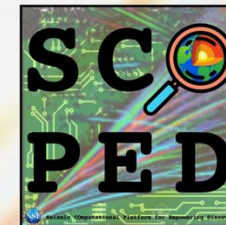


Tracking Temporal Changes in the Subsurface Structure Near Faults and Populated Areas

Marine Denolle

Kuan Fu Feng, Tim Clements, Yiyu Ni, Loïc Viens, Kurama Okubo,
Laura Ermert, Congcong Yuan, Fabian Diewald



A photograph of a road on the San Andreas Fault at Parkfield. The road is paved and has a white guardrail on the right side. A crack is visible in the guardrail, and a sign with the number 438 is attached to it. In the background, a car and a pickup truck are parked on the road, and several people are standing nearby. The landscape is dry and hilly.

**The San Andreas
Fault is still creeping
at Parkfield**

Global Coastal Subsidence



NYT

California floods



Los Angeles Times
(Shmuel Thaler / Santa Cruz Sentinel via Associated
Press)

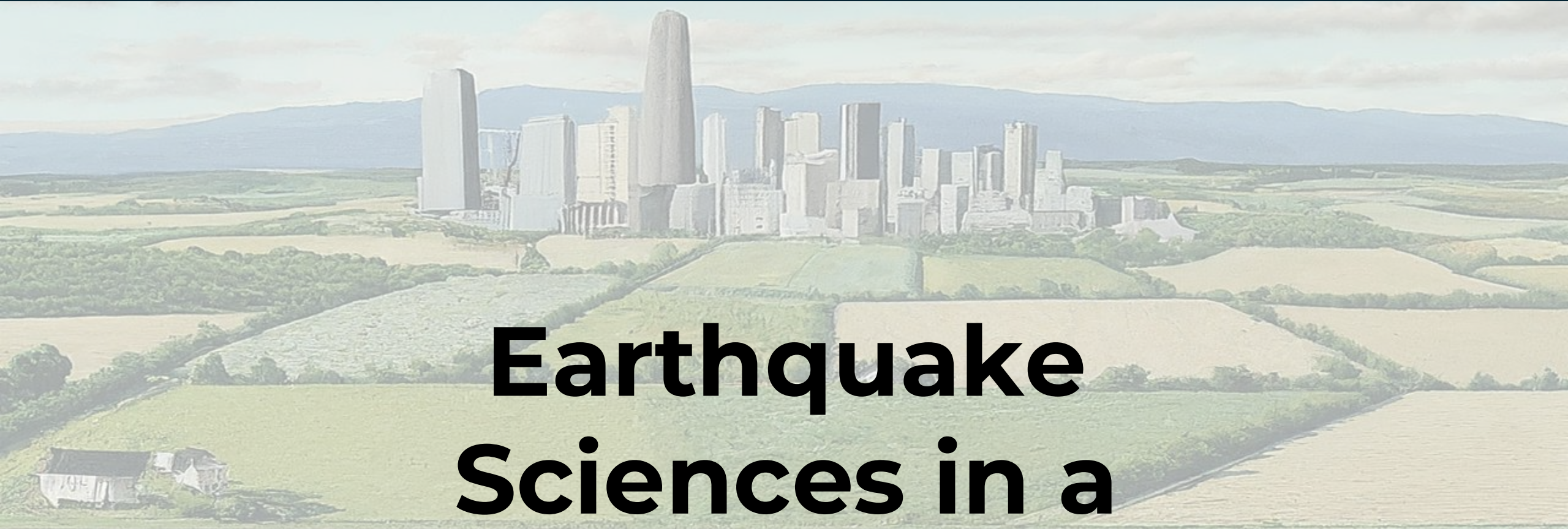
California dries up



BH₂  *Beverly Hills is Conserving*
www.beverlyhills.org/conservation

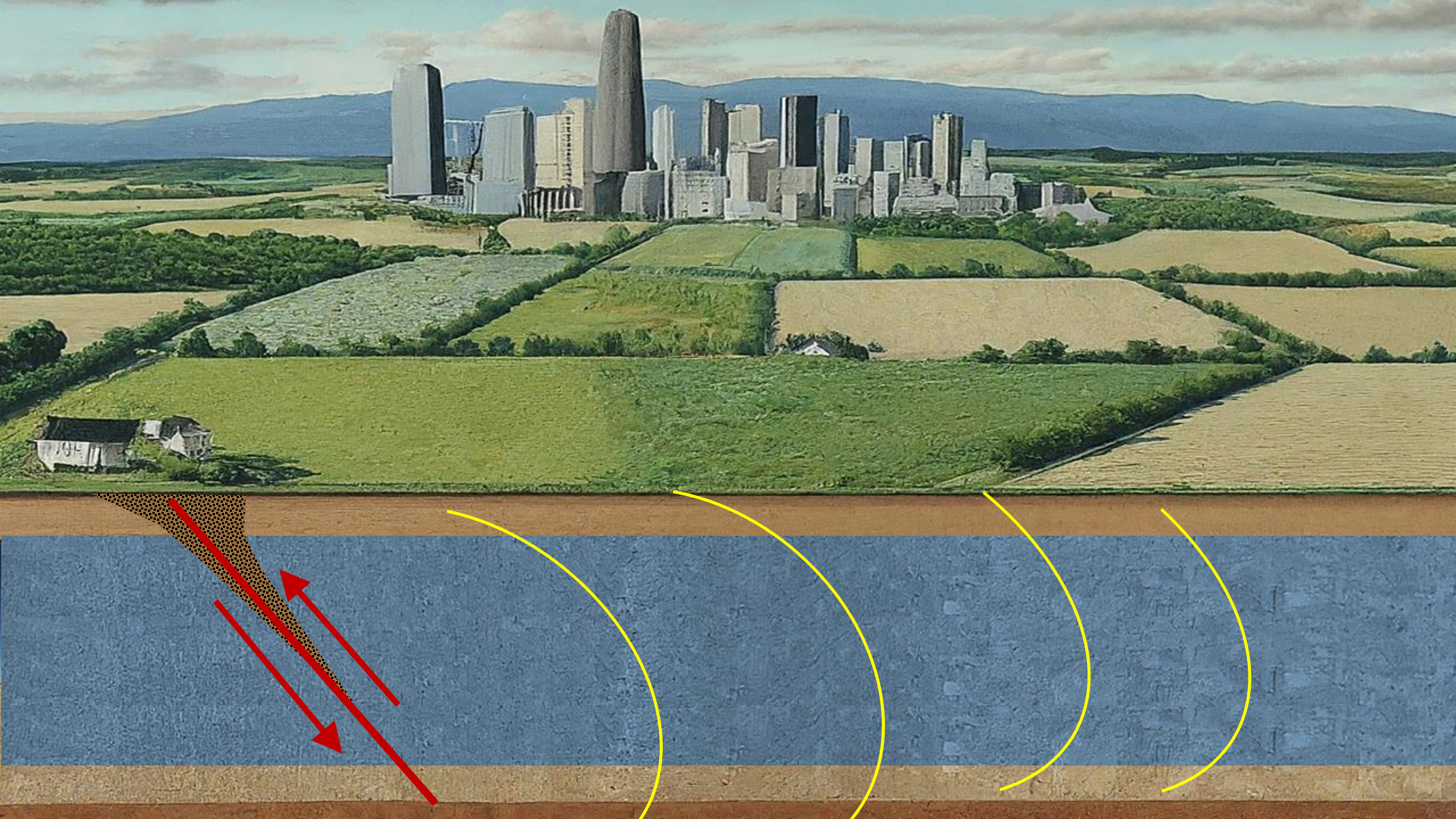
**Water to the
City's grass
medians has
been turned off
due to the
drought**

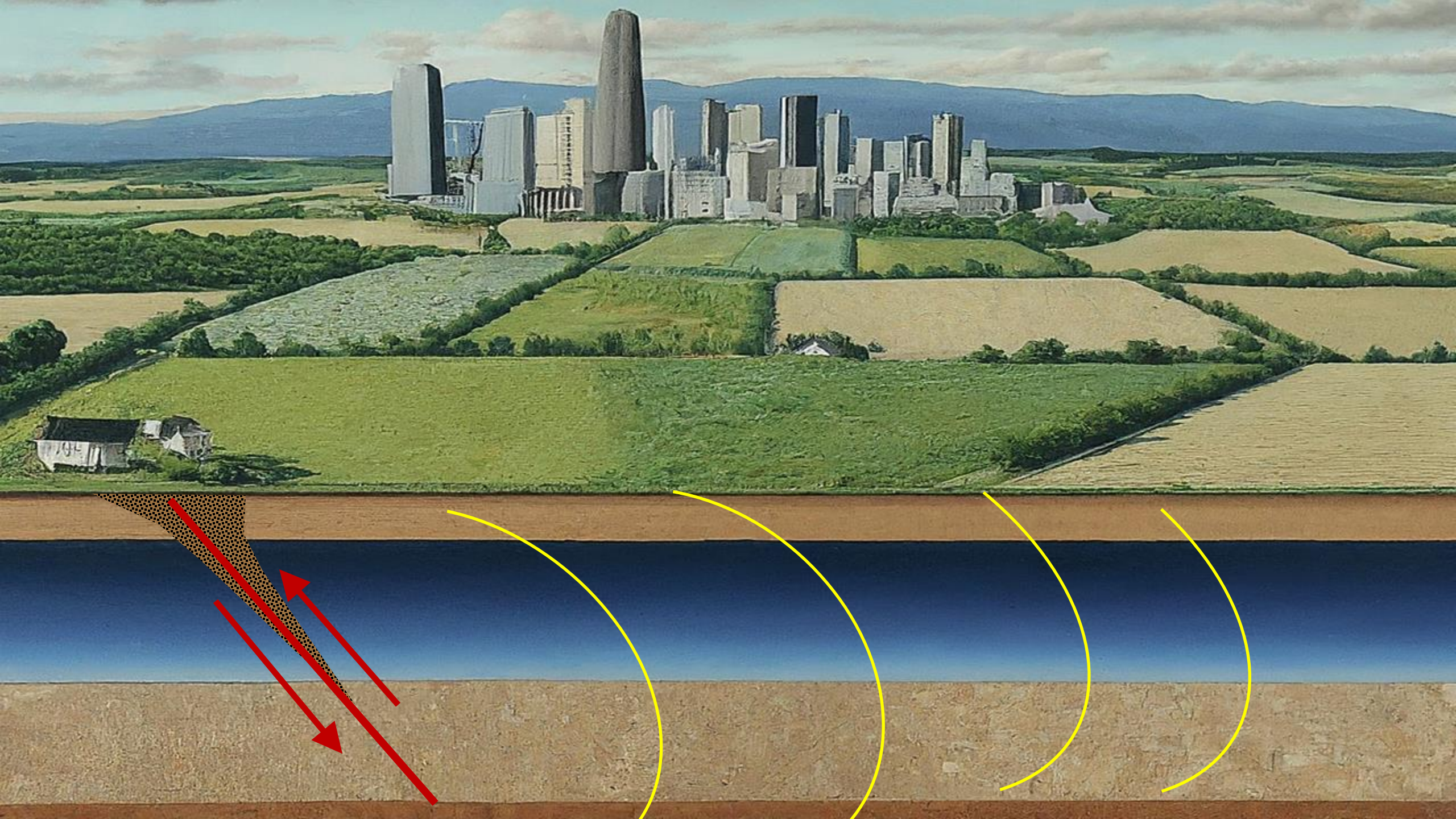
Ted Soqui—Demotix/Corbis
The Time

An aerial photograph of a city skyline, including a prominent tall, tapered tower, situated on a hillside. The foreground shows a valley with green fields and a small, damaged building. The background features rolling hills and mountains under a cloudy sky. The text is overlaid on the center of the image.

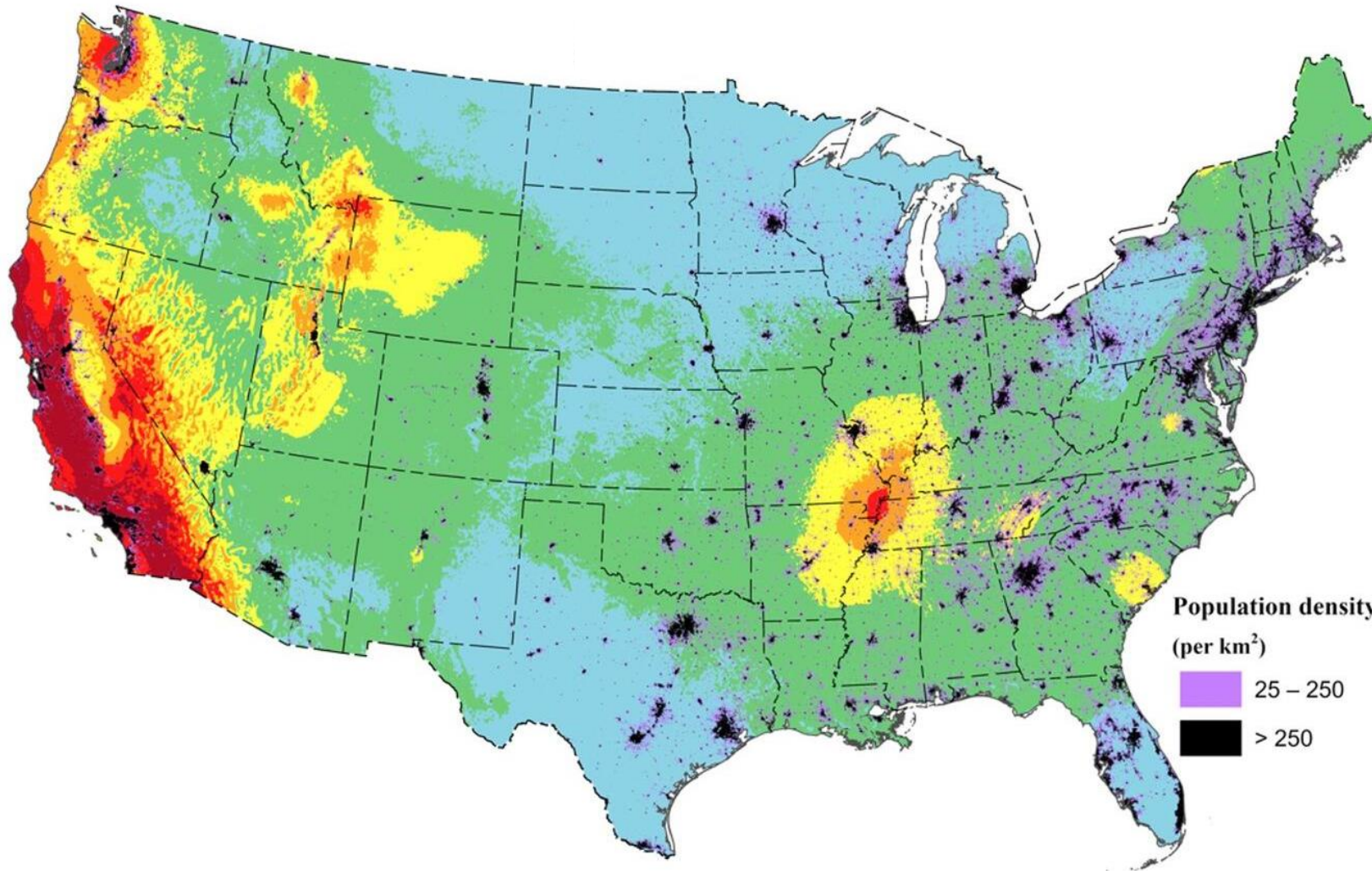
Earthquake Sciences in a Dynamic Earth





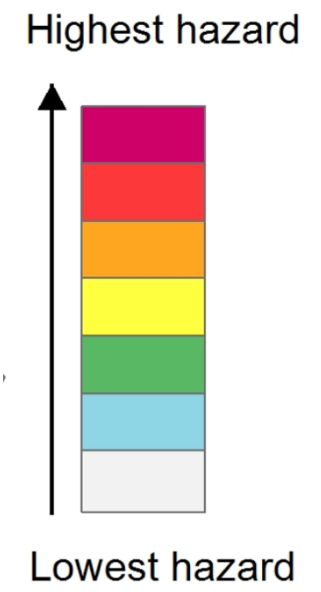


Long-term seismic hazard map



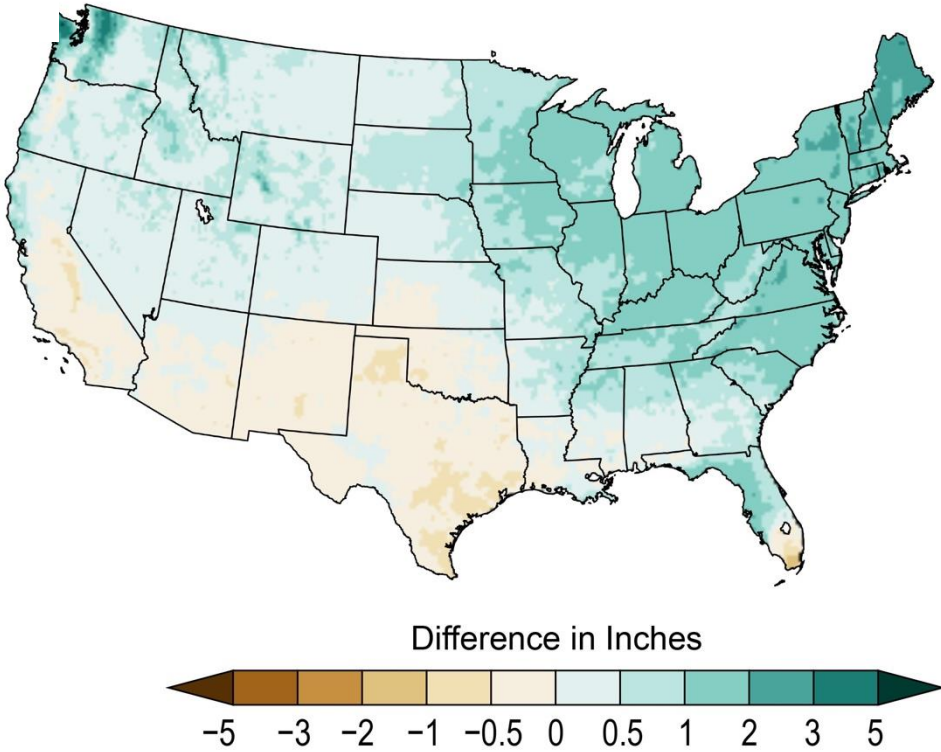
Population density
(per km²)

