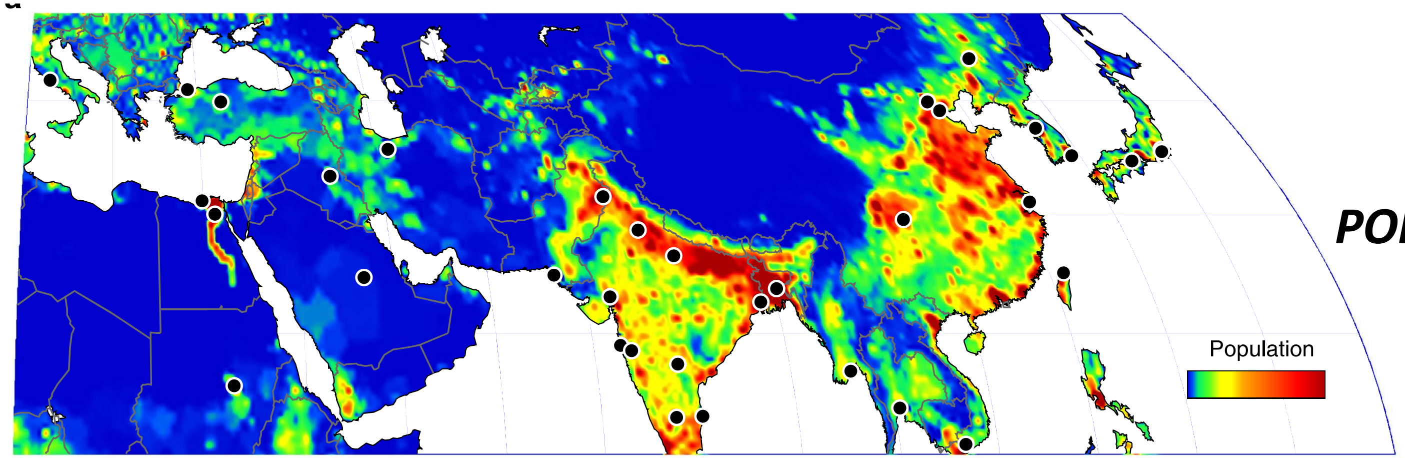
Estimates of Seismic Moment Accumulation Rate from Geodesy

Katherine Guns, David Sandwell, Xiaohua Xu, Yehuda Bock, Lauren Ward, & Bridget Smith-Konter

Outline

- Two methods of calculating moment accumulation rate from geodesy
  - fault-based modeling
  - strain rate-based modeling
- What is the Kostrov layer and how thick is it?
- What is the ratio of off-fault moment accumulation rate to on-fault moment accumulation rate?
- How can InSAR be used to resolve spatial variations in moment accumulation rate?

Large continental earthquakes mainly occur where strain rate exceeds 50 nanostrain/yr



POPULATION

MAGNITUDE

STRAIN

[Elliot et al., 2016]

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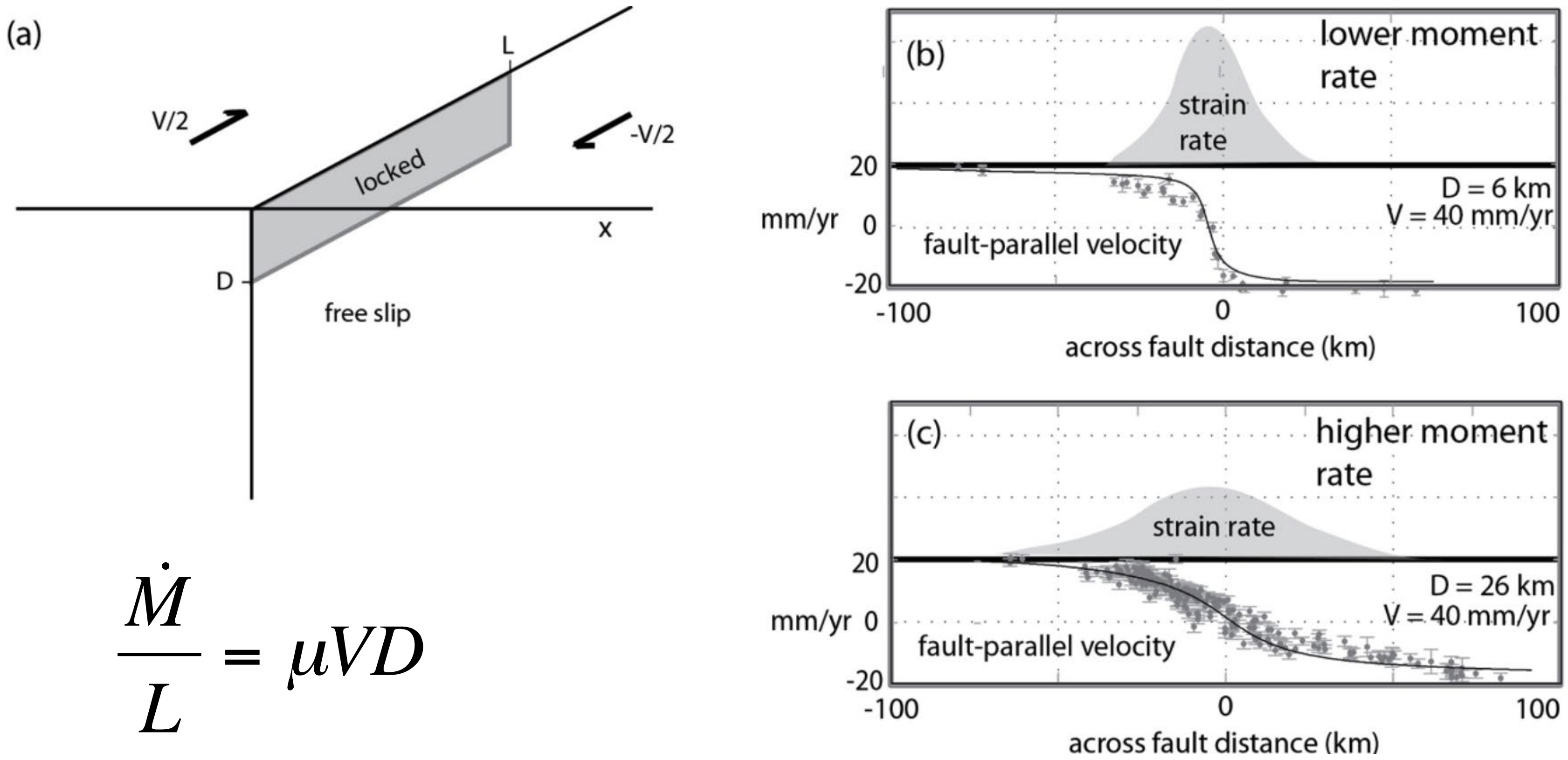
Approach #1 - Fault-based models

