Off-Fault Geodetic Deformation in California May Be Largely Aseismic

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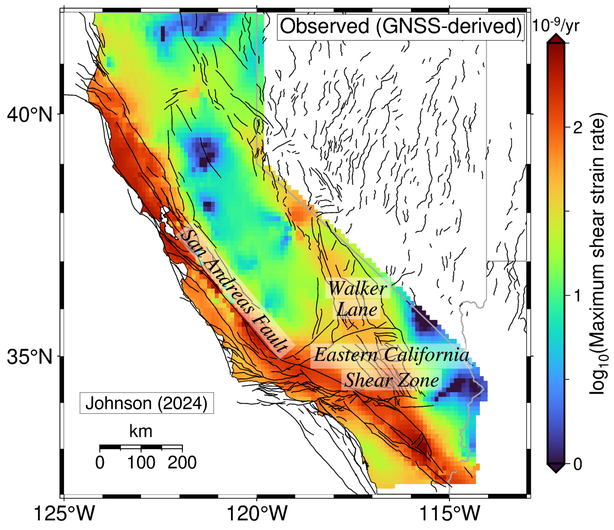
INTRODUCTION

Determining the distribution of on-fault and off-fault deformation is essential for understanding seismic hazards. **Here, we estimate the contributions and uncertainties of on-fault and off-fault deformation to GNSS-derived surface strain rates in California**. For this purpose, we used a model that assumes strain rates in the crust[1] are due to a combination of elastic distortions due to slip deficit rates on 3D faults (fault coupling) and distributed depth-averaged moment rate tensor sources in an elastic plate.

Input data: GNSS-derived strain rates



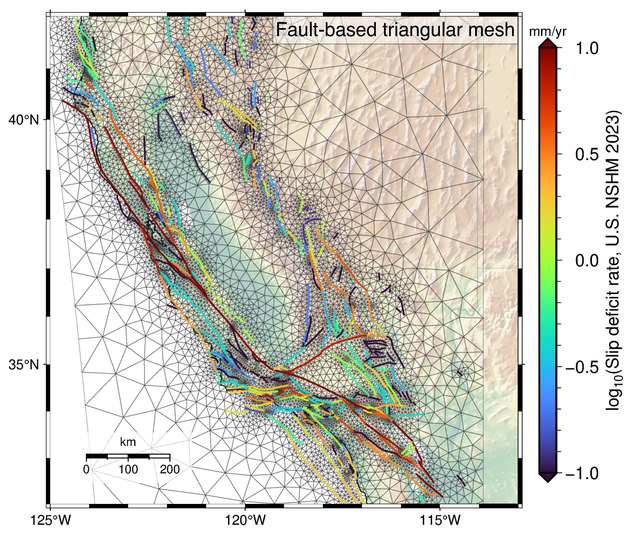
METHOD: INVERSION SCHEME

We inverted surface strain rates for both on-fault and off-fault sources. **The inversion employed least squares estimation and a Monte Carlo approach, generating a posterior distribution of slip deficit rates on 3D fault patches and moment rate sources on the centroids of a triangular mesh,** implementing lower and upper bounds on slip deficit rates based on the U.S. National Seismic Hazard Model (U.S. NSHM)[2].

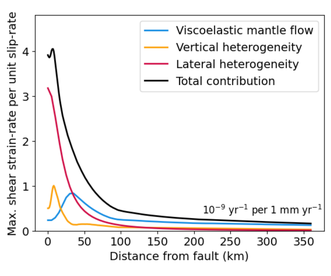
$$\mathbf{d}_\varepsilon = \mathbf{G}_\varepsilon^s \mathbf{s} + \mathbf{G}_\varepsilon^m \mathbf{m} + \epsilon,$$