- 25 – 250
- > 250

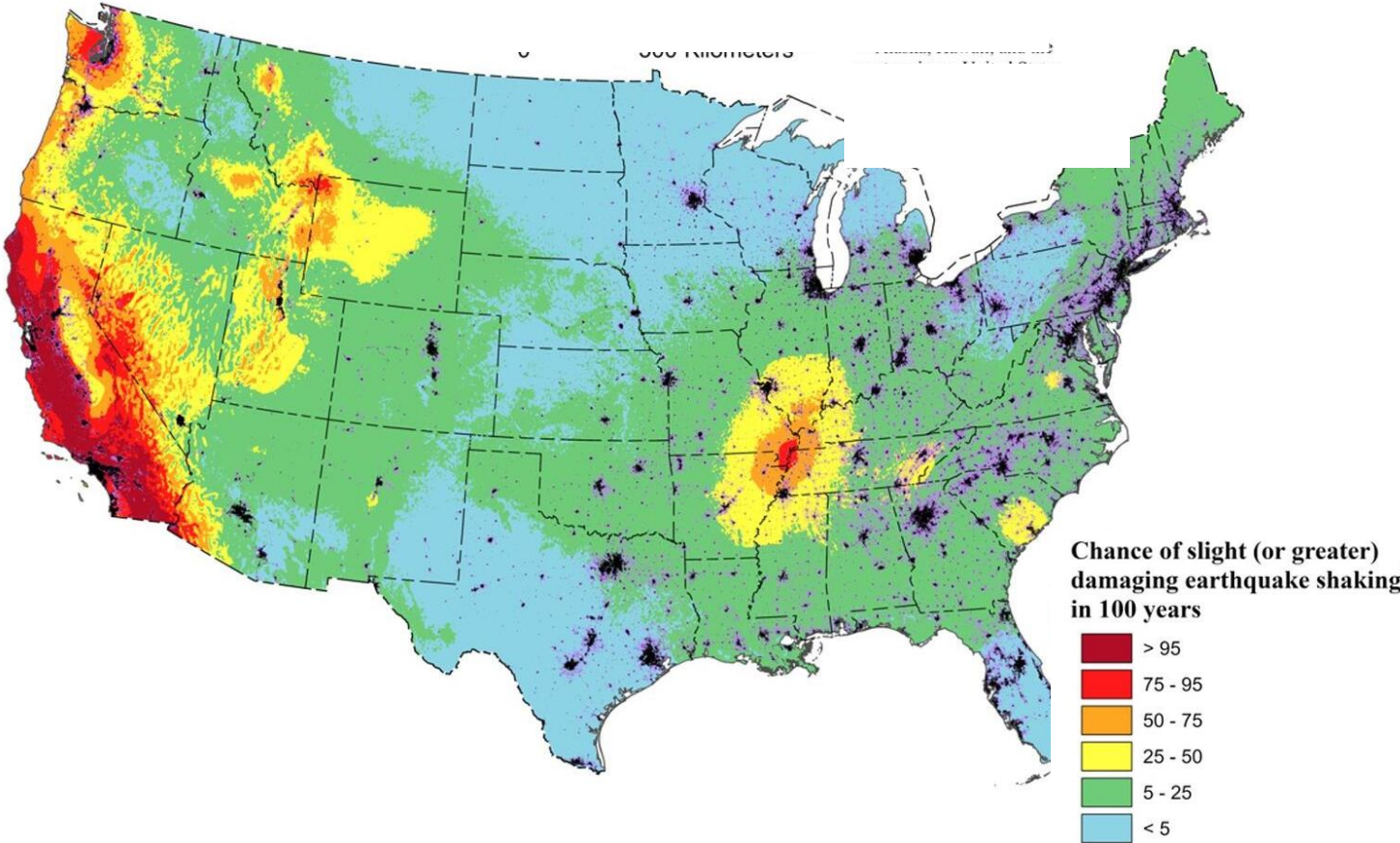


The shallow Earth will change in the next 100 years

Projected Changes in Annual Precipitation by Midcentury
2036–2065 relative to 1991–2020



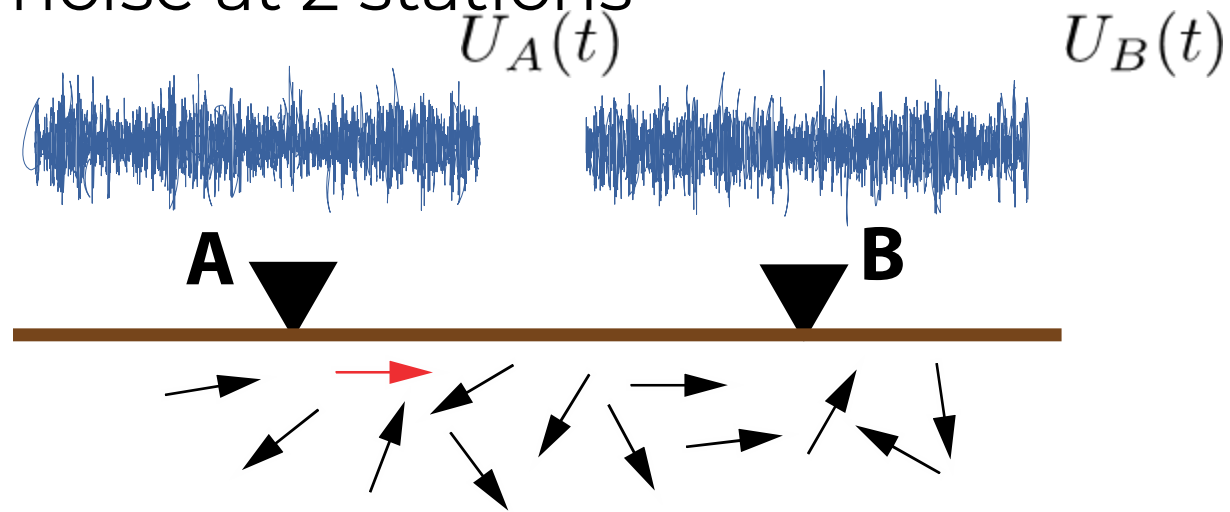
National Seismic Hazard (2023)



**Probing *subsurface*
changes using *ambient*
Earth *vibrations***

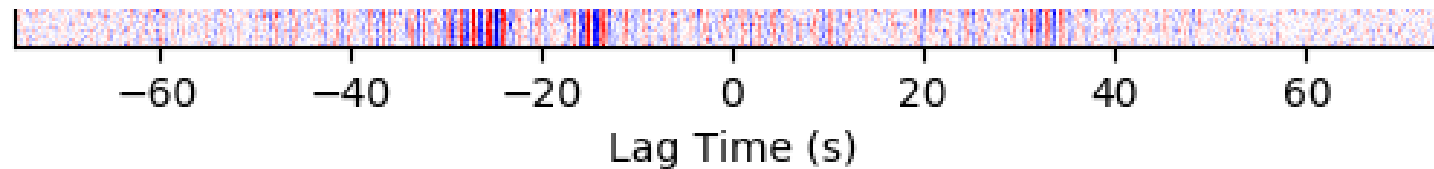
Measure structure change from seismic noise

1. Window seismic noise at 2 stations



2. Cross-correlate noise windows between stations

$$G_{AB}(t) = U_A(t) * U_B(t)$$

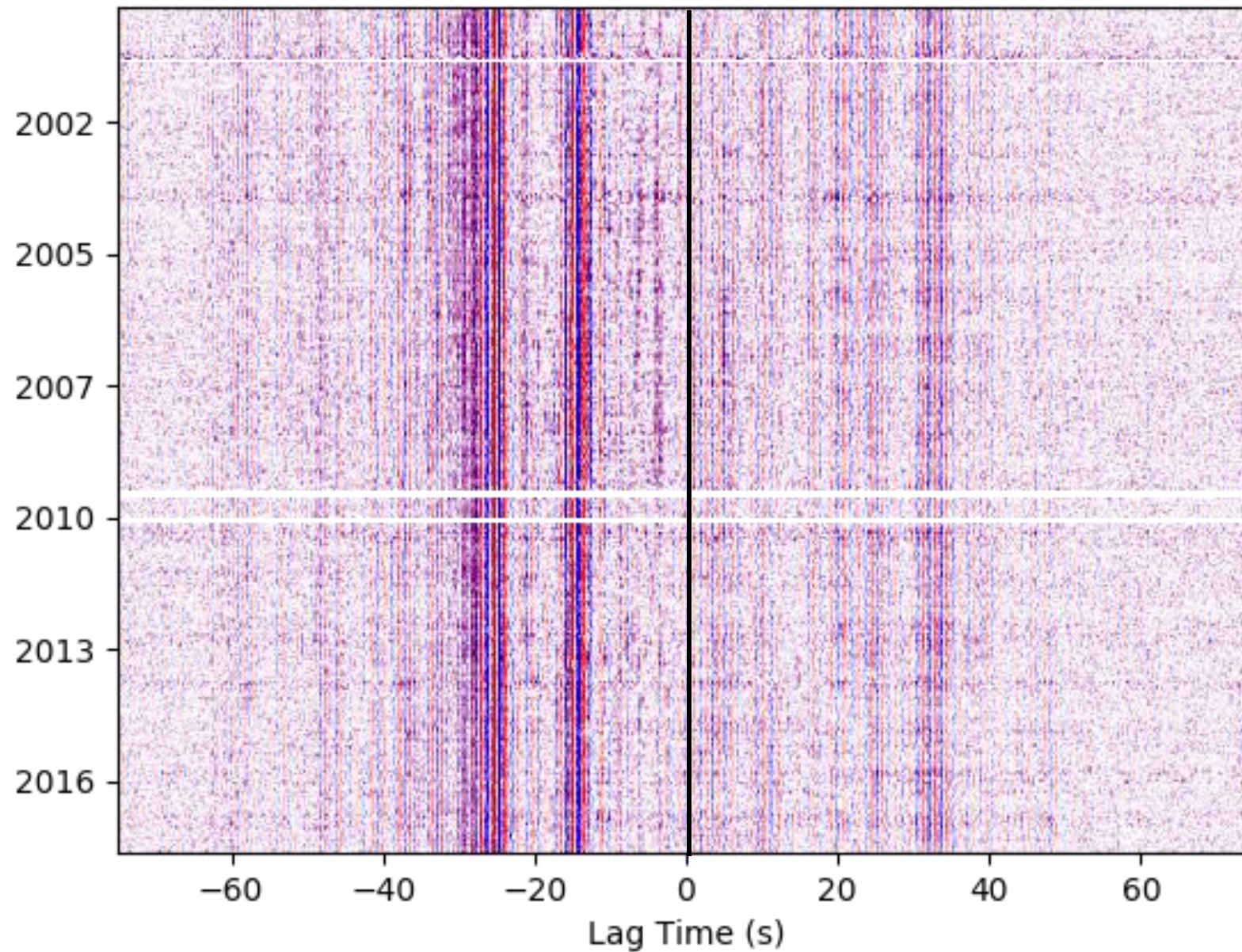


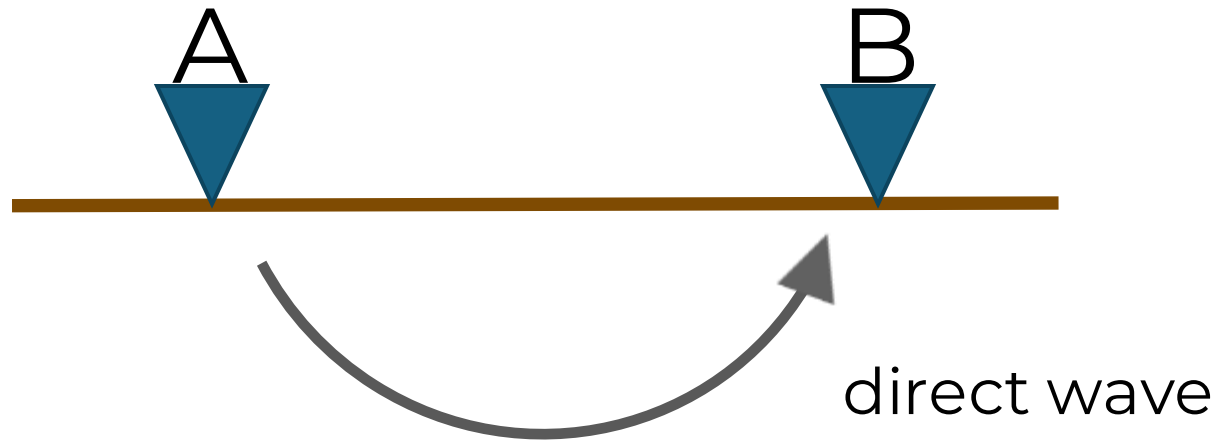
15 years of continuous data.