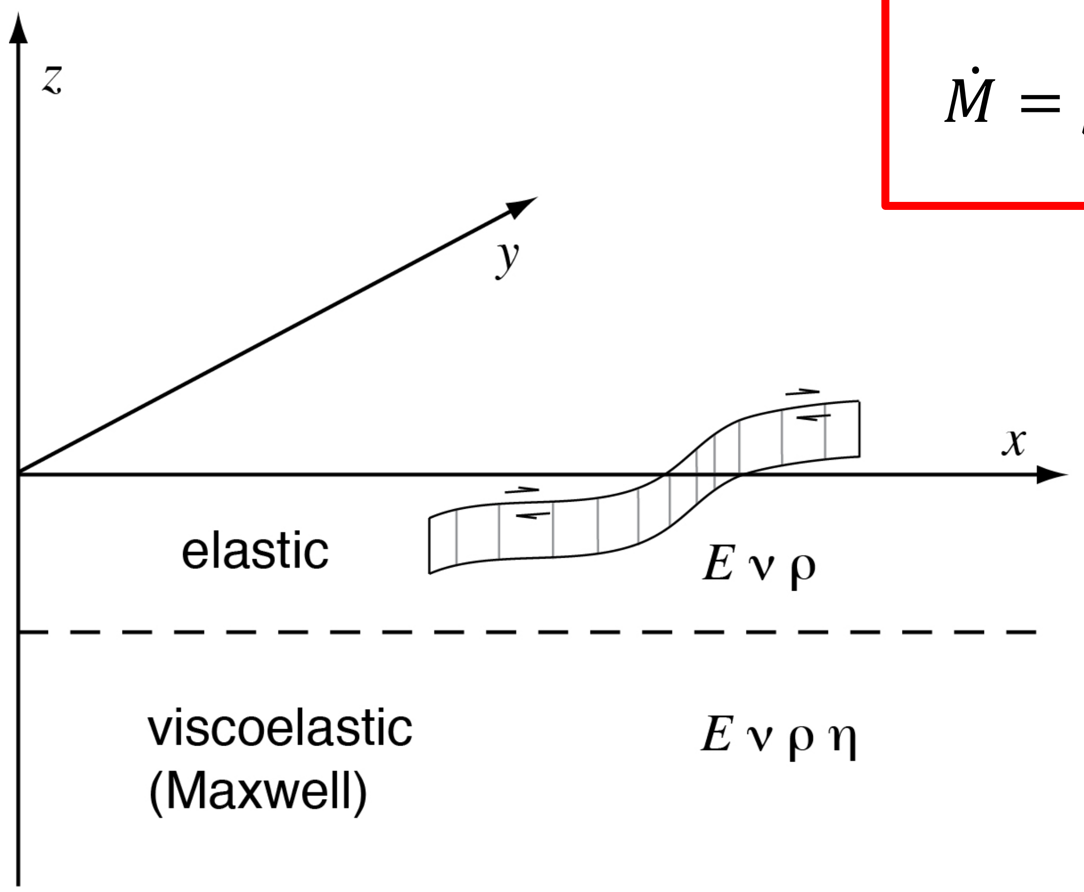


$$\frac{\dot{M}}{L} = \mu V D$$

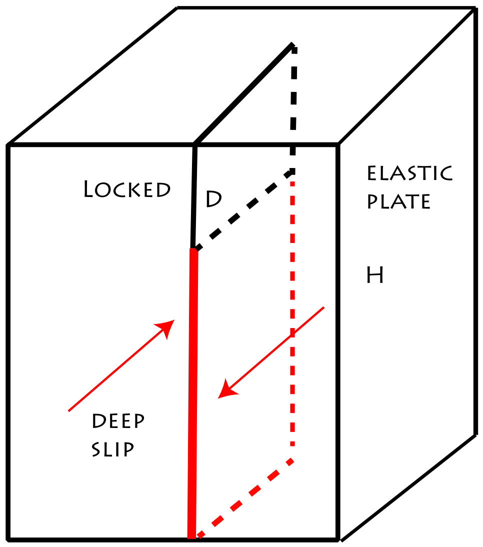
earthquake potential = moment rate X accumulation time X rupture length

Fault-based models

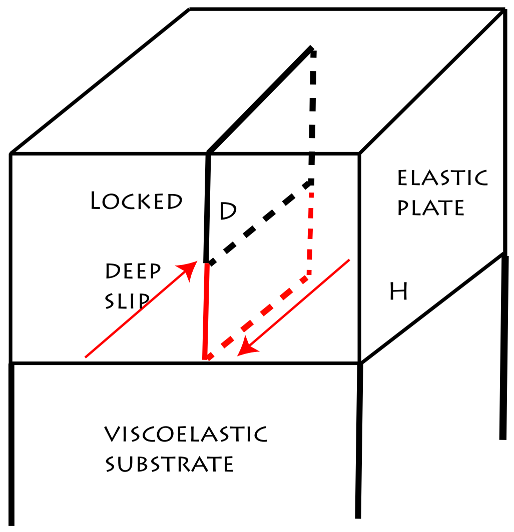
$$\dot{M} = \mu \sum_{i=1}^{N} V_i D_i L_i$$



