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Identifying Potential Seismogenic Structures in the Northern San Andreas Plate Boundary Fault System

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Objectives

The overarching goal of this project was to improve our understanding of the seismogenic potential of plate boundary structures associated with the present-day Pacific-North American-Juan de Fuca interactions at the Mendocino triple junction (MTJ), as well as those associated with the northward migration of the MTJ over the past ~10 Ma (as far south as the Bay Area). Our first objective was to use available geological, geophysical, and earthquake datasets to define the primary plate boundary structures, with a particular focus on identifying features that are buried or offshore. Our second objective was to develop preliminary models using this updated plate boundary structure to assess the implications for earthquake behavior, inter-earthquake stress accumulation, and potential triggering interactions. This project addressed several Statewide California Earthquake Center (SCEC) Science Milestones related to the northern ~400 km of the San Andreas fault system and the Community Fault, Geodetic, Stress, Rheology, and Thermal Models (CFM, CGM, CSM, CRM, CTM). Specifically, this project aimed at filling critical data gaps in the tectonic evolution of the northern San Andreas plate boundary system that define its fault structure (CFM), the deformational nature of these structures (CRM), patterns of inter-seismic loading (CGM, CSM), and thermal structure (CTM).

A key product of this project is a seismotectonic framework model for California from the Bay Area to the MTJ. This framework model is constrained by a combination of datasets, including plate reconstructions, seismic tomography and reflection imaging, inter-earthquake surface displacements, and geological terrane boundaries. In addition, we are testing assumptions about the rheological and seismogenic nature of this model against observations of present-day seismicity, inter-seismic strain accumulation, thermal observables, and rupture characteristics of historic earthquakes, including the 1906 San Andreas event. This framework model is serving as the basis for interpreting seismicity distributions near the MTJ (one of the most seismically active regions in California); reevaluating assumptions about the seismogenic nature of the San Andreas fault system, especially in context of the 1906 earthquake; and generally improving seismic hazard assessment for northern California.

Methodology & Results

Defining the major plate boundary structures in northern California involves integrating a variety of geophysical and geological datasets from the region. The best-known seismogenic structure is the San Andreas fault, which hosted the 1906 earthquake (Lawson, 1908). This earthquake ruptured the San Andreas fault onshore from San Juan Bautista to Point Arena, where it propagated offshore (Fig. 1). Several observations, including strong shaking (Boatwright and

Bundock, 2008), displacements estimated from triangulation survey datasets (Song et al., 2008), and surface rupture near Shelter Cove (Prentice et al., 1999), imply rupture continuing offshore for another ~100 km to the northwest, supporting the inference of Lawson (1908). However, the faulting kinematics are not well constrained offshore. The section of the San Andreas fault that ruptured onshore separates the Salinian block (consisting of Mesozoic granitic rocks similar to those found in the Sierra Nevada; shown in pink on Fig. 1) from the Franciscan terrane (a Mesozoic to Miocene mélange associated with the Farallon subduction accretionary wedge; shown in blue on Fig. 1). In other words, the San Andreas fault represents a terrane-bounding fault. The Salinian block ends just offshore of Point Arena, likely at the Navarro discontinuity associated with abrupt termination of Neogene structures and a magnetic anomaly boundary (McCulloch, 1989). The northern termination of the Salinian block implies that a terrane-bounding San Andreas fault in this region ceases to exist, and the primary fault structure(s) offshore north of Point Arena are likely to be different from the strike-slip faults onshore to the south.

Recent, high-resolution seismic tomographic imagery of Northern California provides new constraints on structures in this region (Furlong et al., 2024). This dataset indicates the existence of a "Pioneer fragment" extending eastward from the ocean floor of the Pacific plate beneath North American (Franciscan) crust (Fig. 1). The Pioneer fragment, first hinted at by Atwater (1970), is interpreted to be a former piece of subducting Farallon plate between the Pioneer fracture zone and Mendocino transform that was captured by the Pacific plate when the MTJ first formed at ~25 Ma. Since then, the fragment has been moving to the northwest along with the Pacific plate underneath North America. It follows in the wake of the southern edge of the Gorda/Juan de Fuca slab at the MTJ, with a wedge of North American crust in the gap between the two. The boundary between the Pioneer fragment and overlying North American crust resembles that of a subduction megathrust: a shallowly dipping detachment, but with dominantly strike-slip displacements resulting from the northwestward motion of Pacific the Pacific plate with respect to the North America plate (Fig. 2a). A major earthquake rupture extending across this region, such as the 1906 event, may be able to propagate onto this detachment if it behaves seismogenically.

