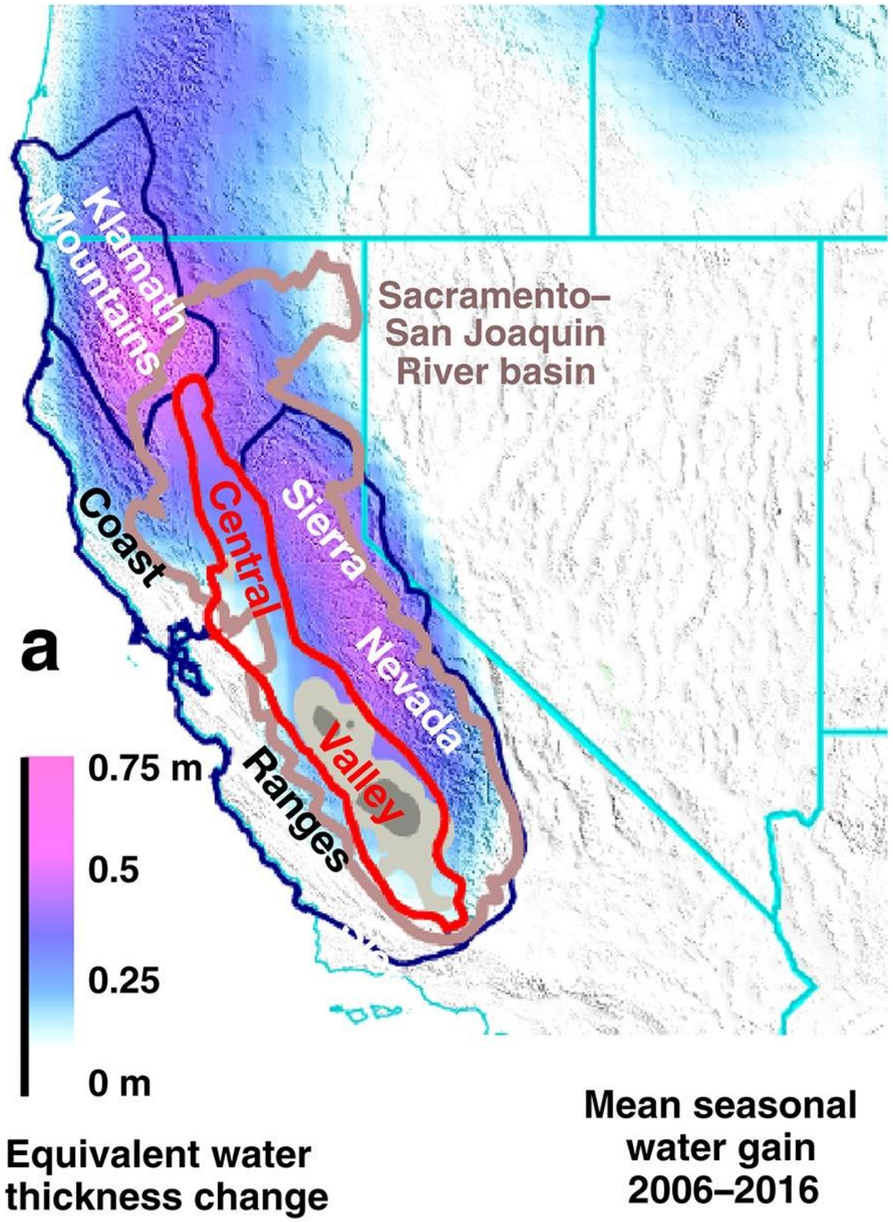
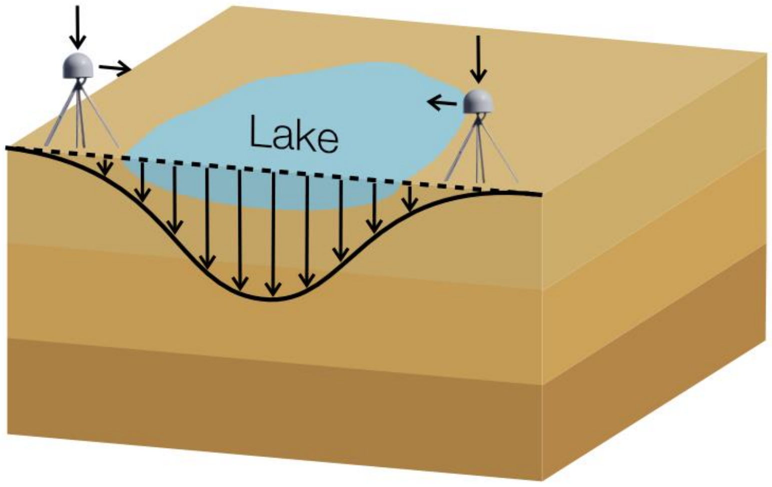


Hydrological loading
Elastic + viscoelastic

How does water deform the solid Earth?



Seasonal water mass fluctuations inferred from GPS displacements (*Argus et al. 2017*)

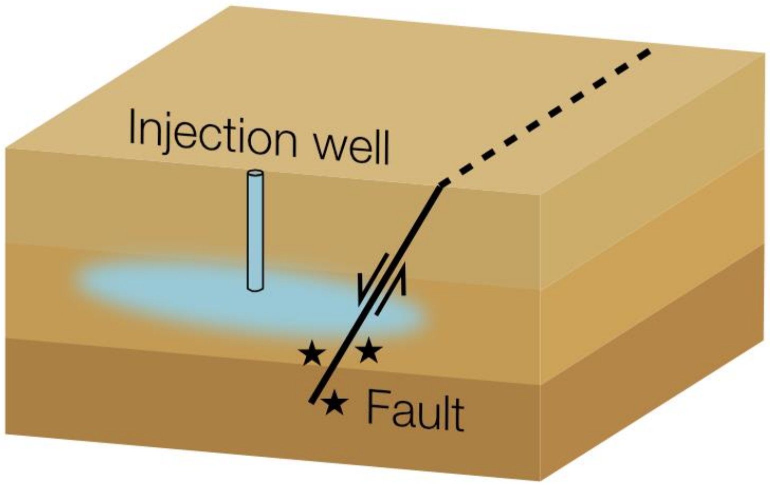


Hydrological loading

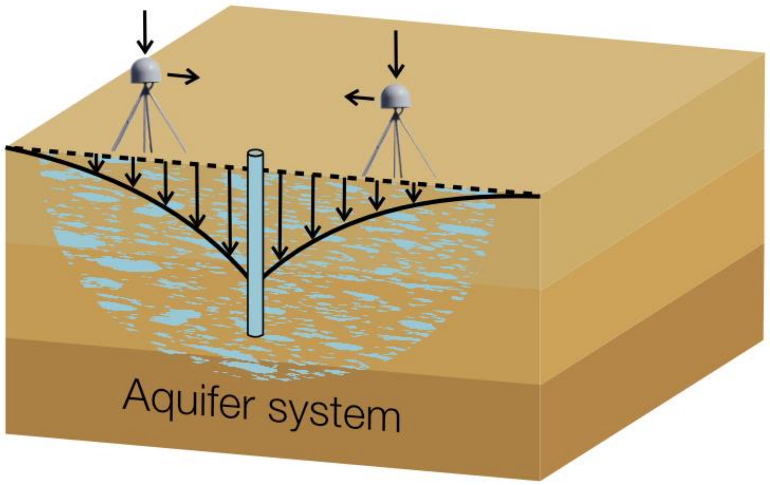
Elastic + viscoelastic

Why should SCEC scientists care about water-driven deformation ?

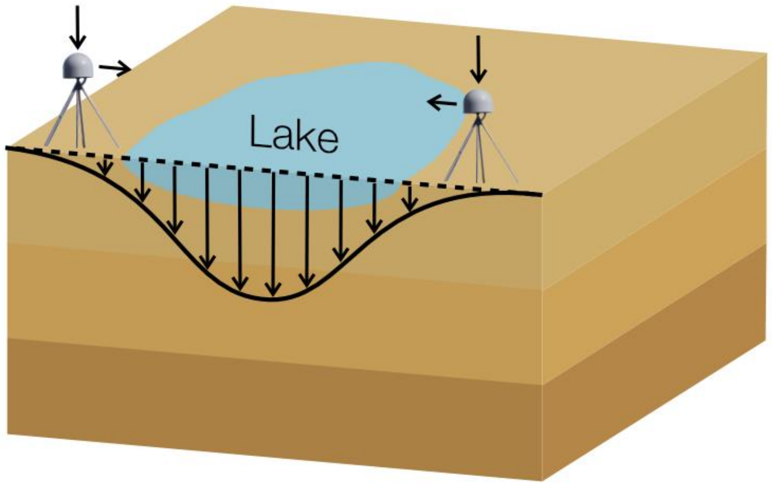
- ✓ Affects the stress state and fluid pressure in and around fault zones
- ✓ Enables extraction of tectonic signals in geodetic datasets
- ✓ Constrains the rheology and hydro-mechanical properties of the solid Earth
- ✓ Informs water resources management



Fluid-induced fault slip
Aseismic + seismic



Porous response
Poroelastic + inelastic

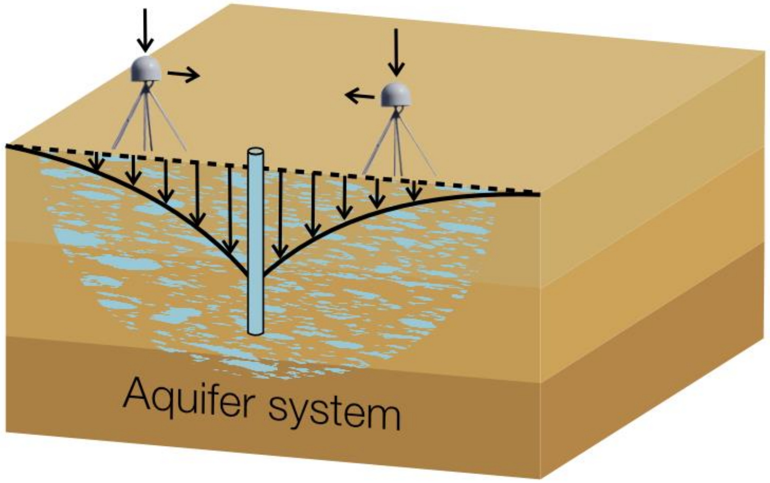


Hydrological loading
Elastic + viscoelastic

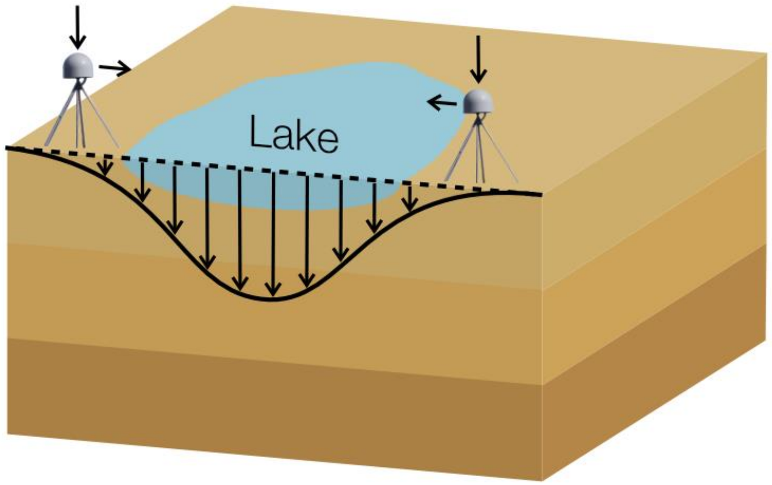
Objectives of the talk:

1. Showcase the power of modern satellite geodesy in measuring these deformation fields.
2. Demonstrate a multi-technique methodology to extract these deformation fields.
3. Highlight insights into rheology, fault-groundwater interactions, and aquifer storage.

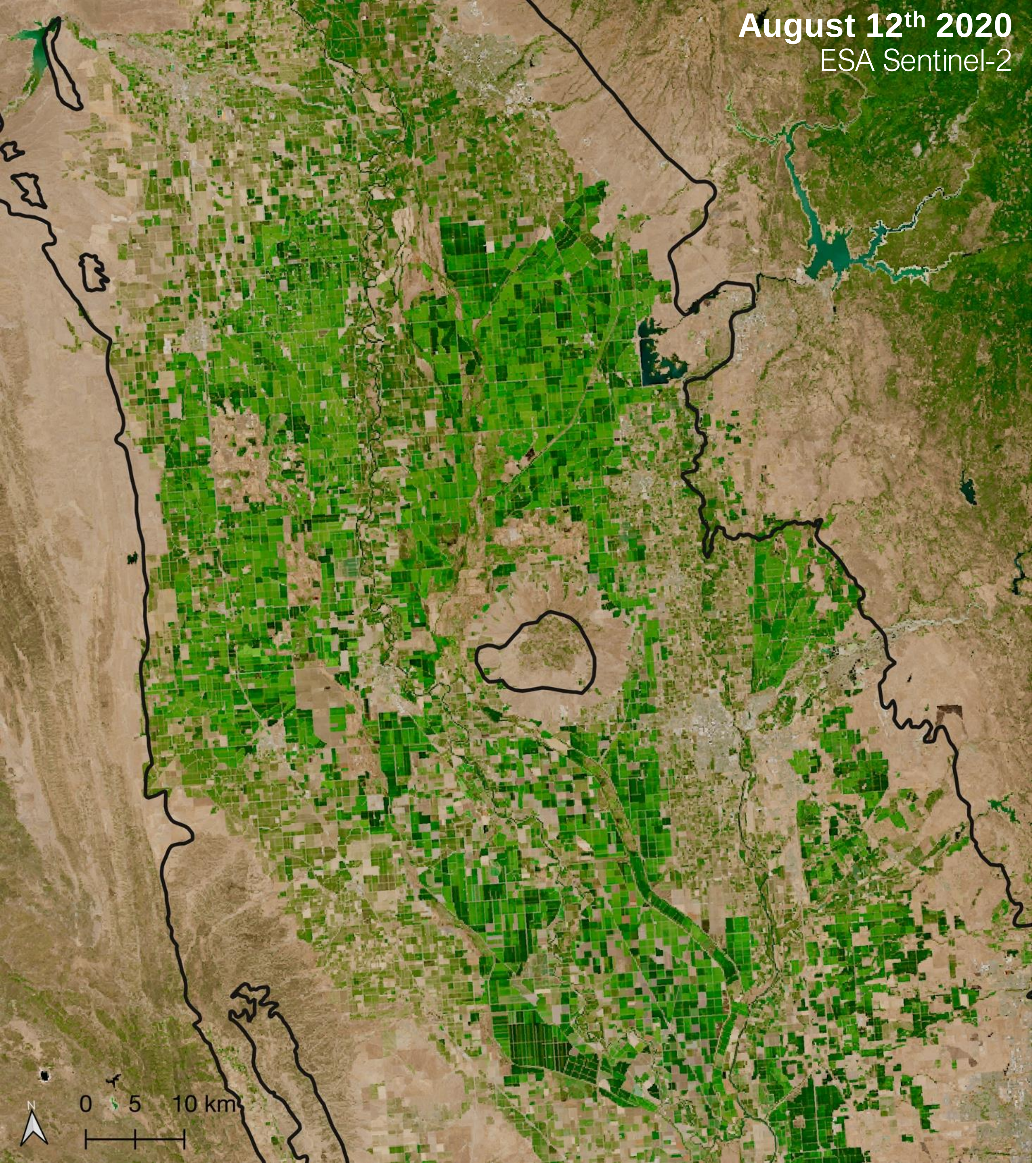
Fluid-induced fault slip
Aseismic + seismic



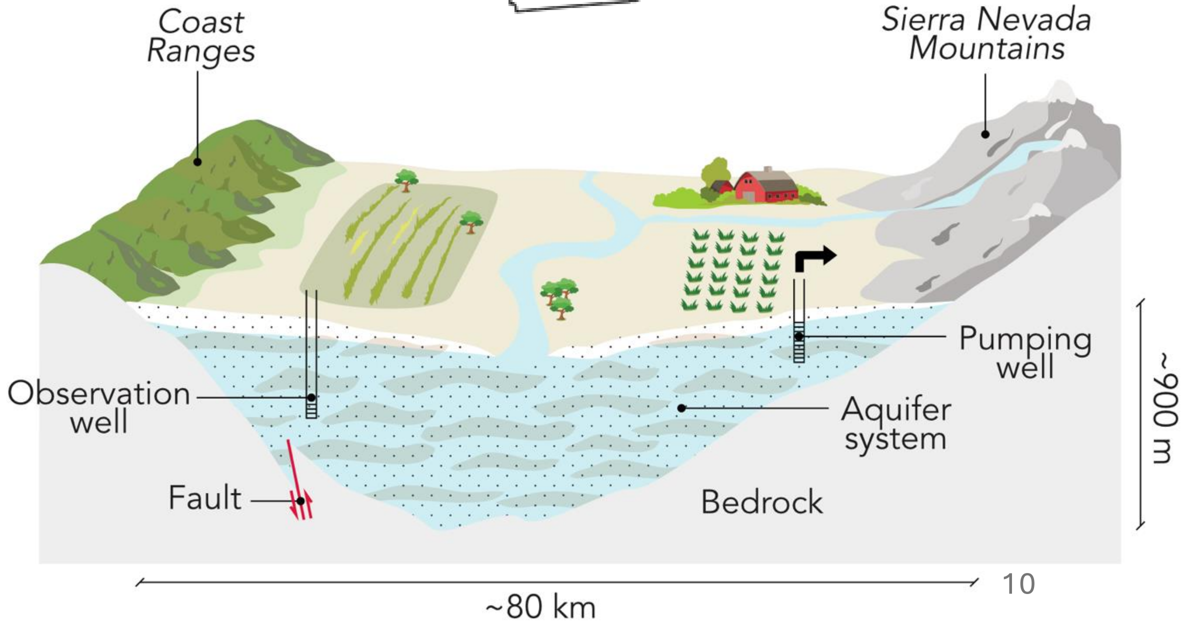
Porous response
Poroelastic + inelastic



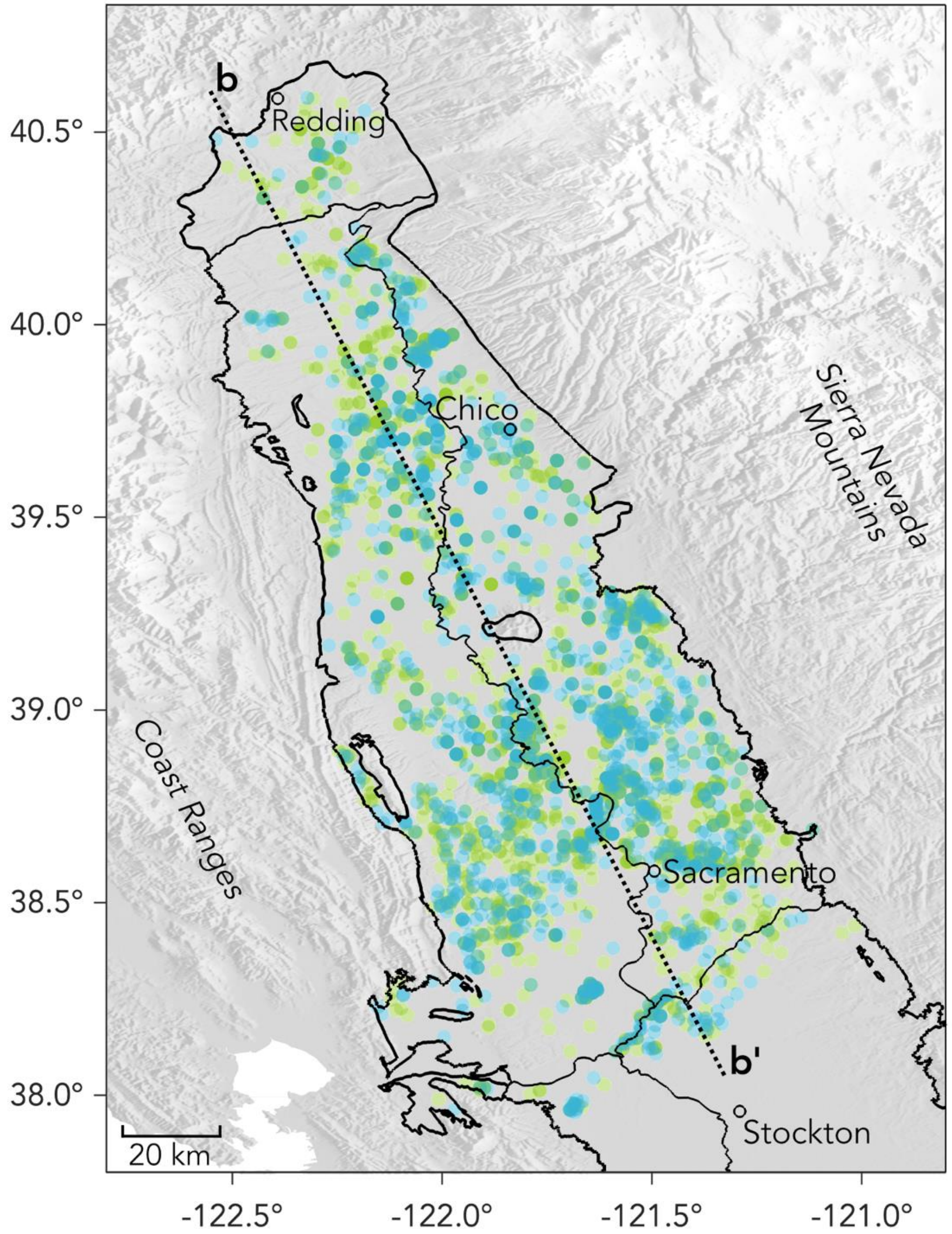
Hydrological loading
Elastic + viscoelastic



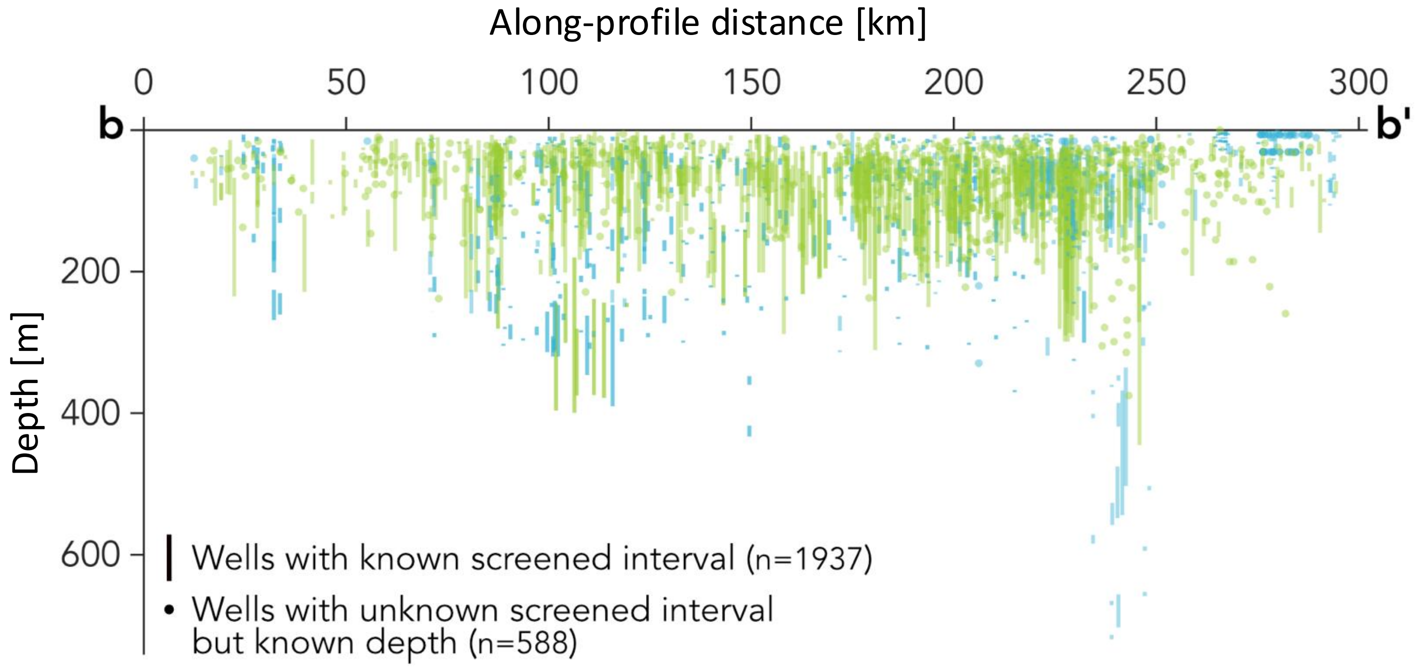
Case Study:
California’s Sacramento Valley