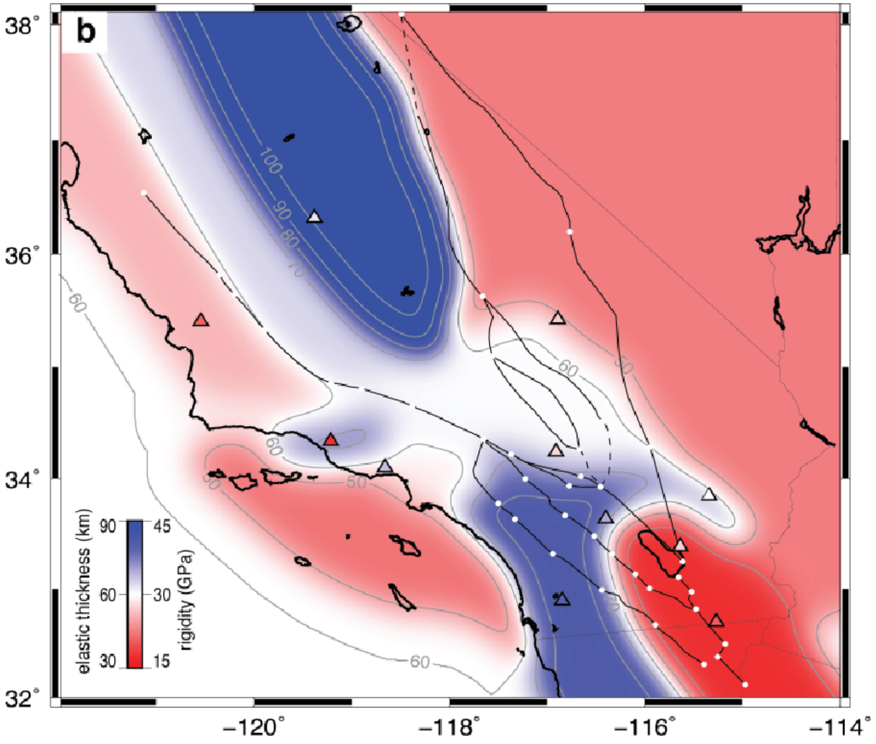
elastic half space



layered half space

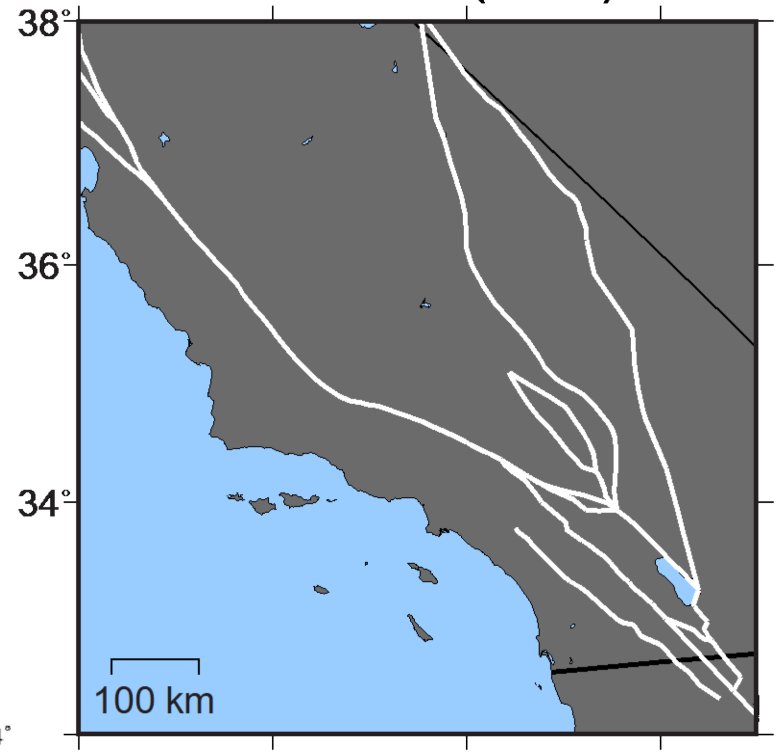


Fault-based models



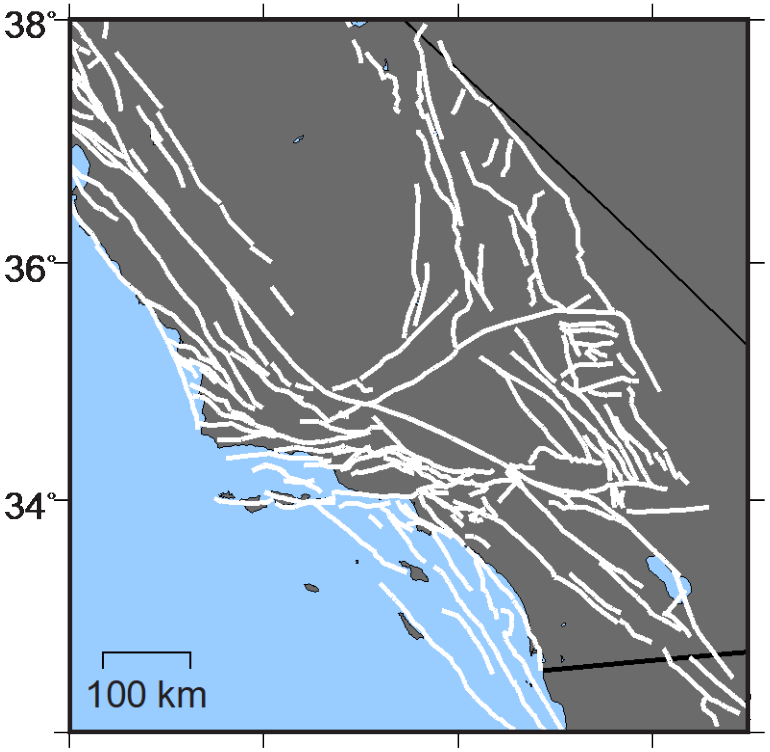
1.20 x 10^{19} Nm/yr
variable rigidity
layered viscoelastic

Ward et al. (2021)



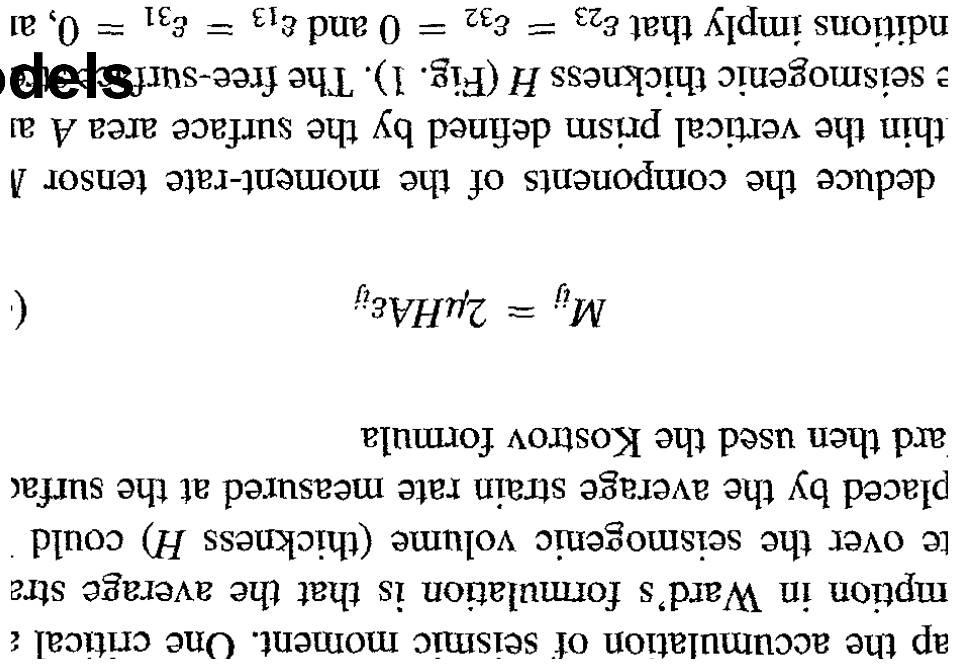
1.52 x 10^{19} Nm/yr
uniform rigidity
layered viscoelastic

Zeng & Shen (2016)