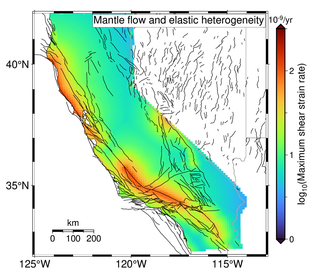
$$\begin{bmatrix} \mathbf{d}_w \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{G}_w^s & \mathbf{G}_w^m \\ \alpha^{-2}\mathbf{D} & \mathbf{0} \\ \mathbf{0} & \beta^{-2}\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{s} \\ \mathbf{m} \end{bmatrix} + \epsilon,$$

s: Slip deficit rates on 3D faults
m: Distributed moment rate sources



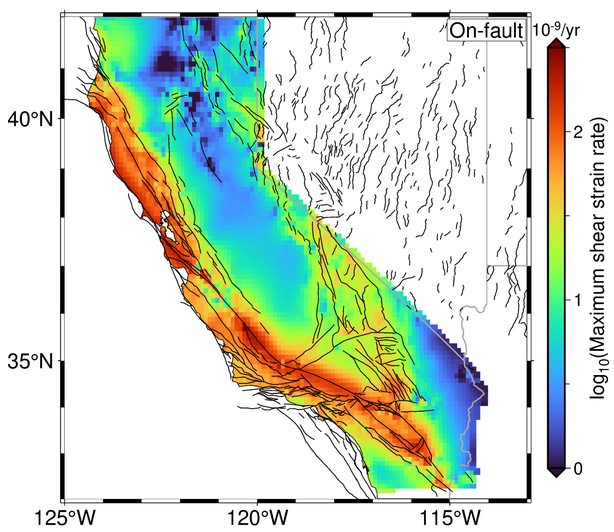
ELASTIC HETEROGENEITY AND VISCOELASTIC MANTLE FLOW EFFECTS



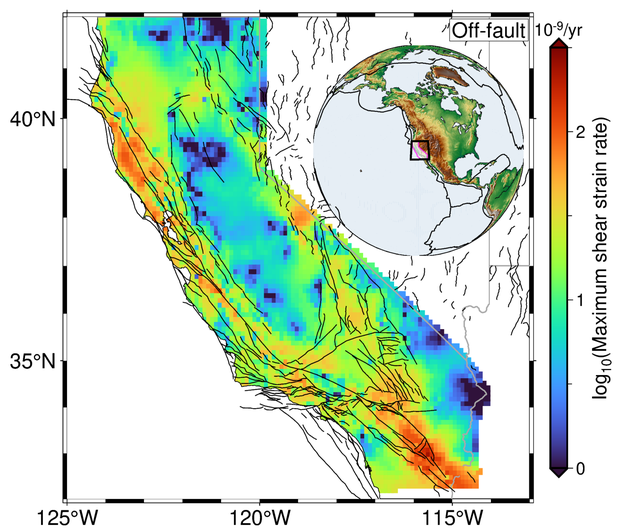


RESULTS

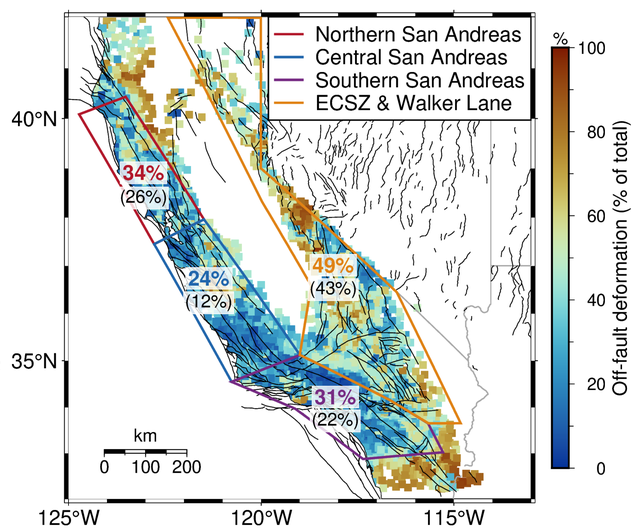
On-Fault strain rate



Off-Fault strain rate



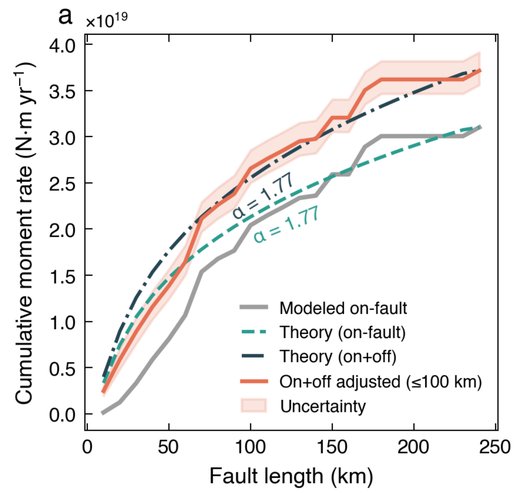