RIO-MWC

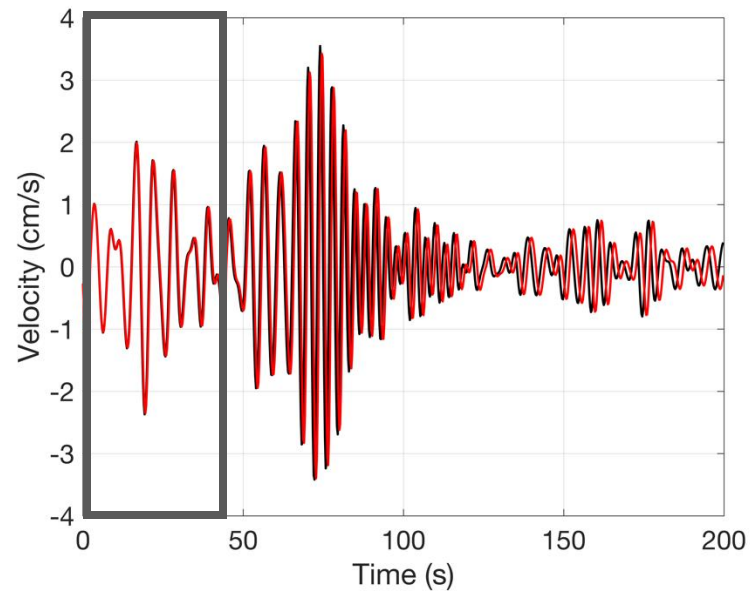


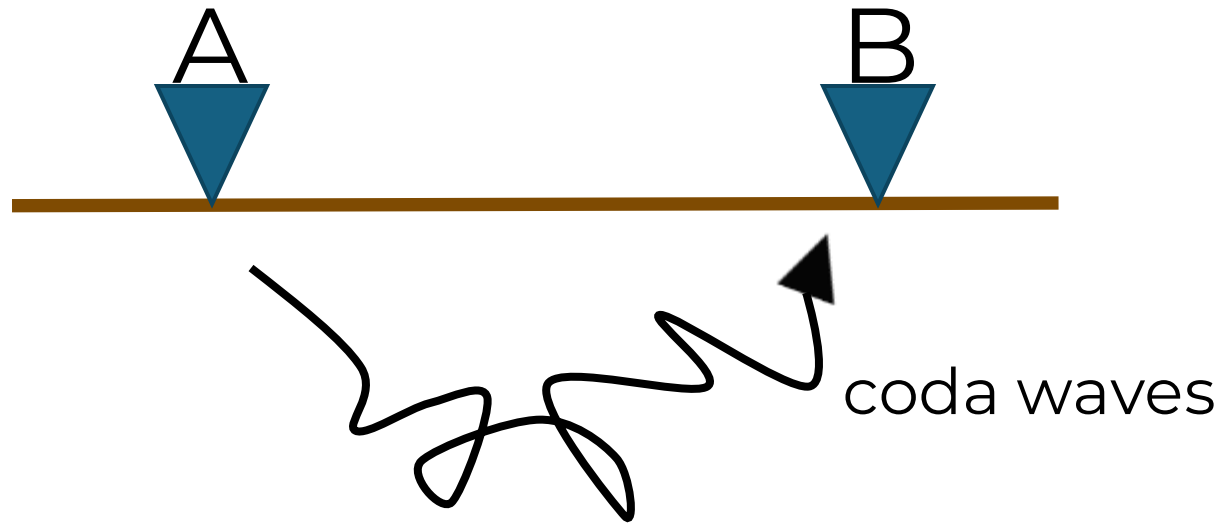
Tim Clements



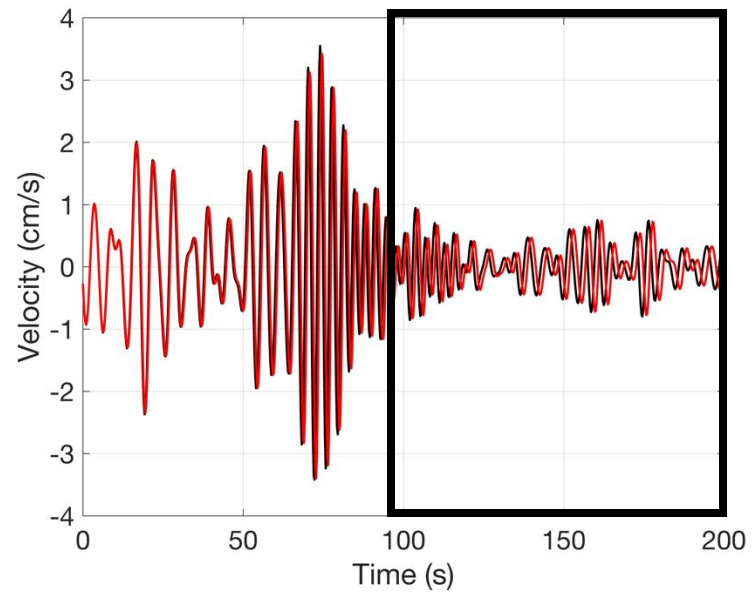


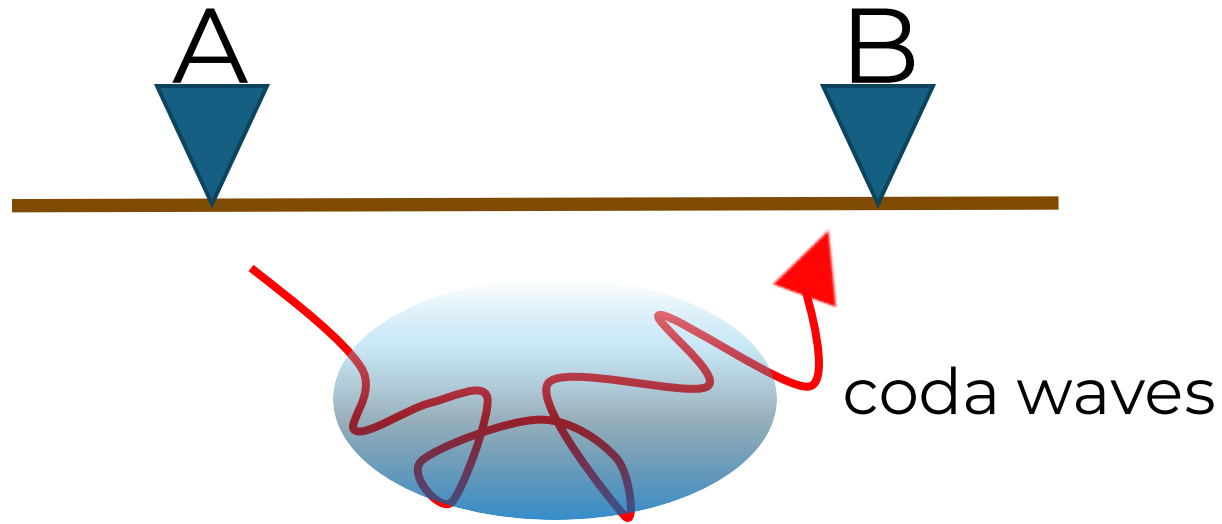
ground motions



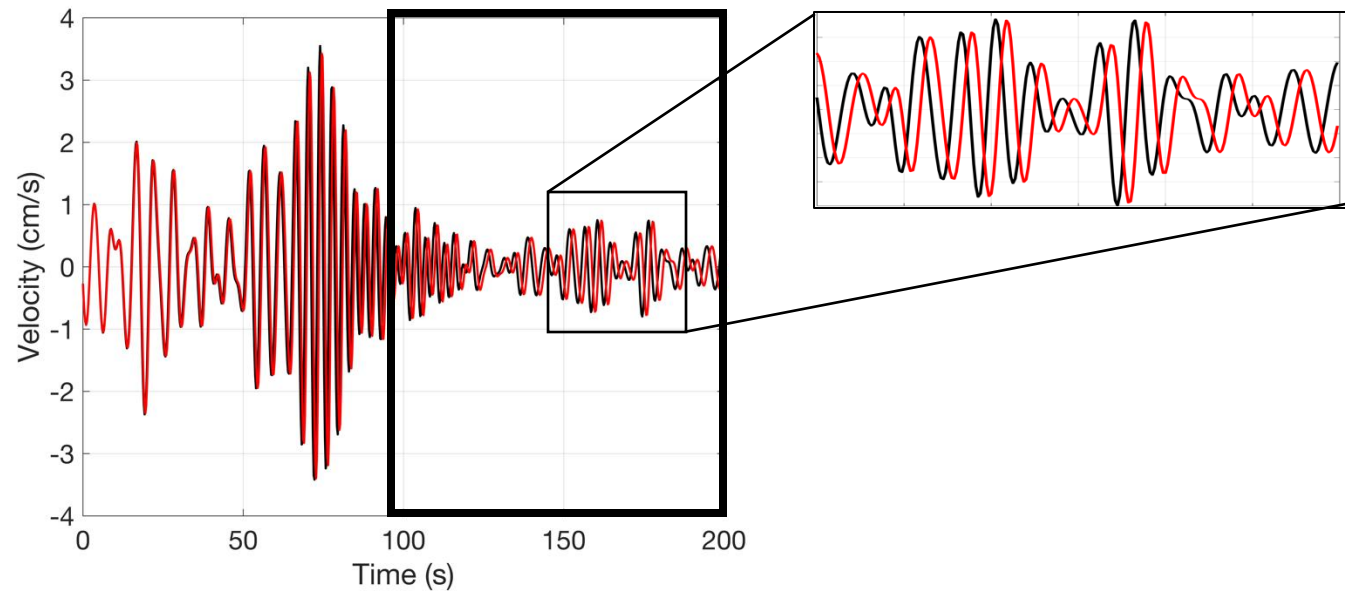


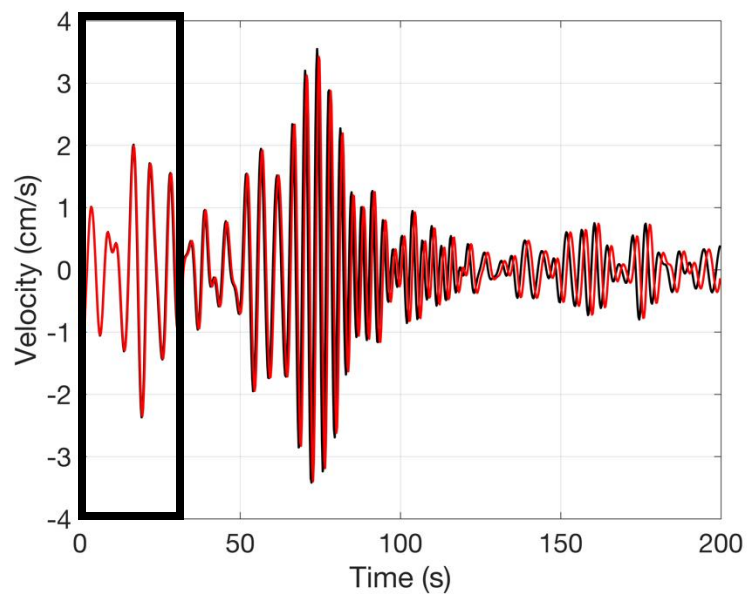
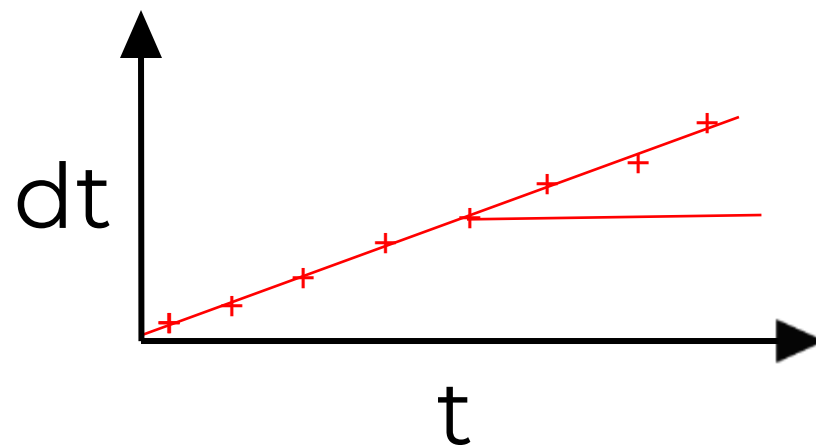
ground motions

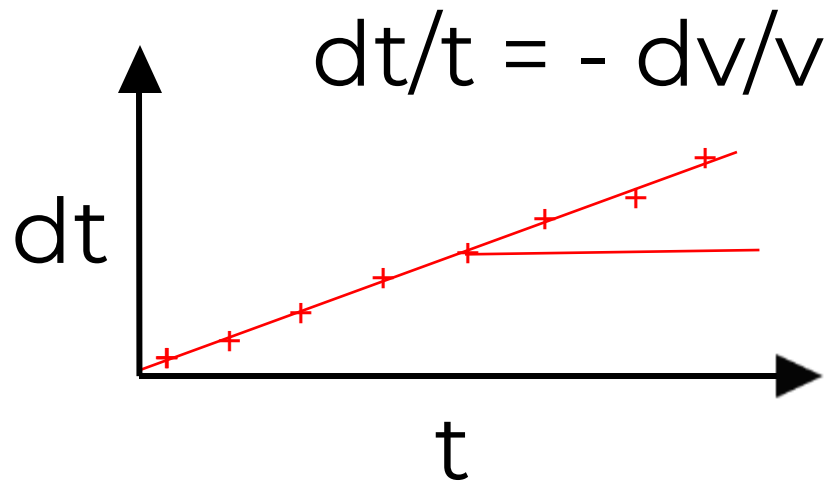




ground motions







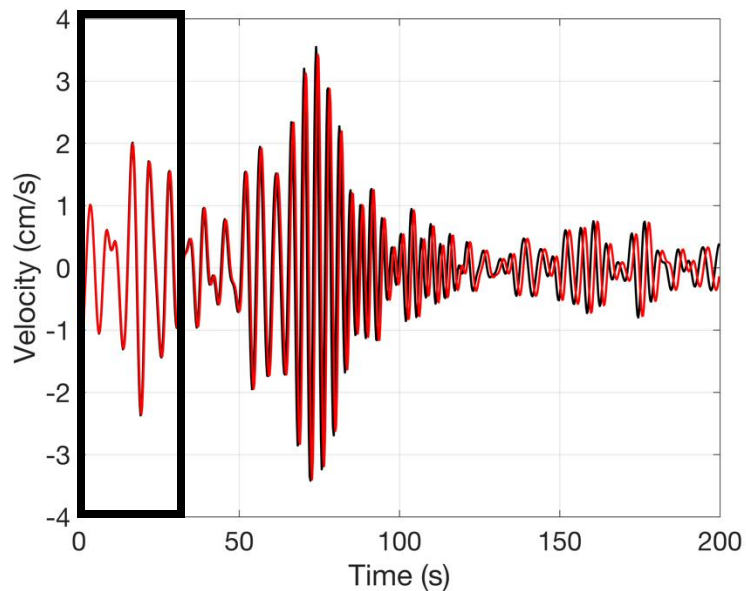
dv/v is proportional to

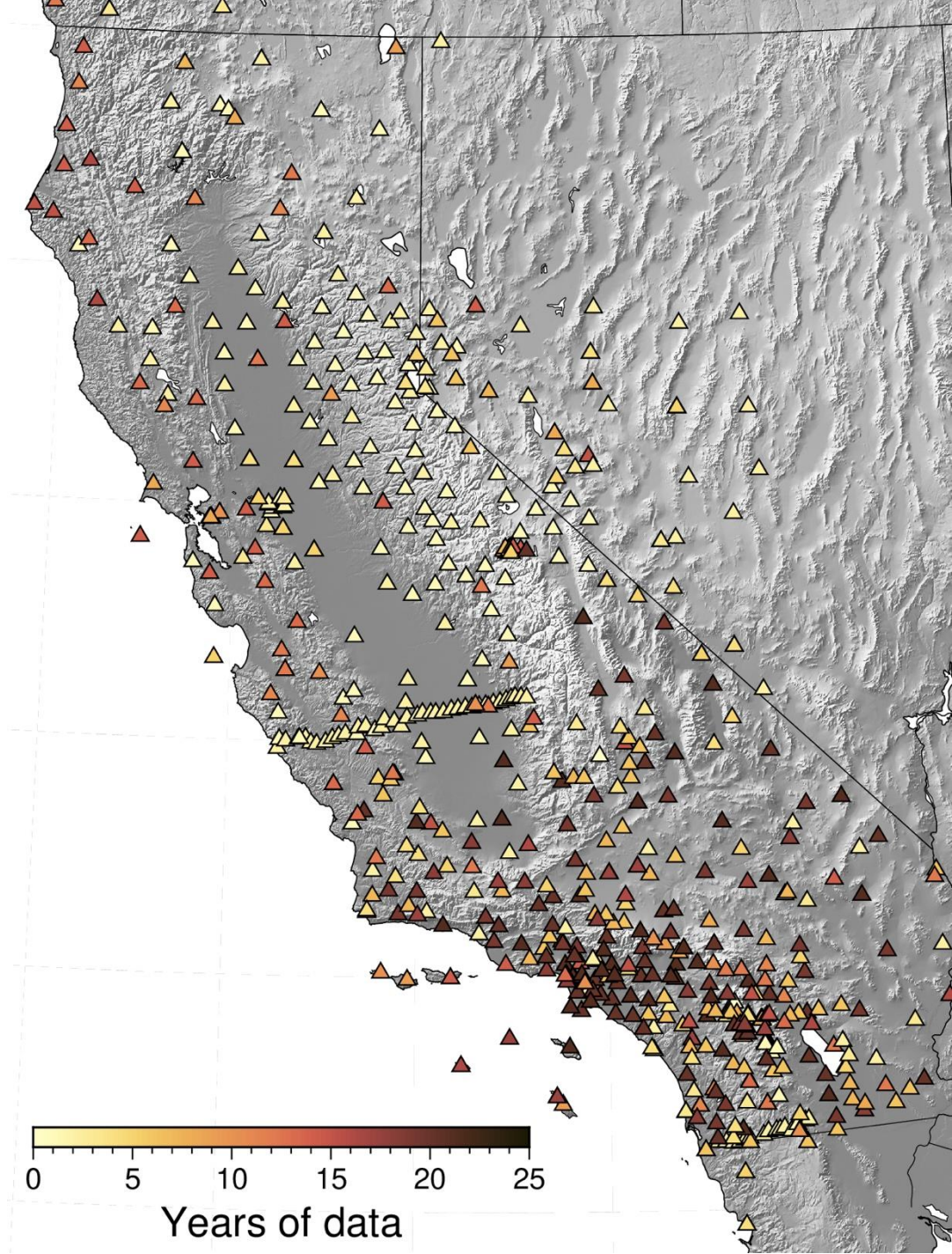
- **Extensional strains**

Nonlinear elasticity & poroelasticity

- **Water content**

suction/capillarity forces in granular media





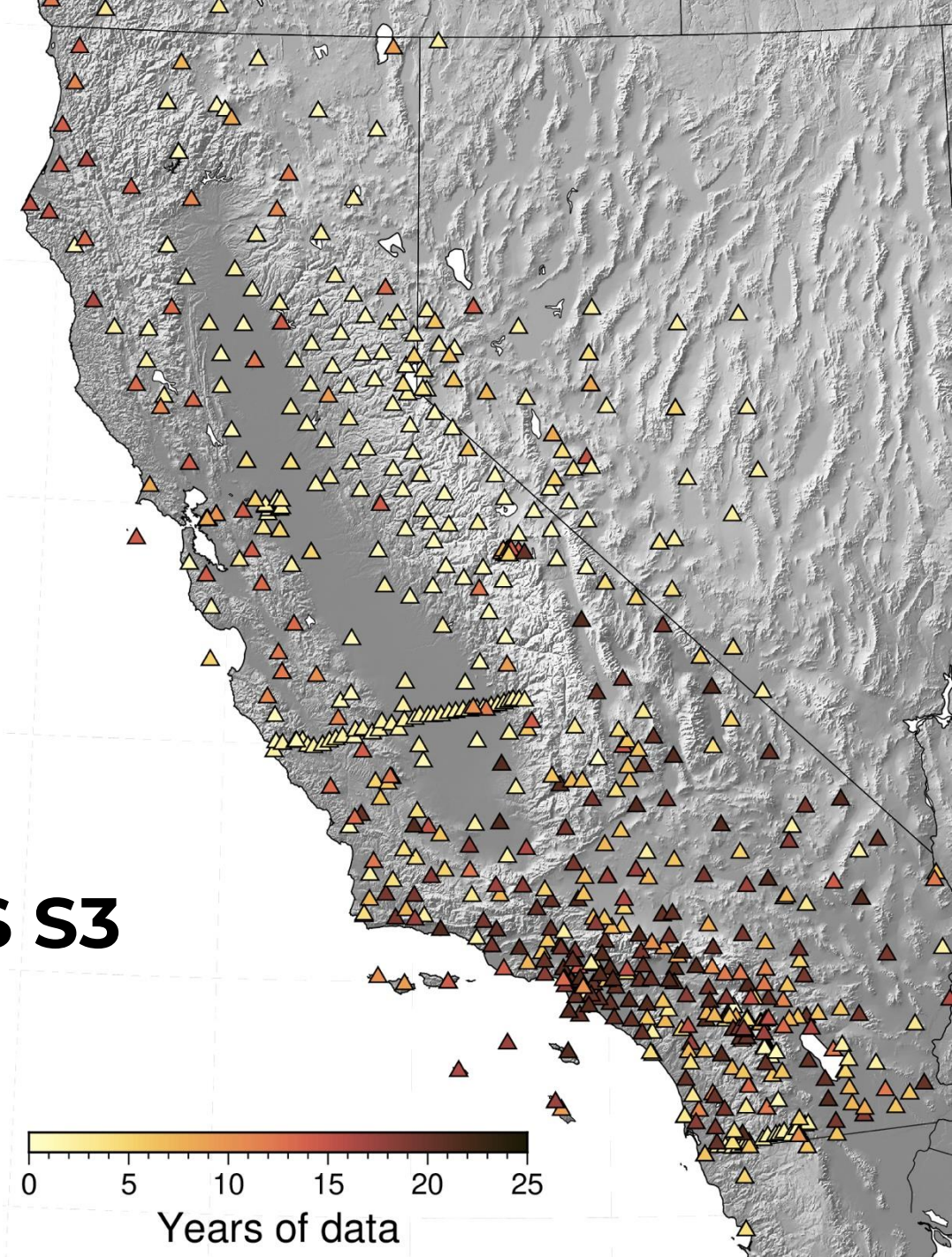
25 years

> 700 sensors

> 150 TBs

of data

on AWS S3





Yiyu Ni



Tim Clements



Kuan-Fu Feng

github.com/noisepy/NoisePy

github.com/JuliaSeismo/SeisNoise.jl



25 years

of data



> 700 sensors



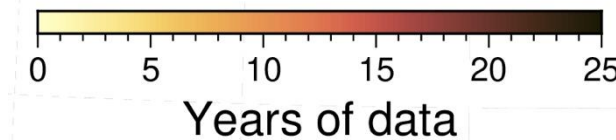
> 150 TBs

on AWS S3

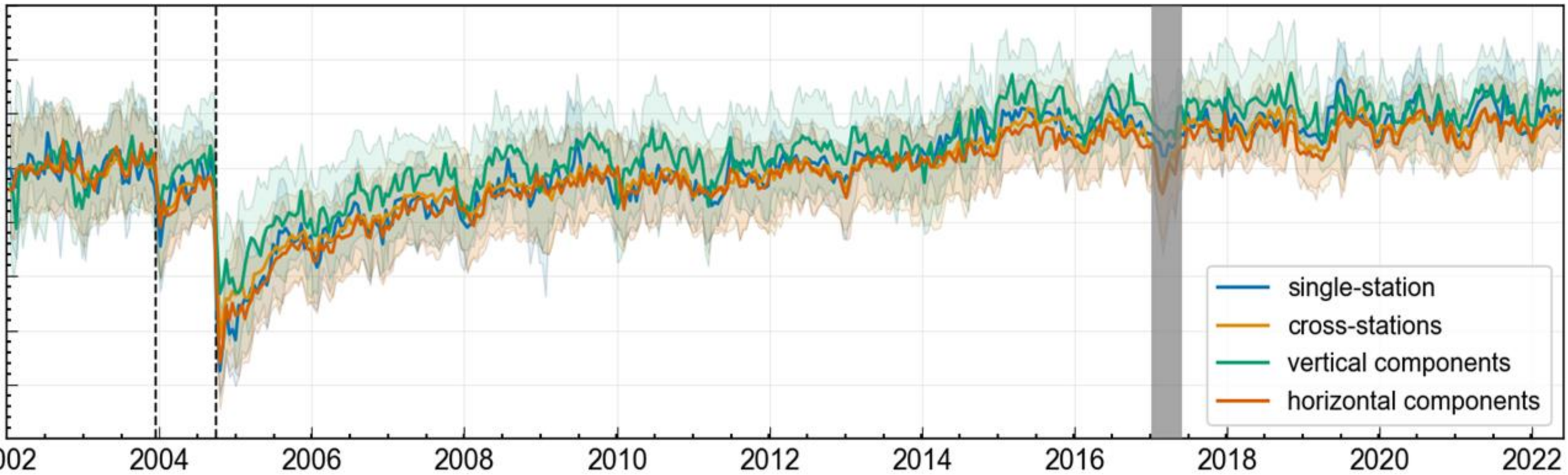


< 1 day

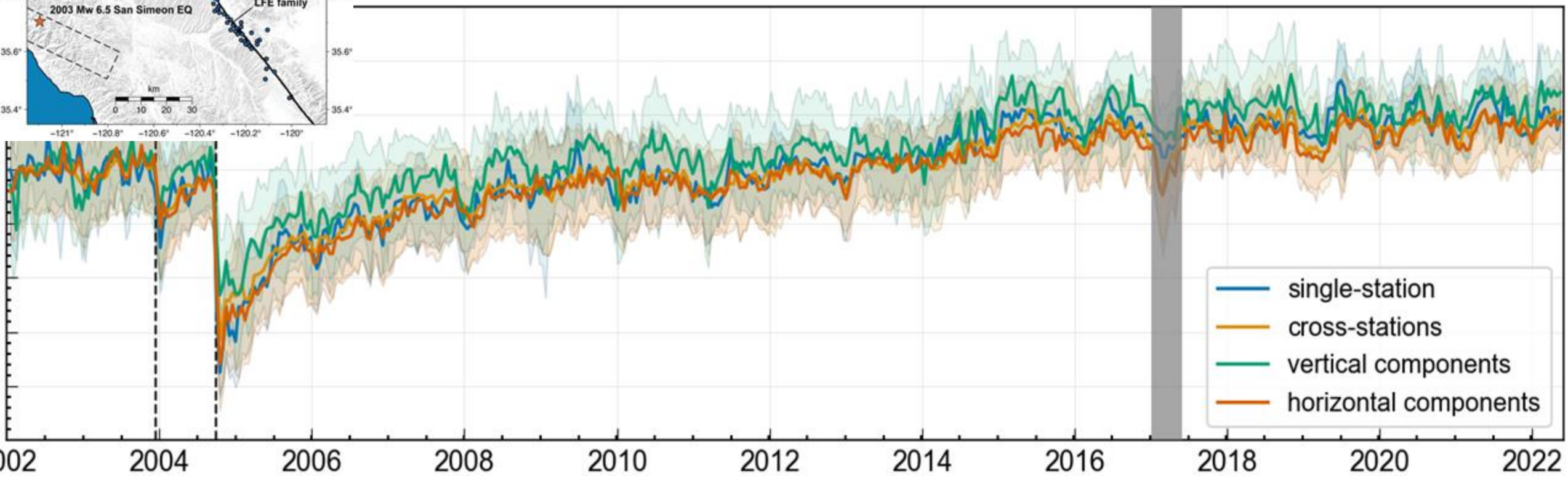
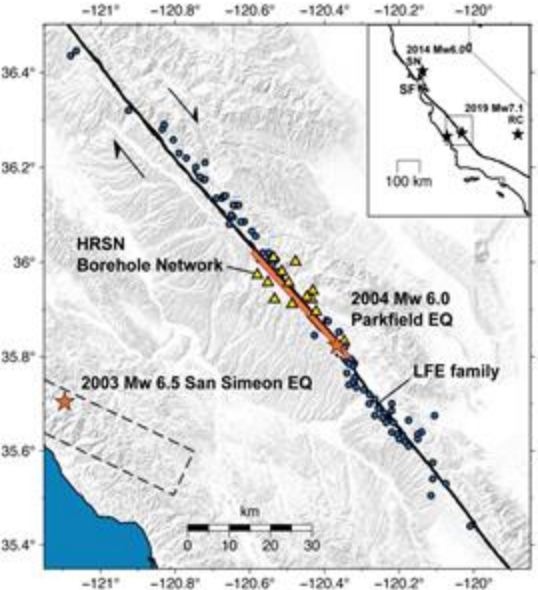
to process on AWS