1.18 x 10^{19} Nm/yr
uniform rigidity
elastic half space

Approach #2 - Strain-rate based models



$$\dot{\boldsymbol{M}} = 2\mu HA \begin{bmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & -\Delta \end{bmatrix}$$

Three, commonly used ways to reduce tensor moment to scalar moment.

$$M_o^W = 2 * \mu HAmax(|\varepsilon_1|, |\varepsilon_2|)$$

$$M_o^{WG} = \mu HA(\varepsilon_1 - \varepsilon_2)$$

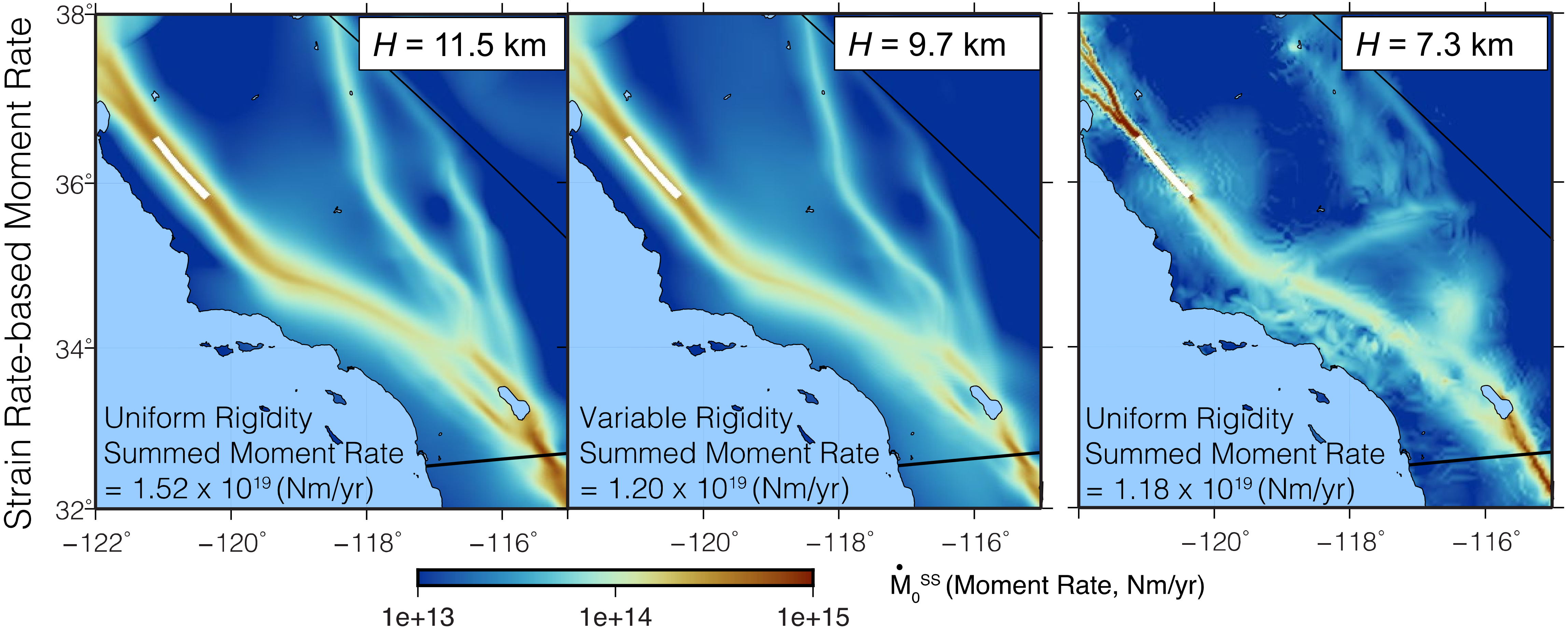
$$M_o^{SS} = 2 * \mu HAmax(|\varepsilon_1|, |\varepsilon_2|, |\Delta|)$$

[Savage and Simpson, 1997]

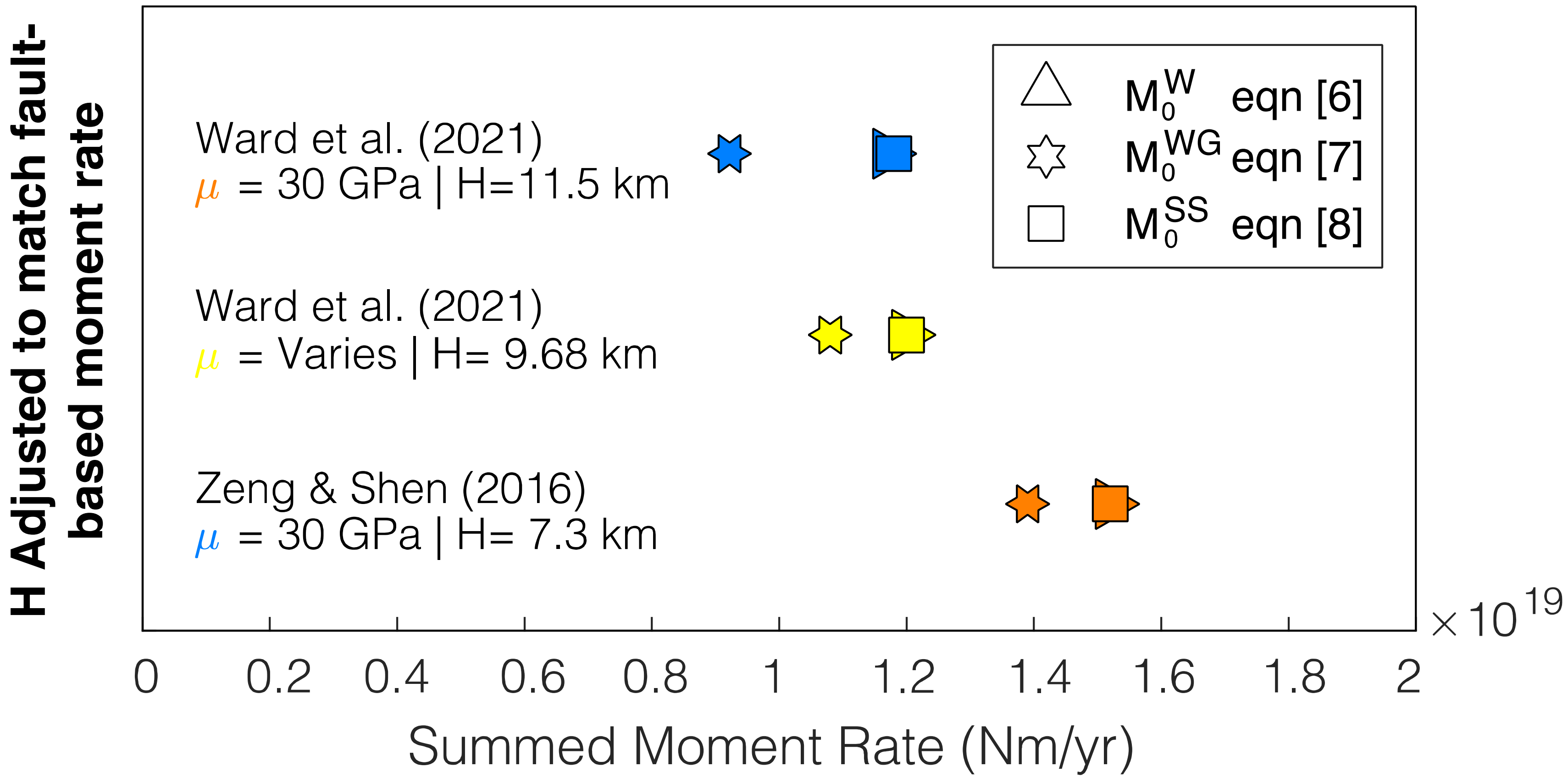
The Kostrov thickness H is equal to the seismogenic thickness on a fault but could be different away from a fault and varies from fault to fault. Moreover, the shear modulus varies spatially so H is simply an unknown parameter [Ward 1994]