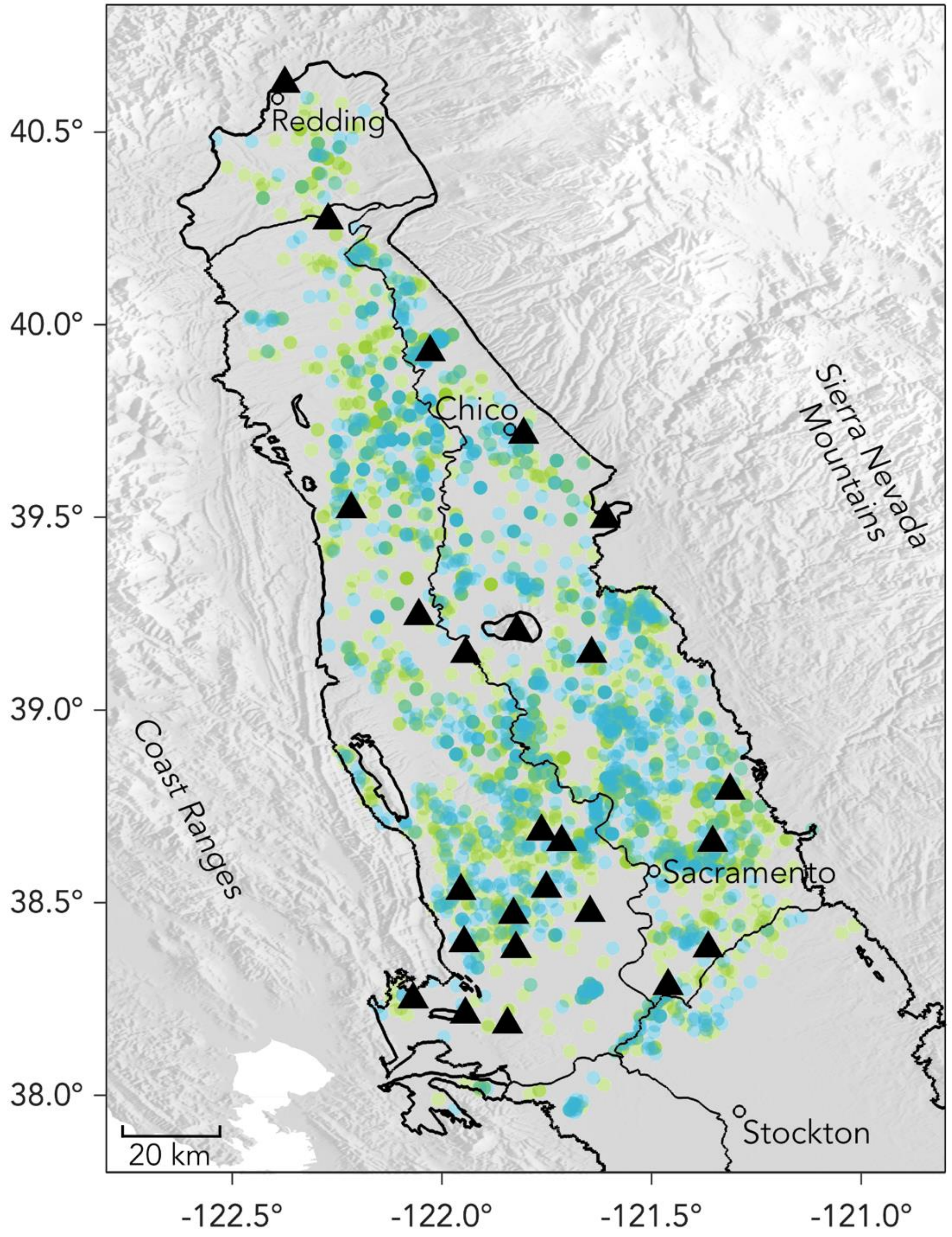
Geodetic & groundwater datasets in the data-rich Sacramento Valley



- Observation wells (n = 1163)
- Pumping wells (n = 1814)
  - ✓ Monthly “continuous” and “periodic” groundwater level time series maintained by California’s Department of Water Resources



Geodetic & groundwater datasets in the data-rich Sacramento Valley



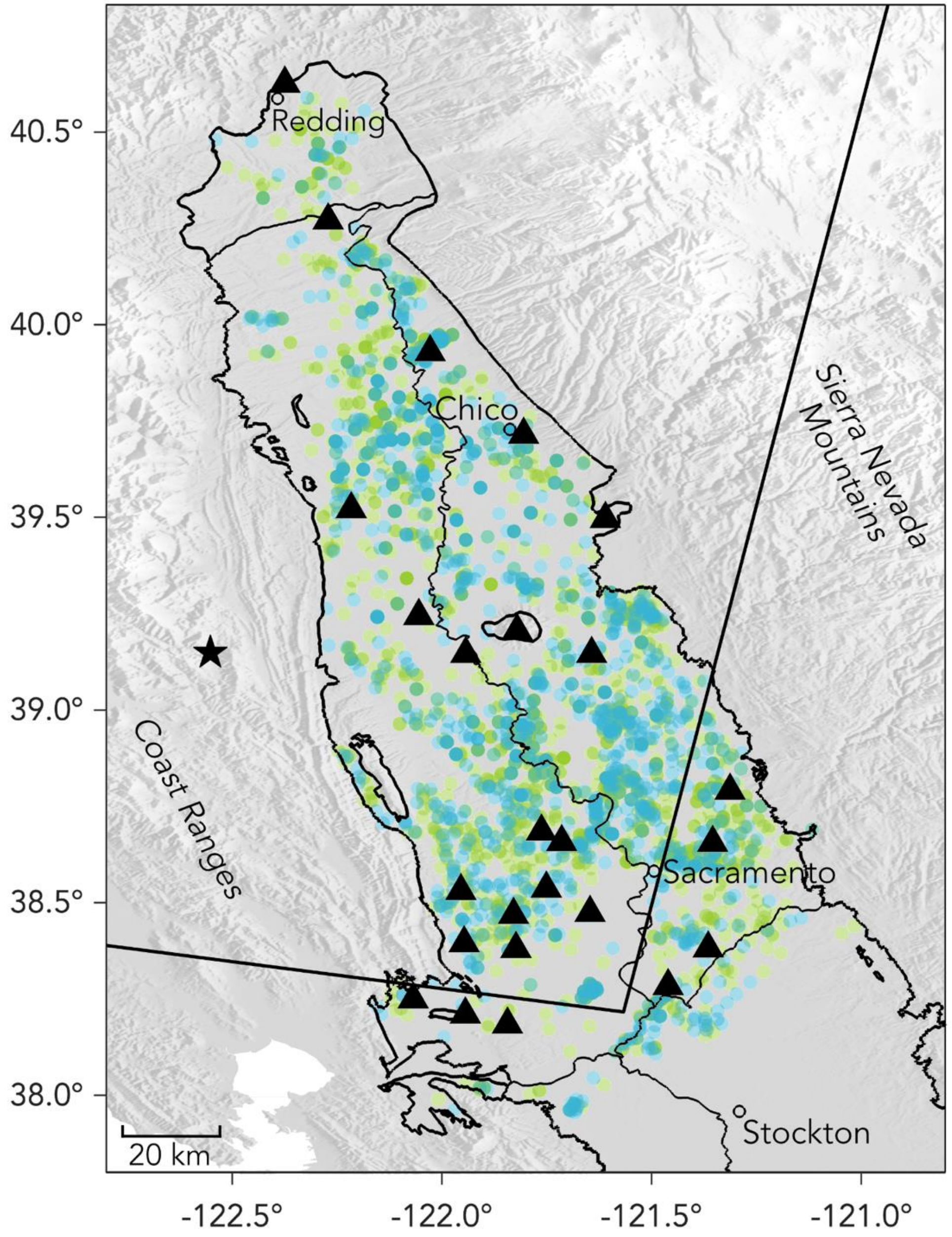
- Observation wells (n = 1163)
- Pumping wells (n = 1814)
- ▲ Continuous GNSS (n = 25 stations)

✓ Daily position time series processed by NGL (*Blewitt et al. 2018*) and post-processed by JPL (*Argus et al., 2021*)

✓ ITRF2014 reference frame (*Altamimi et al. 2016*)

✓ Corrected for offsets and non-tidal atmospheric + oceanic loading (*Dill and Dobslaw 2013*)

Geodetic & groundwater datasets in the data-rich Sacramento Valley



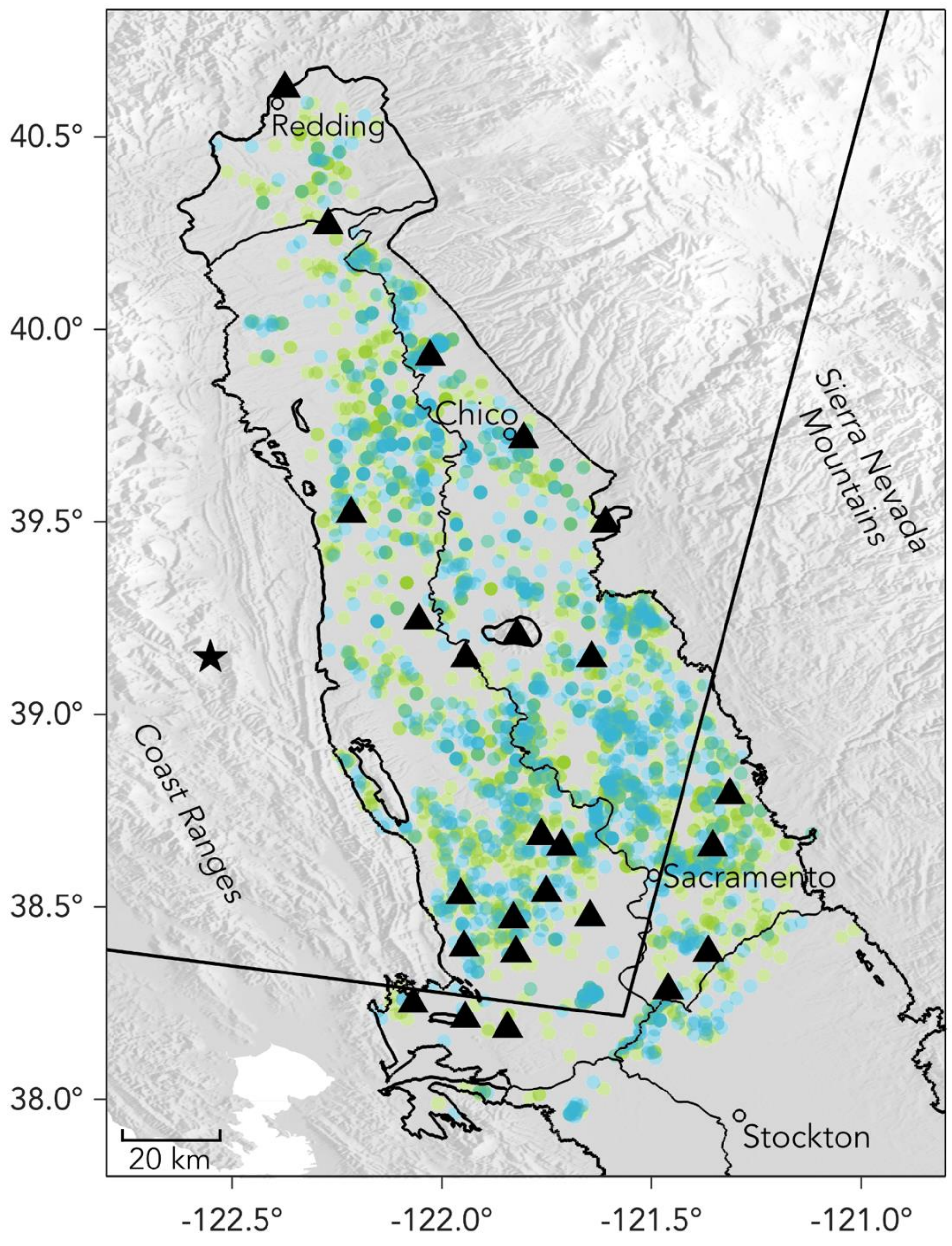
- Observation wells (n = 1163)
- Pumping wells (n = 1814)
- ▲ Continuous GNSS (n = 25 stations)
- Sentinel-1 InSAR (Descending Track 115)

✓ ISCE-derived interferograms (*Gurrola et al. 2010; Fattahi et al. 2017*) and phase change temporal evolution from Kalman Filter time series analysis (*Dalaison & Jolivet 2020*)

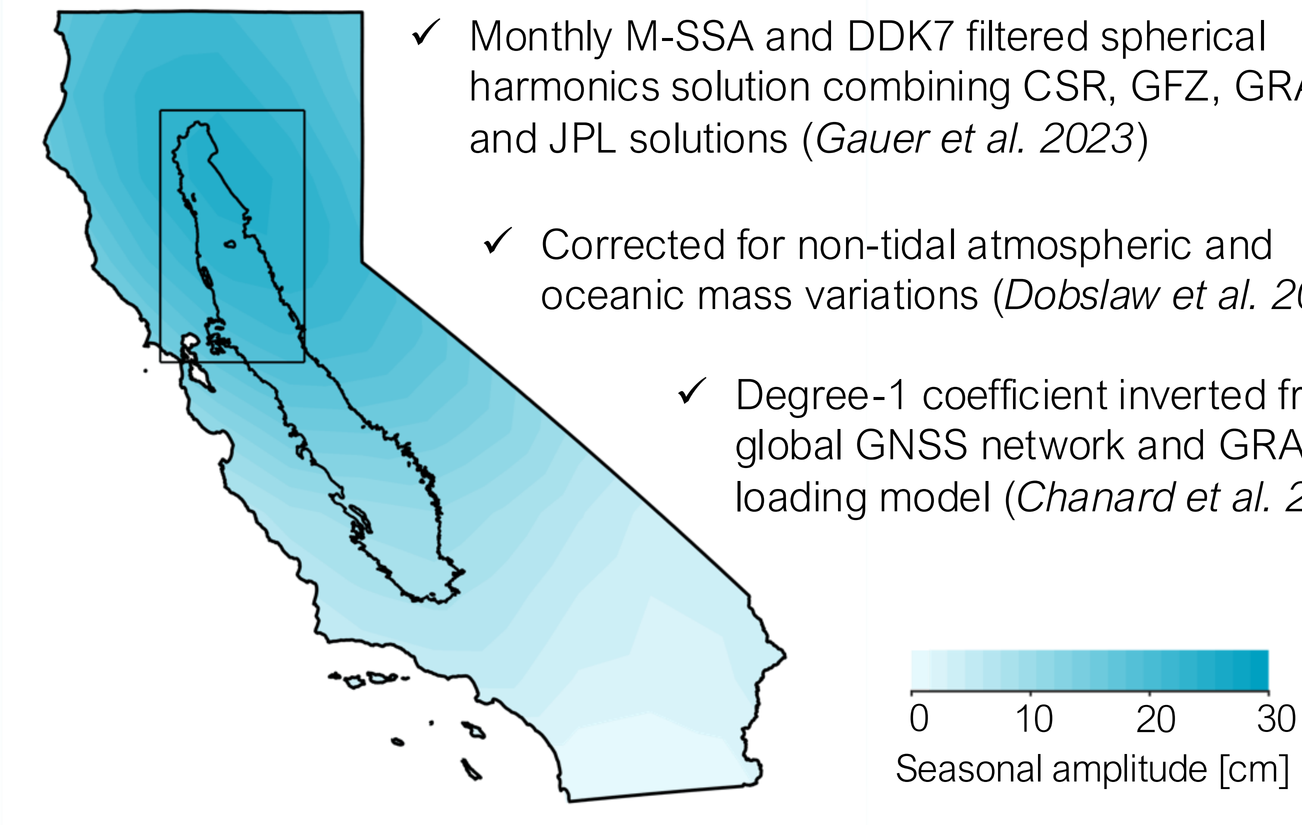
✓ Vertical displacement from projection of descending LOS time series on vertical axis assuming negligible horizontal displacements

✓ Time series are relative to a stable area with high coherence (★ on the map) and fully independent from GNSS.

Geodetic & groundwater datasets in the data-rich Sacramento Valley

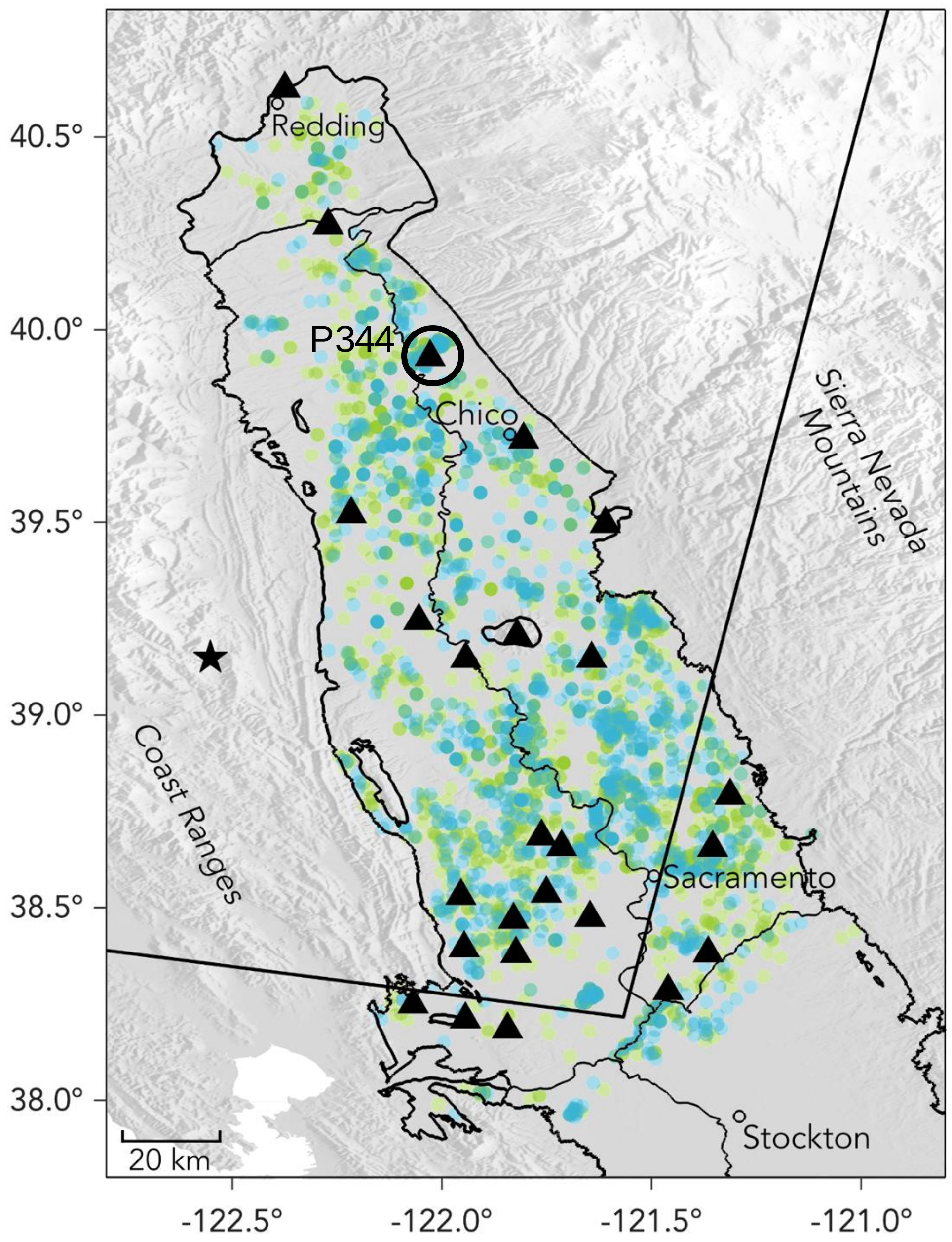


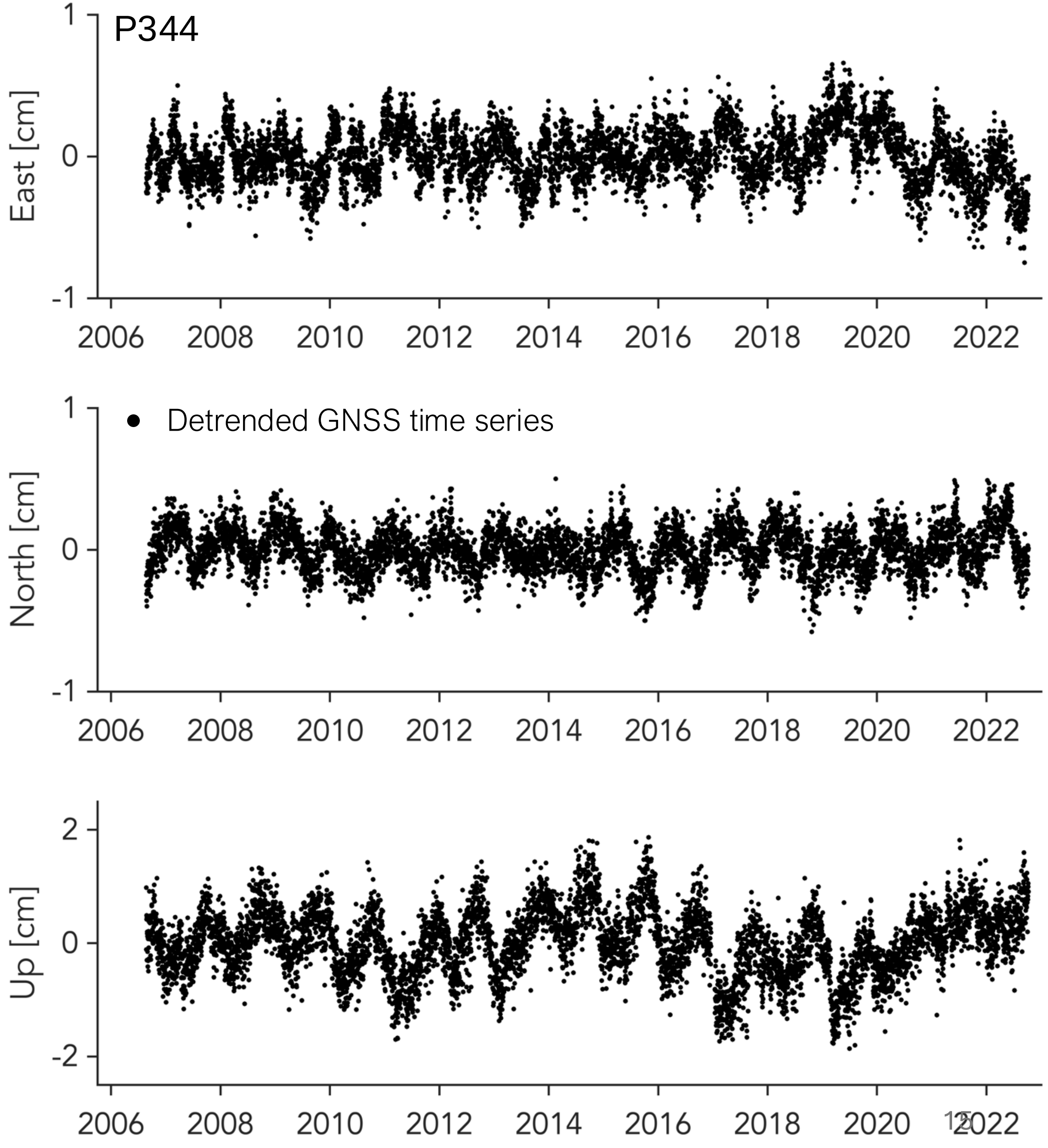
GRACE/GRACE-FO (Gravity Recovery and Climate Experiment)