Tectonic dv/v



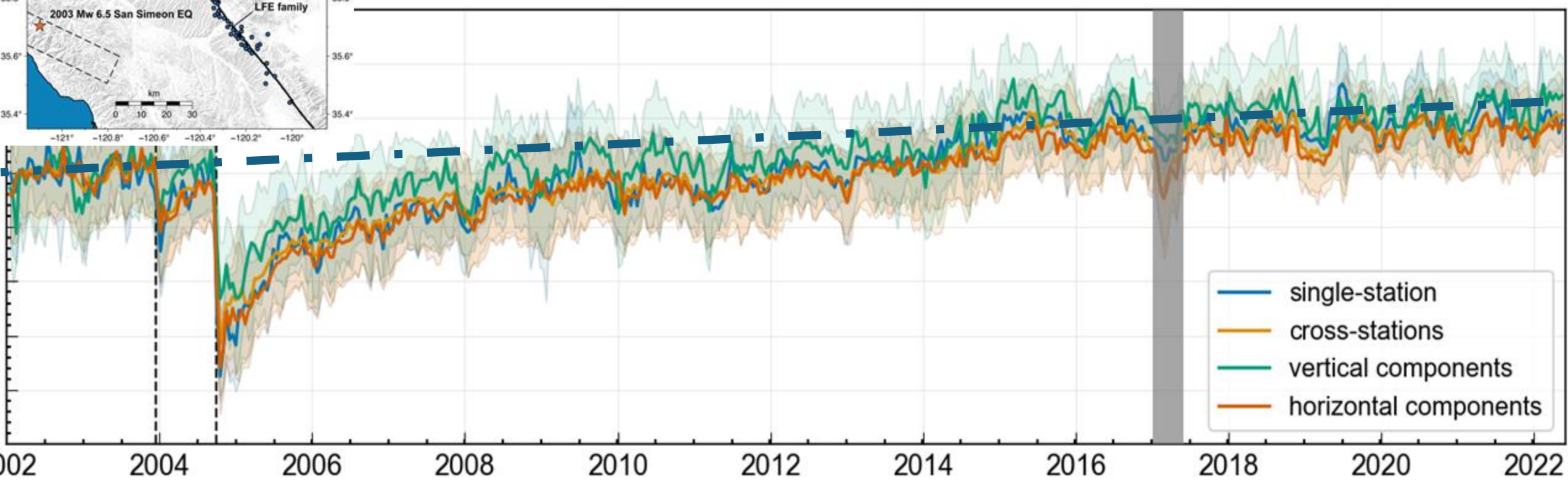
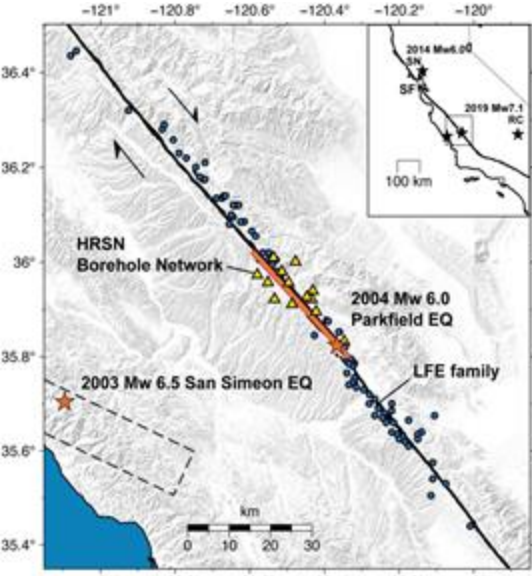
Dr. Kurama Okubo



Dr. Kurama Okubo

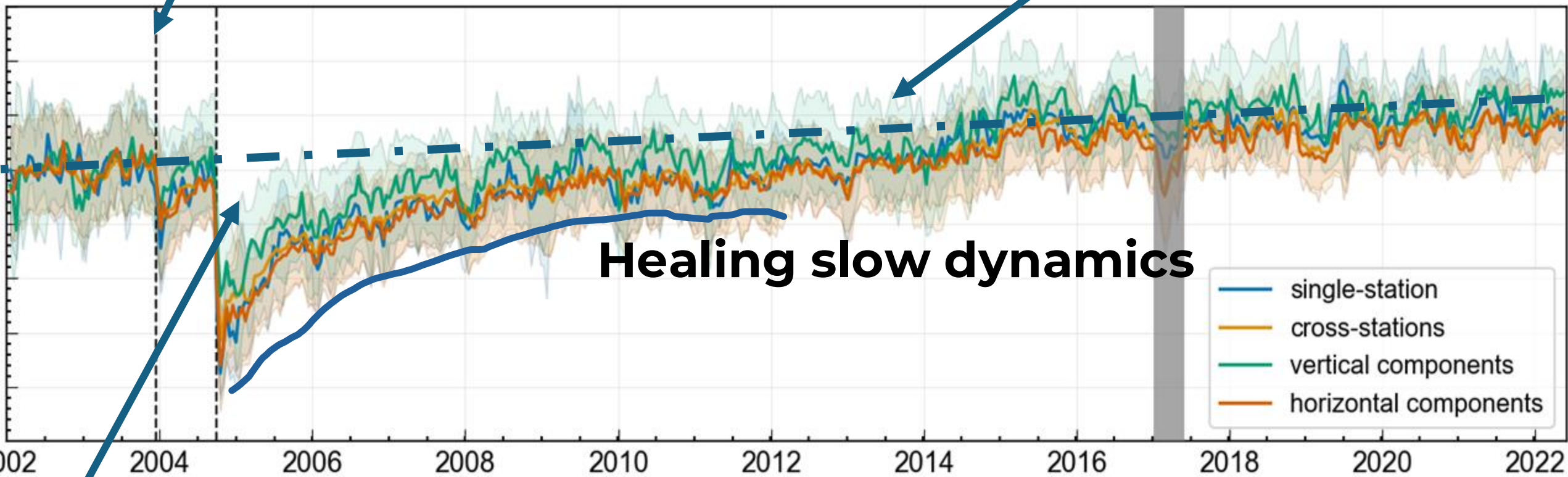


Modeling (Ph.D.)
Big-data (postdoc)
Laboratory (researcher)



Shaking induced damage

Tectonic loading



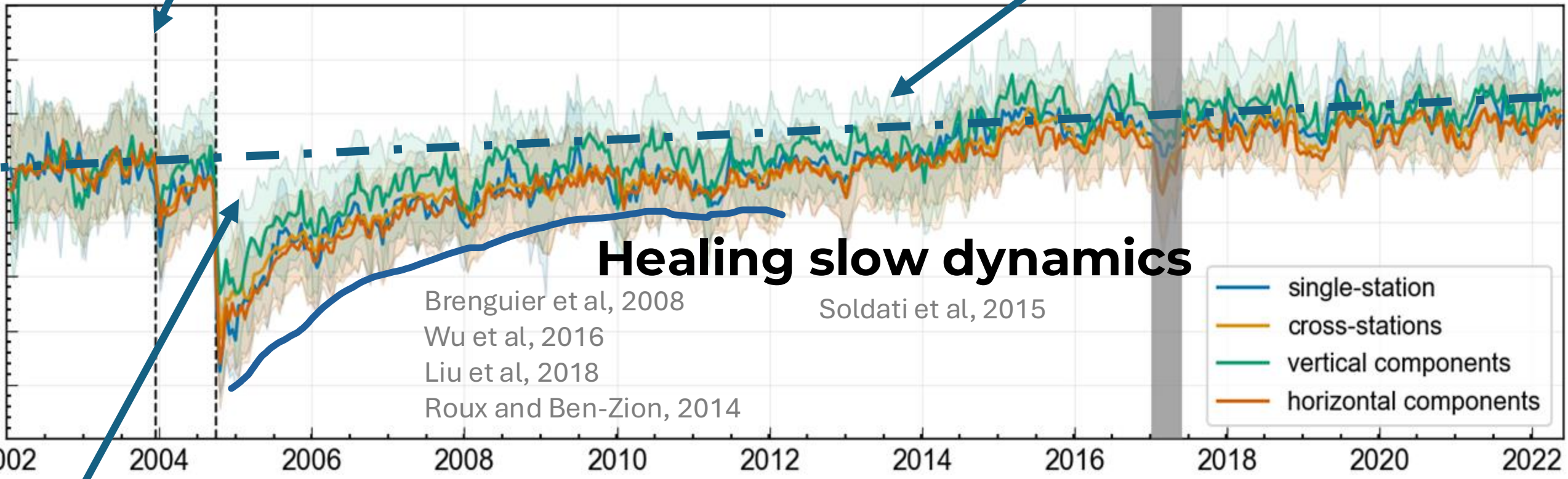
Near-fault damage

Shaking induced damage

Bonilla et al, 2019
Viens et al, 2018
Wegler et al, 2009
Bonilla & Ben-Zion, 2021
Rubinstein et al, 2004

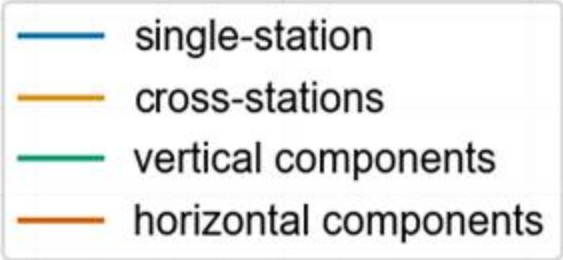
Tectonic loading

Okubo et al, 2024
Ikeda and Tsuji, 2018
Kidiwela, Denolle, et al, 2025?



Healing slow dynamics

Brenguier et al, 2008
Wu et al, 2016
Liu et al, 2018
Roux and Ben-Zion, 2014
Soldati et al, 2015



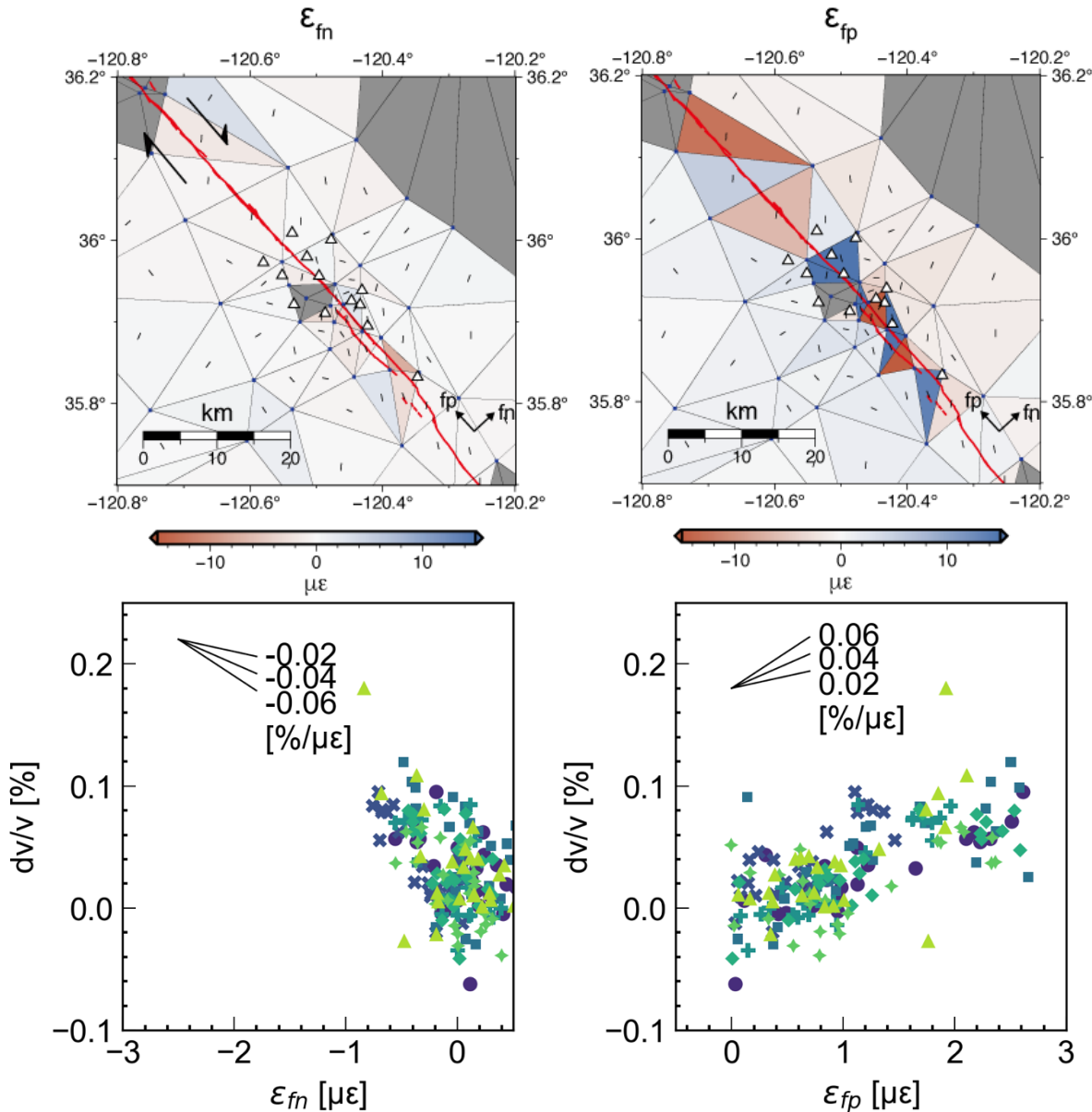
Near-fault damage

Wegler ad Sens-Schonfelder, 2007
Brenguier et al, 2008
Boschelli et al, 2021
Froment et al, 2013

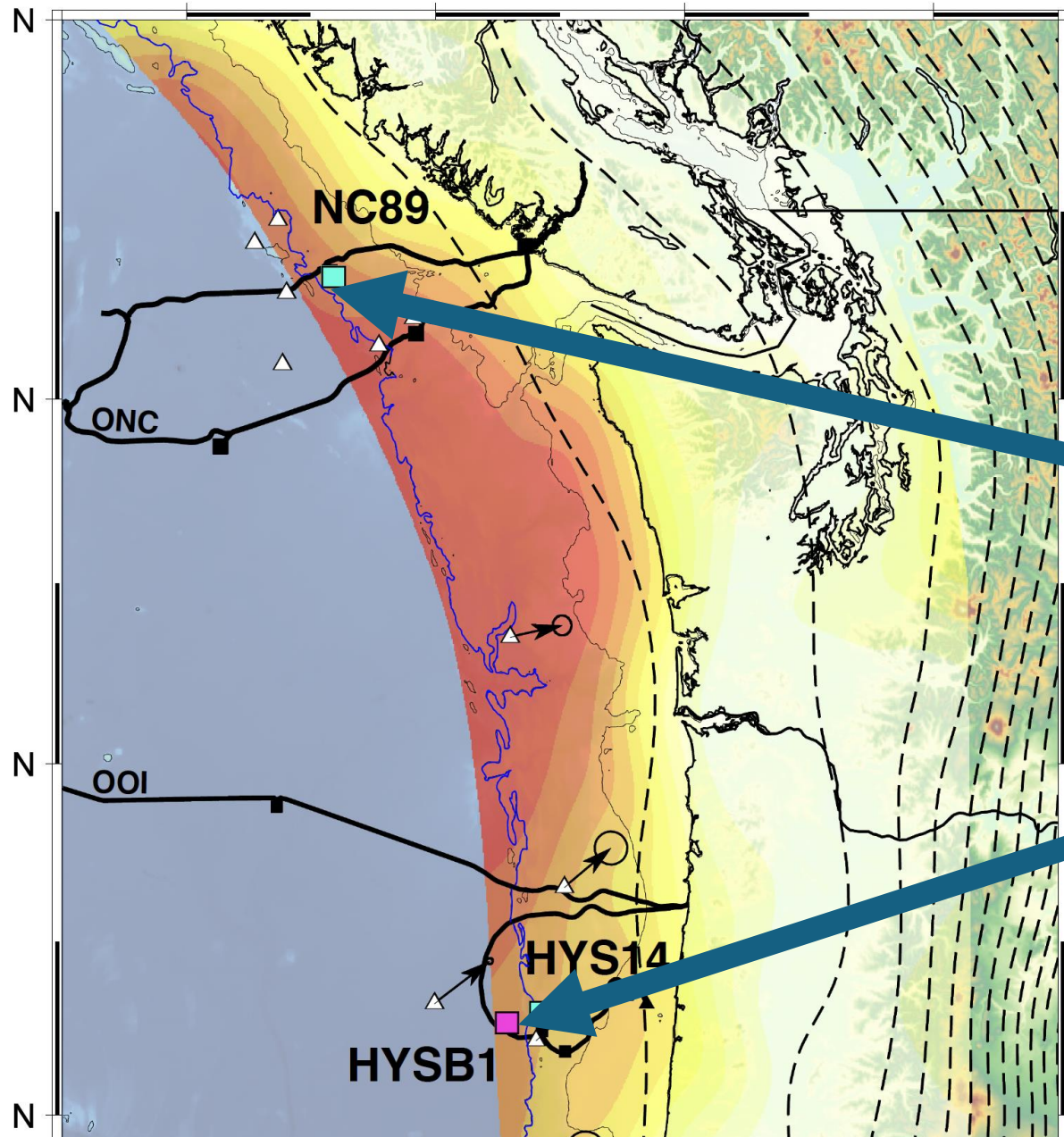
Lu and Ben-Zion, 2022
Obermann et al, 2014
Taira et al, 2015

Okubo et al, (2024)

The long term dv/v is correlated with fault locking

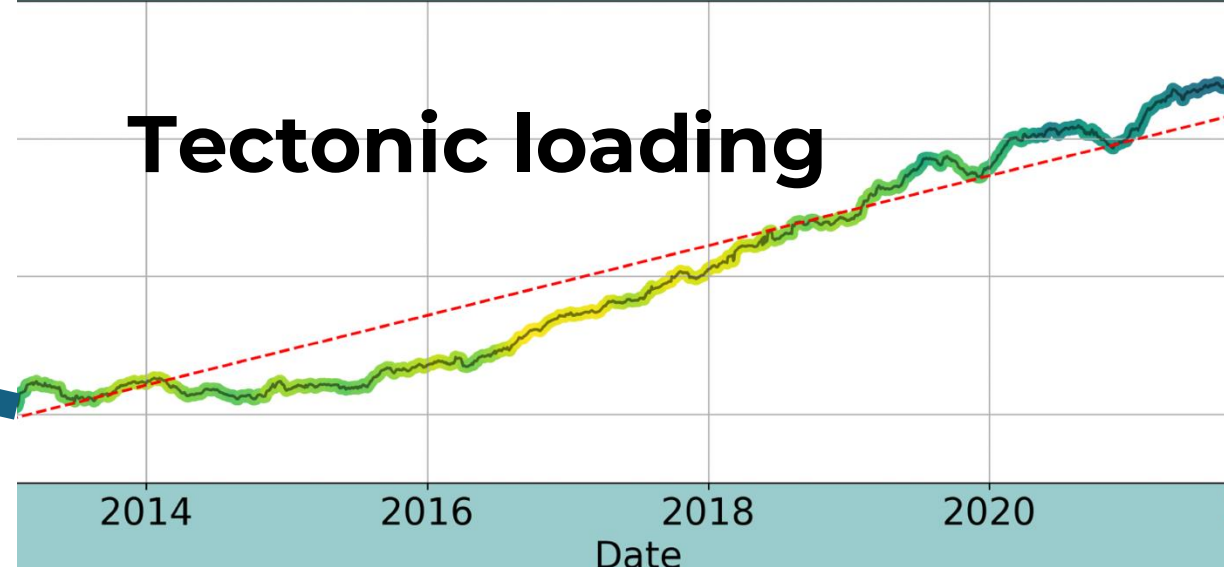


If there is a strong preference for crack orientation, **crack opening** or **closing** would be sensitive to **strain parallel** to their opening mode.