A key component of determining the plate boundary structure is identifying the location of the throughgoing lithospheric transform plate boundary. The pattern of surface velocities around a lithospheric-scale transform plate boundary in between large earthquakes, when shallow, brittle faults are locked and the deeper, ductile shear zone is creeping, is that of an arctangent centered on the creeping shear zone (Savage and Burford, 1973). To locate the transform plate boundary associated with the northern San Andreas fault system, representing the boundary between the Pacific plate and Great Valley Block, we take interseismic velocities relative to the North American plate from the Nevada Geodetic Laboratory (Blewitt et al., 2018). We extract the 30 mm/yr contour, halfway between the Pacific-North America velocity of 50 mm/yr and 10 mm/yr. This 10 mm/yr accounts for the plate motion accommodated between the Sierra Nevada/Great Valley Block and the North American plate in Owens Valley and the Eastern California shear zone. The 30 mm/yr contour coincides with the symmetry point in the arctangent model, representing the location of the lithospheric-scale shear zone. This contour lies below the San Andreas fault south of San Juan Bautista, but to the north it lies ~50 km east of the San Andreas fault, beneath the Calaveras, Hayward, Rodgers Creek, and Maacama fault zones (Fig. 3). It is also coincident with the eastern edge of the Pioneer fragment further north (Furlong et al., 2024; Fig. 1). This indicates the location of the fundamental, lithospheric scale transform plate boundary between the Pacific plate and Great Valley block.

Therefore, the situation along the San Andreas fault from San Juan Bautista to Point Arena is as a major crustal strike-slip fault (the San Andreas fault) offset from the deeper transform plate boundary to the east. To accommodate this configuration, a near-horizontal detachment must extend from near the base of the San Andreas fault to the top of the shear zone (Fig. 2b). This structure was first imaged in the Bay Area Seismic Experiment (BASIX) seismic reflection survey (Brocher et al., 1994). Our results indicate that a similar structure likely extends all the way to the southern end of the Pioneer fragment. As with the detachment along the surface of the Pioneer fragment, the seismogenic nature of the detachment in its southern wake extending to the Bay Area is poorly constrained, and needs further investigation.

We generated a suite of preliminary modeling results to explore the effects of this plate boundary structure on generic earthquake cycle deformation, as well as the specific characteristics of the 1906 earthquake revisited in context of the new fault information. The earthquake cycle modeling was performed using the finite element modeling platform *GTECTON* (Govers et al., 2018), and consisted of a San Andreas fault connected to a deeper shear zone by a sub-horizontal detachment. We also considered the effects of earthquakes on the fault lying above the detachment, such as the Maacama fault. These model results show how slip on the detachment can enhance and shift surface displacements during the resulting earthquake (Fig. 4).

For the 1906 earthquake, we consider whether slip on the Pioneer fragment detachment is compatible with observations from the event. We calculate surface displacements for detachment slip that fit available triangulation survey data reasonably well (Fig. 5). We also use the USGS ShakeMap software (Worden et al., 2018) to estimate shaking from Point Arena to the MTJ. Although the shaking distributions are similar for a near-coastal strike-slip faulting and detachment faulting, a rupture of the Pioneer fragment detachment tends to extend strong shaking further east (Fig. 6).

Future Work

The next goals for this project are to further develop deformation models to explore the effects of seismogenic (brittle) versus aseismic (ductile) detachments. They are at depths near to the brittle-ductile transition, so their behavior during the earthquake cycle is largely unknown. We will compare these model results to available geodetic observations, including data from the new NISAR satellite. We are also in the process of preparing a manuscript reevaluating the northern end of the 1906 earthquake in the context of the updated seismotectonic framework model. Finally, M. Herman is involved with several collaborators to develop a Technical Activity Group (TAG) led by Vera Schulte-Pelkum that focuses on this part of the San Andreas fault system. This TAG intends to further image fault structures, measure ground motions, and refine the seismotectonic framework of this section of the plate boundary.