- ✓ Monthly M-SSA and DDK7 filtered spherical harmonics solution combining CSR, GFZ, GRAZ and JPL solutions (*Gauer et al. 2023*)
- ✓ Corrected for non-tidal atmospheric and oceanic mass variations (*Dobslaw et al. 2017*)
- ✓ Degree-1 coefficient inverted from global GNSS network and GRACE loading model (*Chanard et al. 2018*)

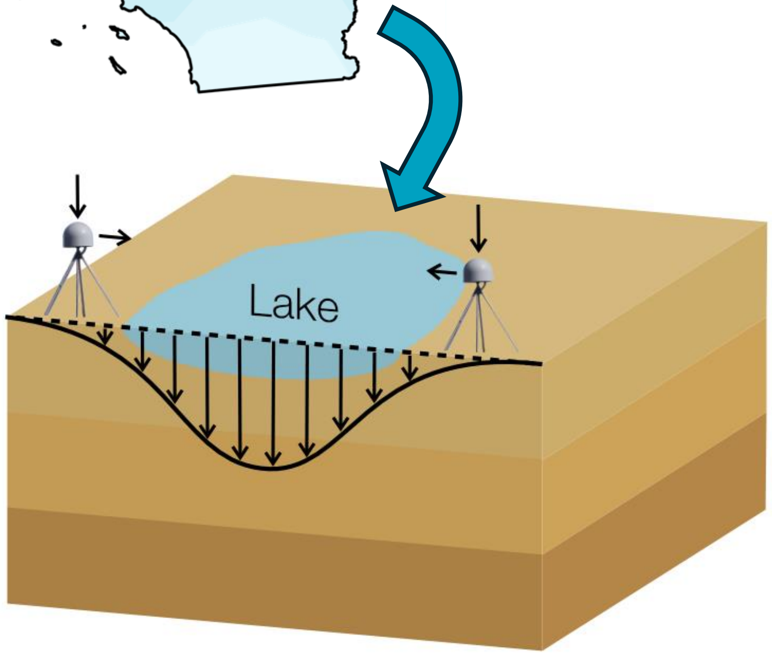
17 years of continuous GNSS displacements in the Sacramento Valley

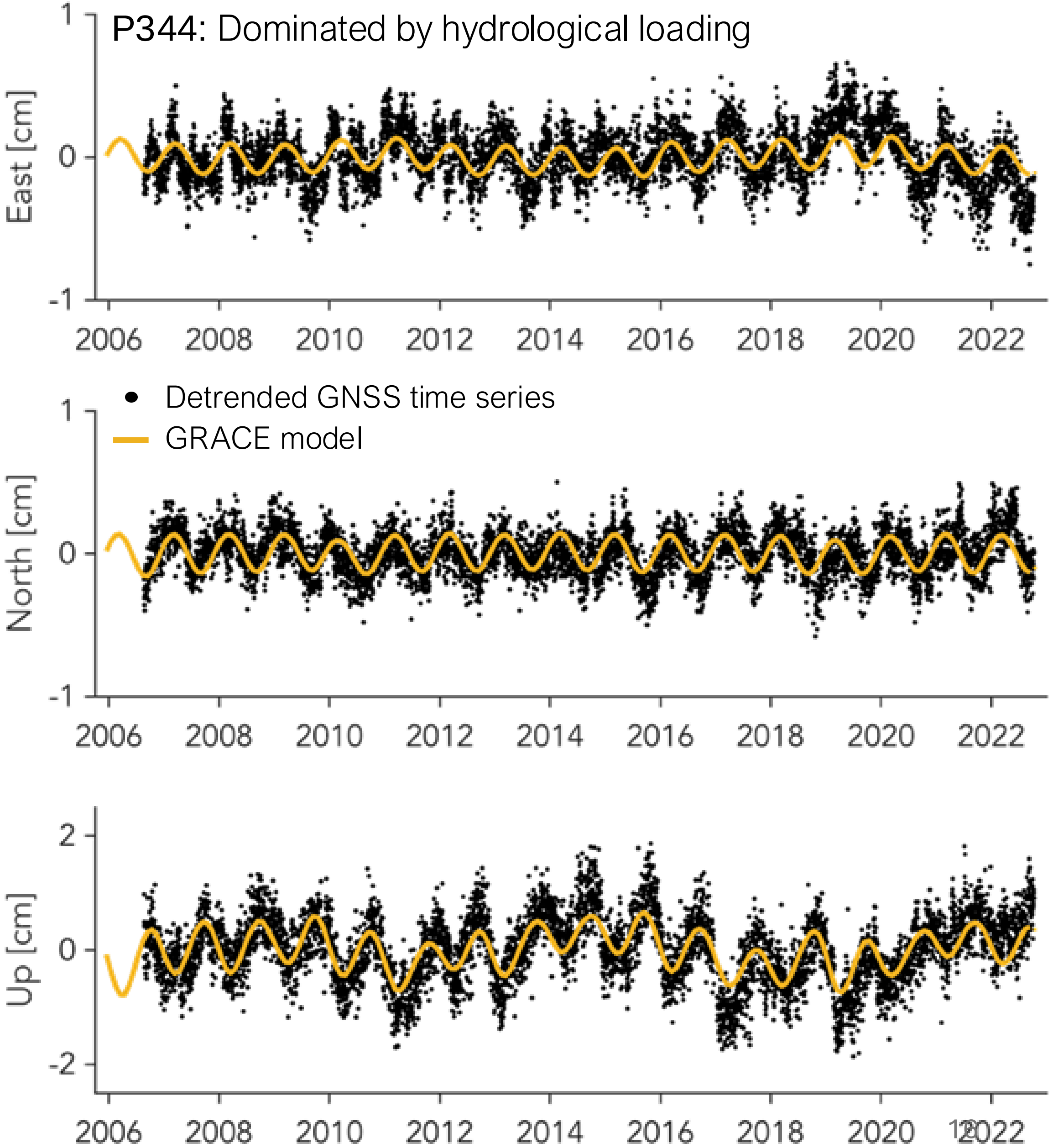




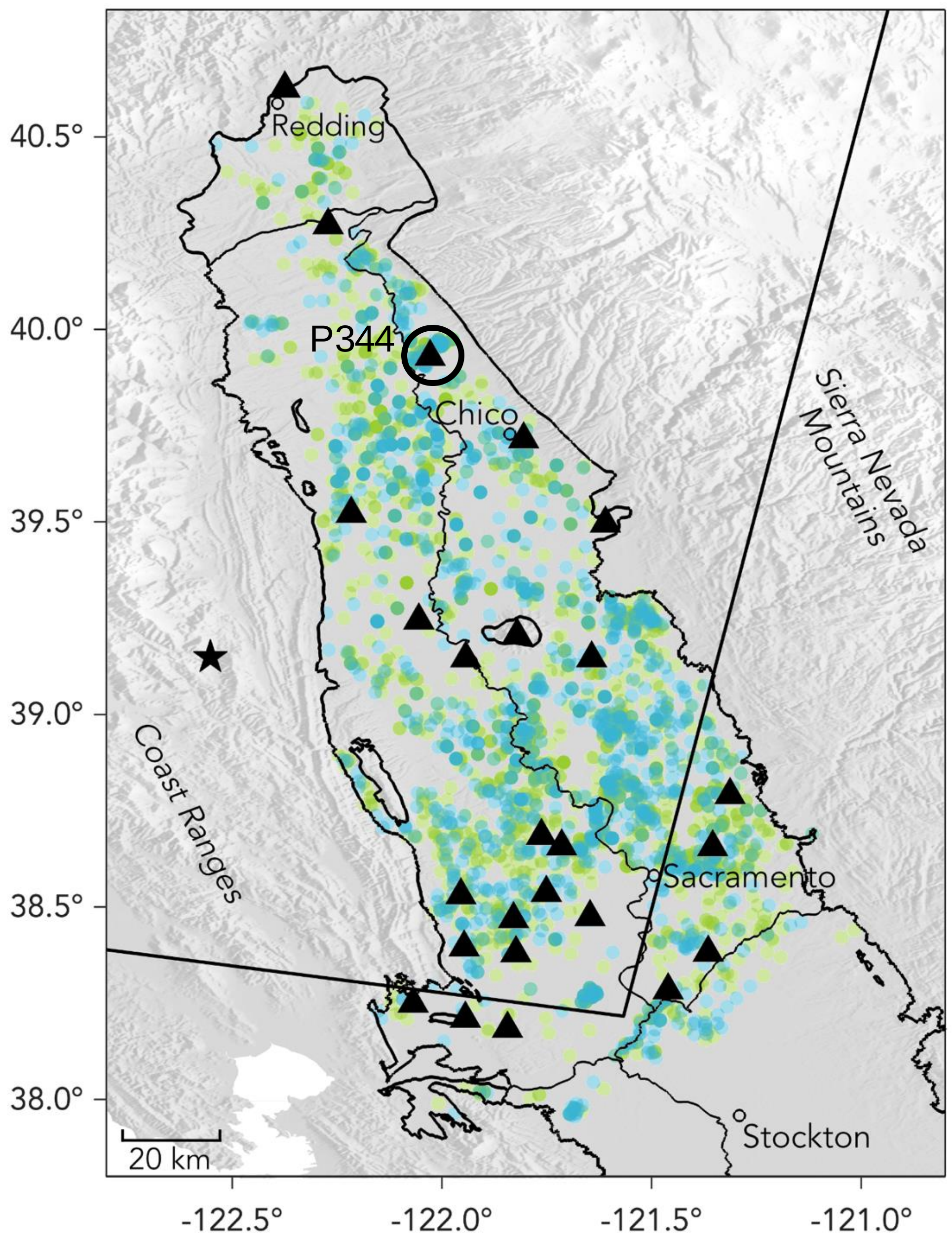
Characterizing large-scale hydrological elastic loading with GRACE/GRACE-FO

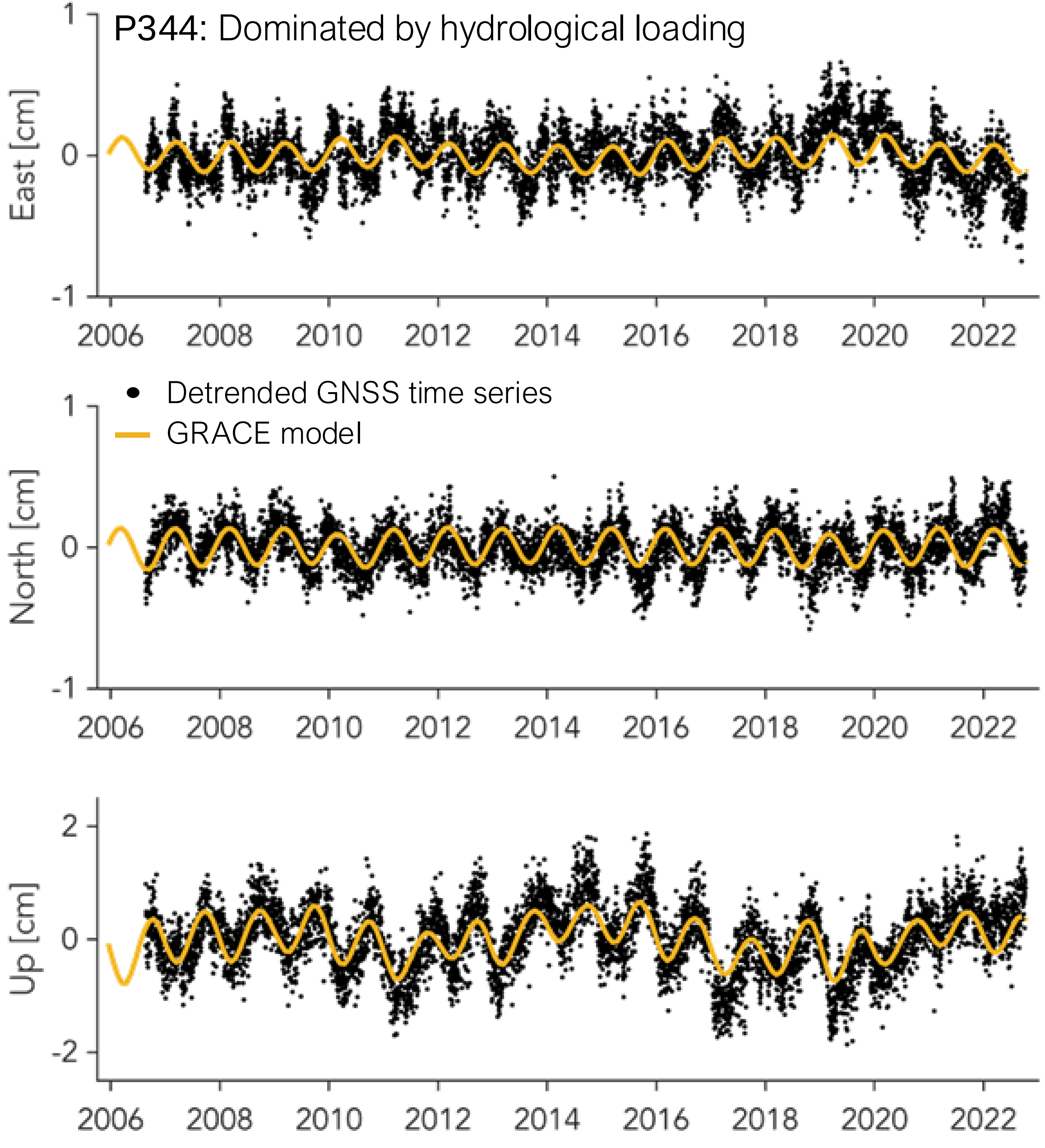
A spherical elastic stratified Earth model loaded with GRACE/-FO measurements (*Chanard et al., 2018*)





Characterizing large-scale hydrological elastic loading with GRACE/GRACE-FO





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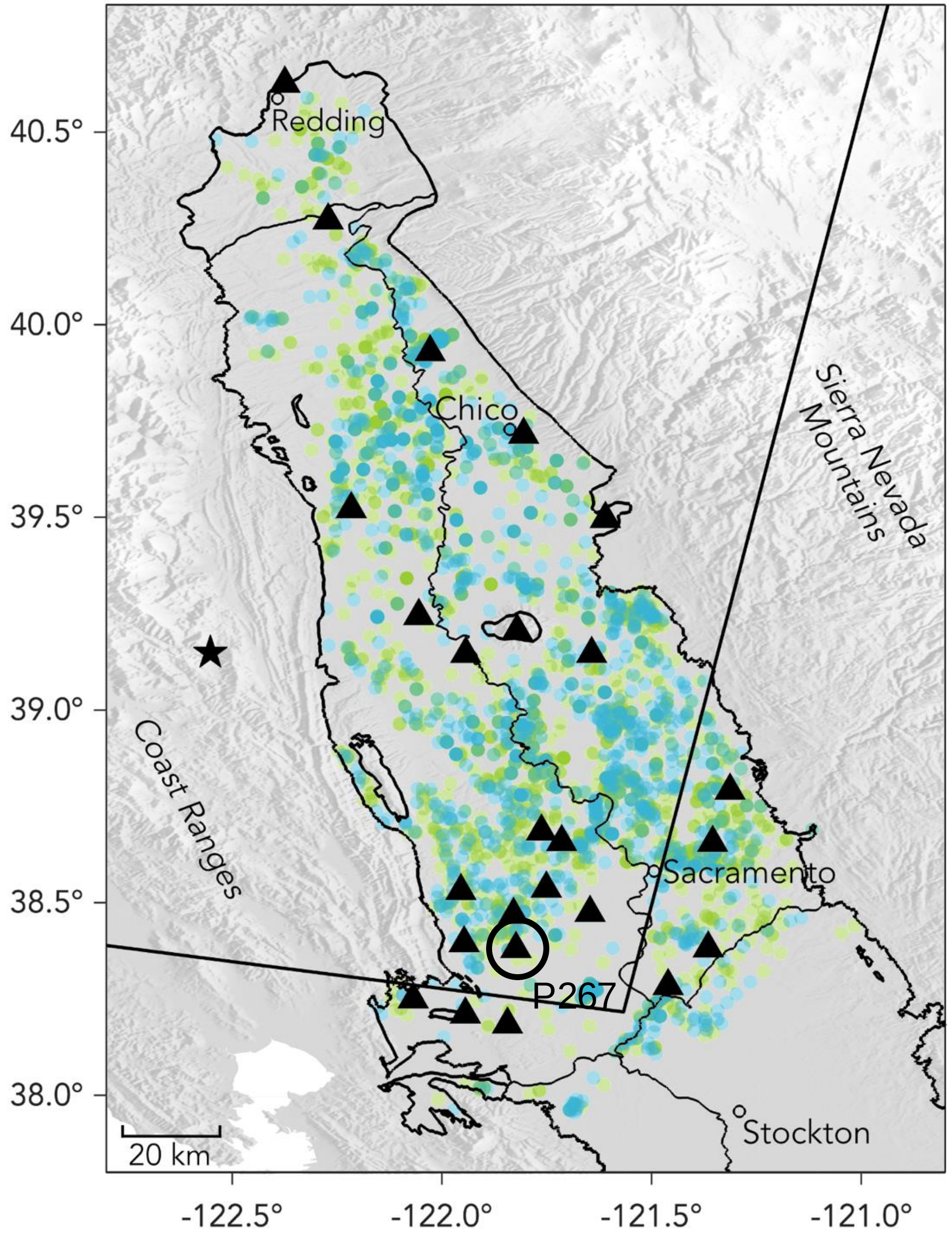
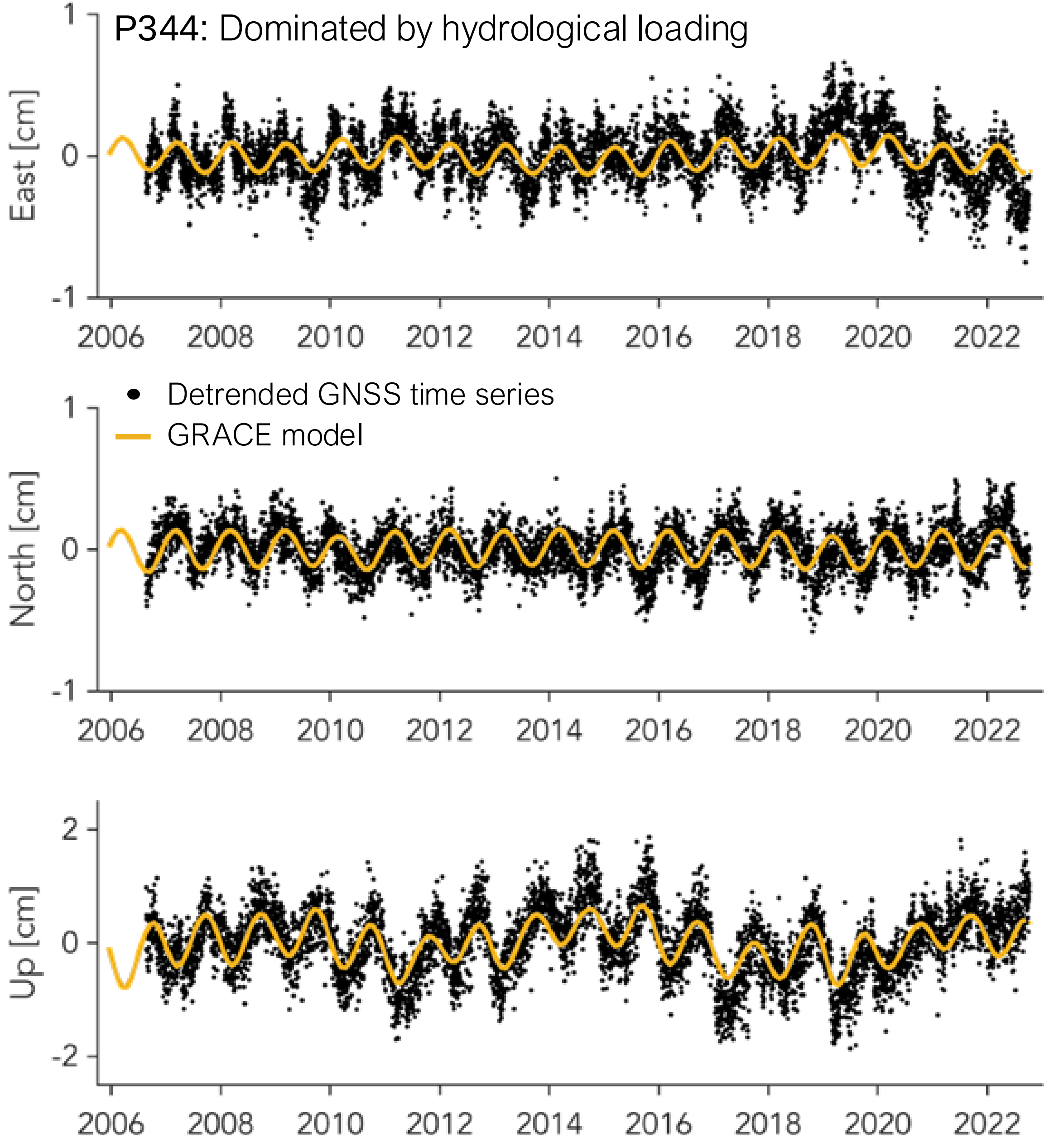
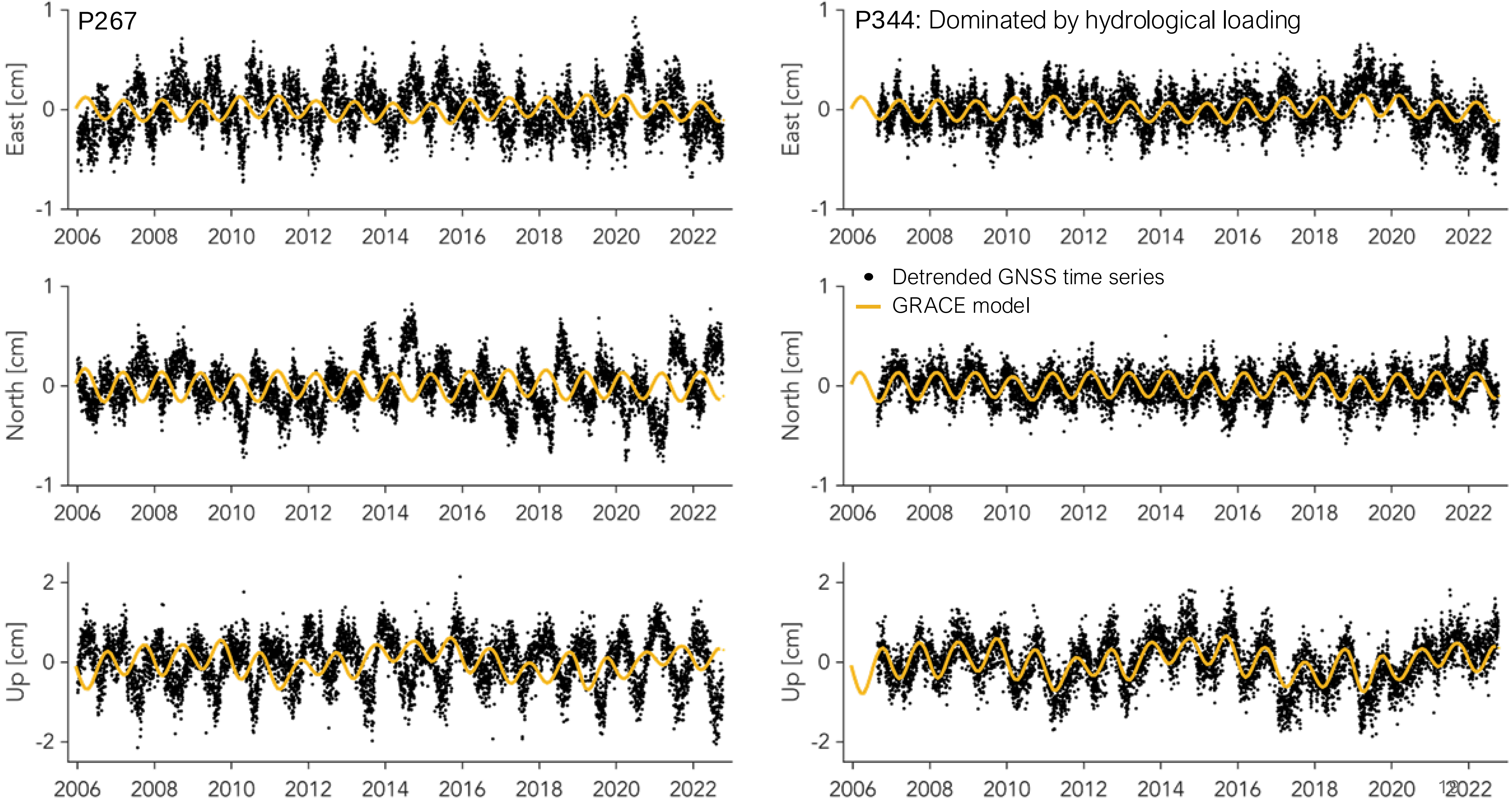
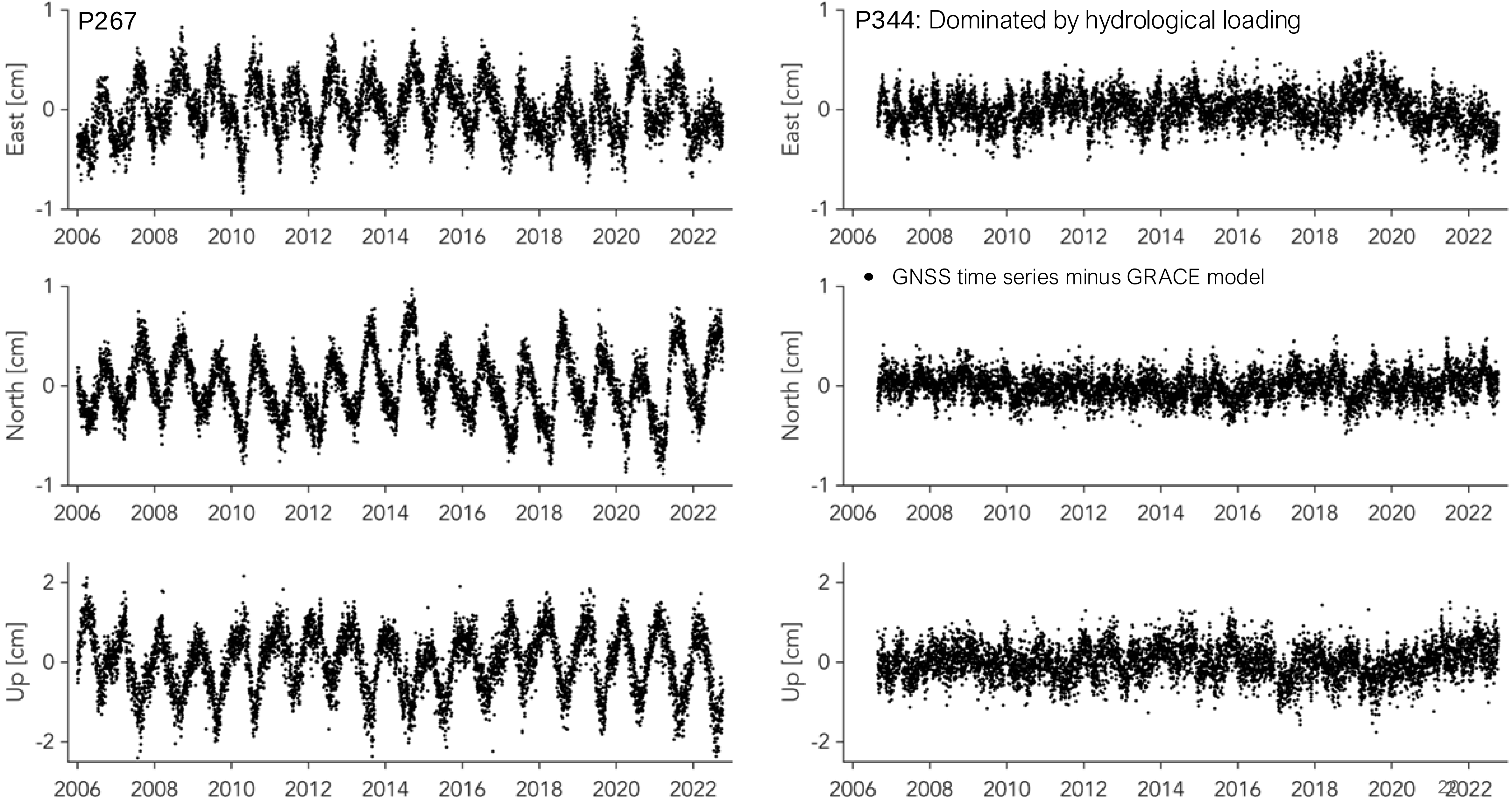