% Off-Fault strain rate

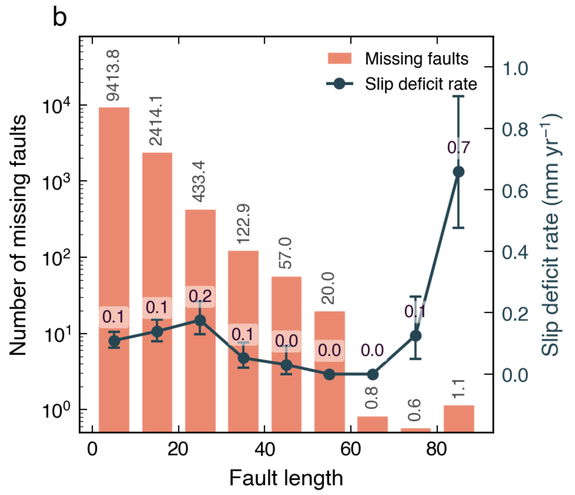


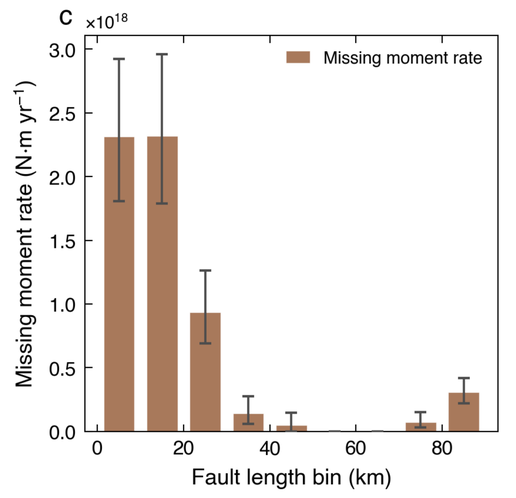
Fraction of total modeled strain rate accommodated by off-fault deformation in the Northern, Central, and Southern San Andreas, Eastern California Shear Zone (ECSZ), and Walker Lane regions. Colored percentages are computed from the strain-rate data within each region; parenthetical values give the corrected estimate relative to the regional strain rate after accounting for viscoelastic earthquake-cycle effects and elastic heterogeneity.

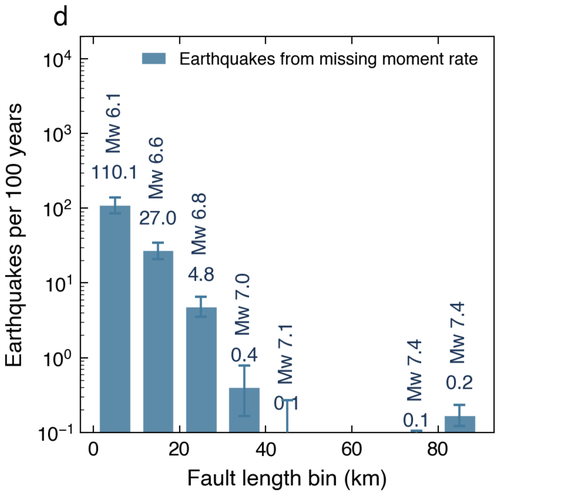
Can off-fault deformation be accomodated on unmapped faults?