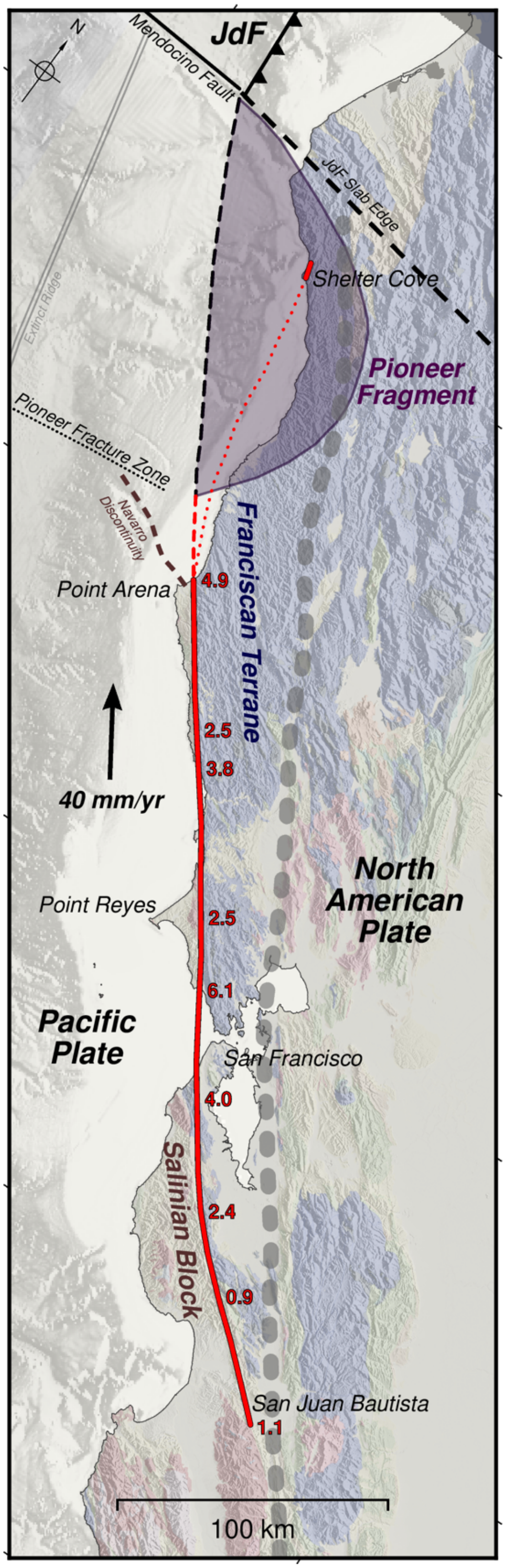

Figure 1. Seismotectonic and geologic map of the northern San Andreas plate boundary, from San Juan Bautista to the Mendocino triple junction between the Pacific, North American, and Juan de Fuca (JdF) plates. The red line indicates the extent of the onshore 1906 San Andreas earthquake rupture. Red numbers next to the fault indicate coseismic surface offset, in m. Previous estimates of the San Andreas fault geometry offshore are shown as a dotted red line connecting Point Arena to surface rupture seen at Shelteer Cove. Note that the San Andreas south of Point Arena divides the Salinian block (pink) from the Franciscan terrane (blue). The Salinian block is inferred to end north of Point Arena at the Navarro discontinuity. Northwest of Point Arena, the location of the Pioneer fragment constrained by seismic tomography imaging (Furlong et al., 2024) is shown as a purple region extending under North American crust between the Pioneer fracture zone and Mendocino fault. A cross section through the Pioneer fragment region is shown in Fig. 2a. A cross section through the Bay Area is shown in Fig. 2b. The total velocity between the Pacific plate and North American plate (or Great Valley block) is 40 mm/yr, nearly parallel to the San Andreas fault. The location of the lithospheric-scale transform plate boundary, as constrained by interseismic GPS velocities (Fig. 3), is indicated by the dashed line. This lies under other hazardous fault zones in northern California: the Maacama, Rodgers Creek, Calaveras, and Hayward faults.