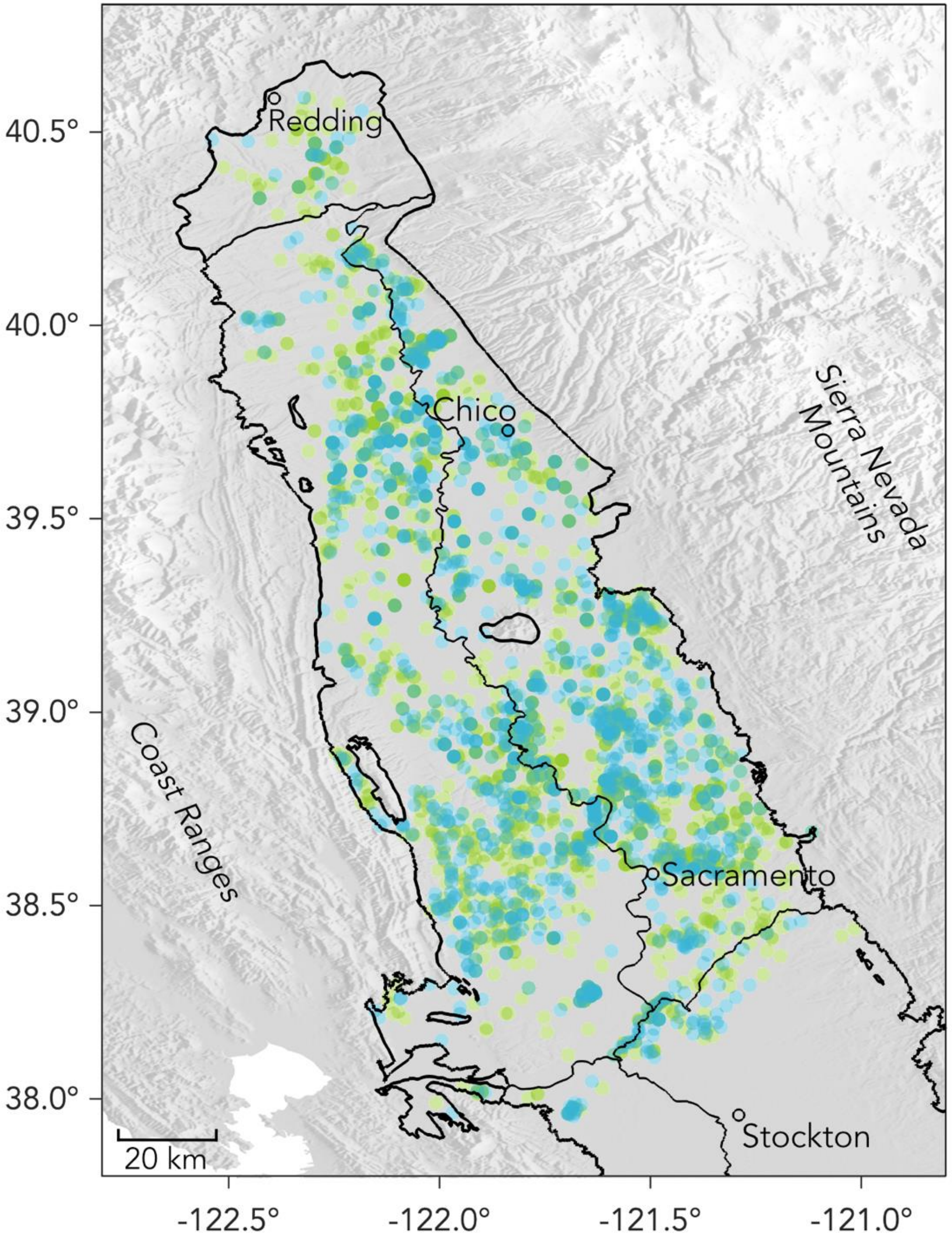
Characterizing large-scale **hydrological elastic loading** with GRACE/GRACE-FO



Characterizing large-scale hydrological elastic loading with GRACE/GRACE-FO

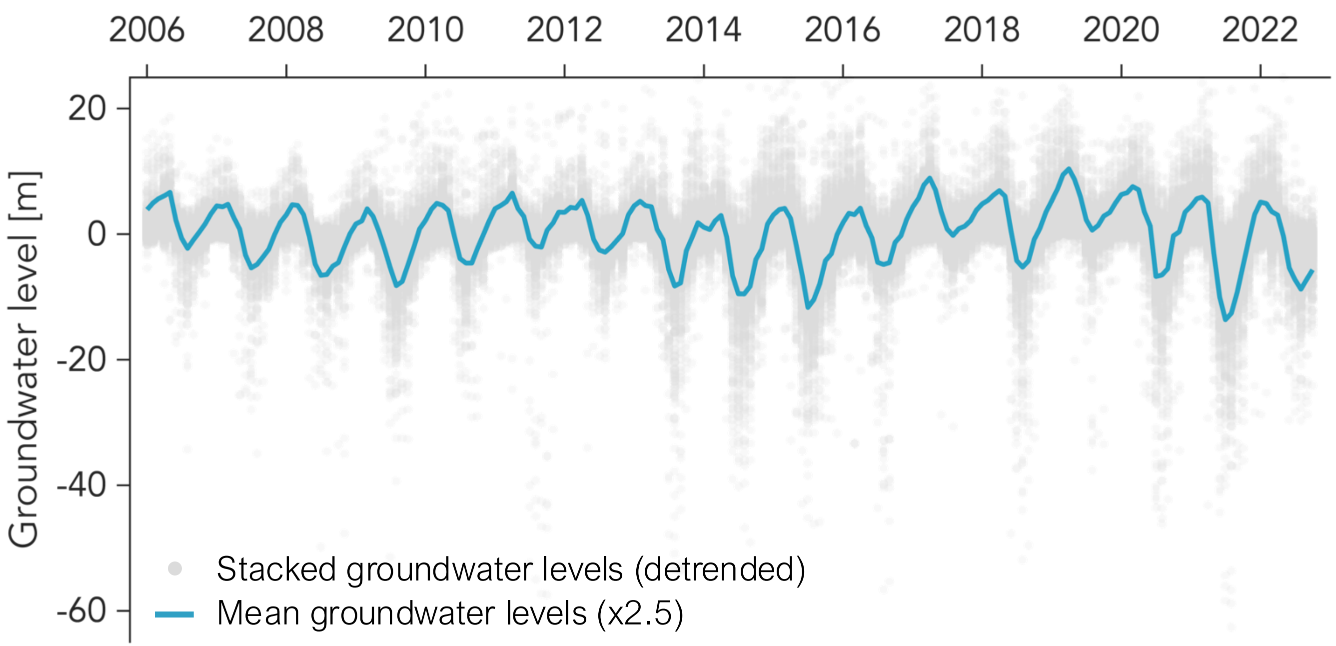


Characterizing aquifer-scale groundwater variations with well observations



Groundwater wells (*n = 2977*):

- Observation (*n = 1163*)
- Pumping (*n = 1814*)



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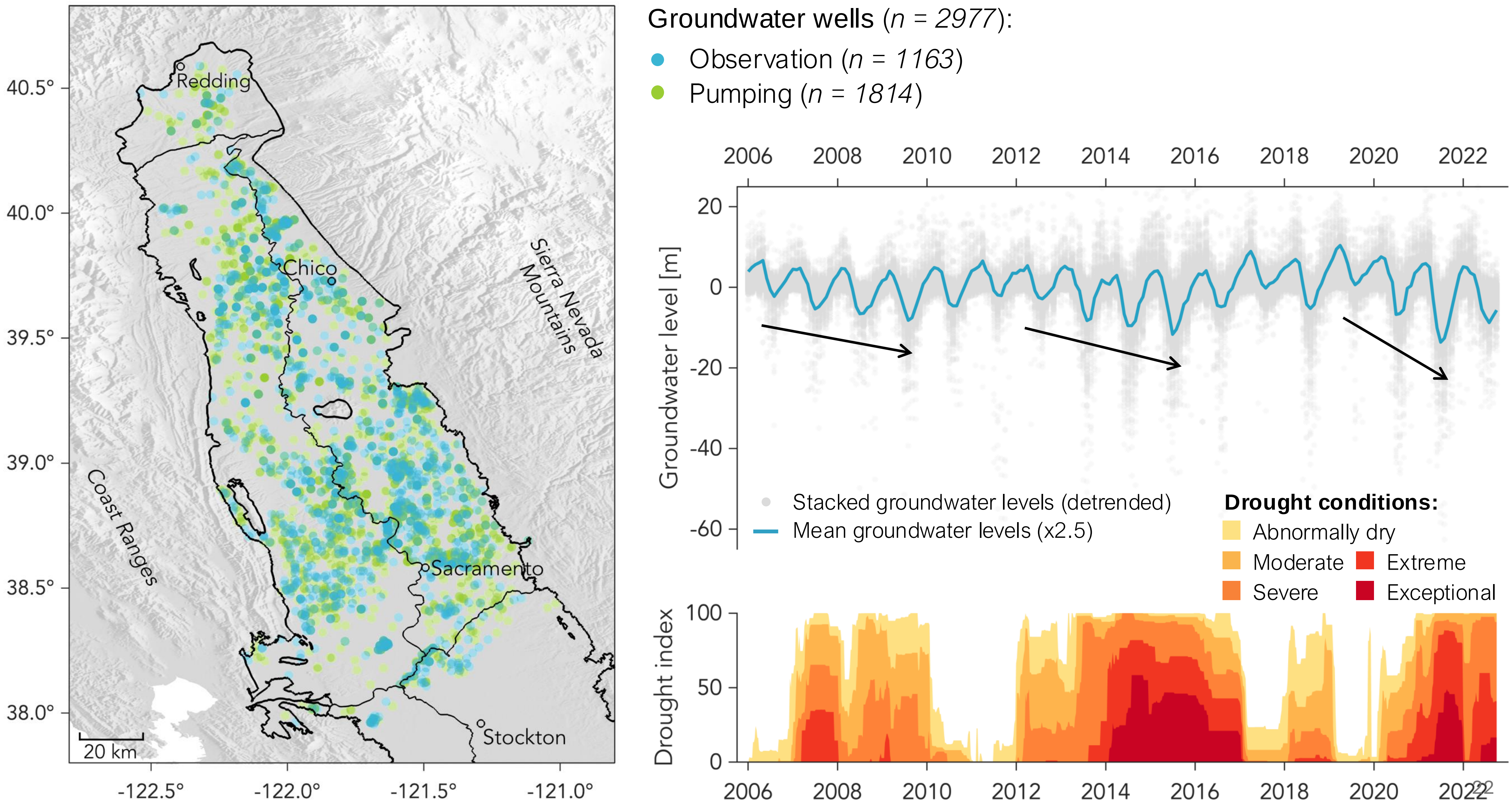
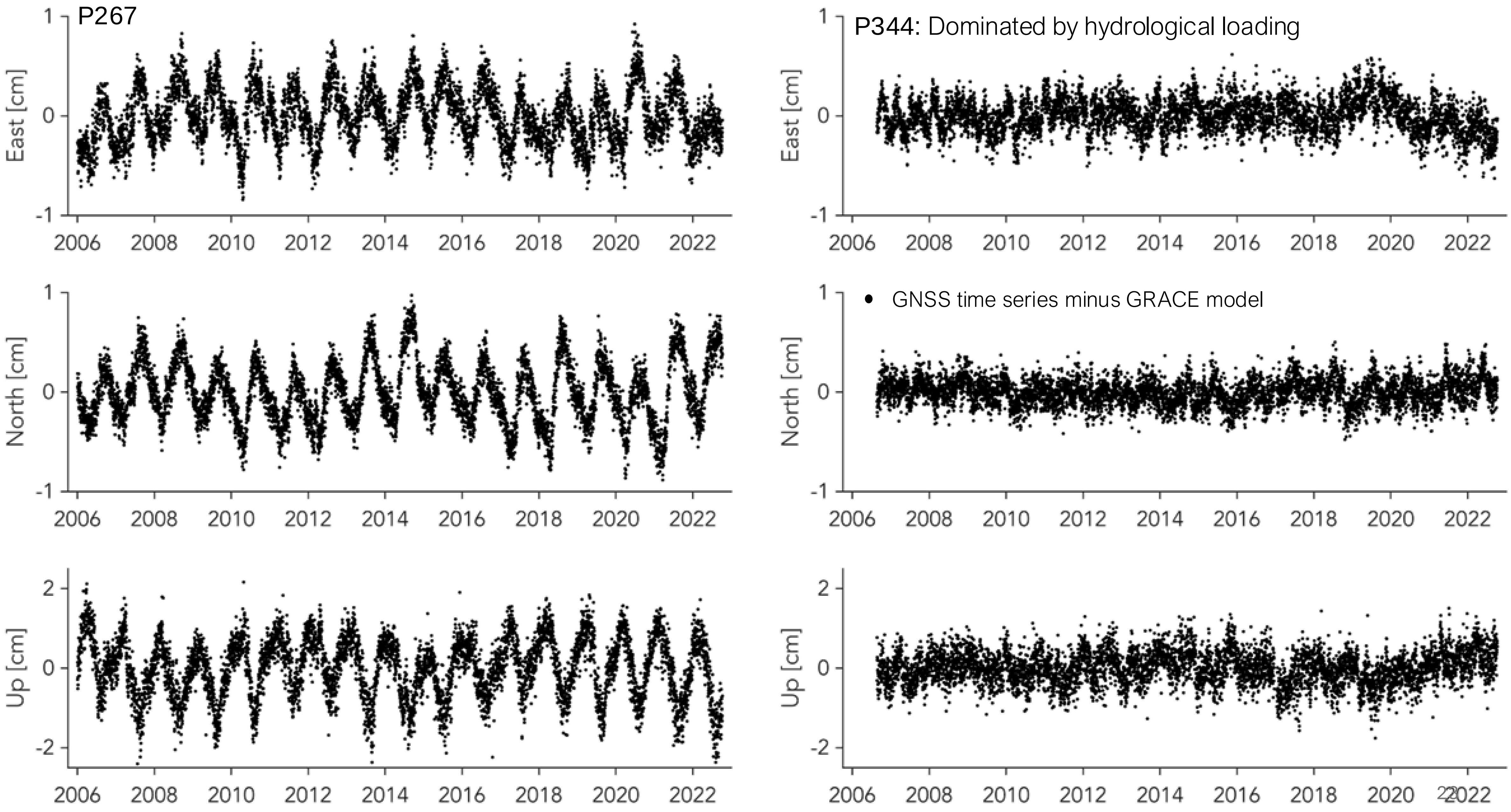