Strain-rate based models

The Kostrov thickness H is adjusted so the strain-rate based and fault-based moments match.

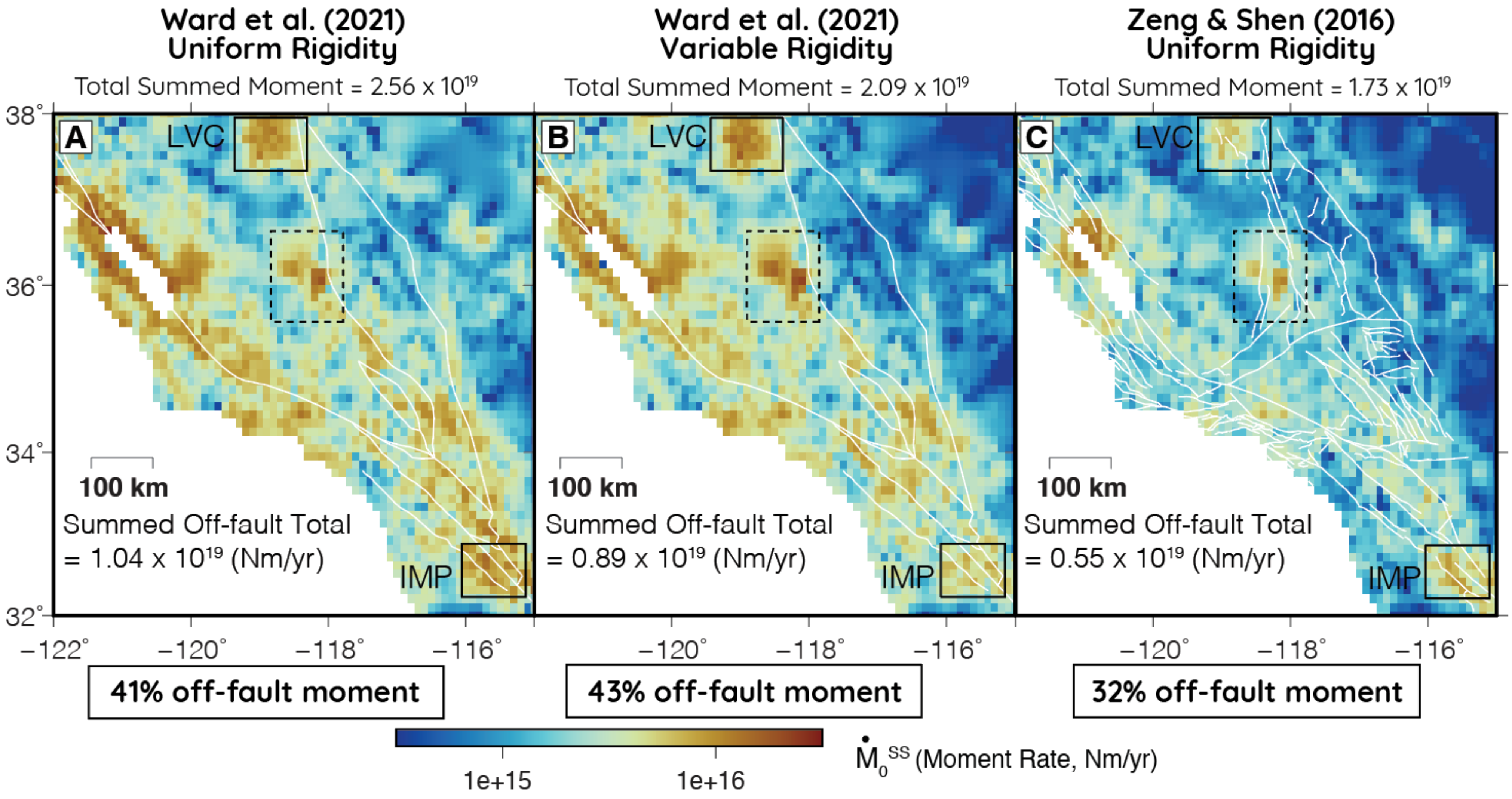


Bounds on Kostrov thickness

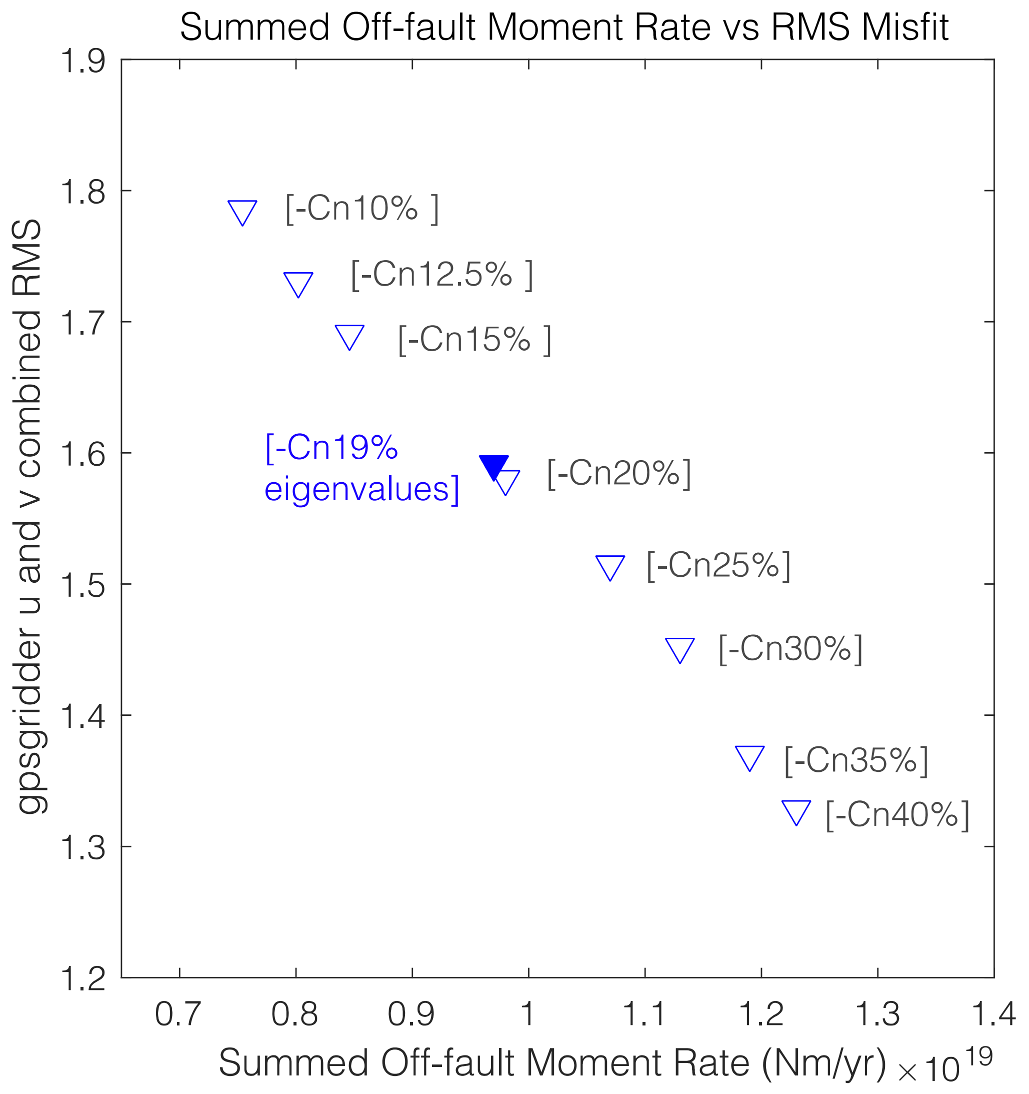


7.3 to 11.5 km < seismogenic thickness of 11 to 20 km

Off-fault moment accumulation rate

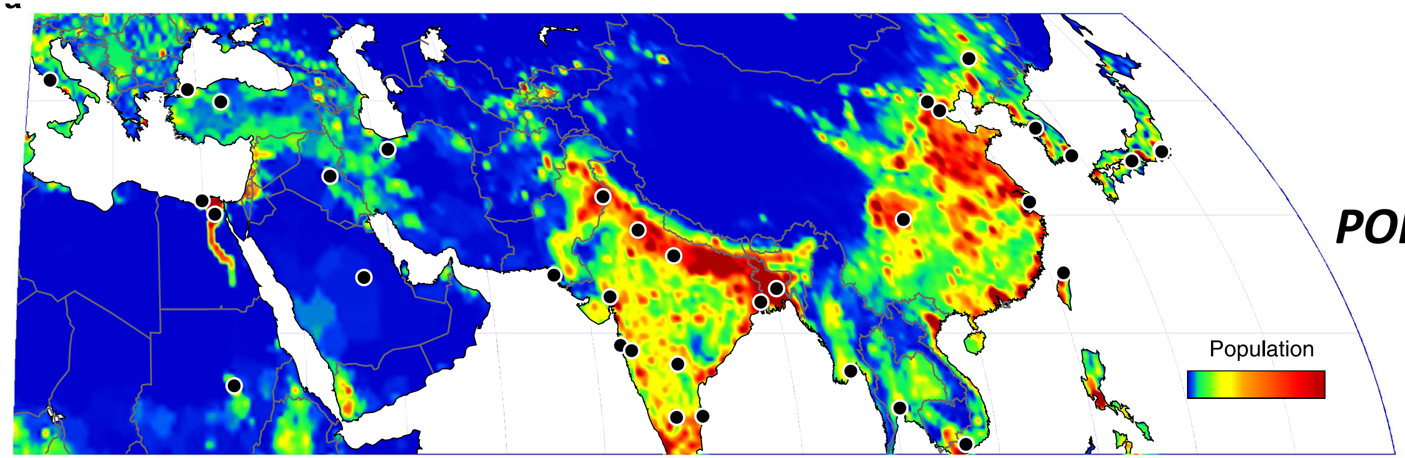