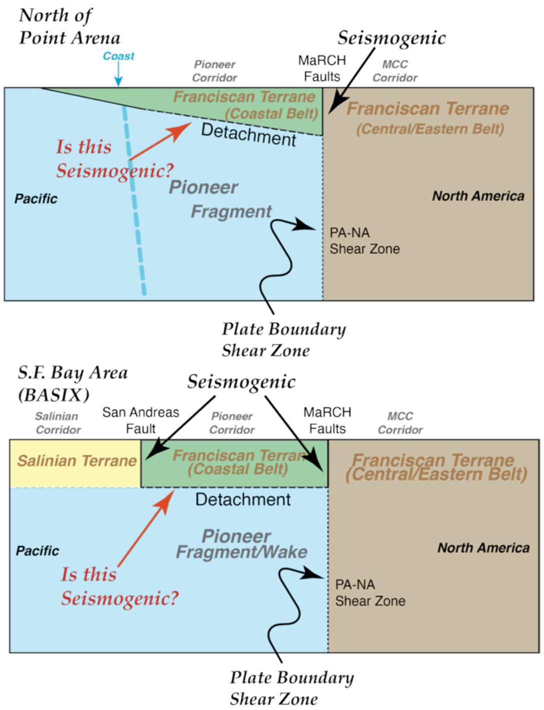

Figure 2. Schematic west-eat cross-sections across the San Andreas plate boundary system. (a) Cross-section through the Pioneer fragment region. (b) Cross-section through the Bay Area region.

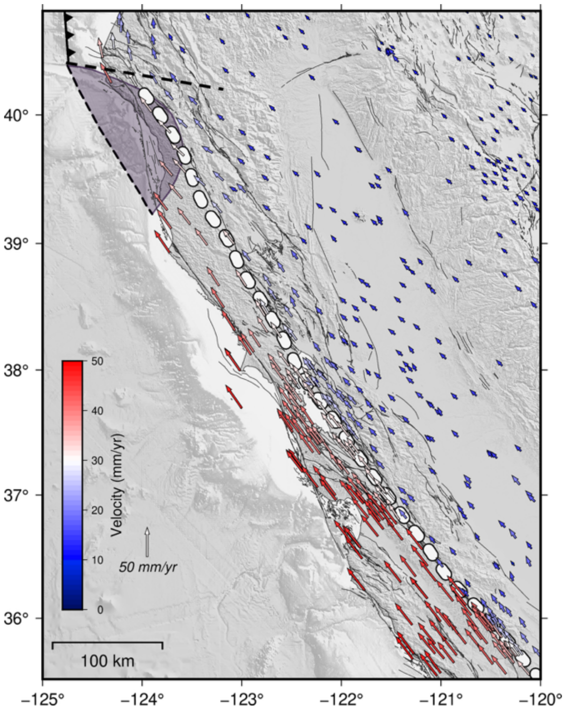

Figure 3. Transform plate boundary from GPS velocities. Speeds >30 mm/yr are in red and speeds < 30 mm/yr are in blue. The 30 mm/yr contour, coinciding with the shear zone, is indicated by a dashed line.

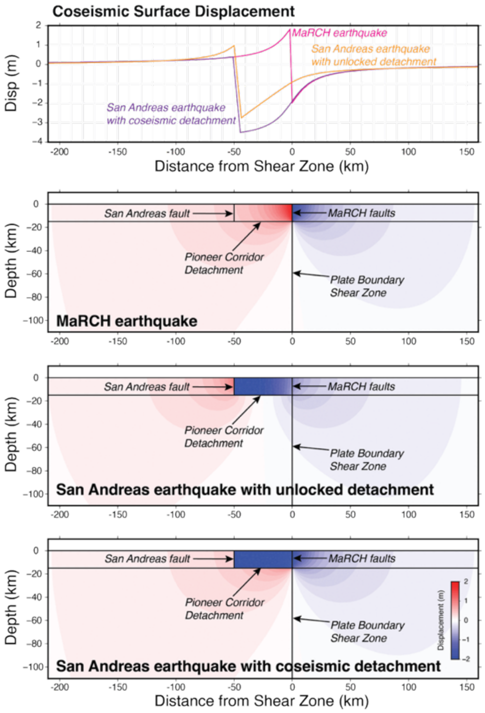

Figure 4. Models of coseismic slip on the San Andreas and Maacama, Rodgers Creek, Calaveras, and Hayward (MaRCH) faults under different unlocking scenarios for the horizontal detachment. A coseismic detachment tends to enhance the displacements of the surface directly above it.

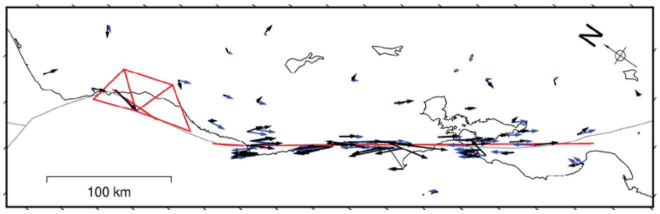

Figure 5. A model of surface displacements (blue) in the 1906 earthquake that includes a Pioneer fragment detachment rupture (triangles) produces reasonable fits to coseismic displacements determined from triangulation observations (black).