Extracting the poroelastic deformation field from GNSS time series



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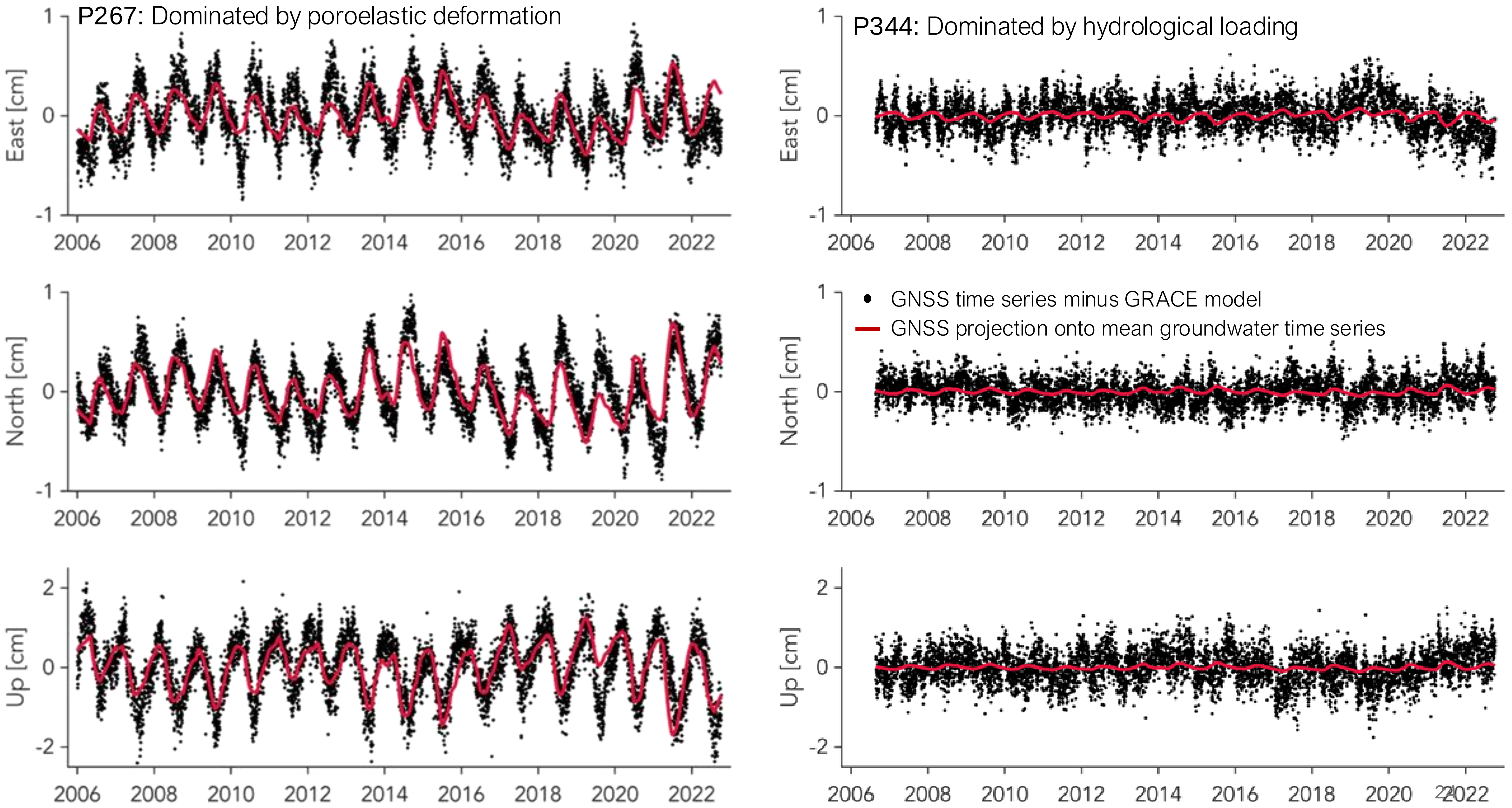
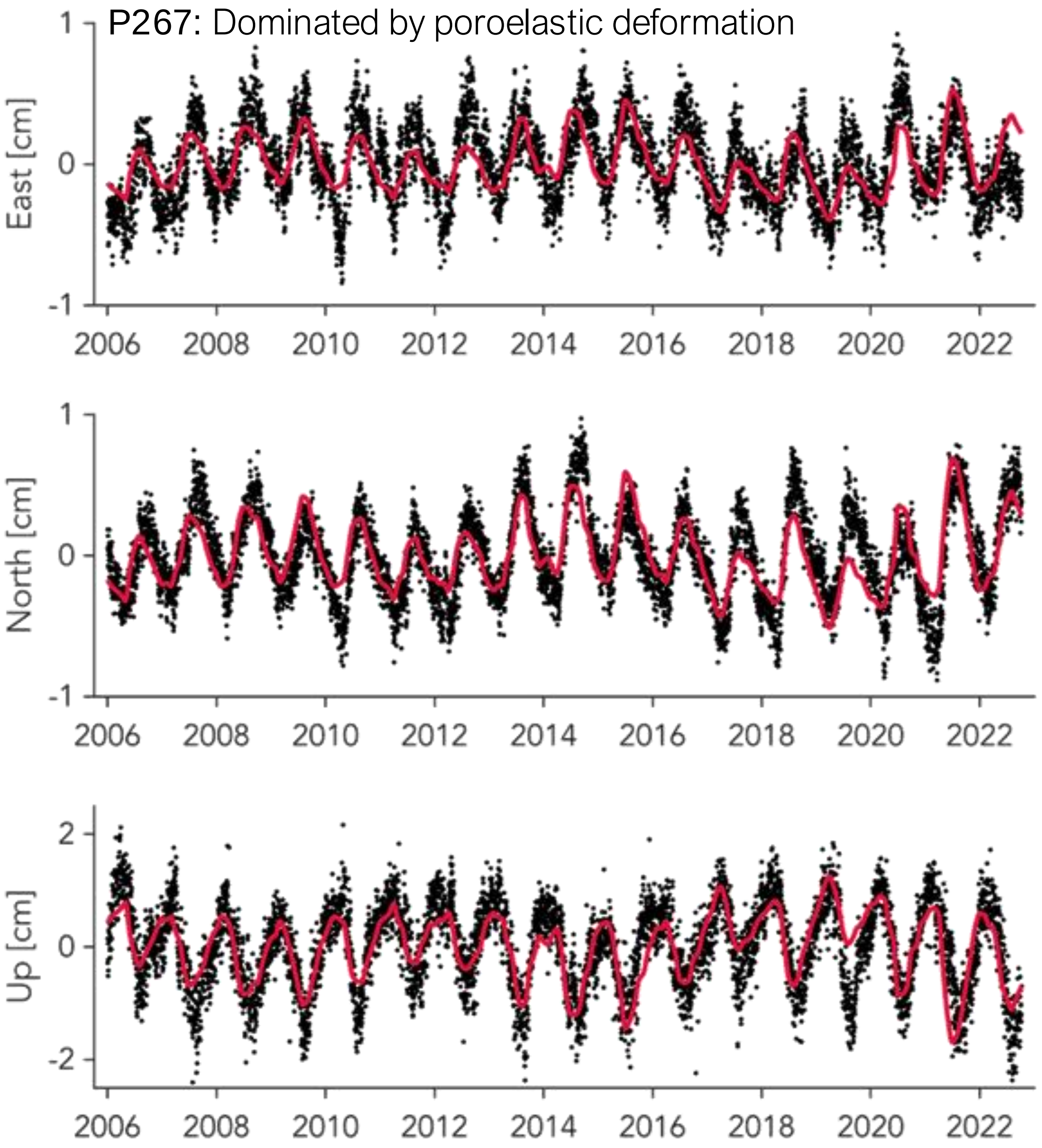


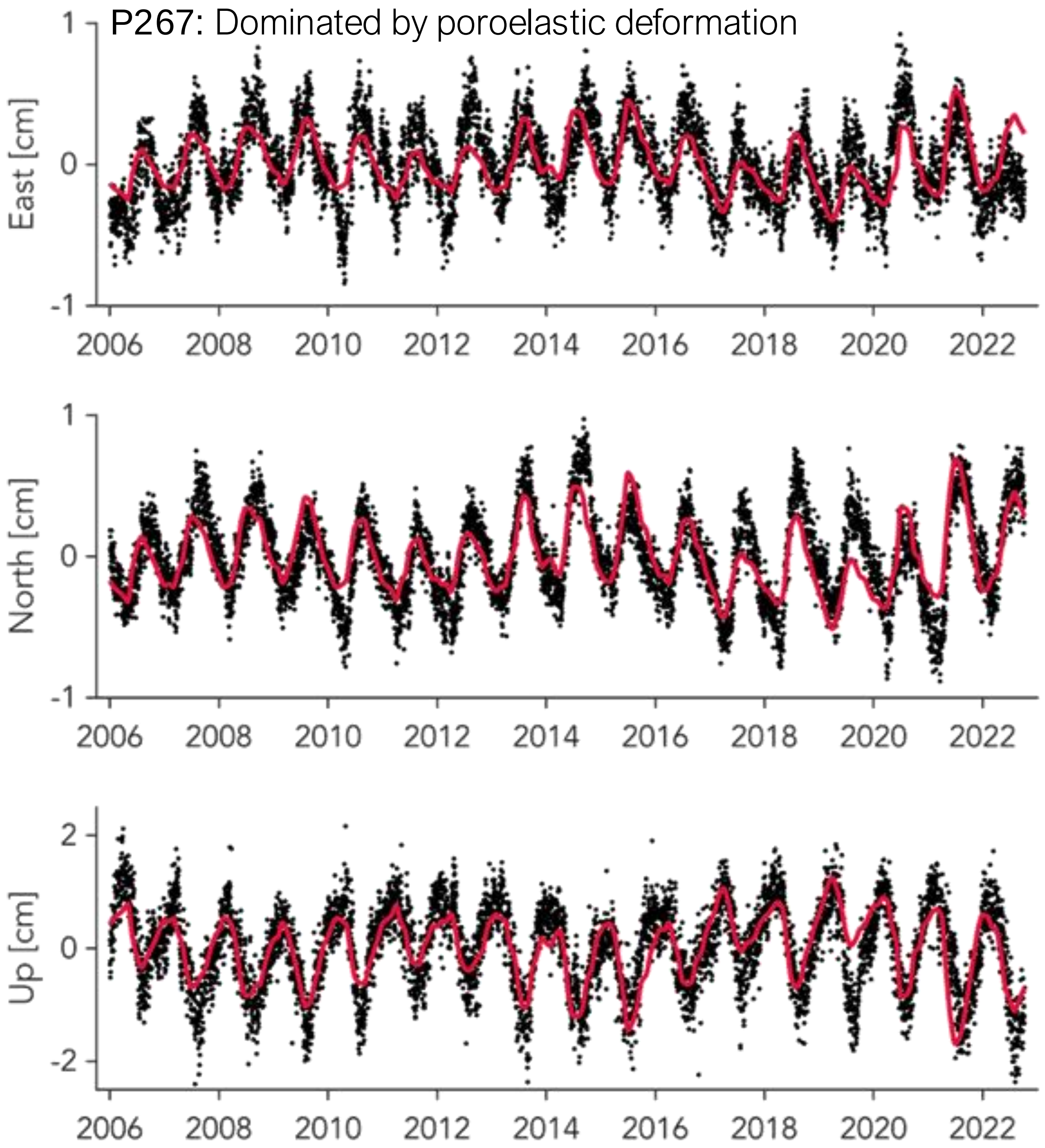
Extracting the <u>poroelastic</u> deformation field from GNSS time series

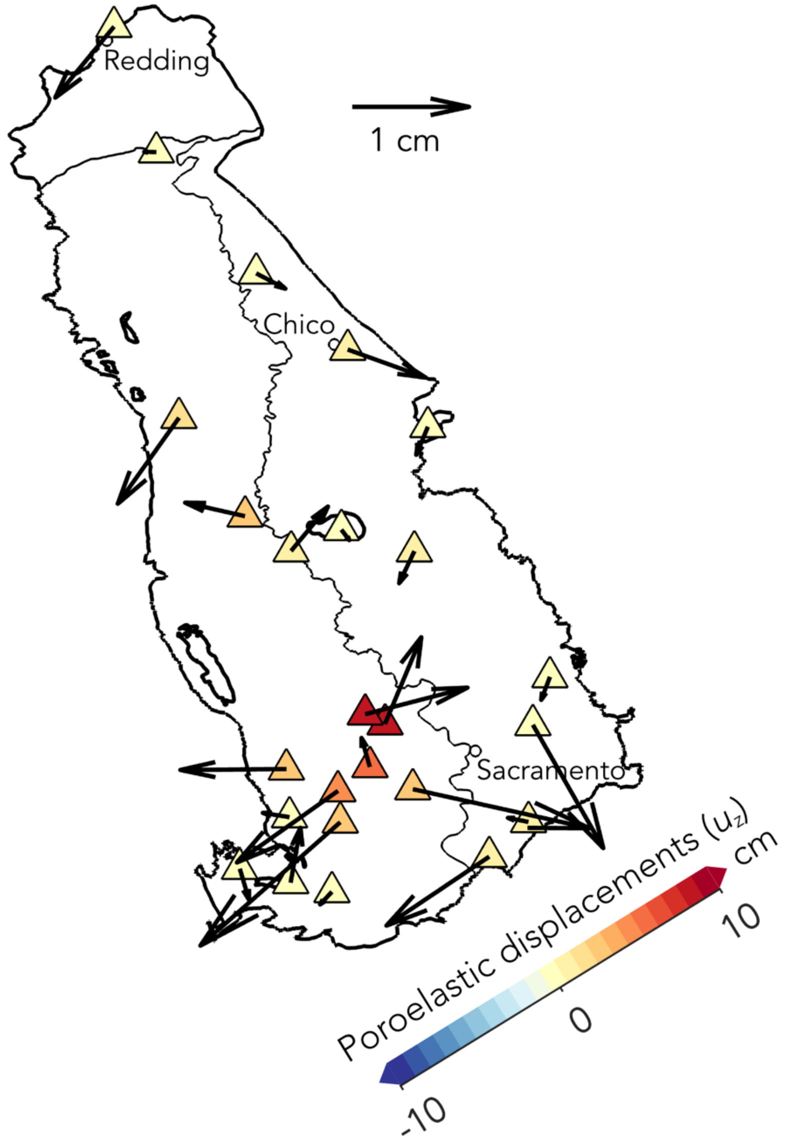


1.7 cm of <u>horizontal</u> poroelastic displacement

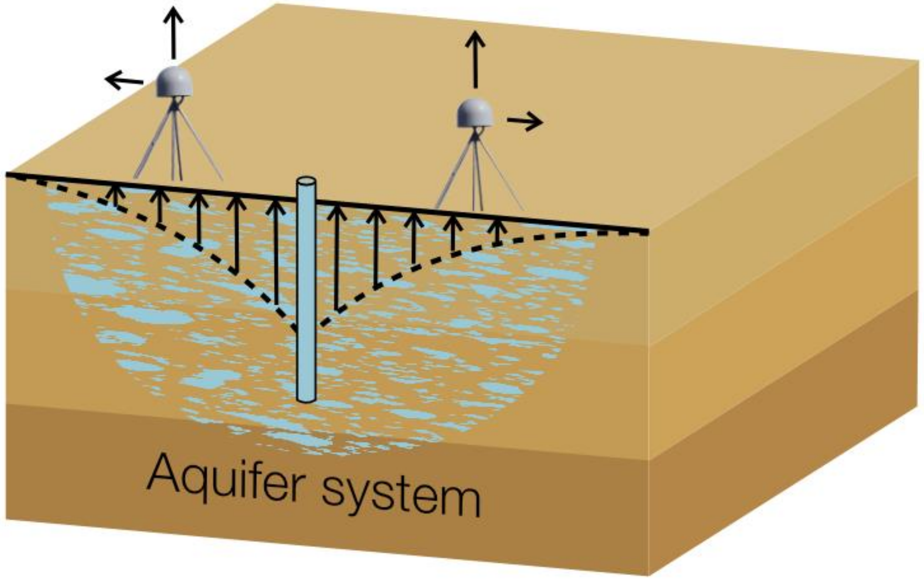
3.1 cm of <u>vertical</u> poroelastic displacement

Extracting the poroelastic deformation field from GNSS time series

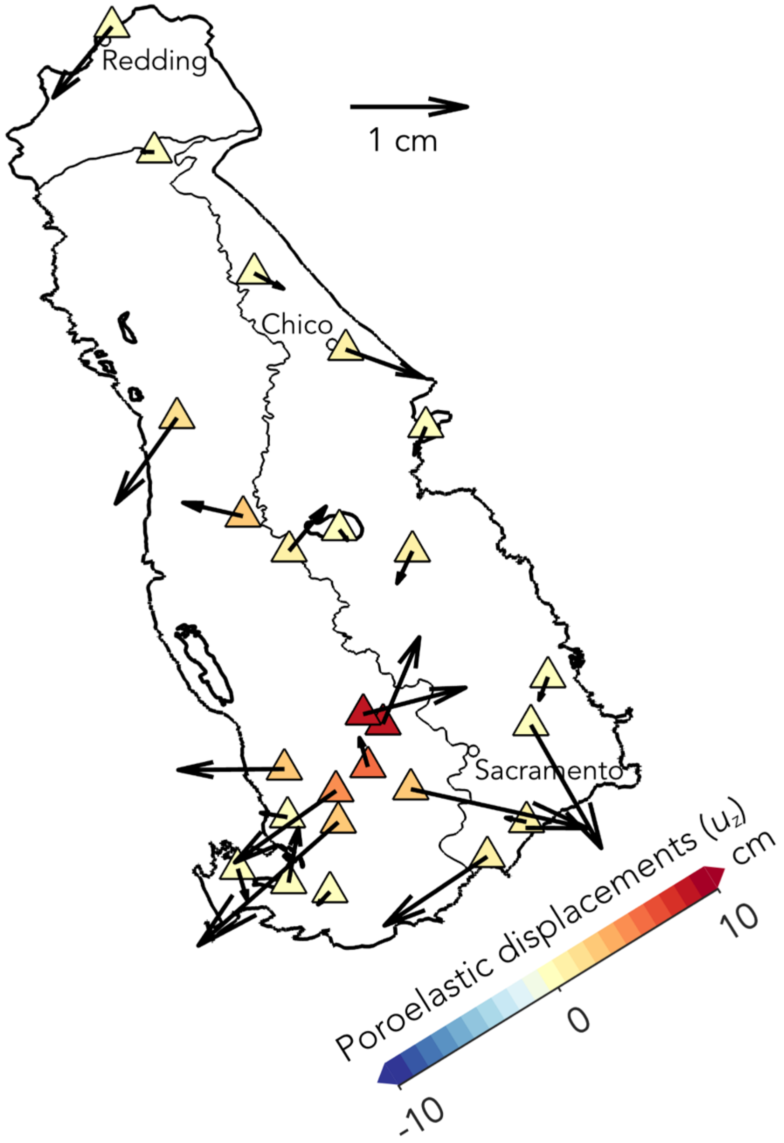




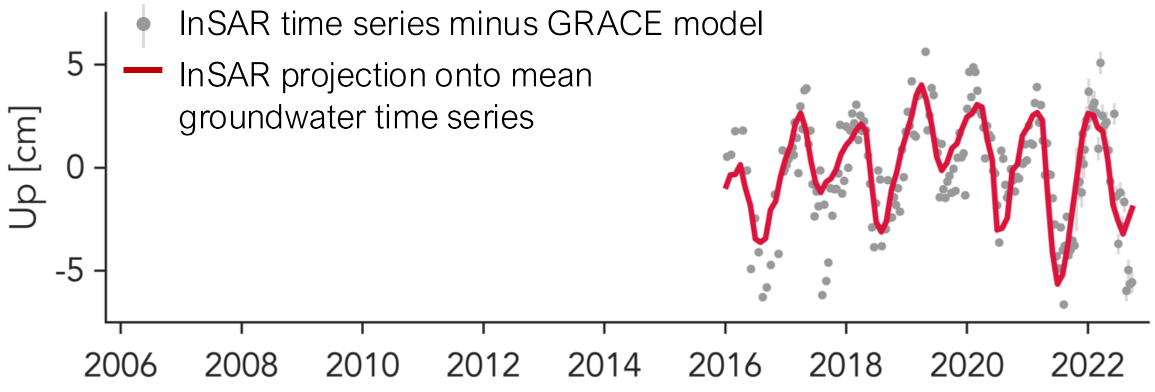
Extracting the poroelastic deformation field from GNSS time series

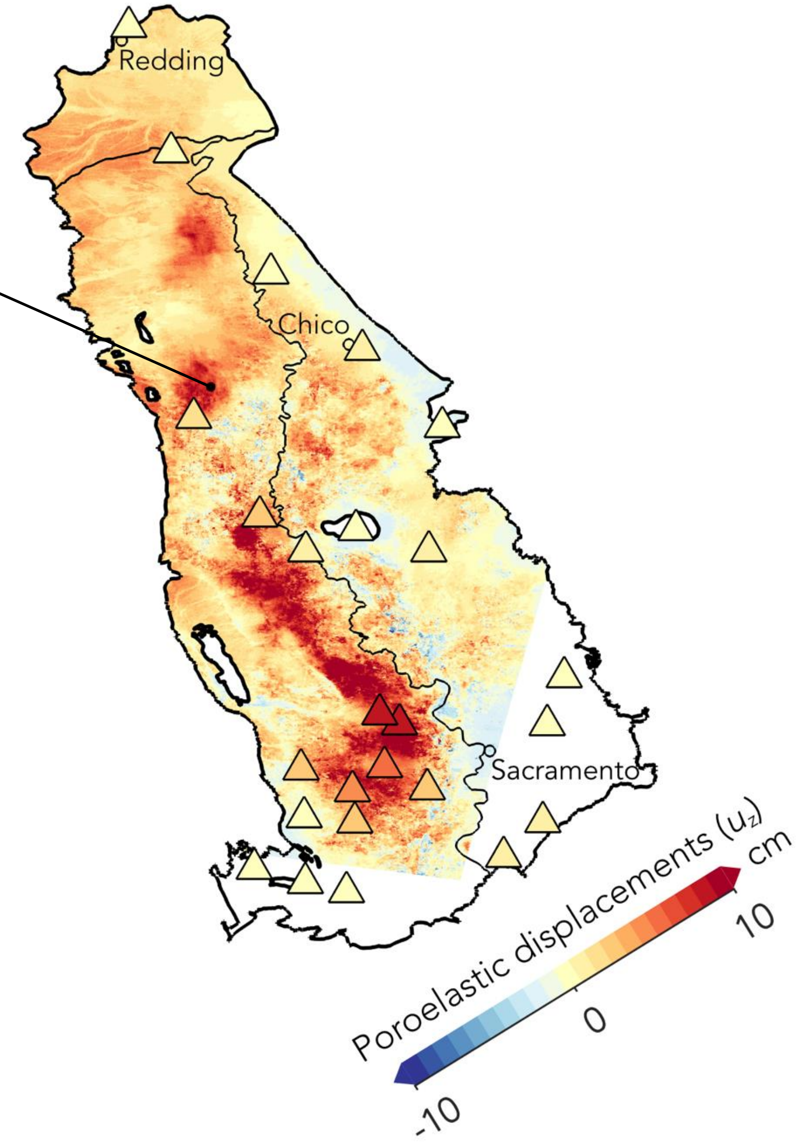


Poroelastic deformation due to groundwater recharge

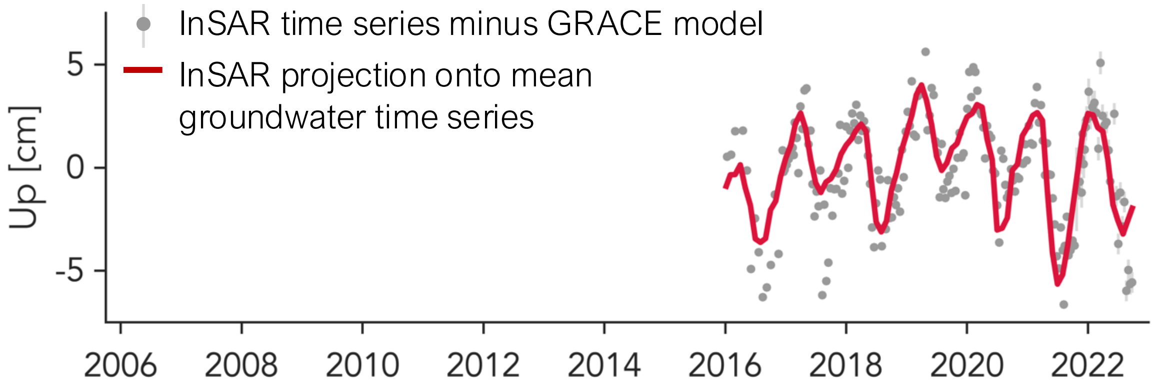


Extracting the poroelastic deformation field from vertical GNSS and InSAR time series