Uncertainty in off-fault moment accumulation rate due to gridding method/parameters [e.g., Maurer and Materna, 2023]



Uncertainty due to gridding method ~ 17%

Large continental earthquakes mainly occur where strain rate exceeds 50 nanostrain/yr



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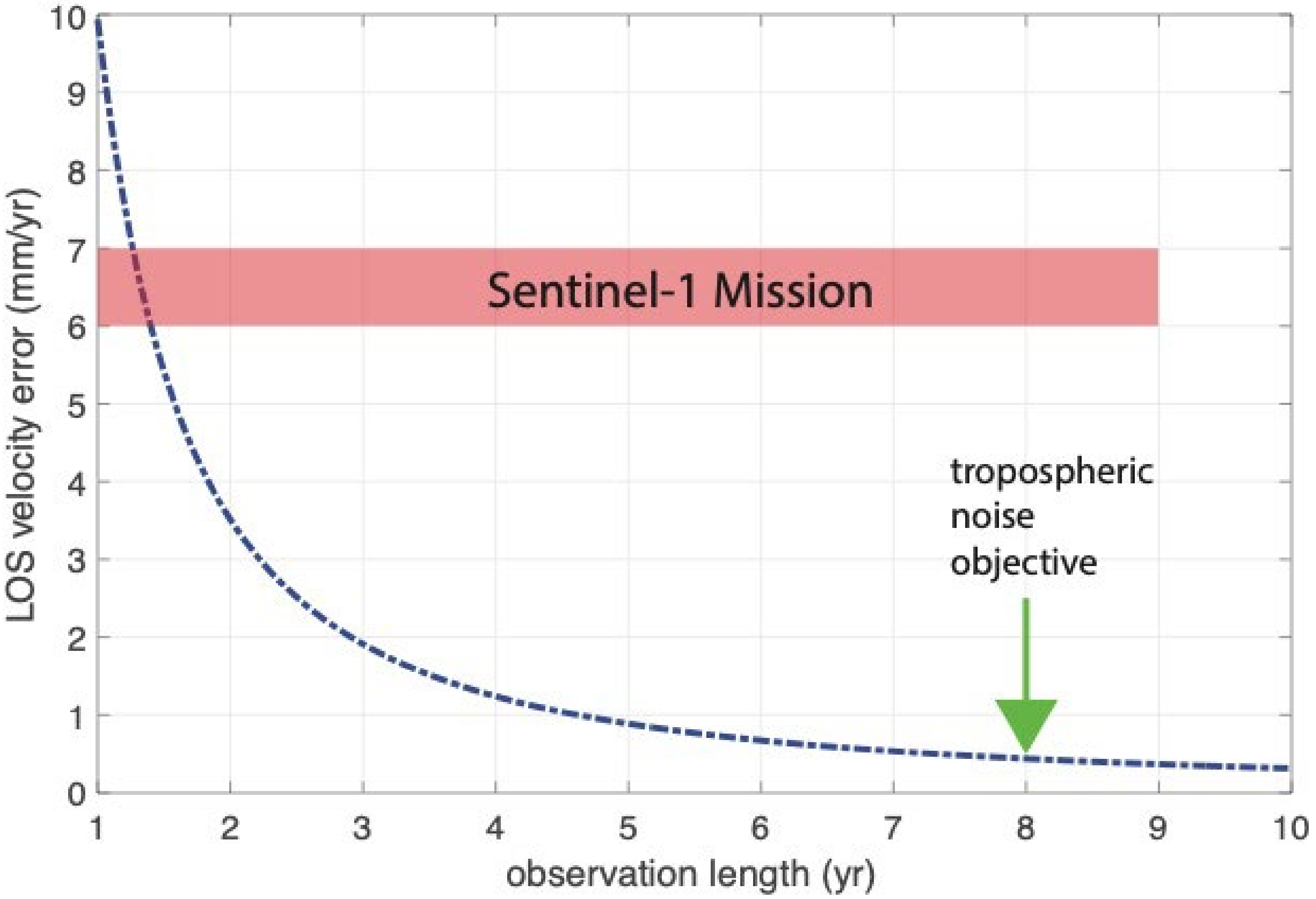
[Elliot et al., 2016]