Fault populations follow a power-law length distribution $N(L) \propto L^{-\alpha}$,where α is the Pareto index[3]. Empirical compilations spanning micro-cracks to crustal-scale faults yield α~2, equivalent to a Gutenberg-Richter b-value of 1. The U.S. NSHM fault database follows this scaling in California with α=1.77, but shows a clear deficit at lengths below 100 km, where faults are likely underrepresented in the catalog. **Distributing the off-fault moment budget across the 5-100 km fault length range requires more than 16,000 additional faults, each sustaining slip-deficit rates of 0.1-0.2 mm/yr**. For context, this number of unmapped faults is roughly 30 times larger than the 528 faults currently documented in the Quaternary Fault and Fold Database in California.

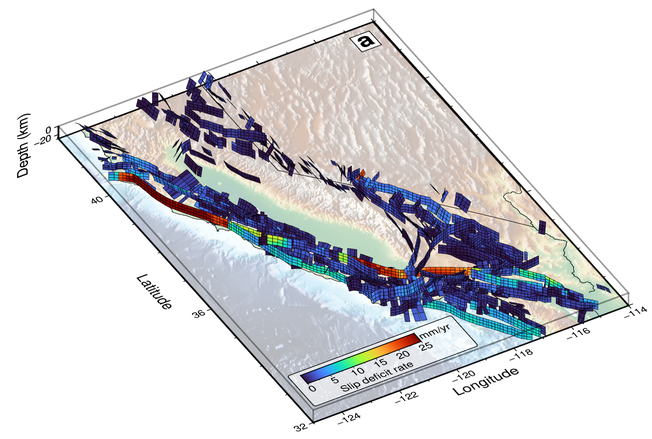




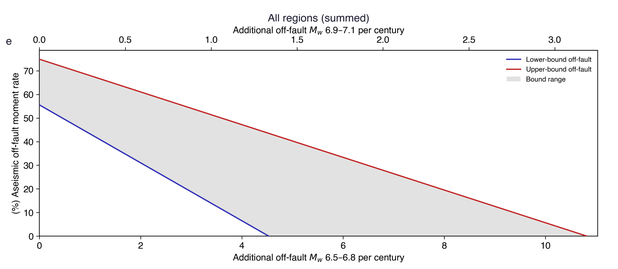




Slip dedicit rates on 3D faults



% Aseismic off-fault moment rate as a function of the number of additional off-fault earthquakes required to close the moment deficit relative to a 40-year instrumental catalog[4]



CONCLUSIONS

- ~35% of geodetically-derived surface strain rates in California can be attributed to off-fault deformation.
- Accommodating the off-fault moment rate seismically would require more than 16,000 unmapped faults shorter than 100 km, each sustaining slip-deficit rates of 0.1-0.2 mm/yr.

FUTURE WORK

- Accounting for earthquake catalog incompleteness using Monte Carlo simulations with both truncated Gutenberg Richter and tapered Pareto magnitude distributions.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Johnson, K. M. (2024). Disagreements in geodetically inferred strain rates in the western US with stress orientations and geologic moment rates. Journal of Geophysical Research: Solid Earth, 129(4).

[2] Hatem, A. E., Collett, C. M., Briggs, R. W., Gold, R. D., Angster, S. J., Field, E. H., & Powers, P. M. (2022). Simplifying complex fault data for systems-level analysis: Earthquake geology inputs for US NSHM 2023. Scientific data, 9(1), 506.

[3] Zou, X., & Fialko, Y. (2024). Can large strains be accommodated by small faults: “Brittle flow of rocks” revised. Earth and Space Science.

[4] Cheng, Y., Bürgmann, R., Taira, T., Liao, Z., & Allen, R. M. (2026). Stress model of California: Fault-stress interactions across a complex plate boundary system from focal mechanisms of small earthquakes. Journal of Geophysical Research: Solid Earth, 131