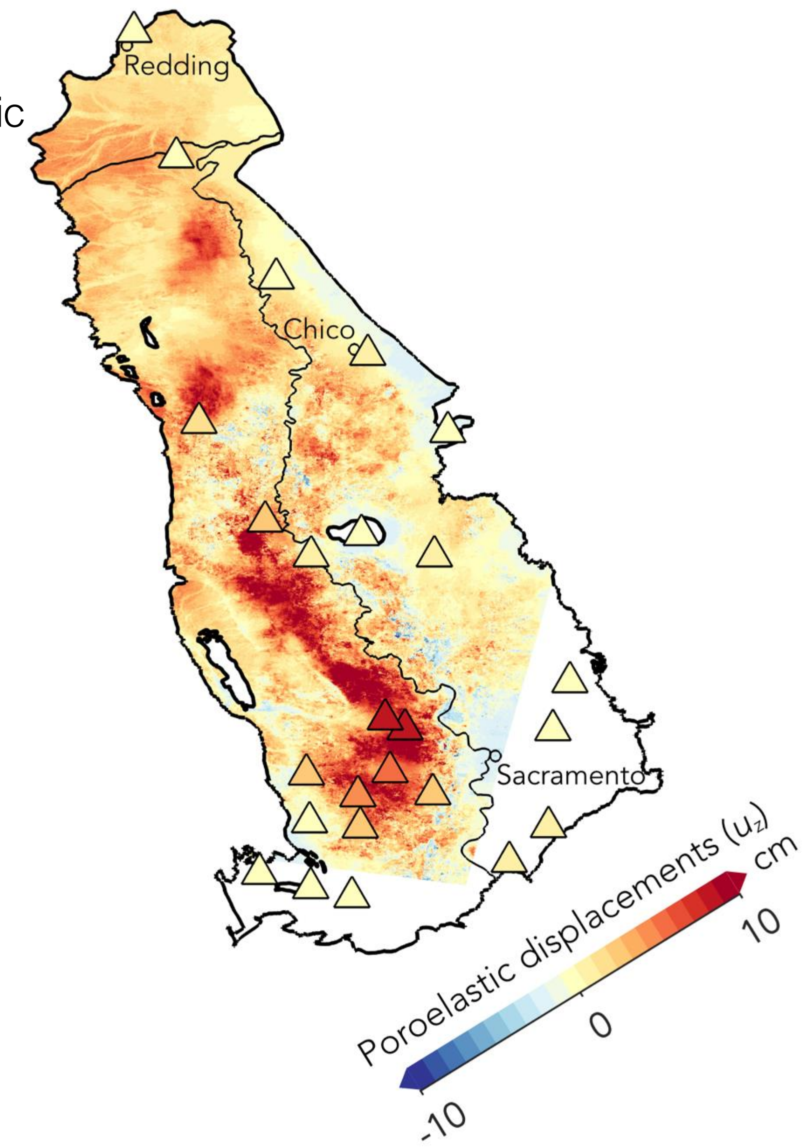




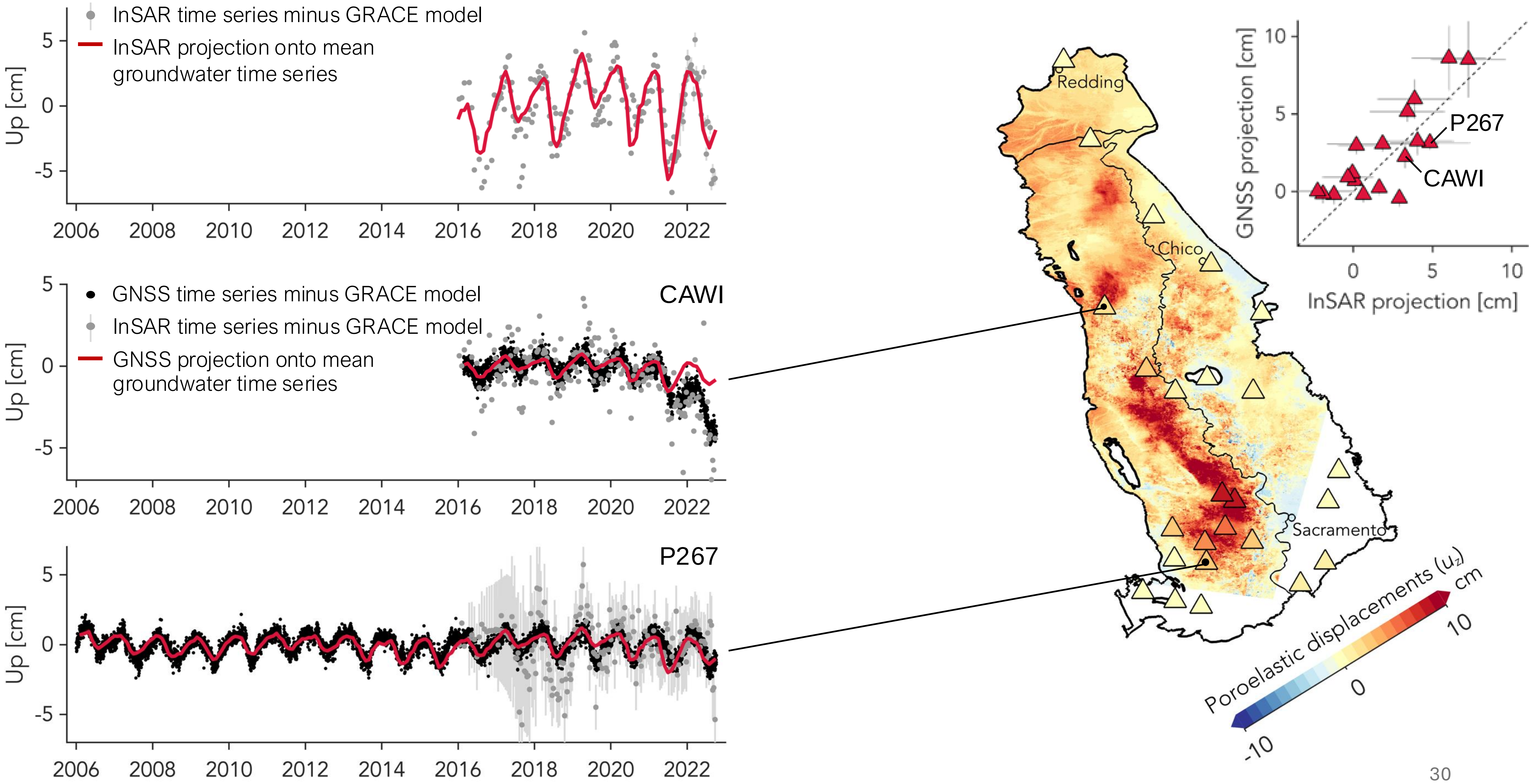
Extracting the poroelastic deformation field from vertical GNSS and InSAR time series



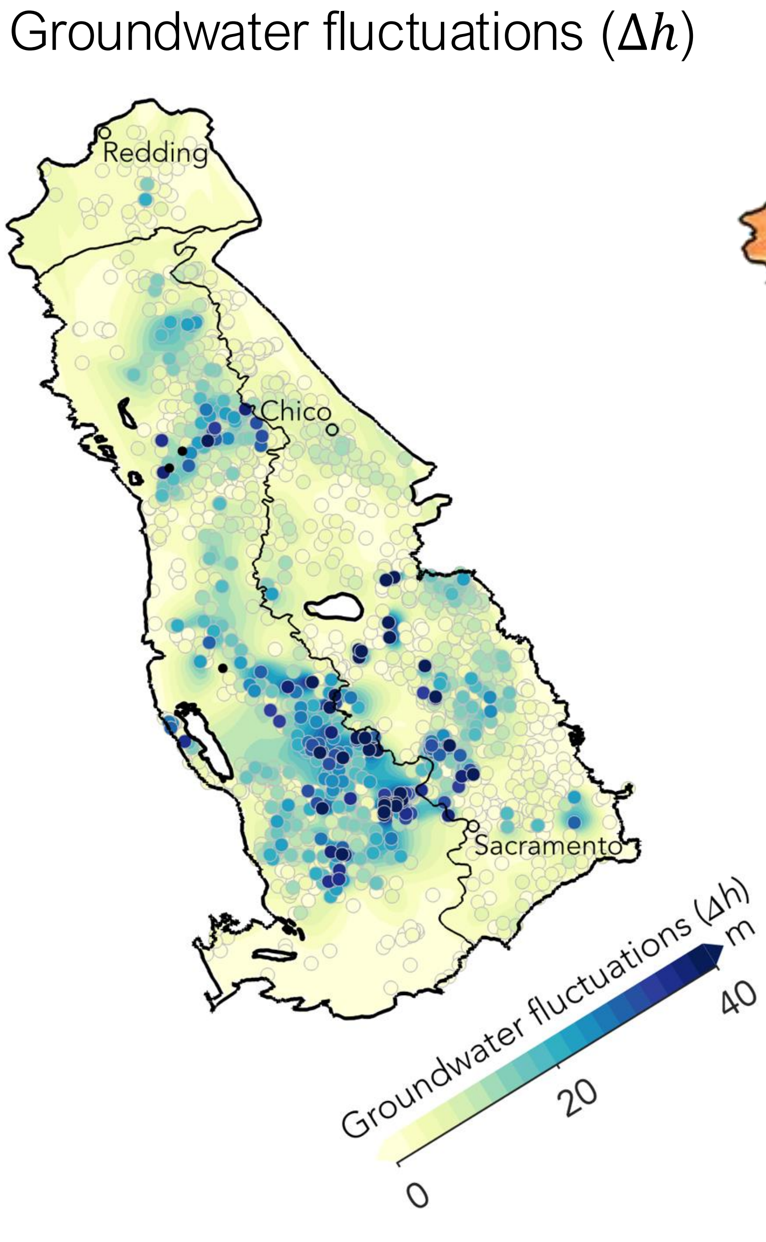
10.4 cm of
vertical poroelastic
displacement

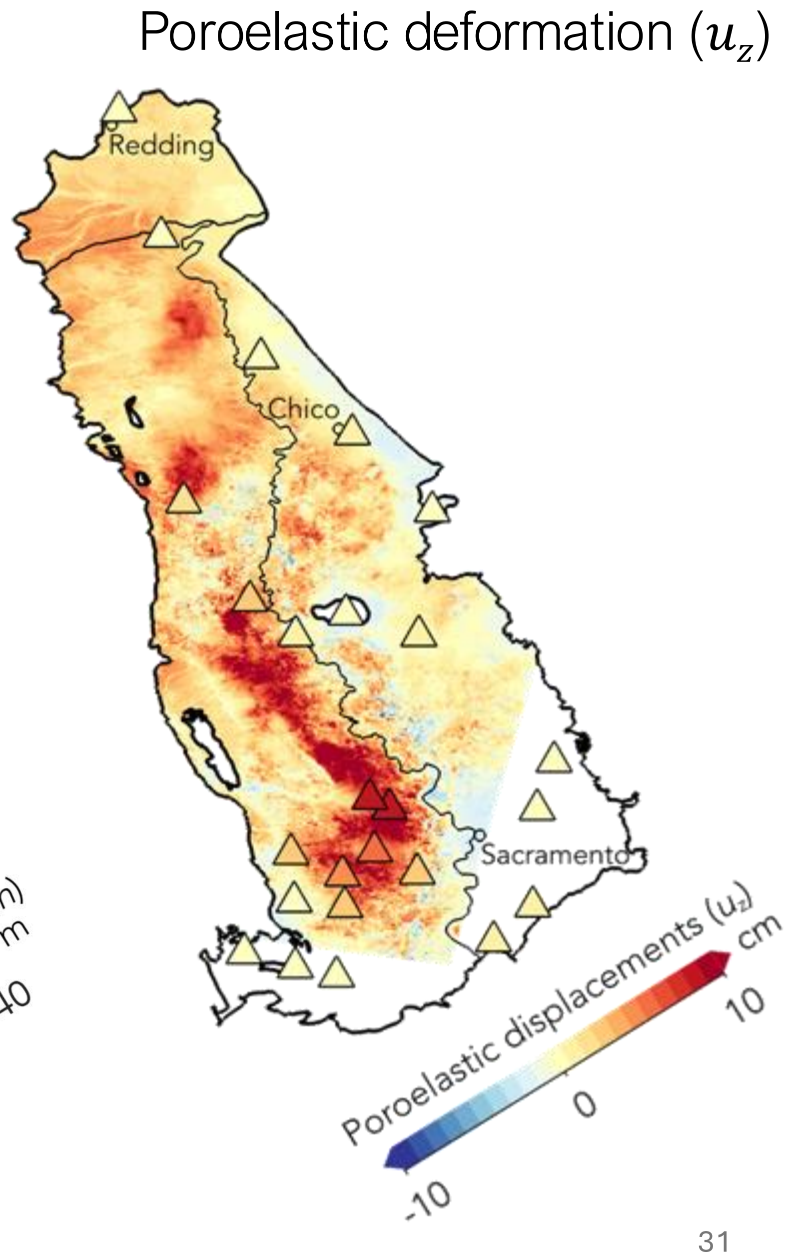


Extracting the poroelastic deformation field from vertical GNSS and InSAR time series



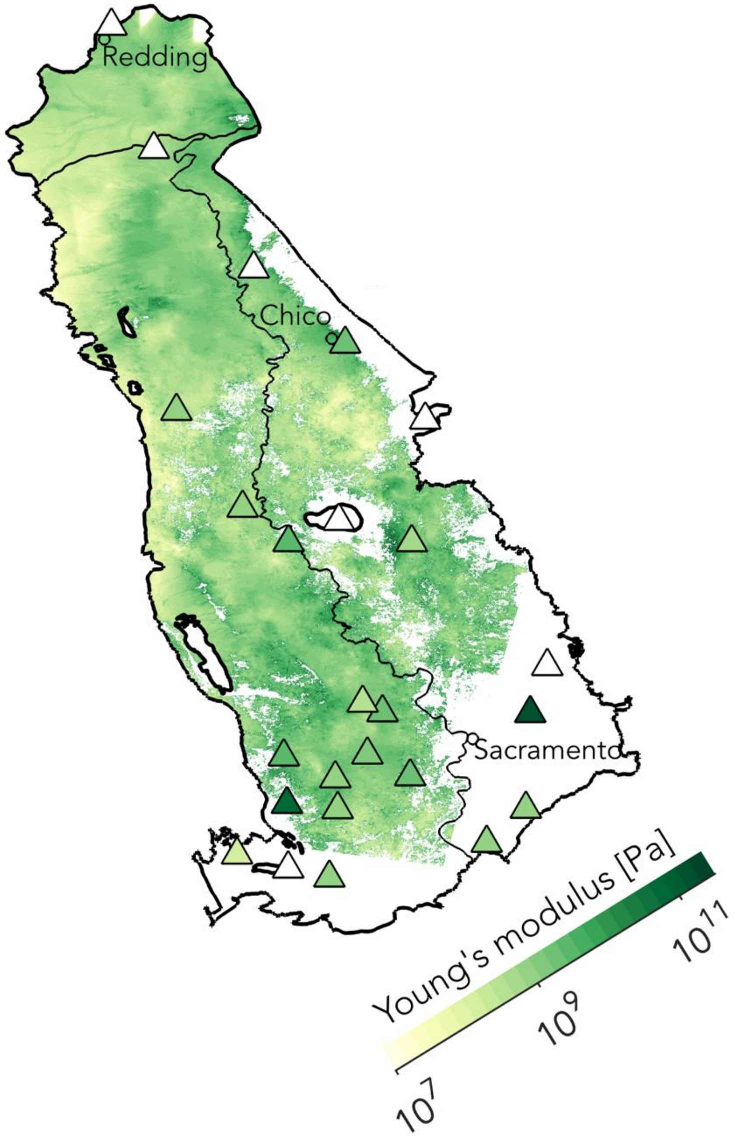
Spatial correlation between groundwater variations and poroelastic deformation



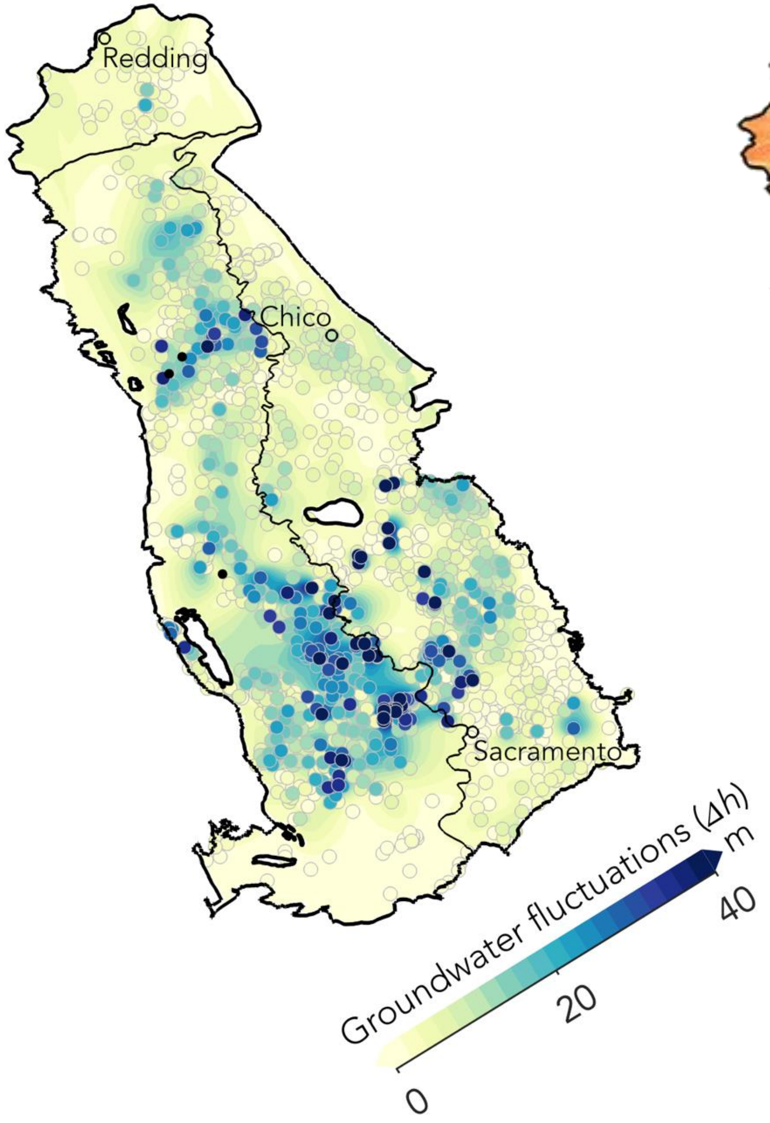


Constraining the elastic properties of the deforming units

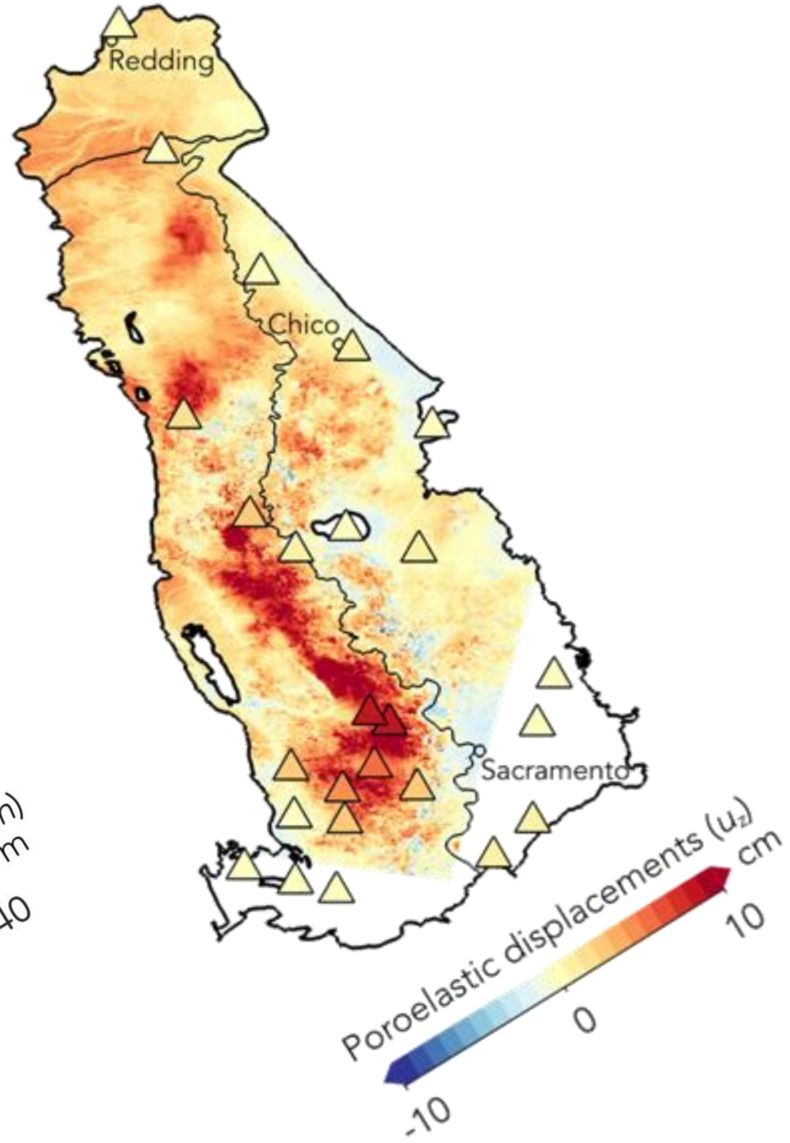
Young's modulus ($E \propto \Delta h / u_z$)



Groundwater fluctuations (Δh)



Poroelastic deformation (u_z)