InSAR can improve the accuracy of this interpolation.

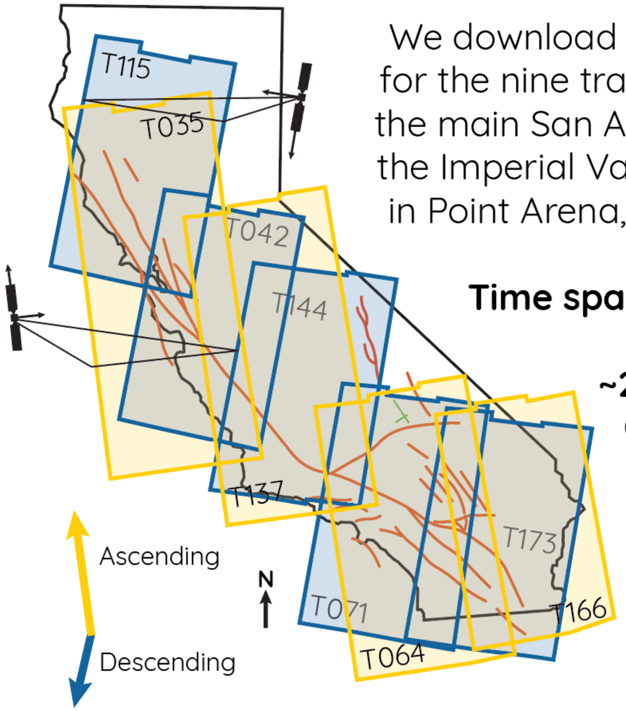


Most destructive earthquakes occur in regions where the tectonic strain rate exceeds 50 nanostrain/yr . This corresponds to an average velocity accuracy of 0.5 mm/yr over the 10 km averaging distance. [Elliott et al., 2016]

[Emardson et al., 2003]

Improve strain rate accuracy with GNSS and InSAR [Guns et al., in prep.]

Data



We download ESA Sentinel-1A/B SAR data for the nine tracks in California that cover the main San Andreas plate boundary from the Imperial Valley to the northern extent in Point Arena, CA.

Time span: 2014.8500 — 2022.0

~2300+ Level 1 Single Look Complex Files

Figure 1. Approximate data coverage extents in our analysis for nine Sentinel-1 SAR satellite tracks over the faults of the San Andreas Plate boundary (red lines).

Methods

x9 tracks

Trimming & stitching Frames together

Co-registration & Alignment to Reference Image [Xu et al., 2017]

Calculating Interferograms + Unwrapping (SNAPHU, [Chen & Zekber, 2002])

- 400-m spatial filter
- 90 days/150 m baselines

GACOS Correction [Yu et al., 2018]

- GACOS 0.1º Tropospheric Correction (ECMWF model)
- http://www.gacos.net/

Elevation Dependent Atmospheric Phase Correction [Elliott et al., 2008]

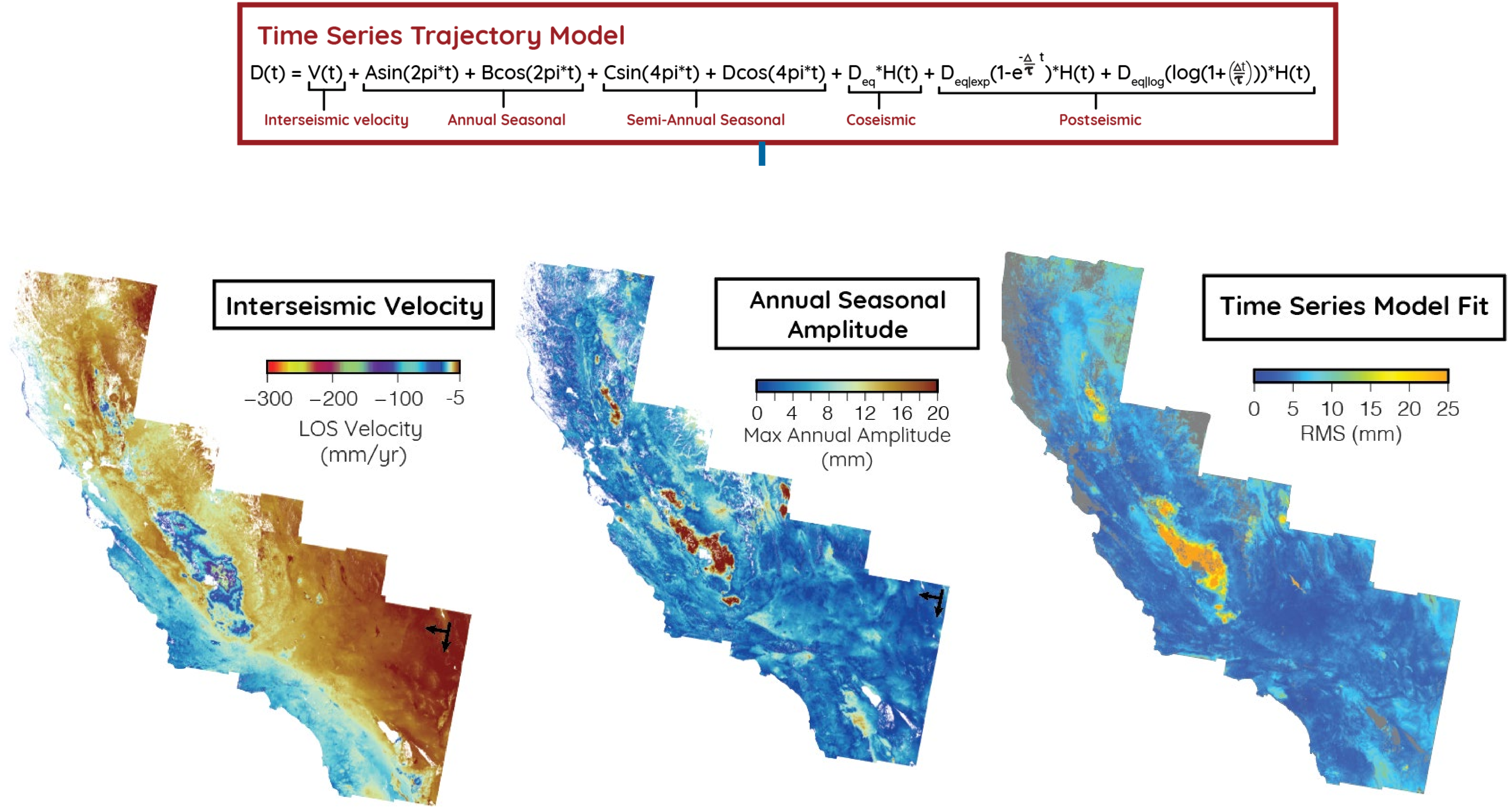
GNSS data-based correction [see Xu et al., 2021]