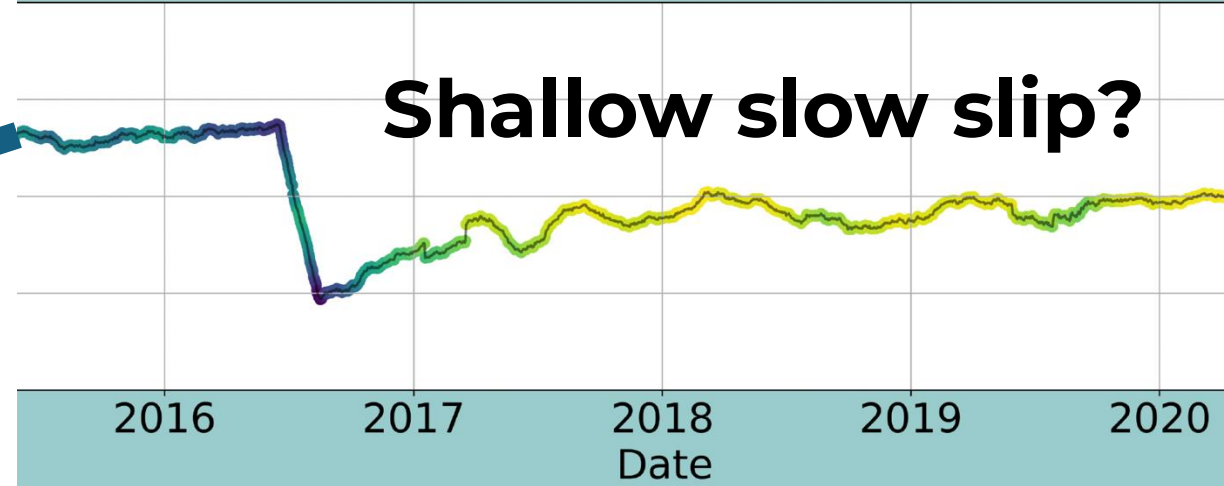
NC89 1-3 Hz

Tectonic loading

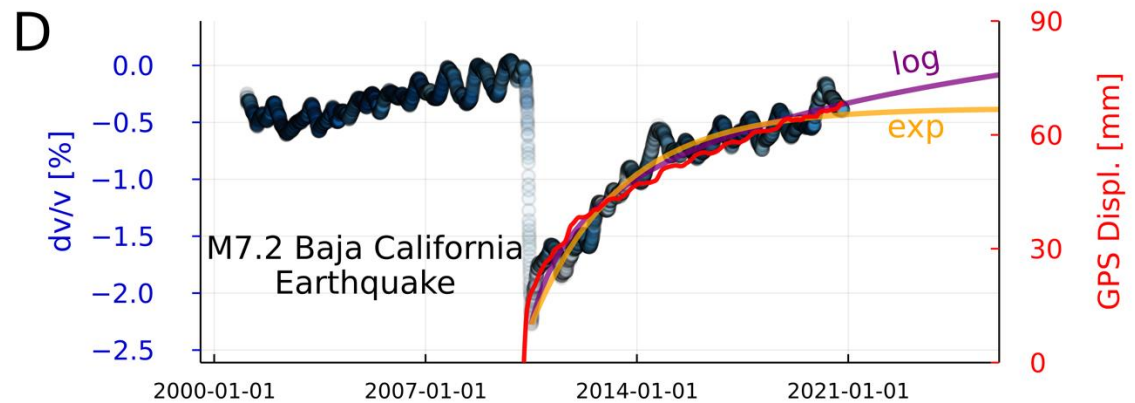
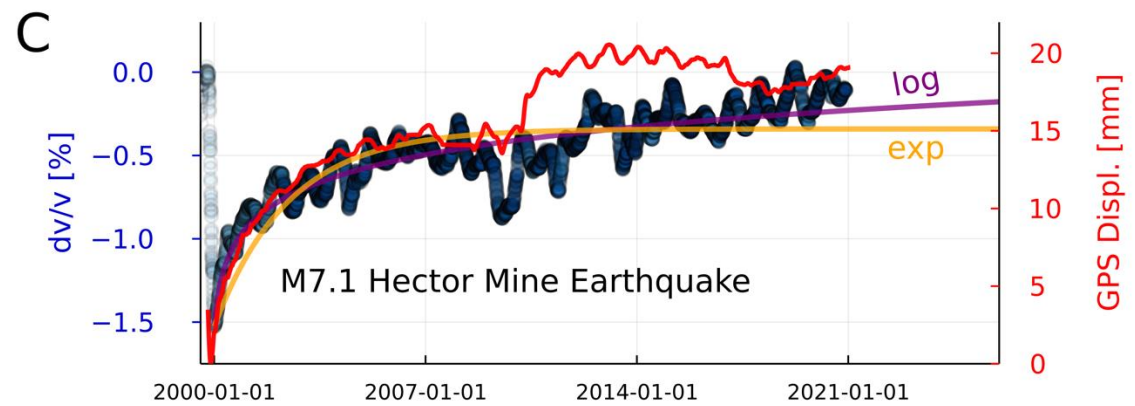
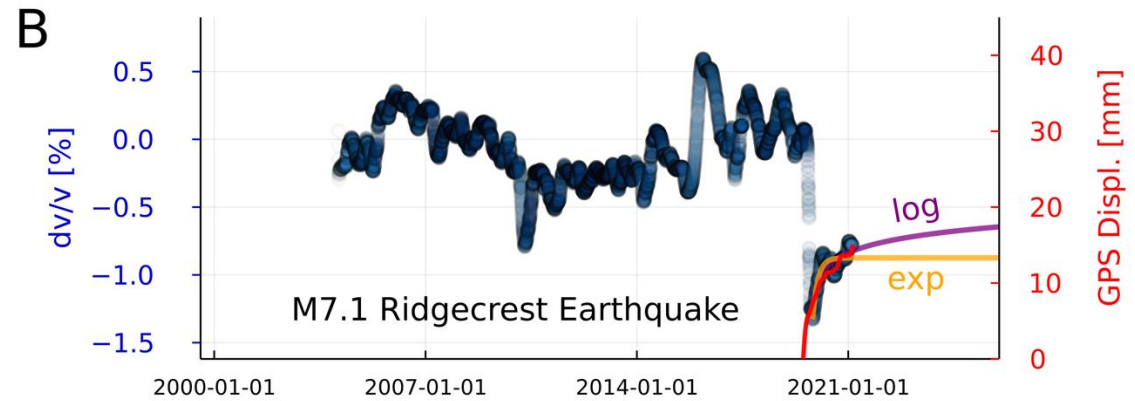
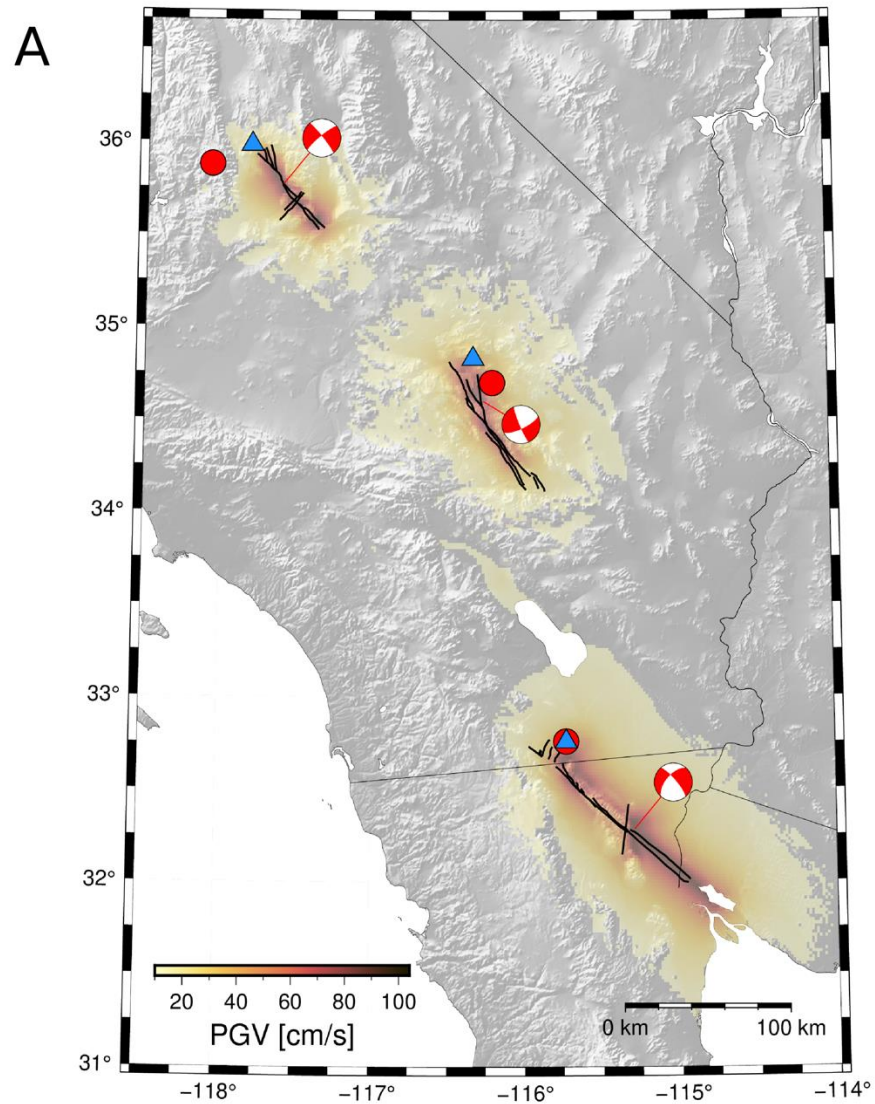


HYSB1 3-5 Hz

Shallow slow slip?

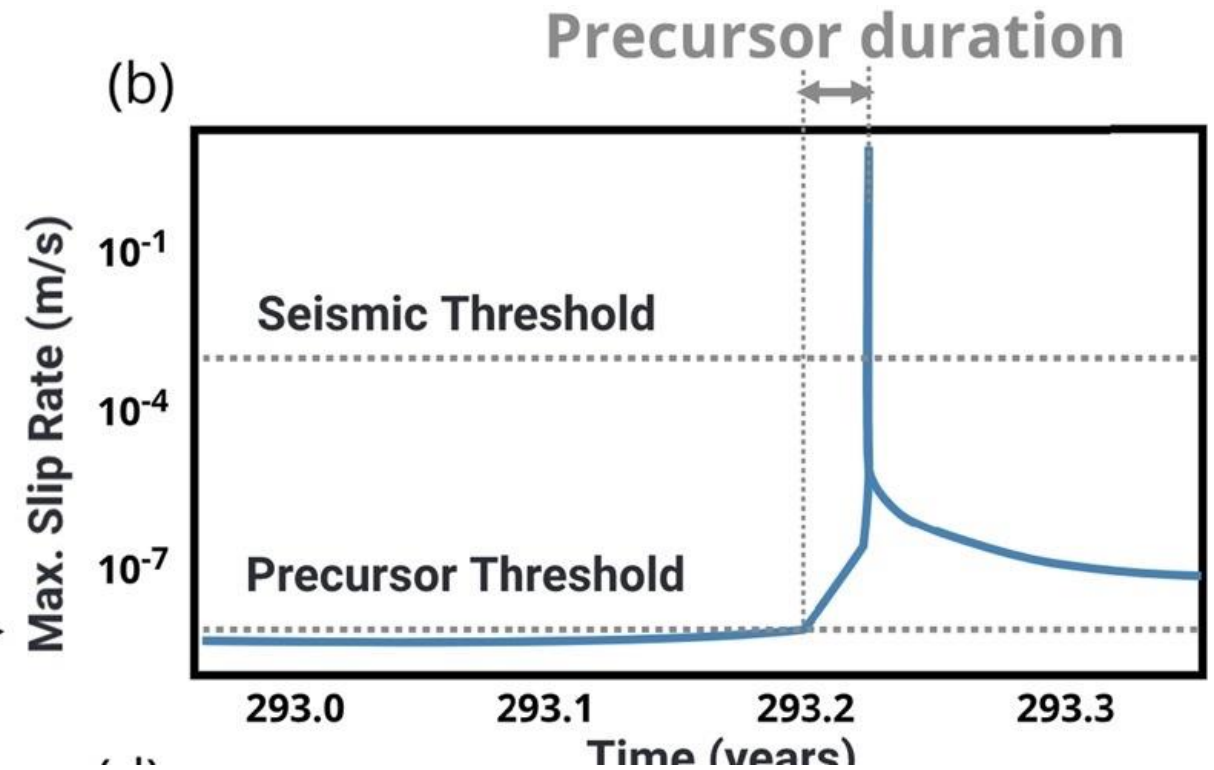
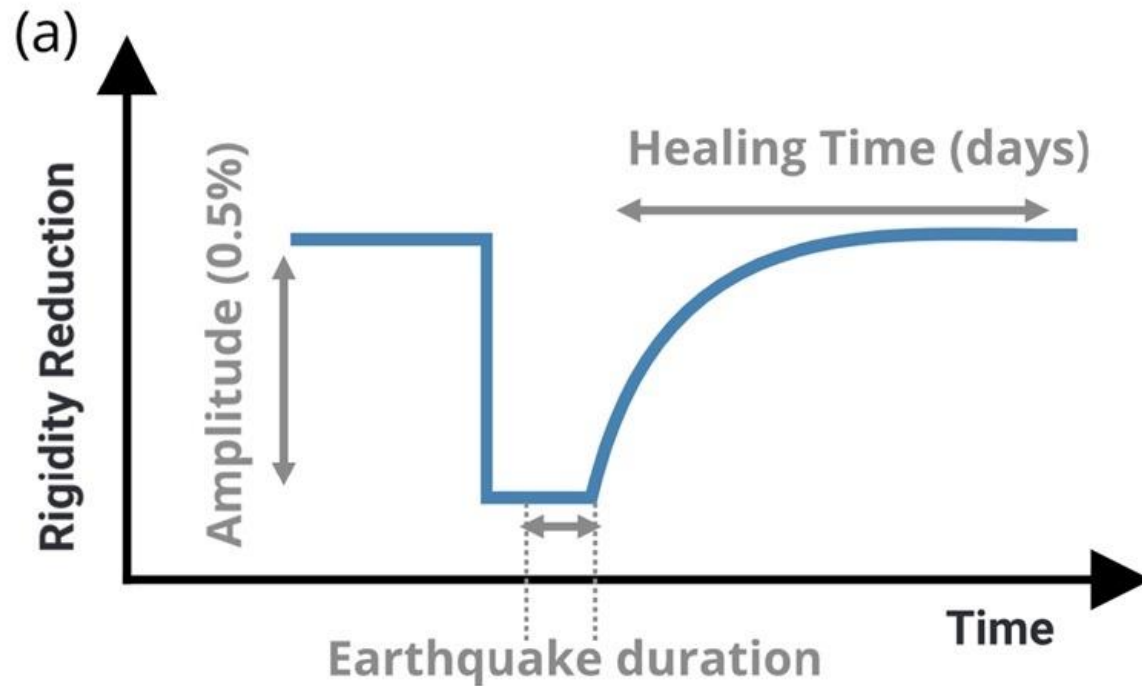


Near-fault healing can last 20+ years



Prescribing laboratory and natural observations of seismic velocities on earthquake cycle models (e.g., Thaku and Huang, 2023)

“One primary effect of the imposed velocity precursor is on the earthquake nucleation phase.”



Near Site and People

Where Seismology meets Geotechnical Engineering and Hydrology

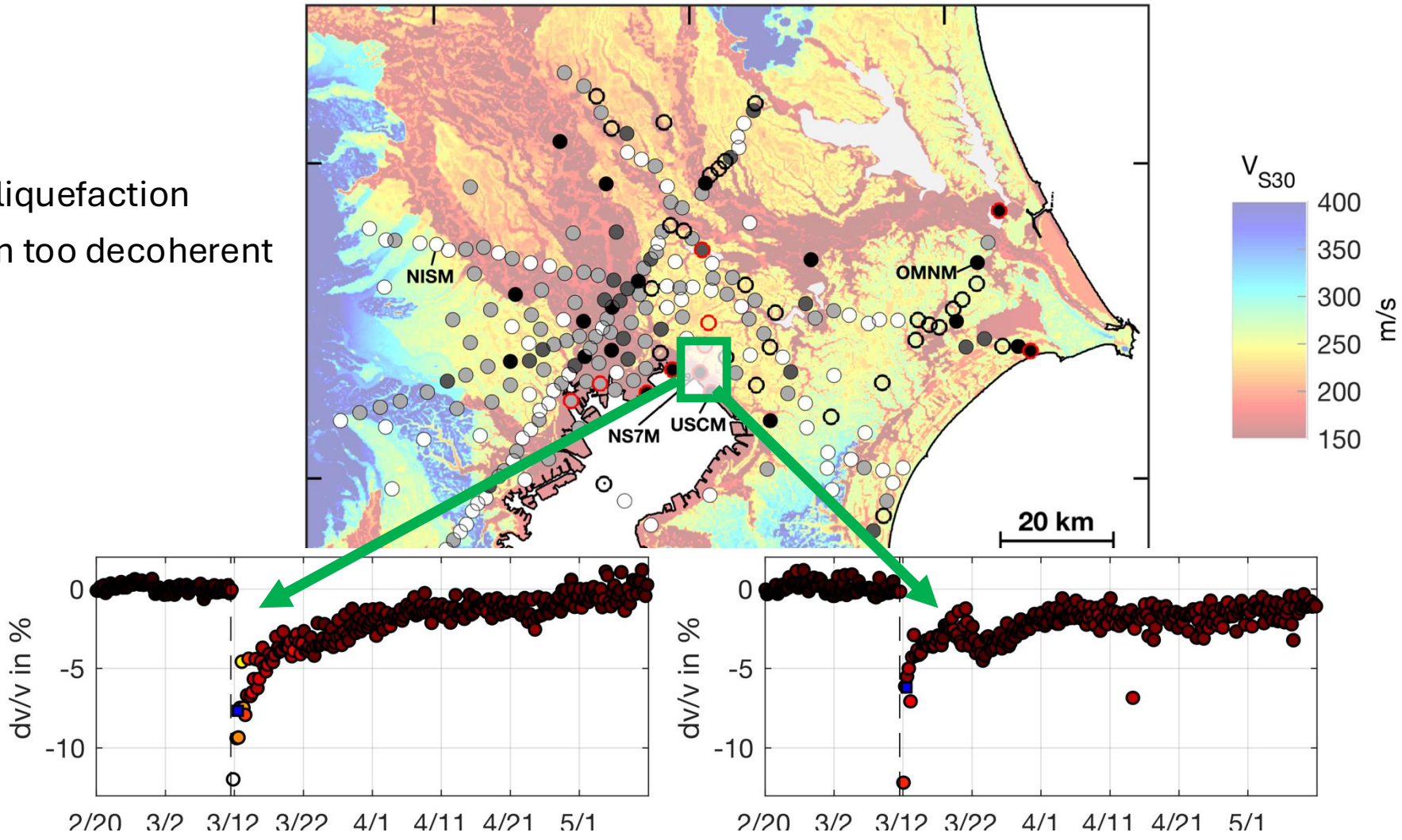


Dr. Loïc Viens

Measuring the coseismic shaking damage

~ 240 20m-deep borehole instruments in 2011.