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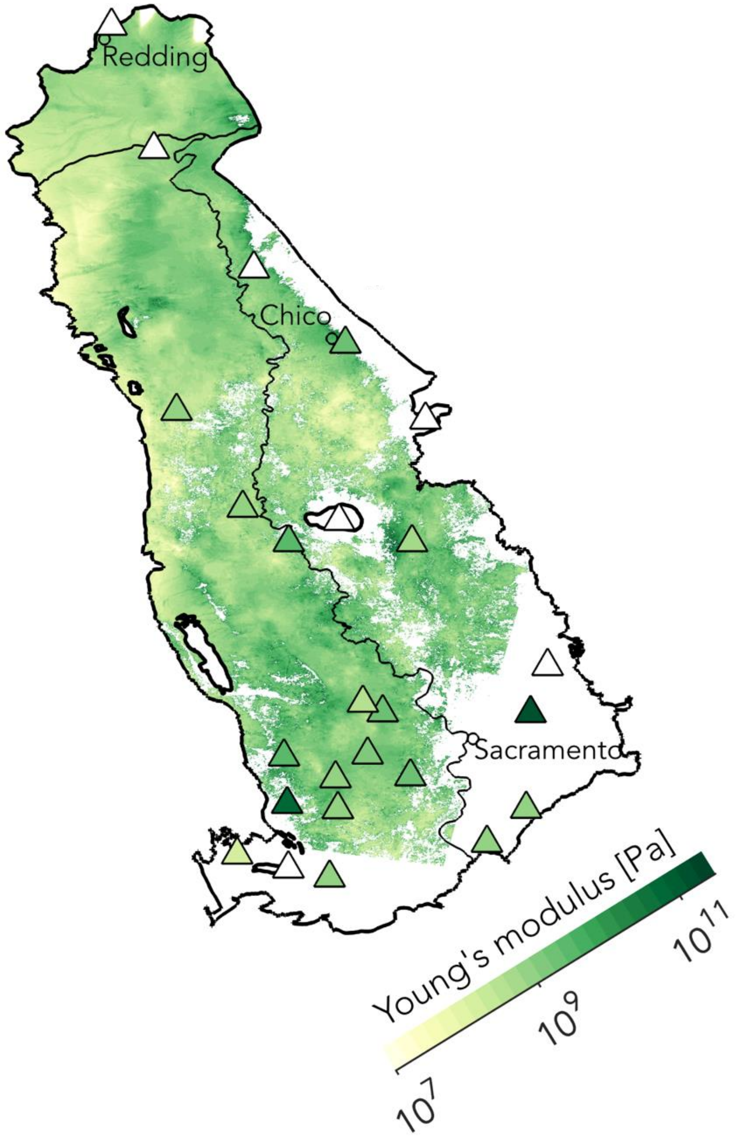
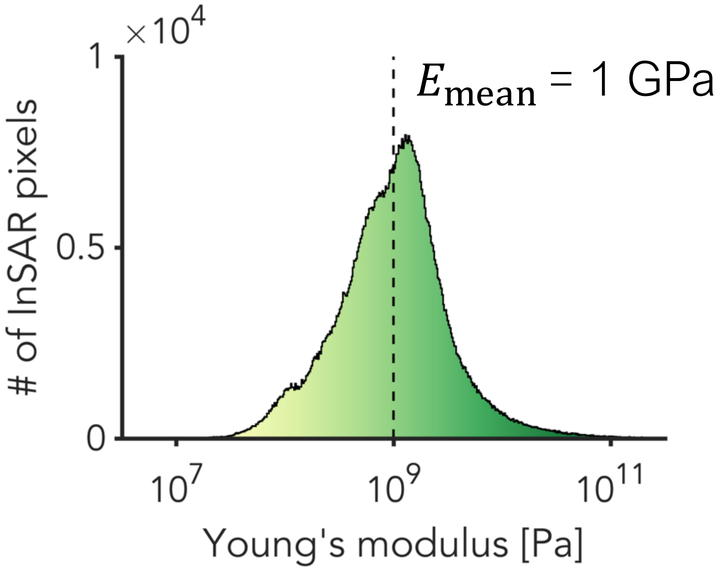
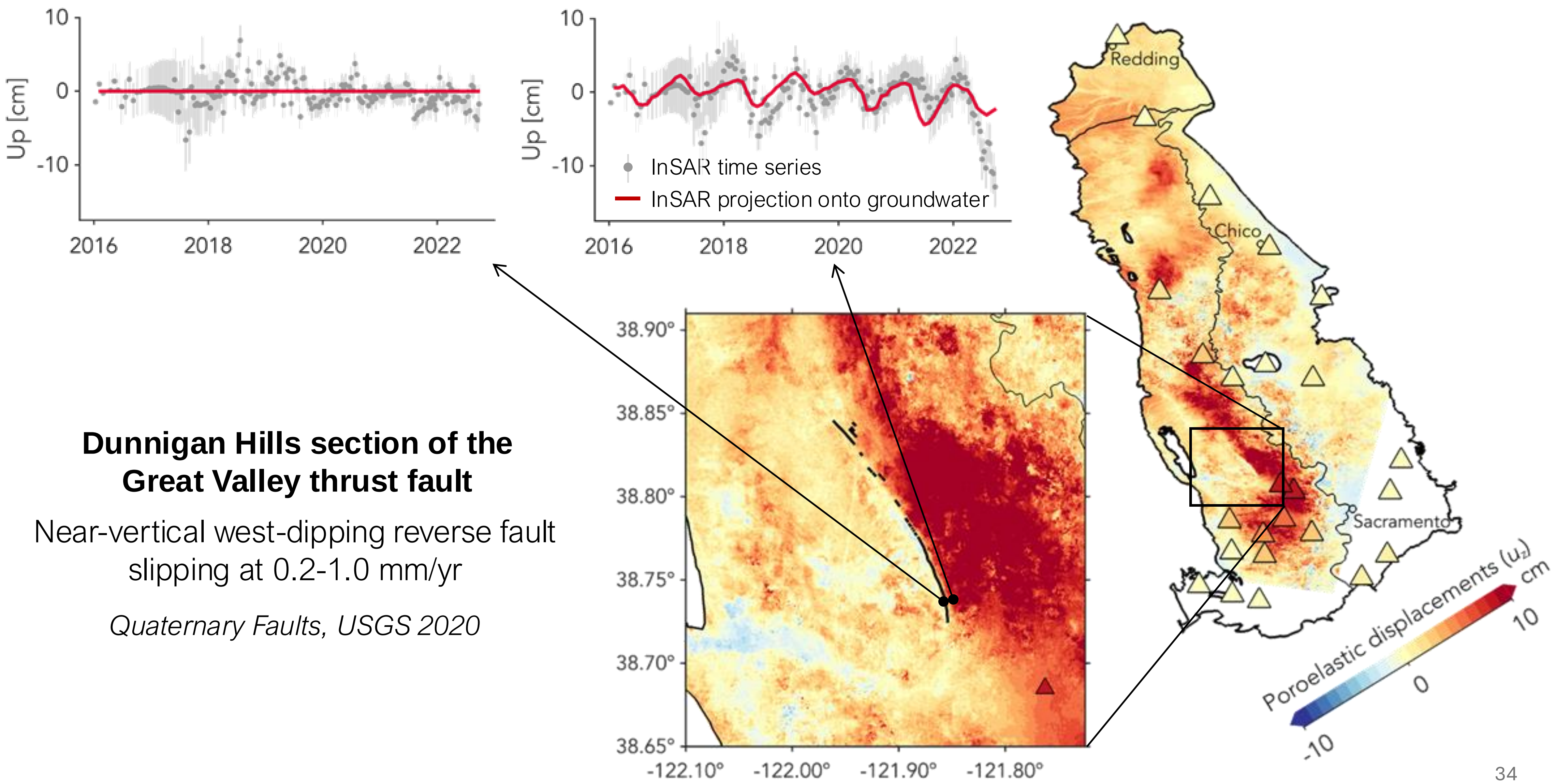




Assumes:

- ✓ Uniaxial strain (no horizontal displacements)
- ✓ Incompressible solid grains ($\alpha = 1$)
- ✓ Uniform Poisson's ratio ($\nu = 0.3$)
- ✓ Deformation over entire known sediment thickness (b)

Fault-bounded poroelastic deformation field

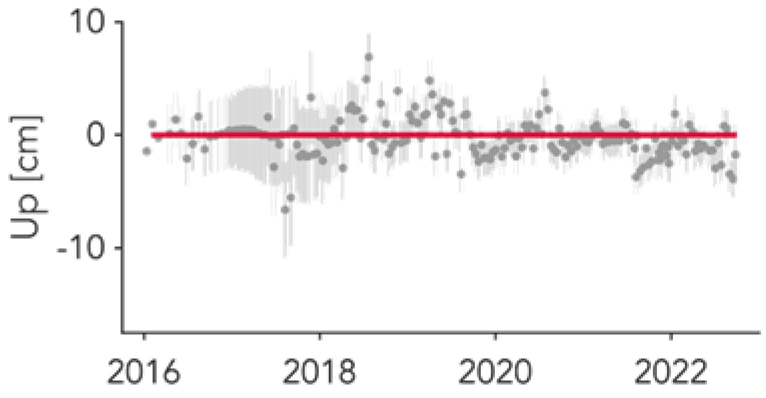


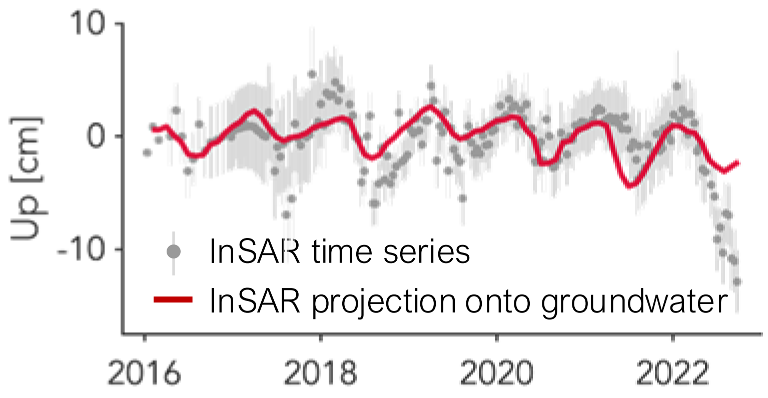
Dunnigan Hills section of the Great Valley thrust fault

Near-vertical west-dipping reverse fault slipping at 0.2-1.0 mm/yr

Quaternary Faults, USGS 2020

Fault-bounded poroelastic deformation field



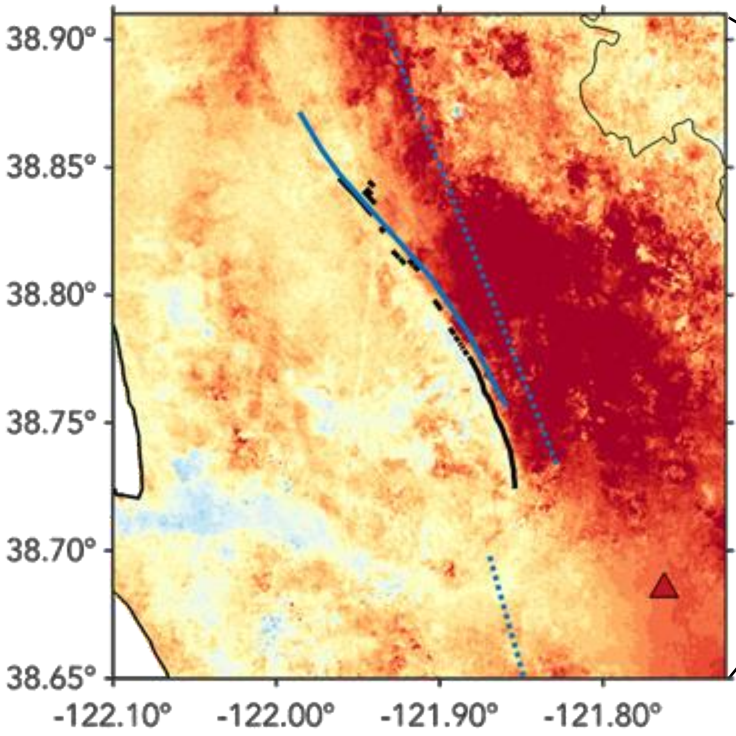


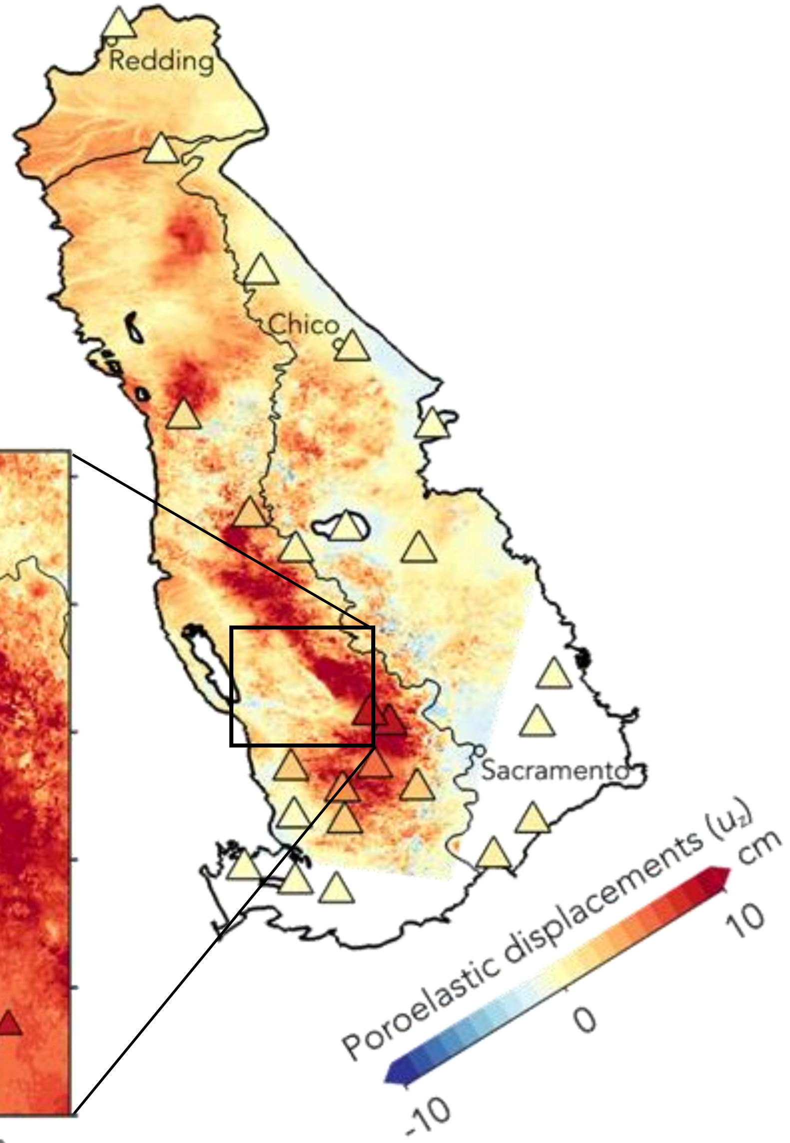
Dunnigan Hills section of the Great Valley thrust fault