(1) Apply 7-day Median filter to NASA MEaSURES GNSS time series [Klein et al., 2019; Bock et al., 2022]
(2) Calculate interferogram level displacement over date pair from GNSS
(3) Project GNSS to LOS
(4) Extract InSAR displacement from interferogram at GNSS station locations
(5) Calculate point residuals (InSAR - GNSS)
(6) Interpolate a residual surface with GMT Surface
(7) Filter Surface with wavelength = 80km
(8) Correct interferogram (InSAR - Filtered Residual Grid)

Coherence-based SBAS [Tong & Schmidt, 2016] + Common-Scene-Stacking Atmospheric Correction [Tymofyeyeva & Fialko, 2015]

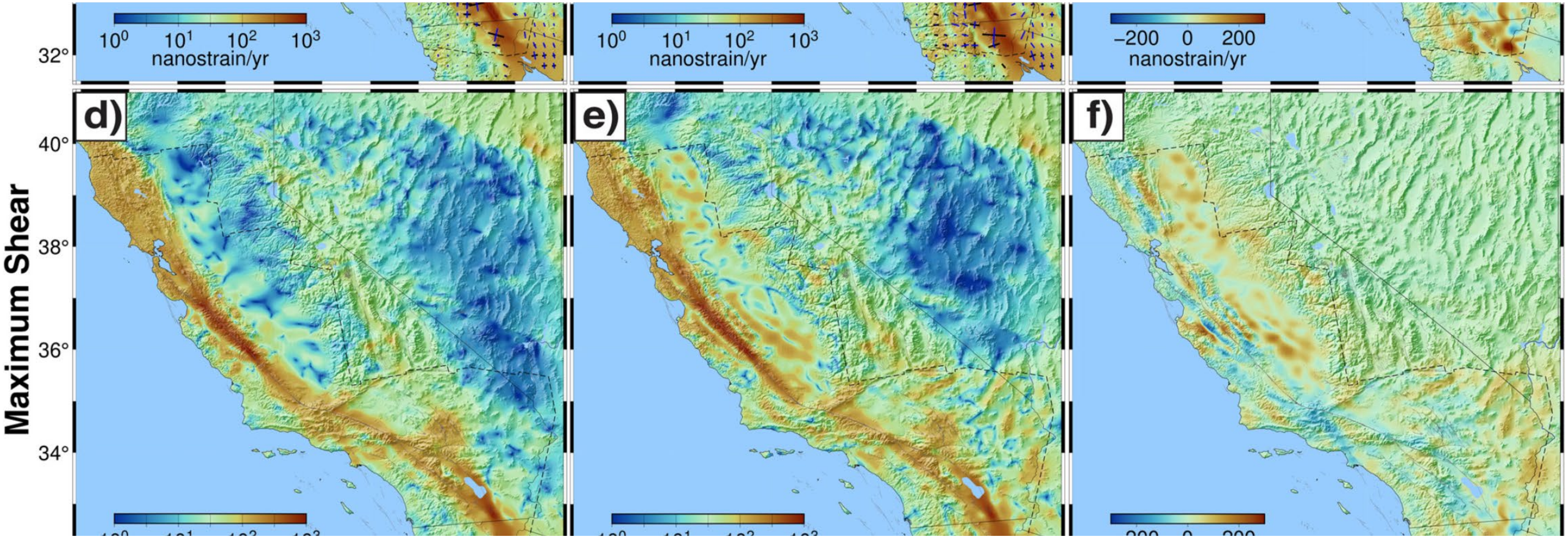
Coseismic Correction, if necessary [Guns et al., 2022]

LOS Displacement Time Series + Velocity



Time Series Trajectory Model
D(t) = V(t) + Asin(2pi*t) + Bcos(2pi*t) + Csin(4pi*t) + Dcos(4pi*t) + D_eq*H(t) + D_eq|exp(1-e^(-Δt/τ))*H(t) + D_eq|log(log(1+(Δt/τ)))*H(t)
Interseismic velocity
Annual Seasonal
Semi-Annual Seasonal
Coseismic
Postseismic
Interseismic Velocity
−300 −200 −100 -5
LOS Velocity (mm/yr)
Annual Seasonal Amplitude
0 4 8 12 16 20
Max Annual Amplitude (mm)
Time Series Model Fit
0 5 10 15 20 25
RMS (mm)

InSAR can improve the accuracy of this interpolation.



[Xu et al., 2021]

Strain rate based on 4.5 years of Sentinel-1 data have errors > 100 nanostrain/yr. **This is currently being revised with 3 more years of data.**

Conclusions

- Three earthquake cycle models are used to estimate:
  - Kostrov thickness of 11.5, 9.7 and 7.3 km
  - off-fault moment rates of 41%, 43% and 32%

- The model with variable crustal rigidity has 21% lower moment rate

- The model having more faults has a lower off-fault moment rate.

- The largest uncertainty (17%) in calculating moment rate from strain rate is the amount of smoothing used to grid the GNSS velocity data.

- Combined InSAR/GNSS velocity estimation should reduce this interpolation error.

Geodetic moment accumulation rate versus **Seismic** moment release rate