- > 4%
- 2--4%
- < 2%
- close to liquefaction
- waveform too decoherent



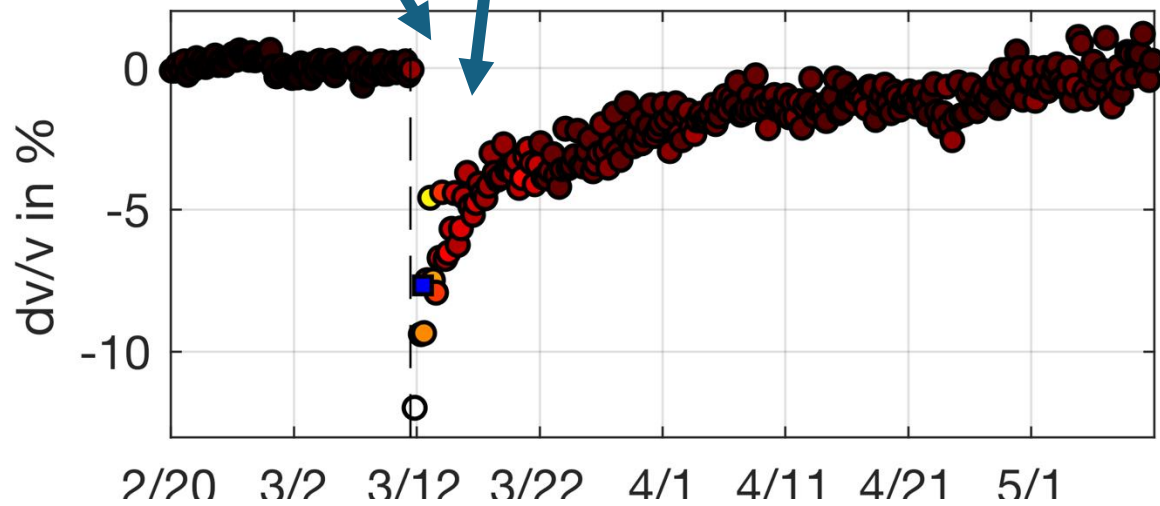
Measuring the coseismic shaking damage



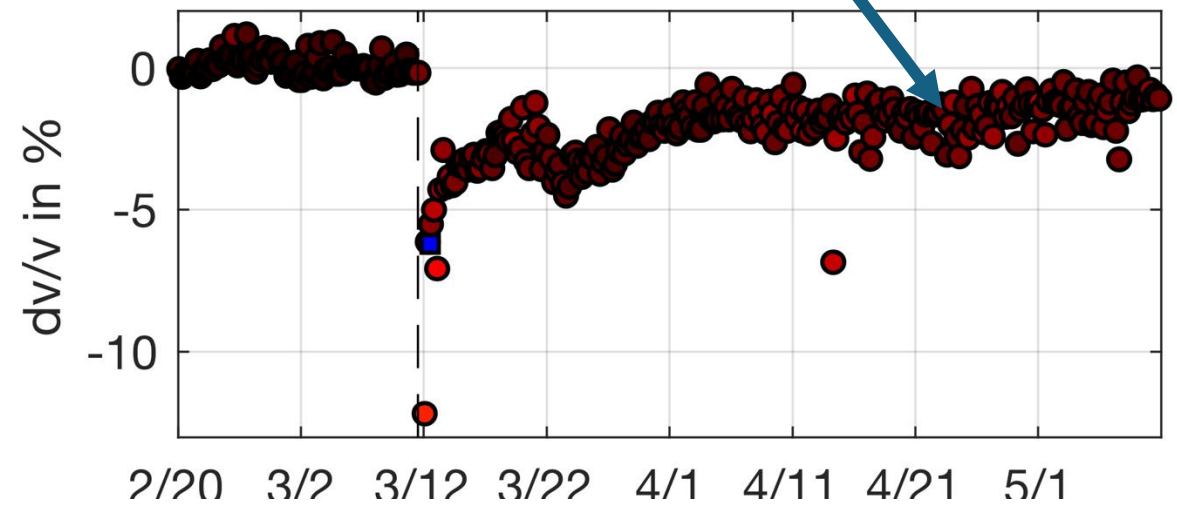
Dr. Loïc Viens

damage

visco-elasticity

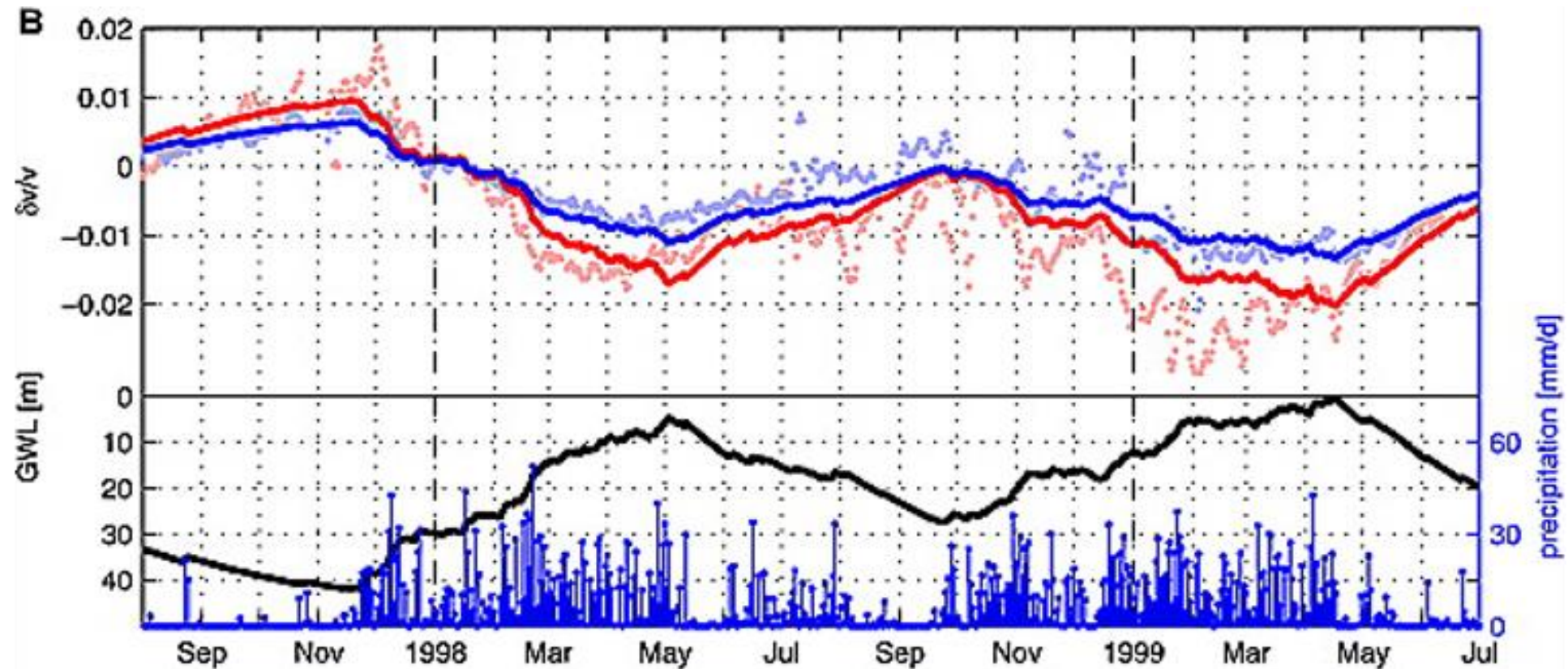


brittle



$dv/v \sim$ -Ground Water Level

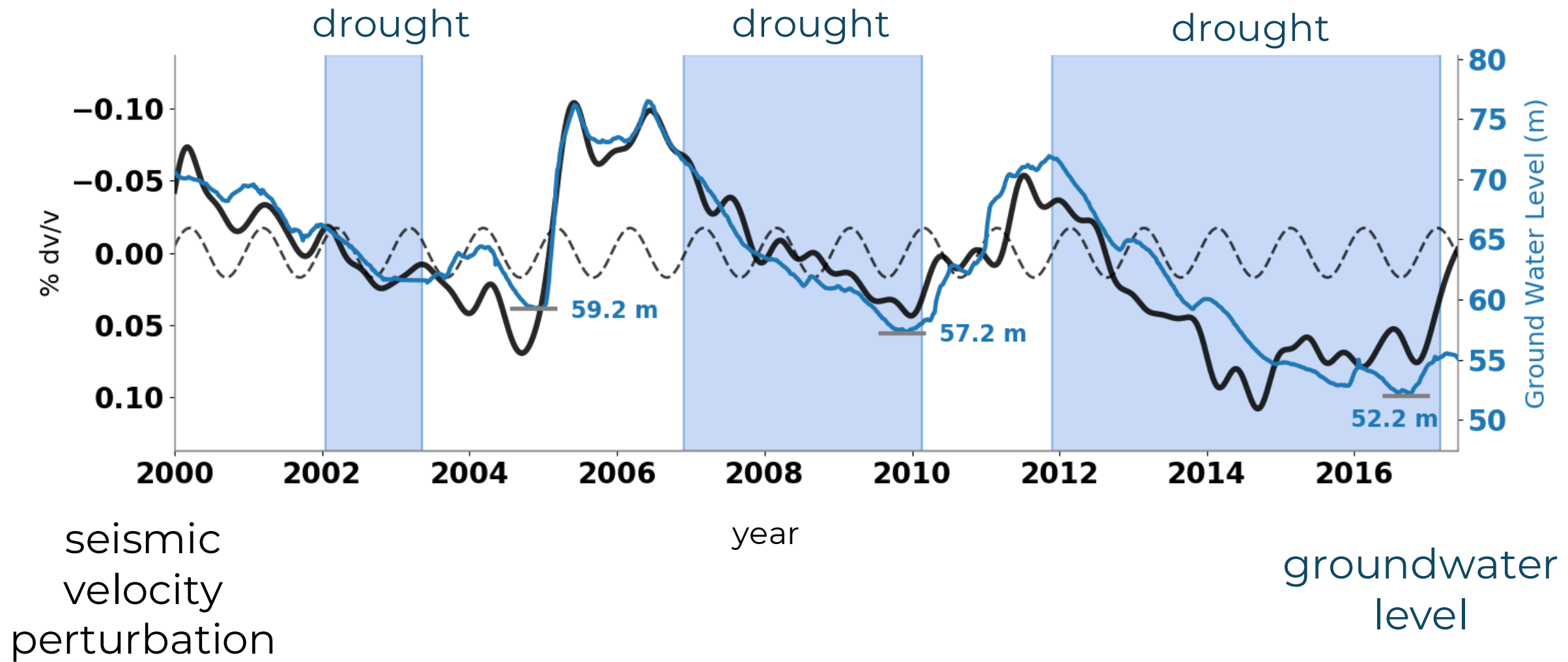
Changes in seismic velocity dv/v anticorrelated with Groundwater Level **GWL**. First proposed by **Sens-Schönfelder and Wegler, 2006** on Merapi Volcano.



Monitoring ground water in California

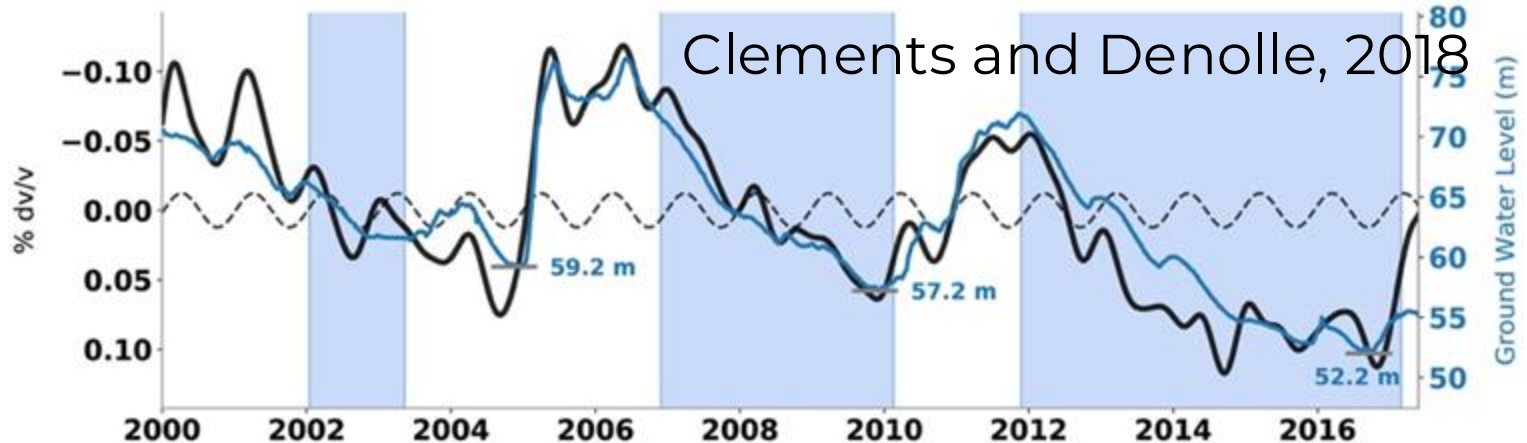
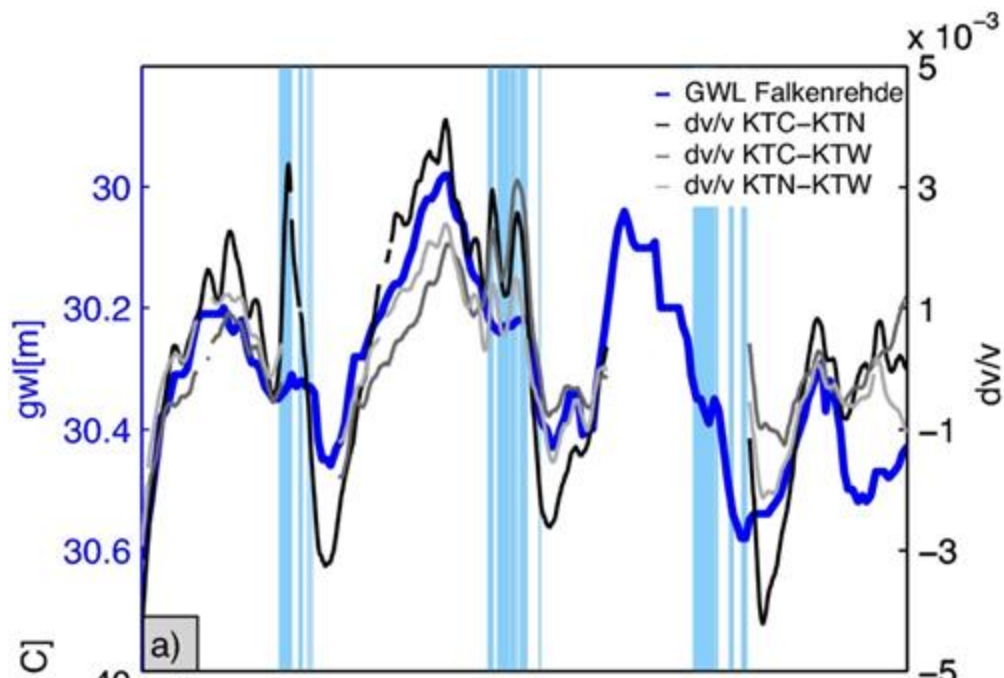
unconfined aquifer in San Gabriel Valley

20m drop in the 2012-2016 drought. All-time low since 1932.