Near-vertical west-dipping reverse fault slipping at 0.2-1.0 mm/yr

Quaternary Faults, USGS 2020

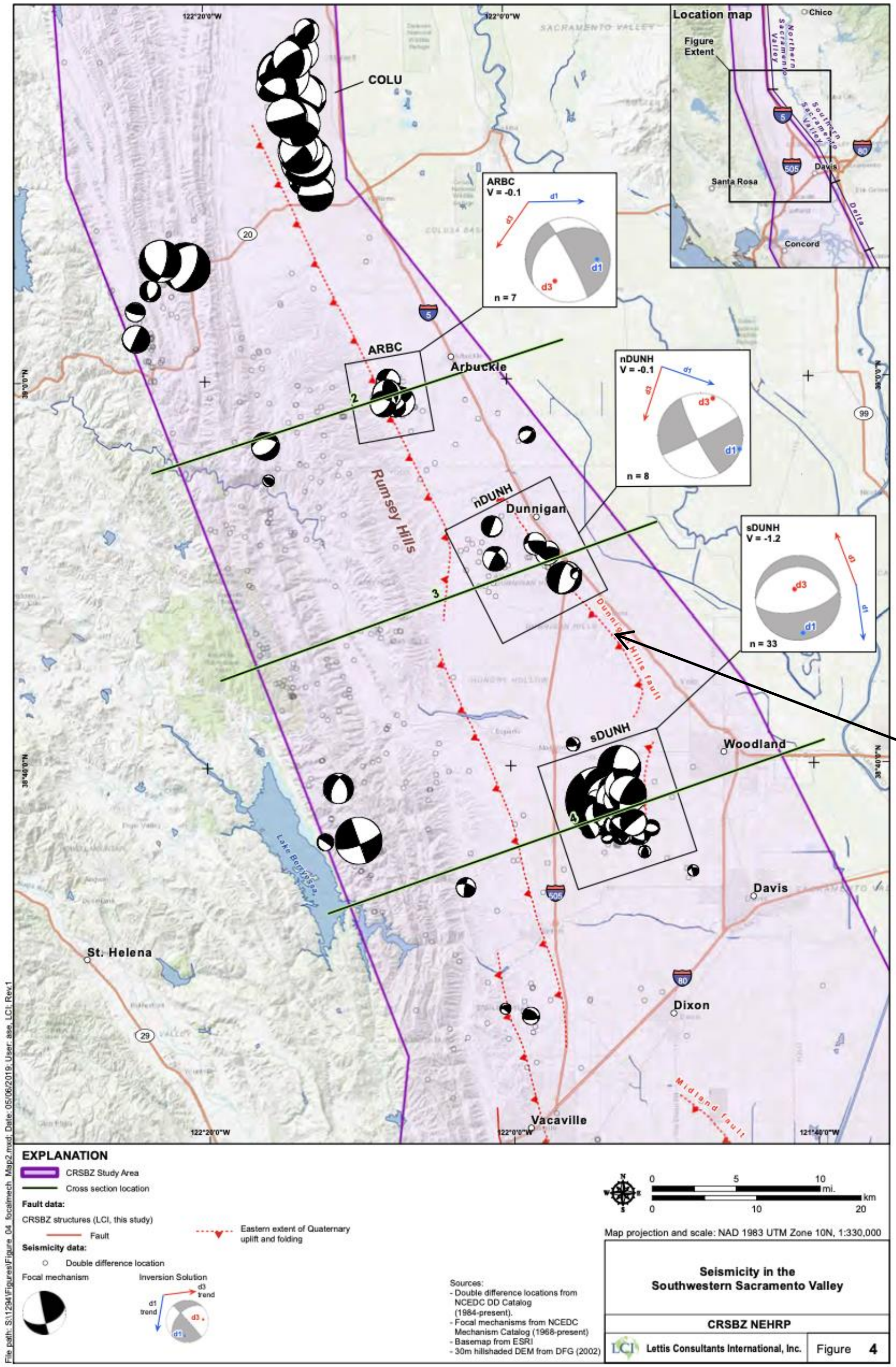
SCEC Community Fault Model Version 7.0

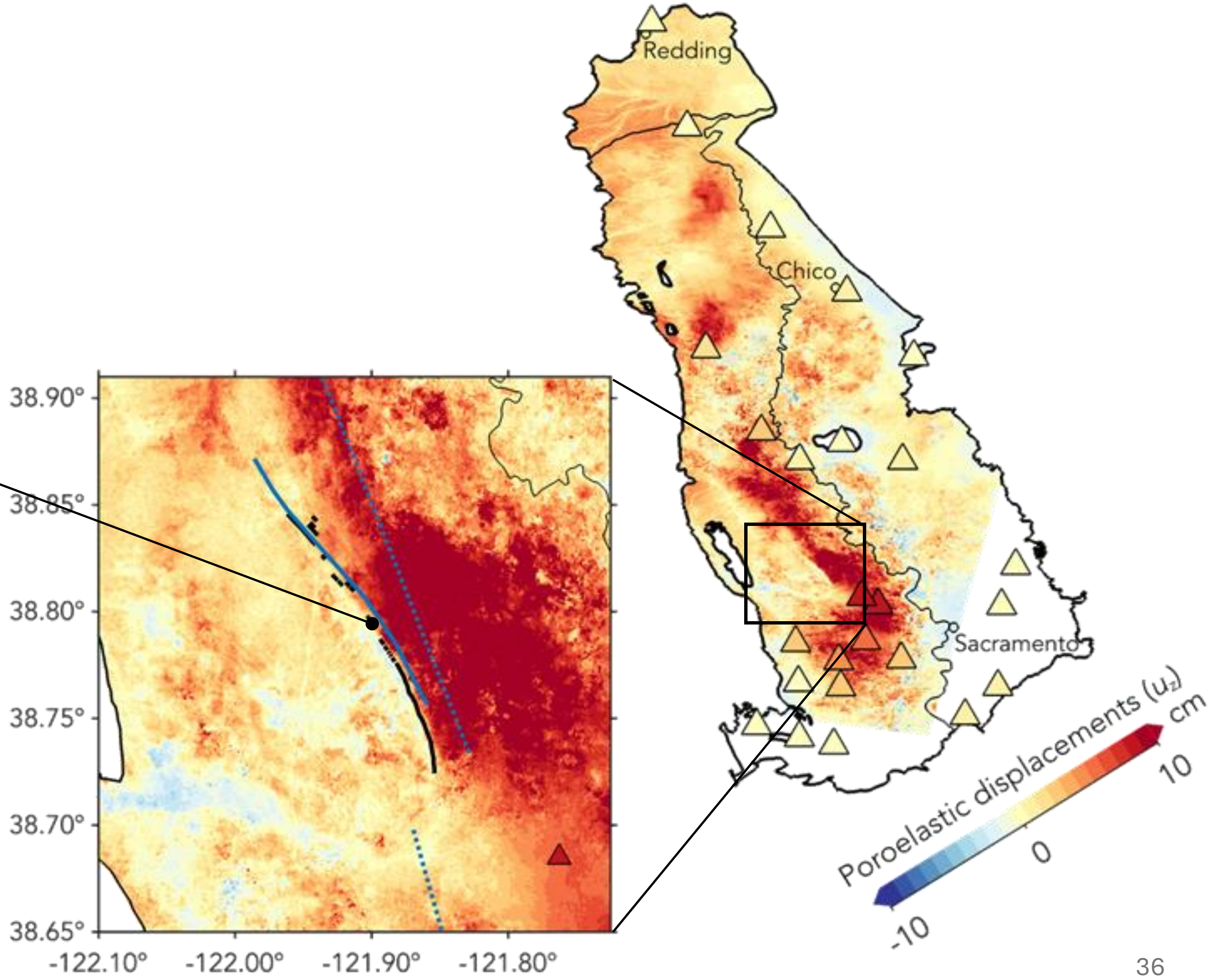


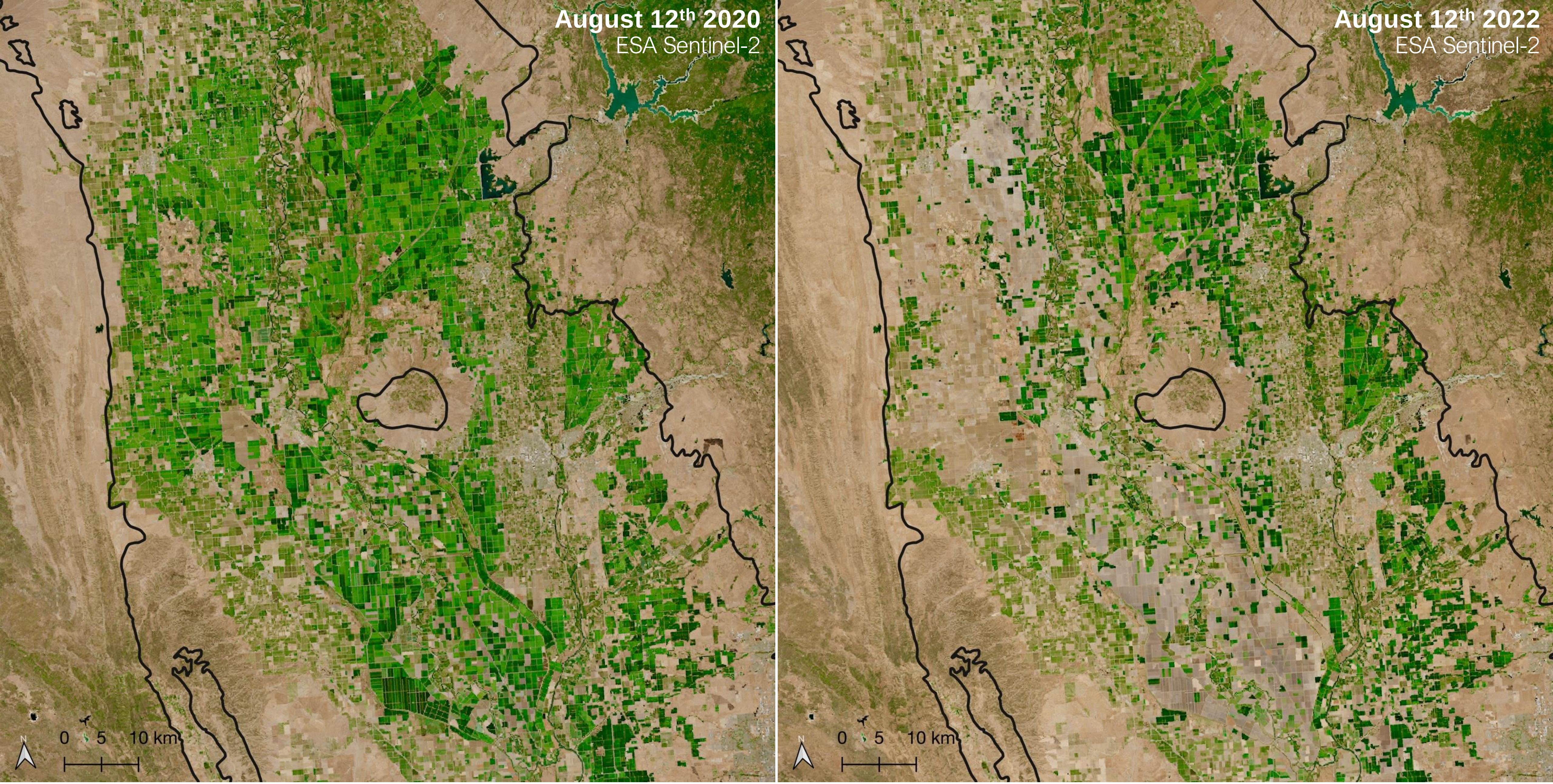


Seismicity of the Southwestern Sacramento Valley

Unruh et al, 2019

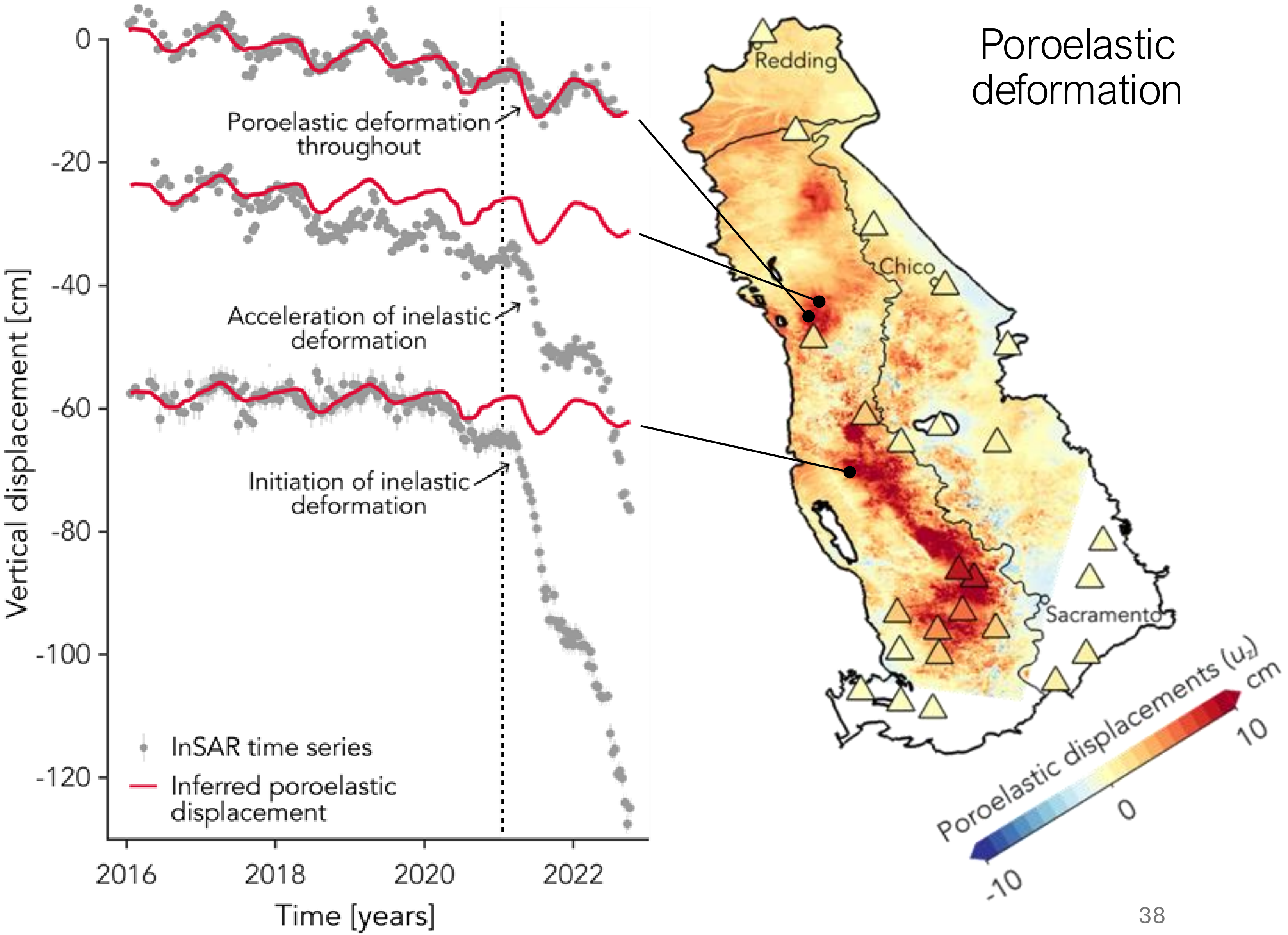






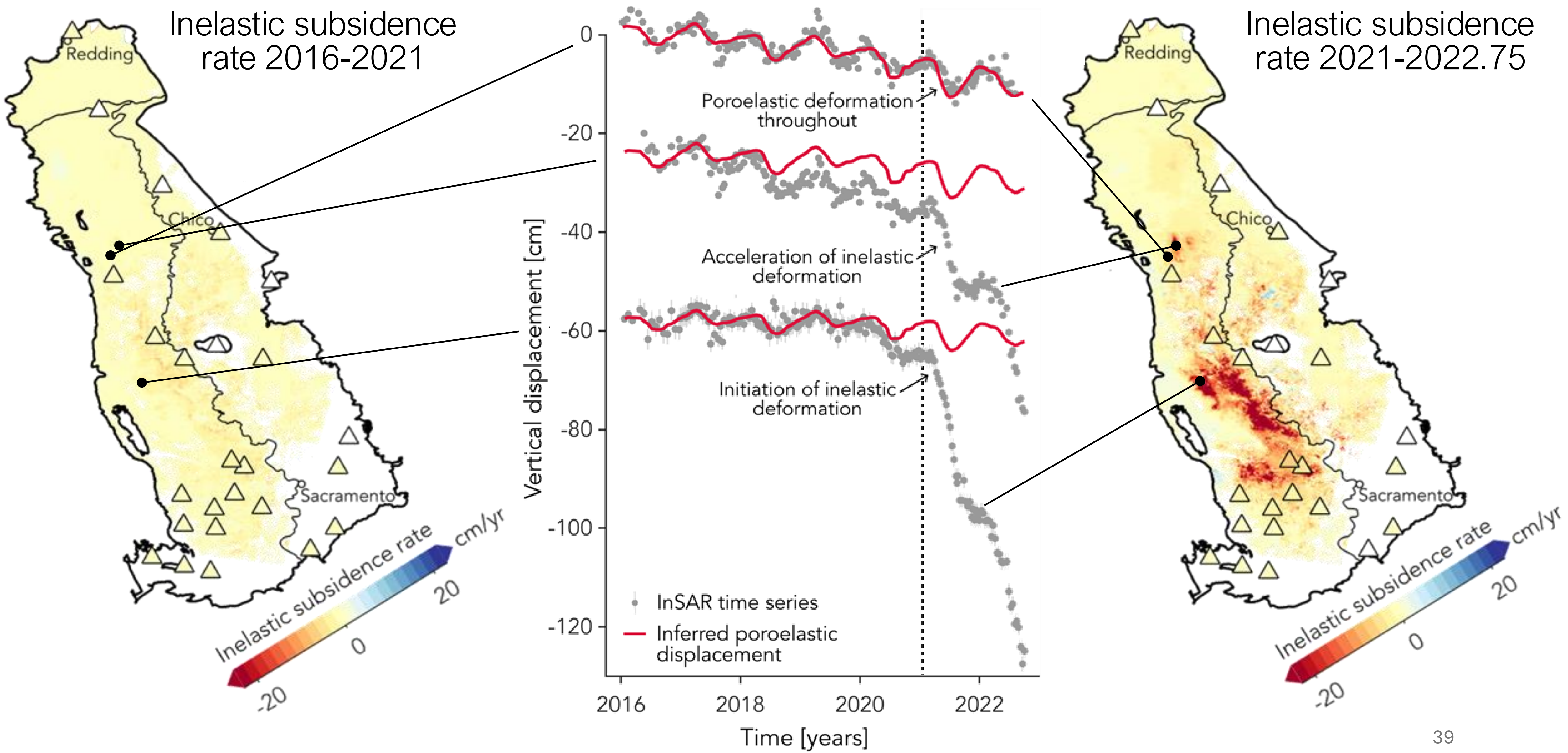
Sacramento Valley’s 2020-2022 historic drought

Abrupt acceleration of inelastic compaction over the 2020-22 drought



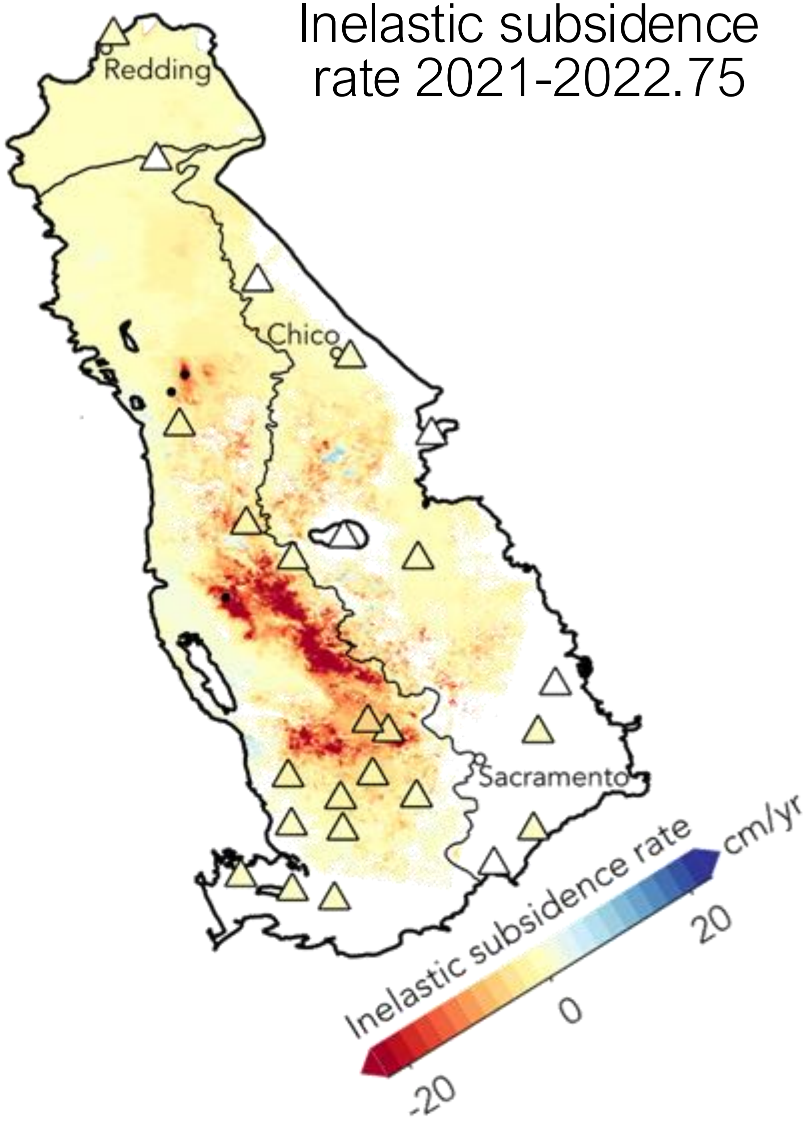
Poroelastic deformation

Abrupt acceleration of inelastic compaction over the 2020-22 drought



Abrupt acceleration of inelastic compaction over the 2020-22 drought

Inelastic subsidence rate 2021-2022.75

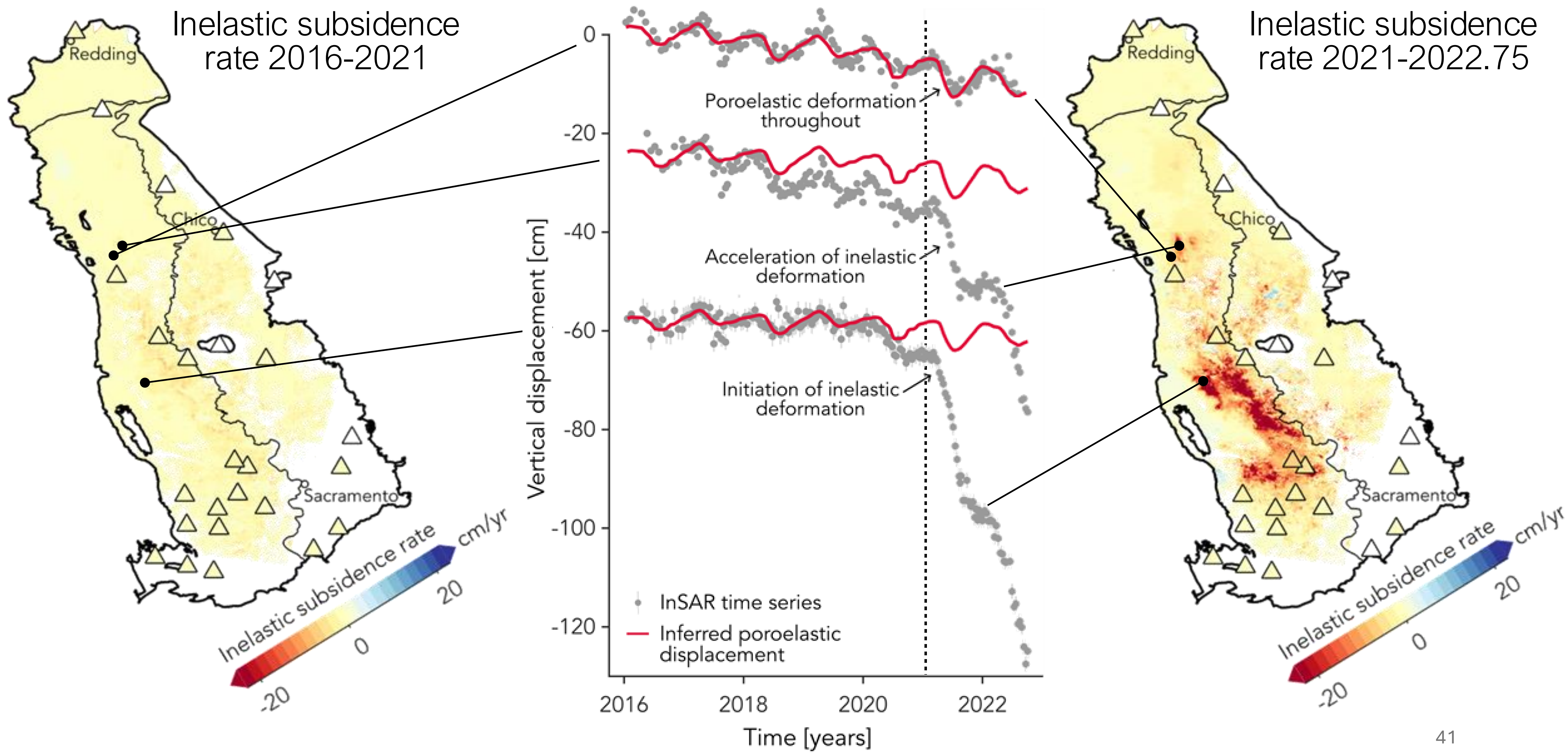


Estimated loss of permanent aquifer storage:

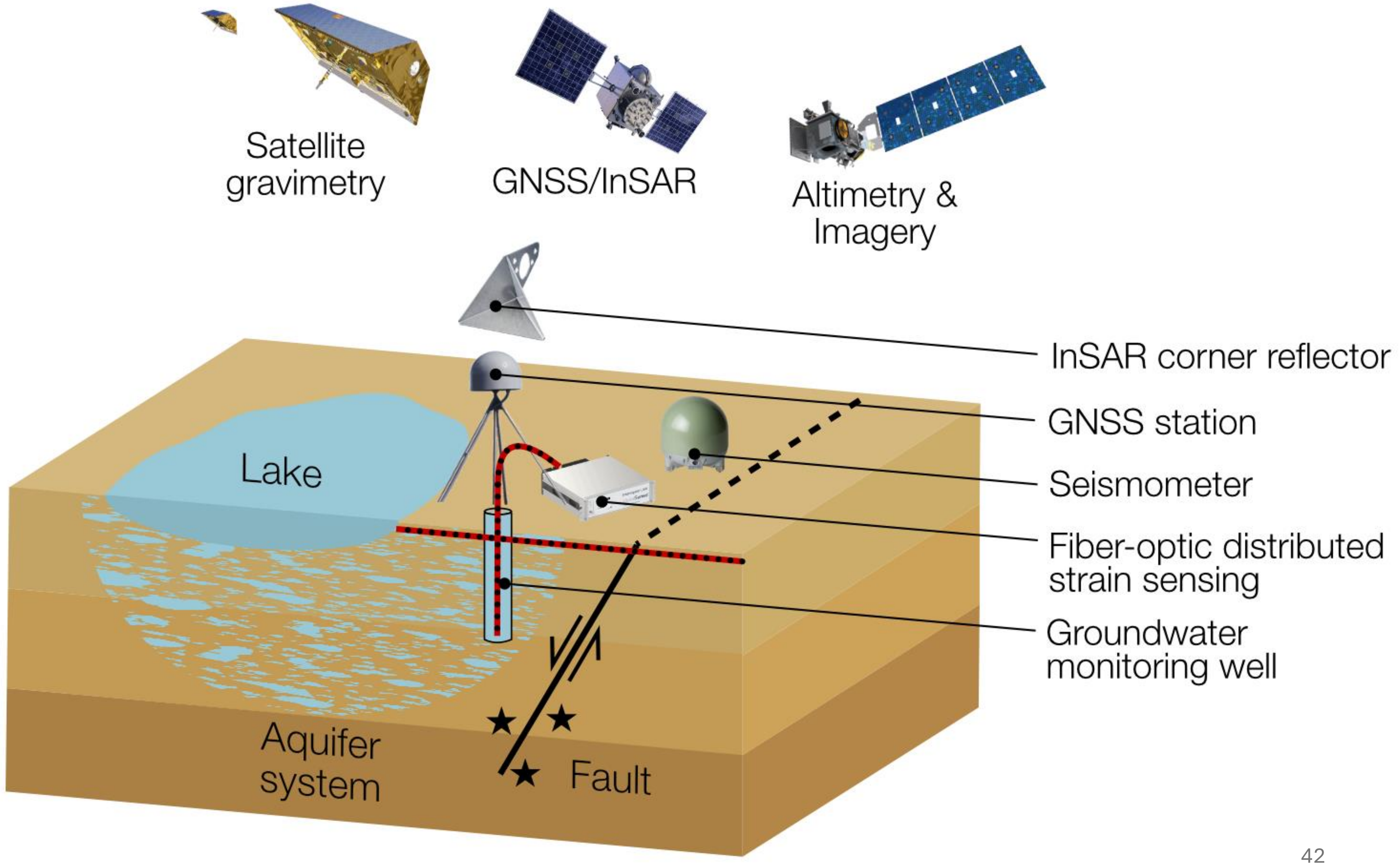
0.2 km^3 /year

Equivalent to ~30% of Los Angeles' annual water consumption

Abrupt acceleration of inelastic compaction over the 2020-22 drought

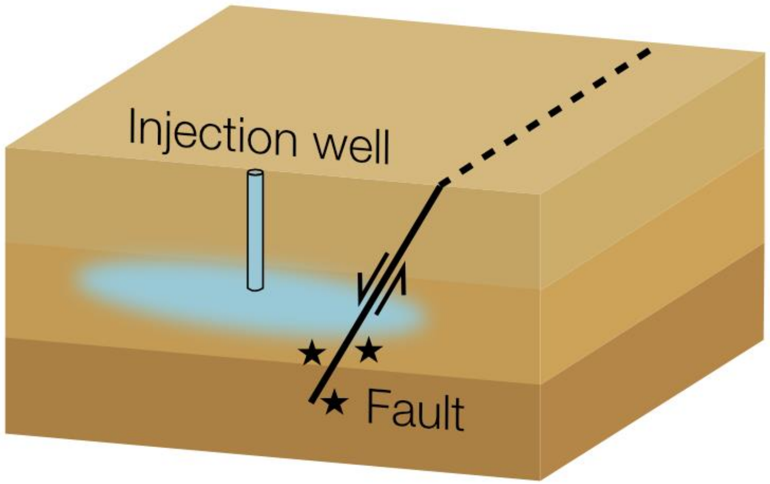


Multi-technique hydro-geophysical stations

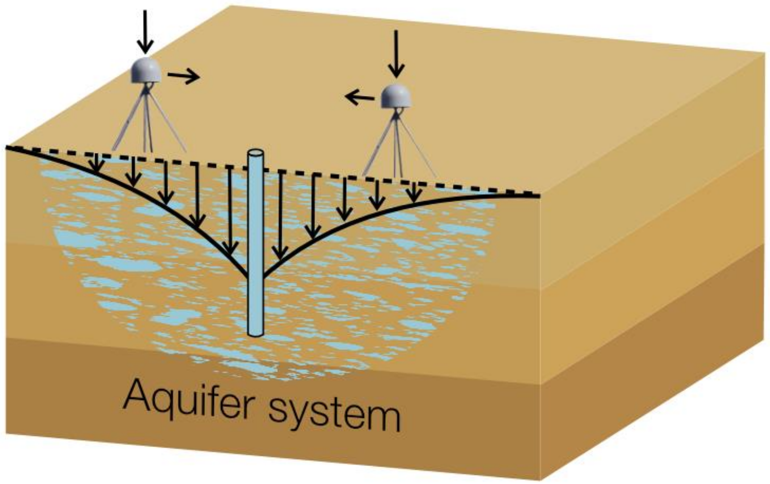


Summary

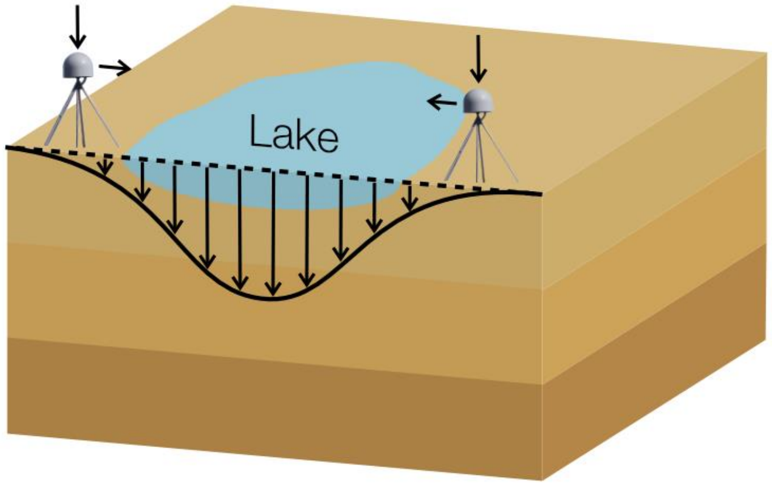
1. Modern satellite geodesy is a powerful tool for measuring hydrology-driven deformation.
2. We developed a methodology to extract these signals from GNSS and InSAR time series in the data-rich Sacramento Valley.
3. We constrained rheology, fault-groundwater interactions, and aquifer storage loss in the Sacramento Valley.
4. We need multi-technique hydro-geophysical stations near fault zones!



Fluid-induced fault slip
Aseismic + seismic



Porous response
Poroelastic + inelastic



Hydrological loading
Elastic + viscoelastic

Summary

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Thank you!