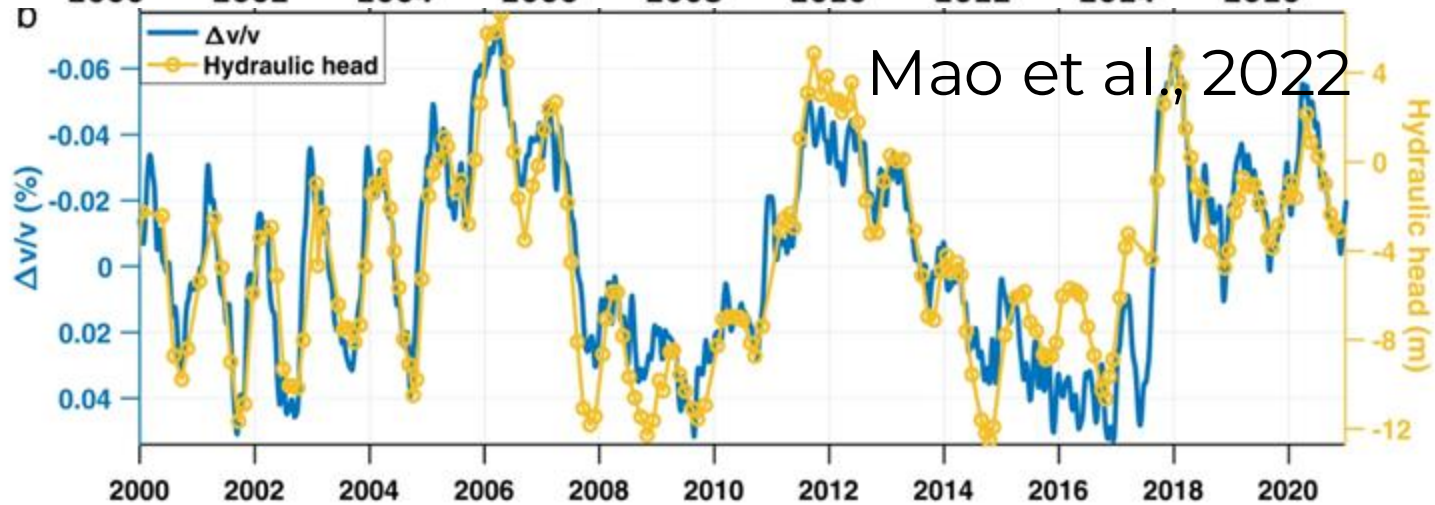
$$dv/v \sim -GWL$$

Gassenmeier et al., 2015

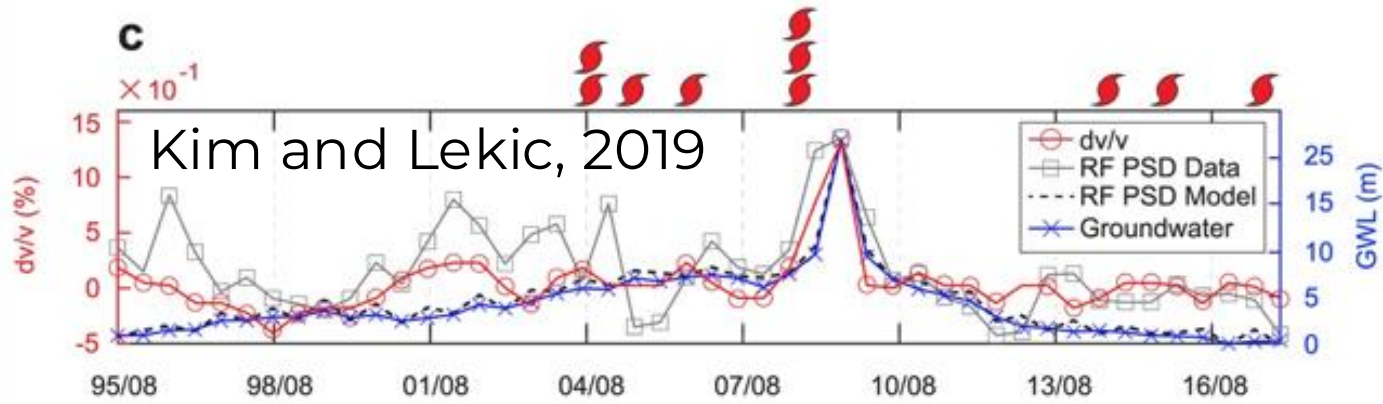


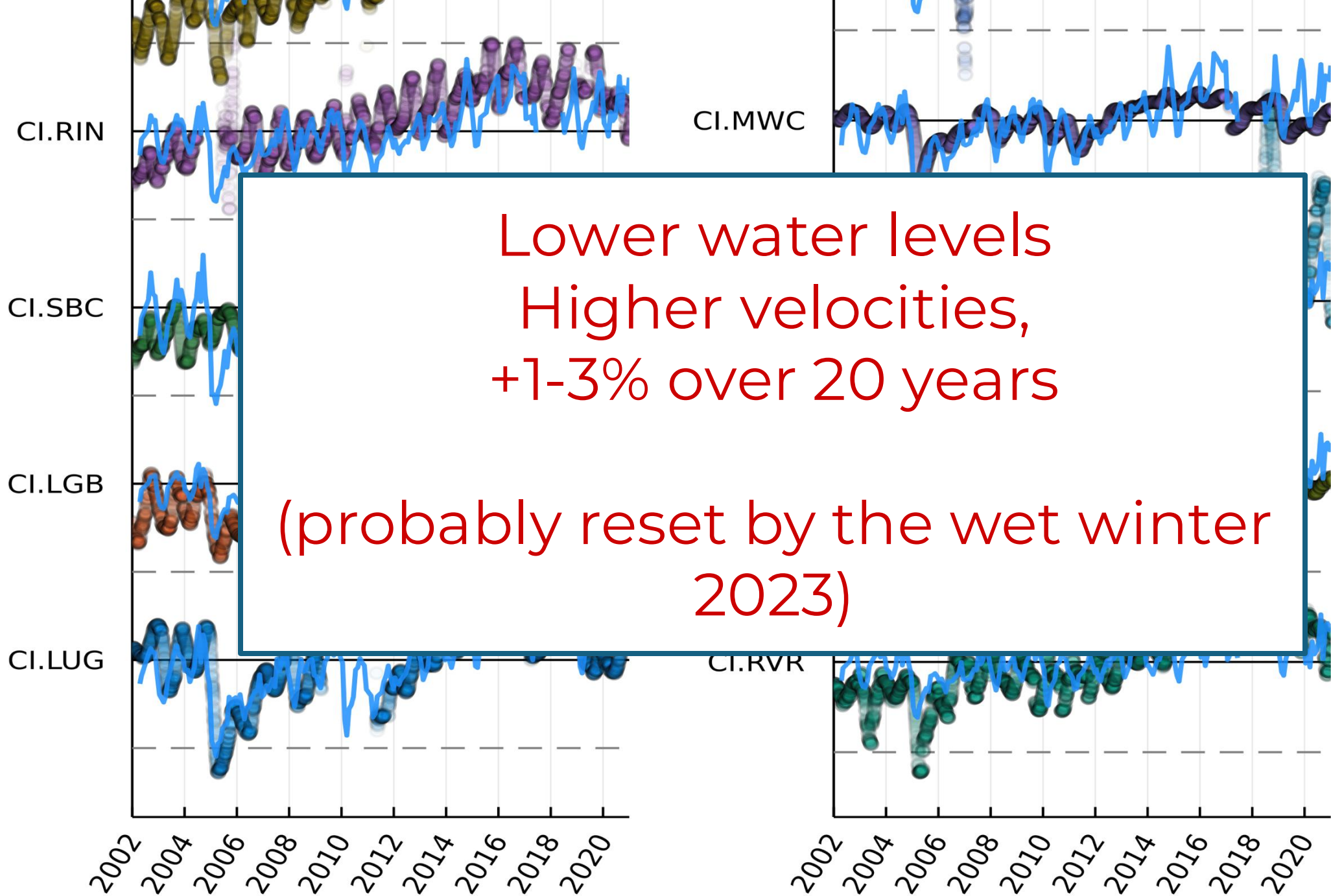
Clements and Denolle, 2018

Mao et al., 2022



Kim and Lelic, 2019

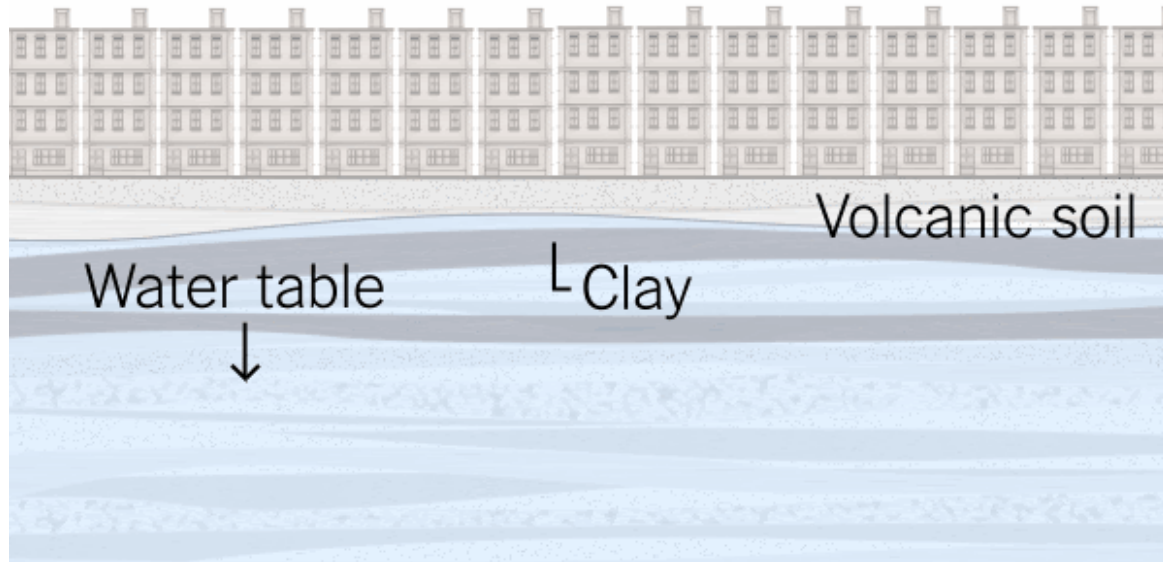




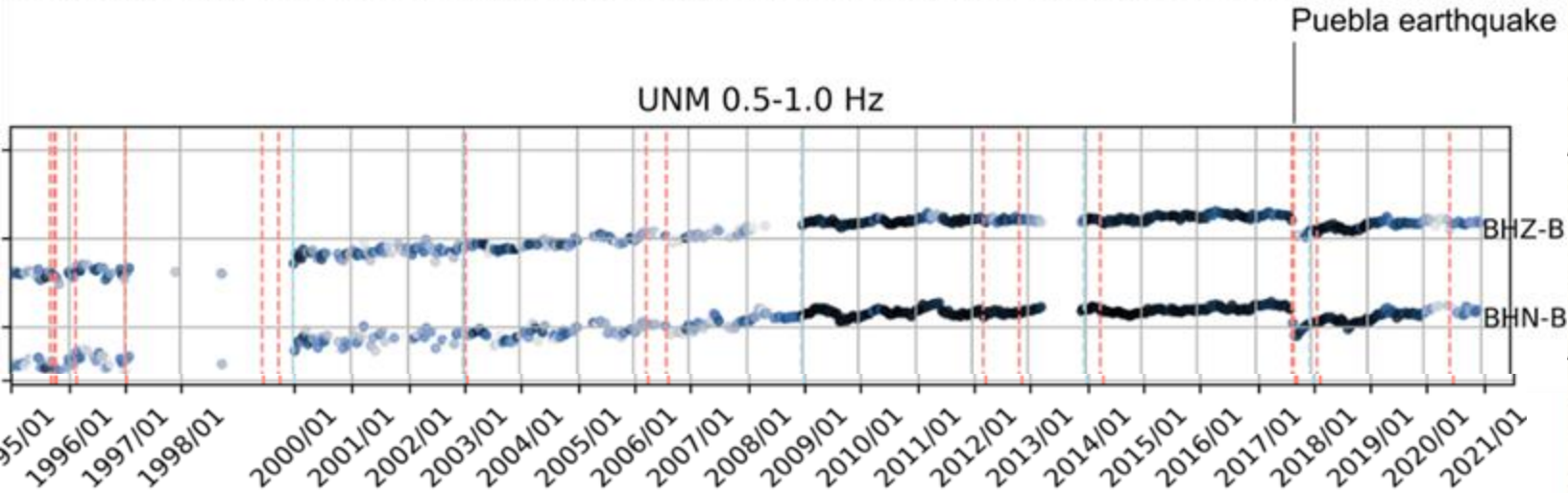
Monitoring site effects in Mexico City



Laura Ermert



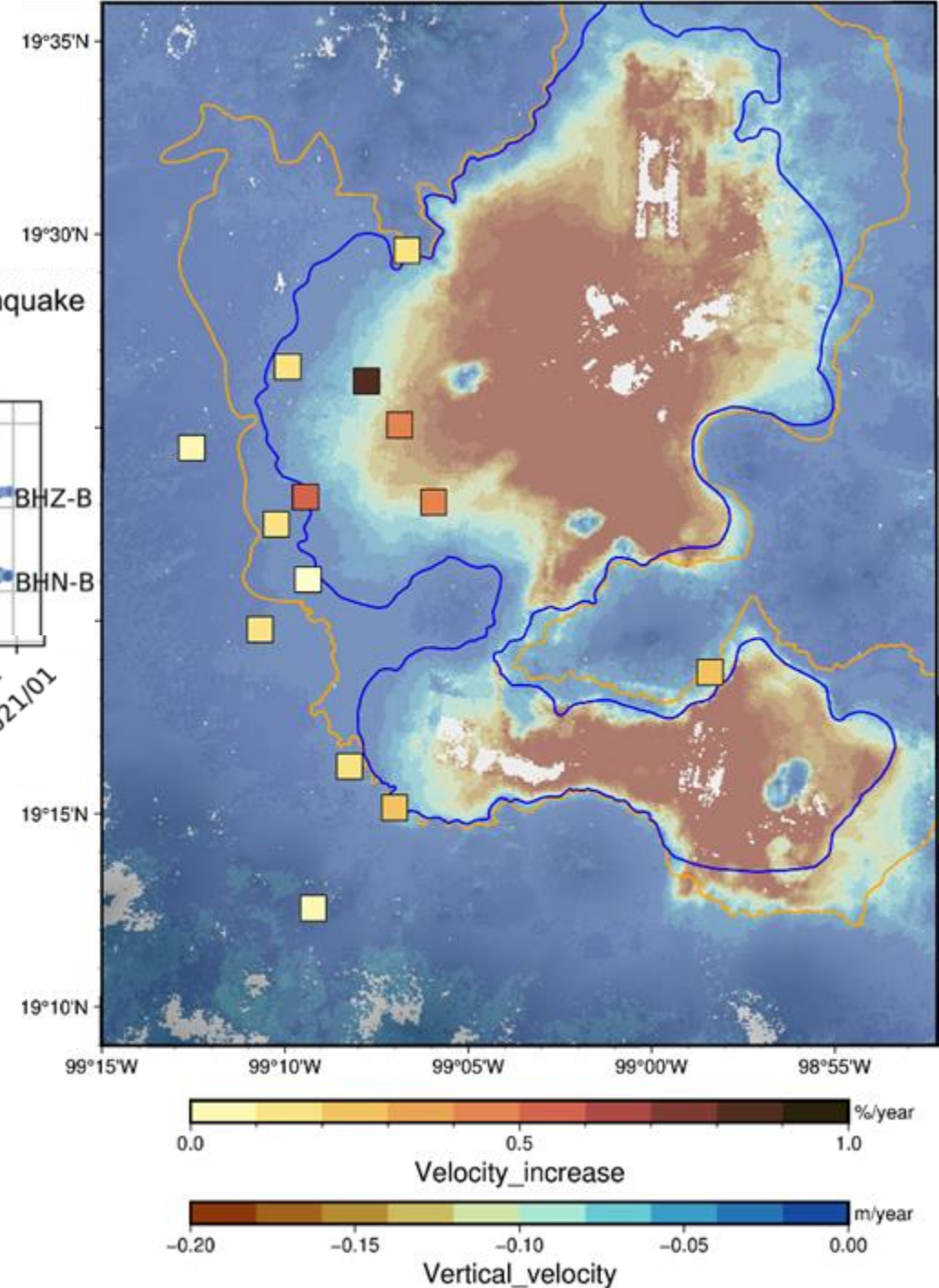
Mexico City is stiffening

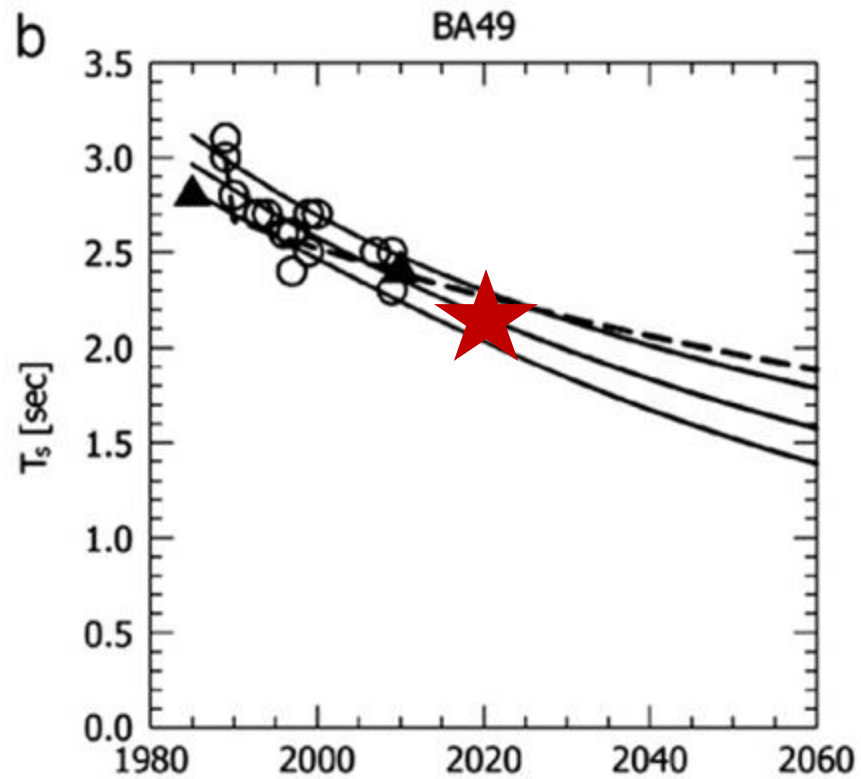


+4 % in 25 years

Rigidity increases linearly with time

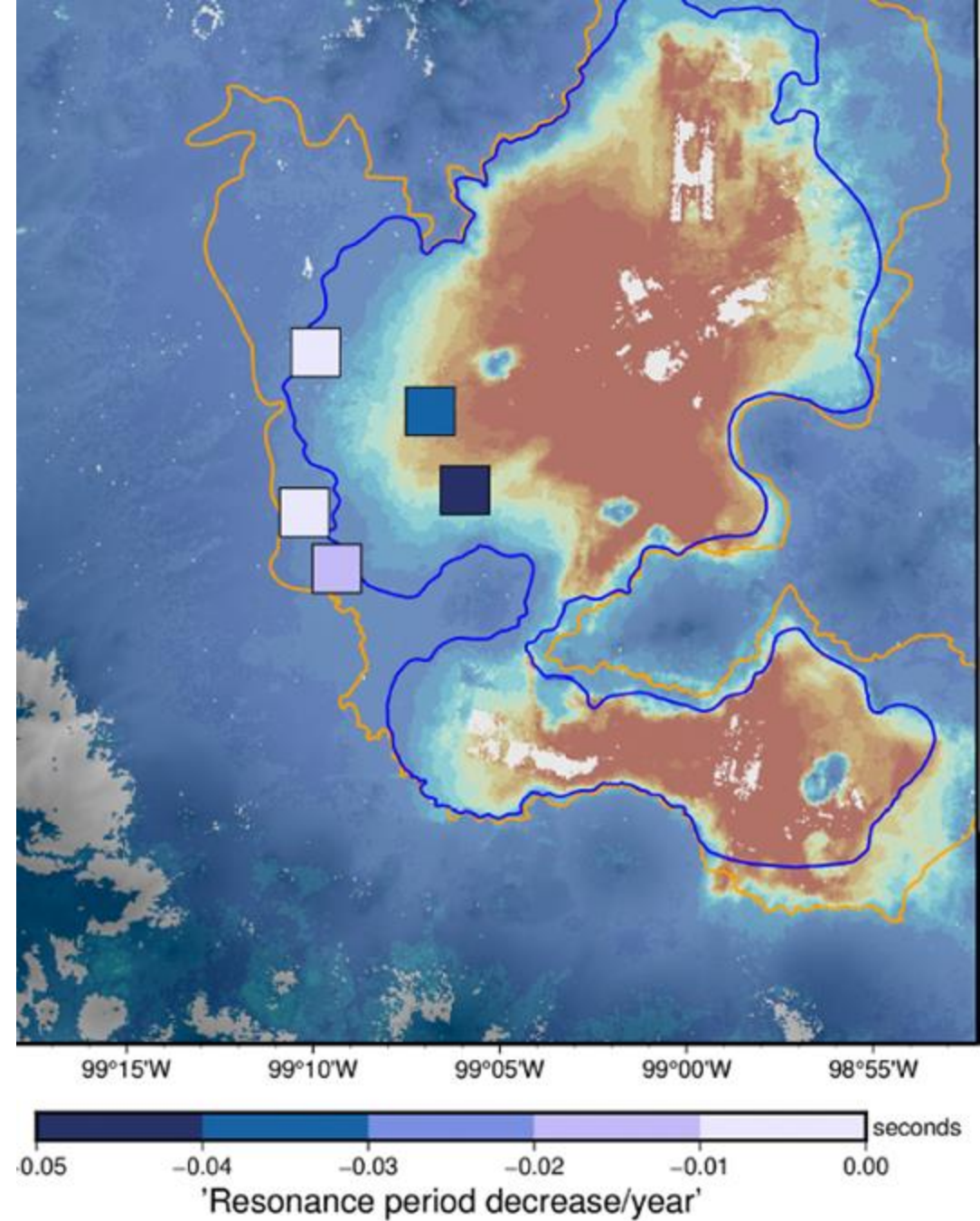
The rate depends on the subsidence rate: at least 1%/year for 20cm/year





Arroyo et al. (2013)
 Ermert et al (2023)

**Up to 1s resonance period change in
 20 years**



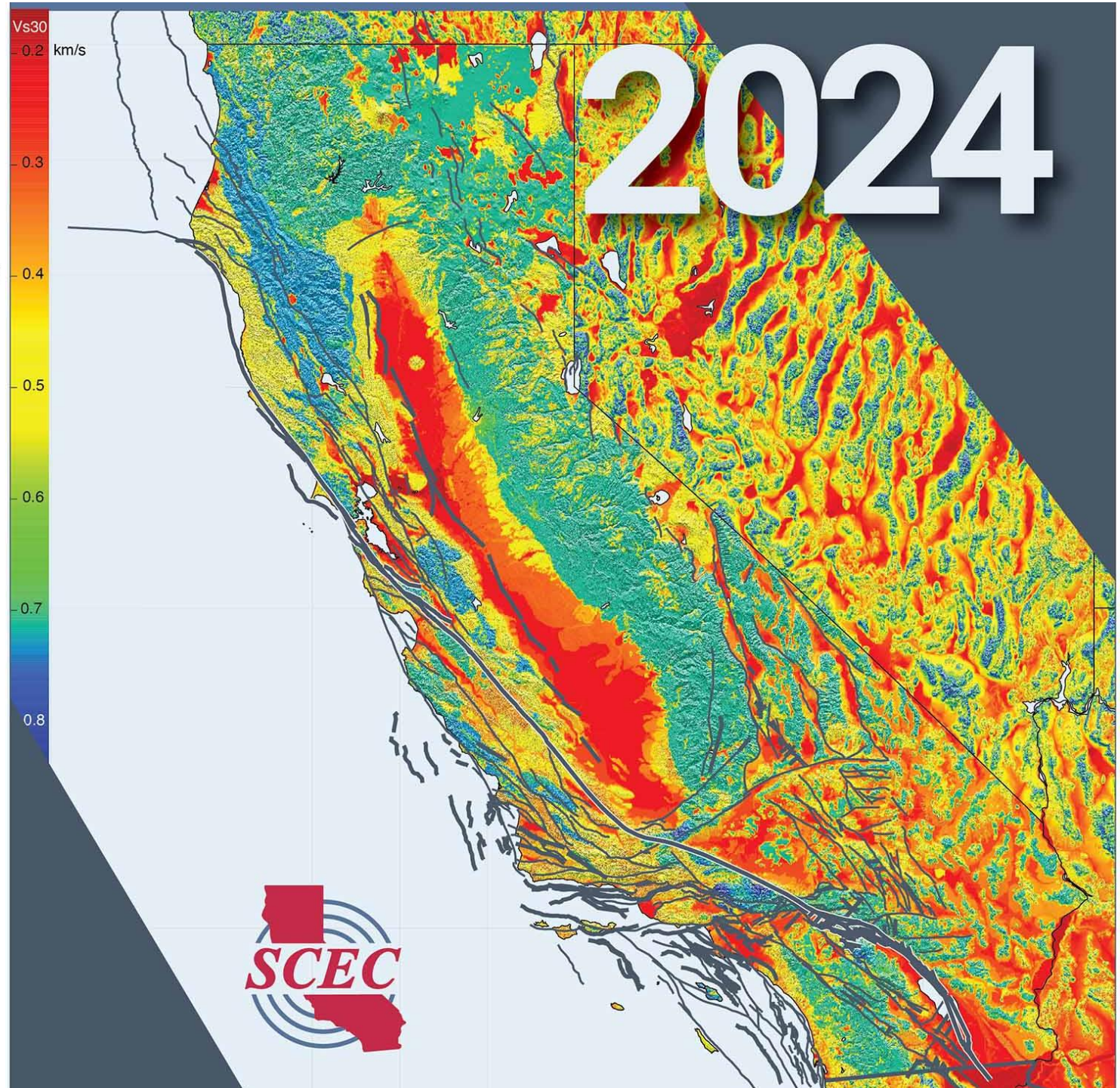
**Why should this matter
to SCEC?**

"Vs30"

A Novel V_{S30} Prediction Strategy Taking Fluid Saturation into Account and a New V_{S30} Model of Türkiye

Hakan Bora Okay¹ and Atilla Arda Özacar^{*1}

Bora et al, 2024, BSSA:
*"the effect of a specific change in saturation degree on V_{S30} may be quantified considering **fluctuations of groundwater depths in time**"*

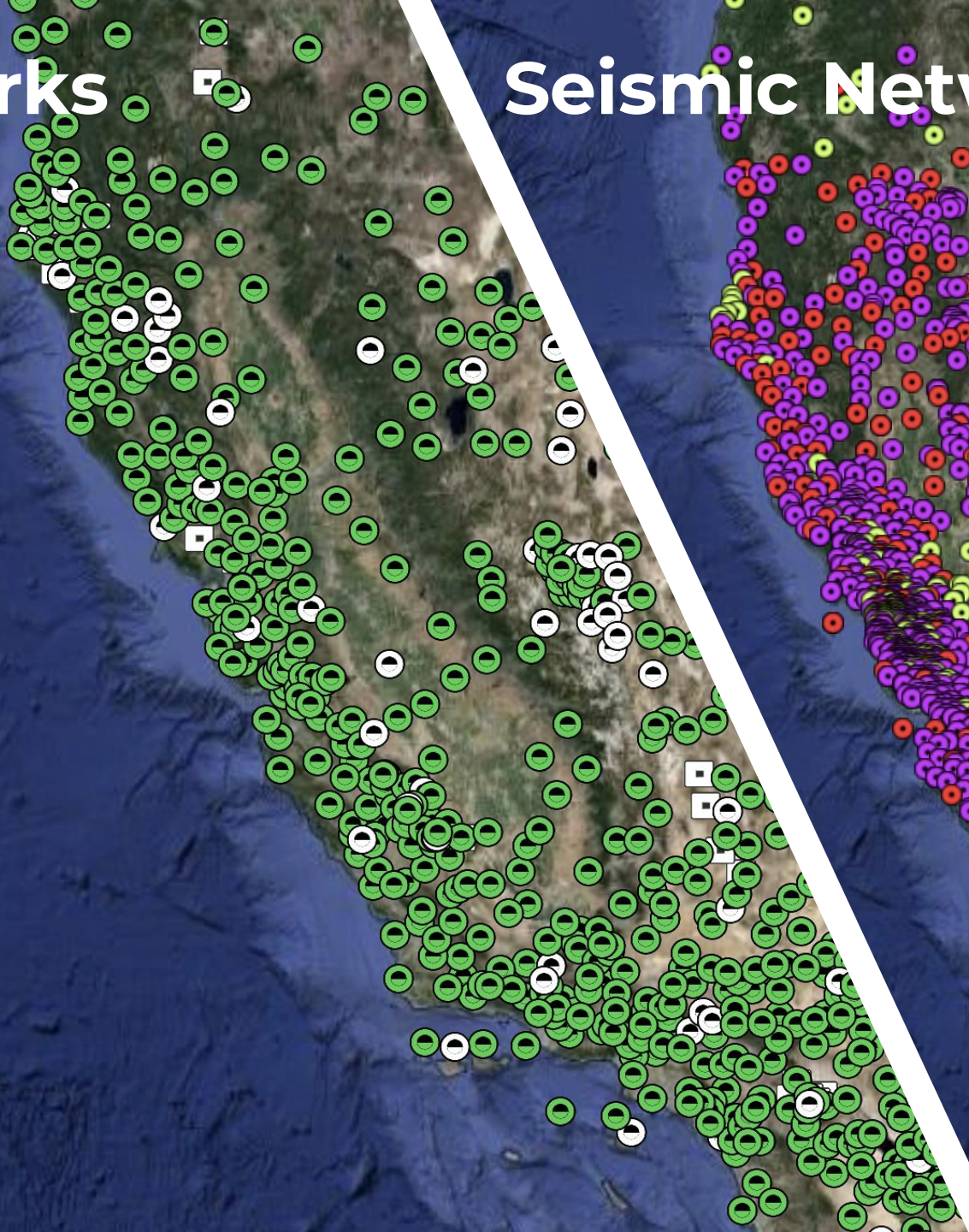


Conclusions

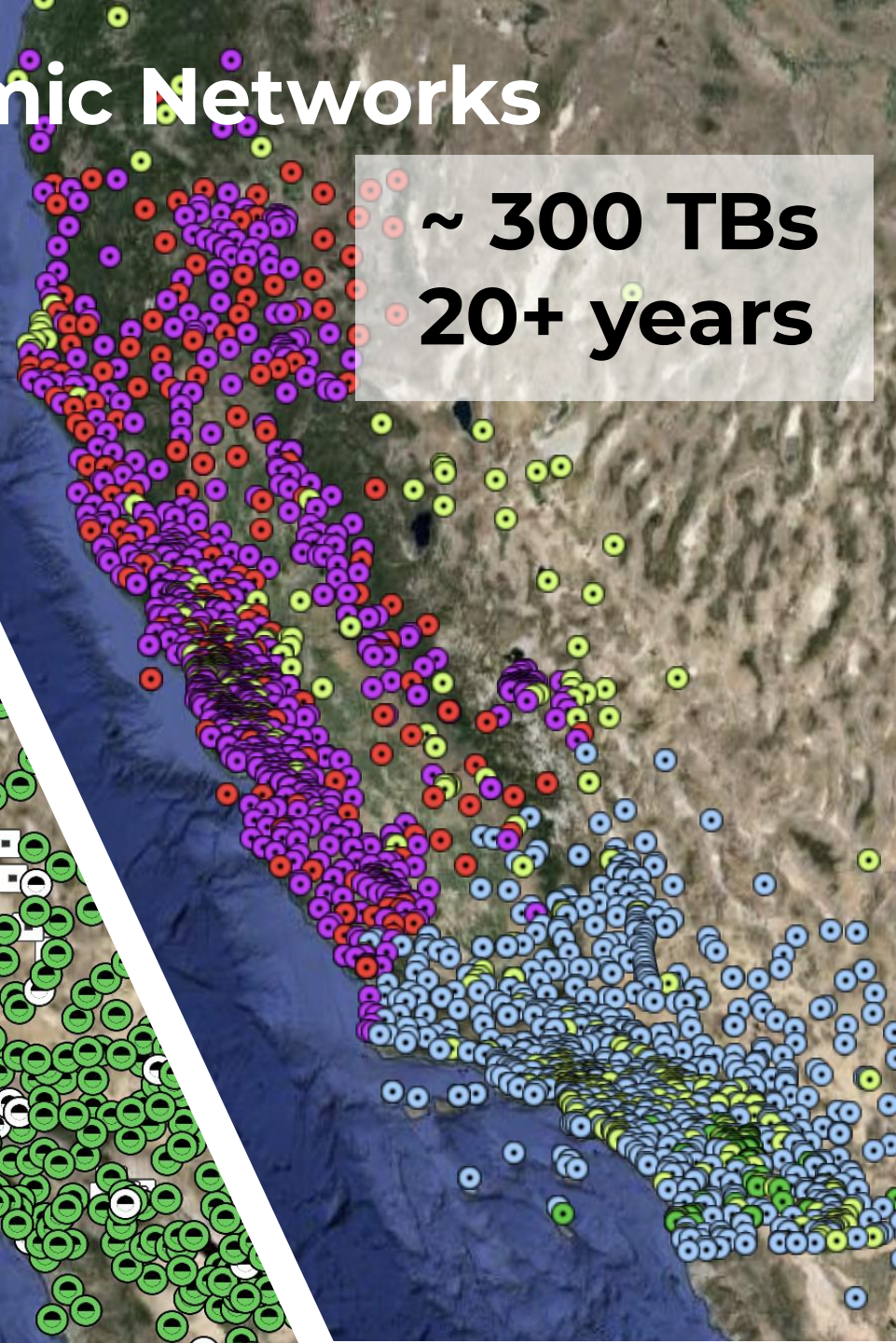
- **Near-fault** processes are evolving at timescales that can be captured by monitoring seismic properties
 - These may provide new constitutive relations and inform physics-based models (e.g., Thakur and Huang, 2023)
- **Near People:** site effects are modulated by hydrology and earthquake damage and have time scale of evolution moderated by climate variability and trend.

Opportunities for a Future SCEC

Geodetic Networks

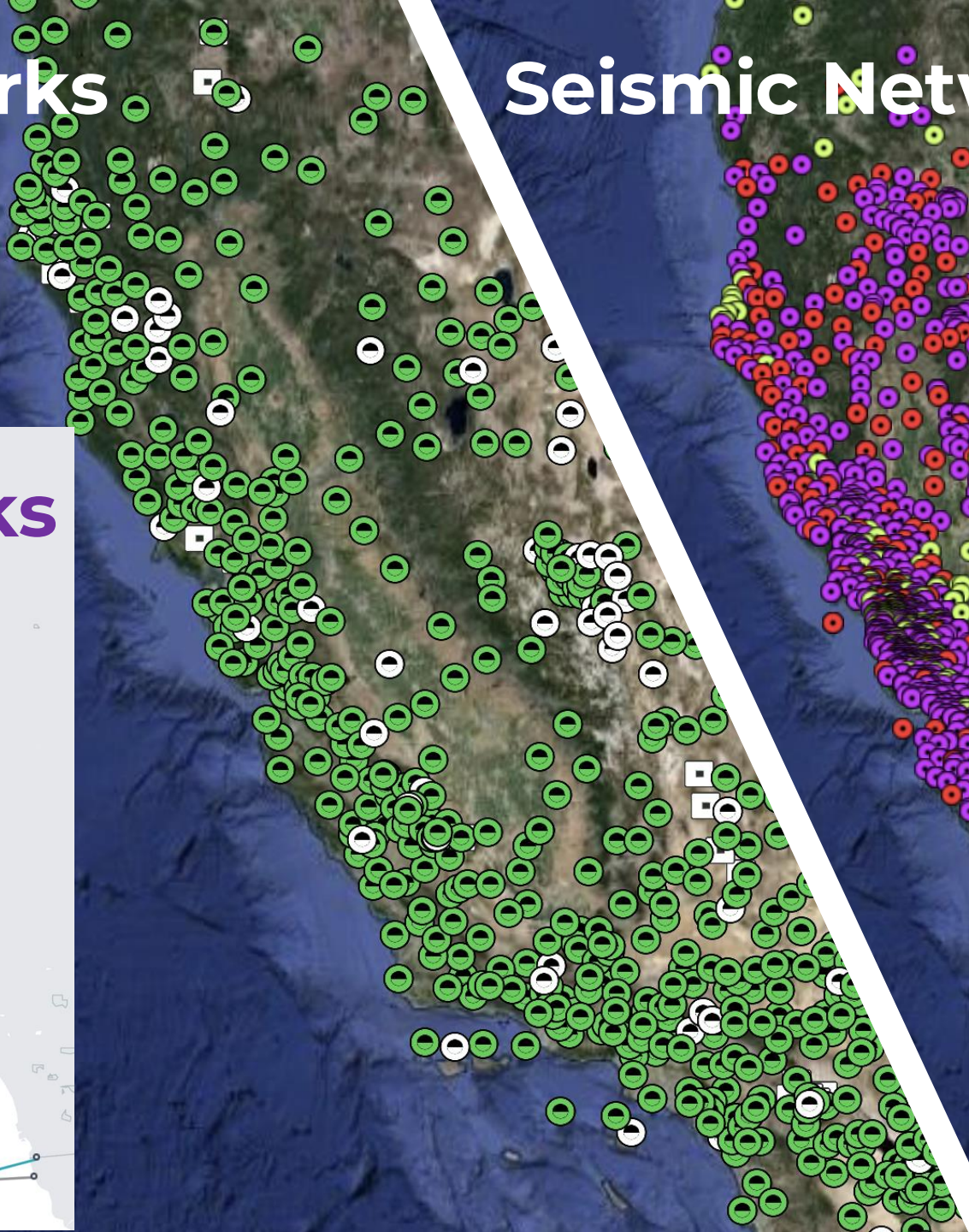


Seismic Networks



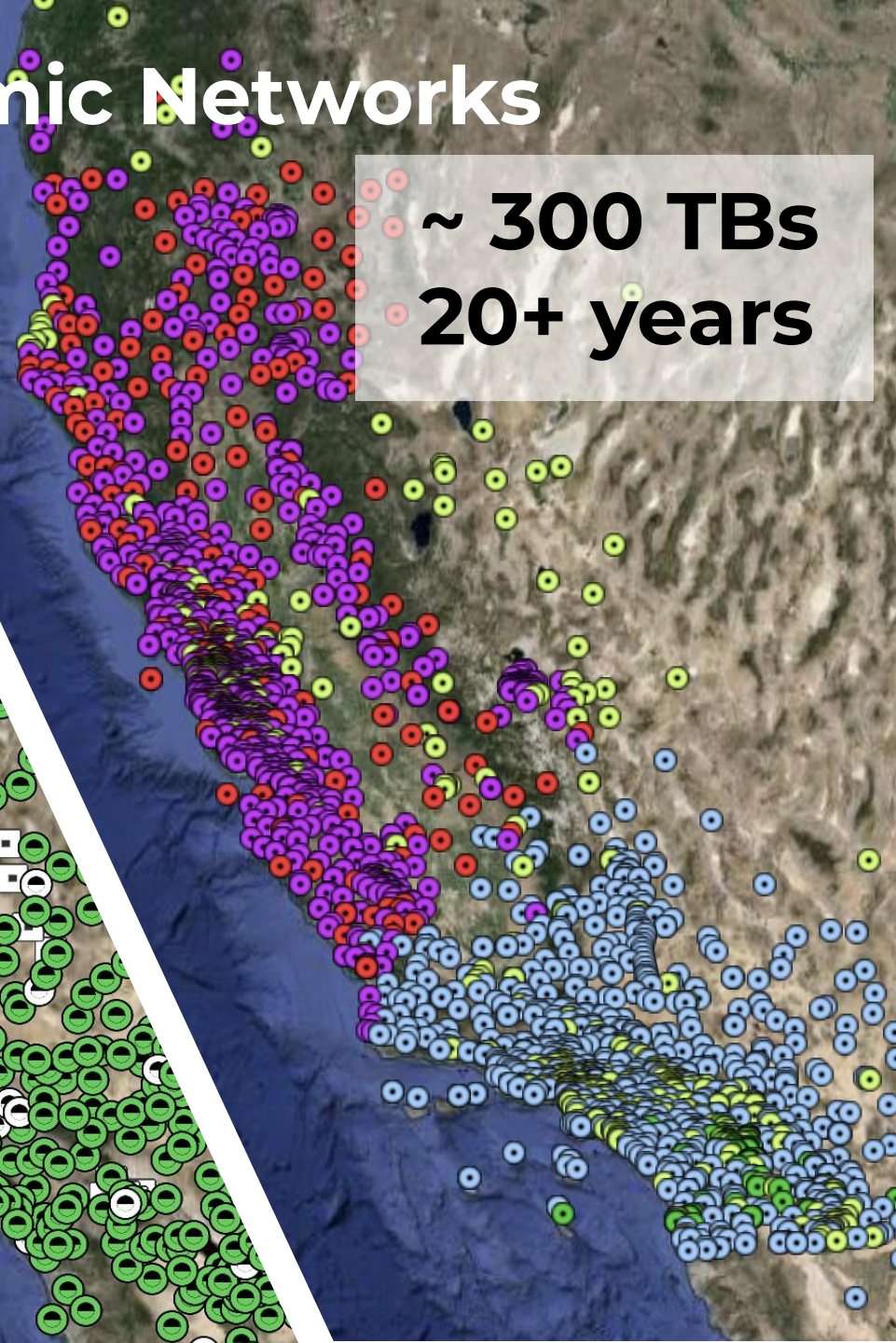
~ 300 TBs
20+ years

Geodetic Networks

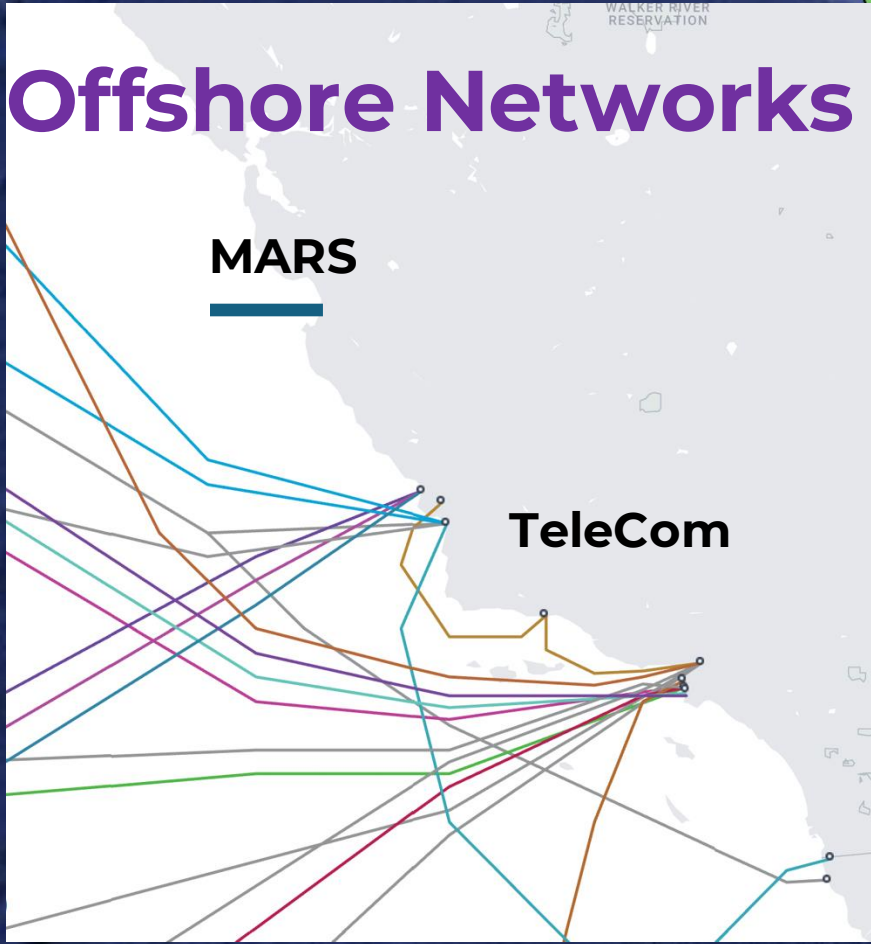


Seismic Networks

~ 300 TBs
20+ years



Offshore Networks





- **Middle Mile Broadband Initiative**

- **DAS can become a permanent network**