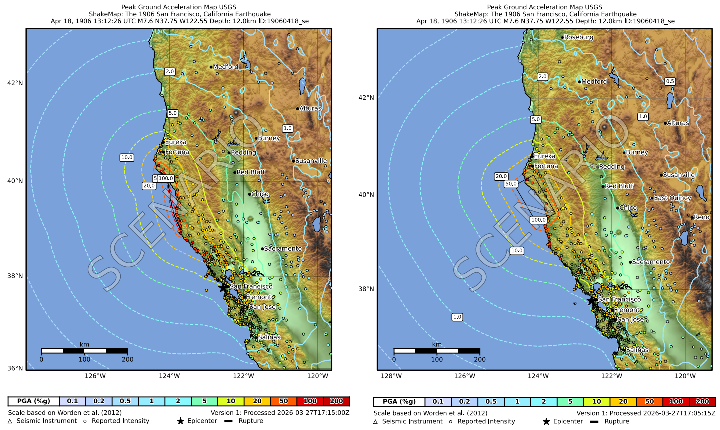

Figure 6. Peak ground acceleration predictions for a magnitude 7.5 earthquake (approximately the size of the 1906 earthquake only considering the offshore region from Point Arena to the MTJ). Left: The typical assumption is that the earthquake was a strike-slip rupture. Right: If the Pioneer fragment detachment ruptured coseismically, then strong shaking would extend further eastward onshore.

Presentations

Furlong, K. (2025). Active tectonics in northern California and the evolving lithospheric thermal structure. Abstract presented at 2025 SCEC Statewide GFM/CTM Workshop, University of California, Davis, 14–15 Aug.

Furlong, K. (2025). The role of heat flow observations in constraining lithospheric deformation at the Mendocino Triple Junction plate boundary transition. Abstract presented at IAGA/IASPEI Joint Scientific Meeting 2025, Portugal, Spain, 1–5 Sep.

Herman, M., Furlong, K. (2025). Tectonic corridors of the northern San Andreas plate boundary system: Developing a new framework crustal deformation model. Poster #084 presented at 2025 SCEC Annual Meeting, Palm Springs, CA, 7–10 Sep.

Herman, M.W., Furlong, K.P., McKenzie, K.A. (2025). Coseismic Interactions Between Plate Boundary Structures and Crustal Faults. Abstract T21B-06 presented at 2025 American Geophysical Union Fall Meeting, New Orleans, LA, 15–19 Dec.

Furlong, K. (2026). Deciphering Crustal Structure in Northern California - Active Processes and Earthquake Implications. Talk at 2026 Northern California Earthquake Hazards Workshop, Virtual from Moffett Field, CA, 10–12 Feb.

Herman, M.W., Furlong, K.P., McKenzie, K.A., Kummerfeldt, S. (2026). Reconciling the Paradox of Offshore Fault Slip in the 1906 San Andreas Earthquake. Abstract to be presented at Seismological Society of America Annual Meeting 2025, Pasadena, CA, 14–18 Apr.

Furlong, K.P., McKenzie, K.A., Herman, M.W. (2026). Deformational Corridors along the San Andreas Plate Boundary: Evidence from Lithospheric Depths to the Surface. Abstract EGU26-8291 to be presented at 2026 European Geoscience Union General Assembly, Vienna, Austria, 3–8 May.

References

Atwater, T. (1970). Implications of Plate Tectonics for the Cenozoic Tectonic Evolution of Western North America. *Geological Society of America Bulletin*, *81*(12), 3513.

Blewitt, G., Hammond, W., & Kreemer, C. (2018). Harnessing the GPS Data Explosion for Interdisciplinary Science. *Eos*, *99*.

Boatwright, J., & Bundock, H. (2008). The Distribution of Modified Mercalli Intensity in the 18 April 1906 San Francisco Earthquake. *Bulletin of the Seismological Society of America*, *98*(2), 890–900.

Brocher, T. M., McCarthy, J., Hart, P. E., Holbrook, W. S., Furlong, K. P., McEvilly, T. V., Hole, J. A., & Klemperer, S. L. (1994). Seismic Evidence for a Lower-Crustal Detachment Beneath San Francisco Bay, California. *Science*, *265*(5177), 1436–1439.

Furlong, K. P., Villaseñor, A., Benz, H. M., & McKenzie, K. A. (2024). Formation and Evolution of the Pacific-North American (San Andreas) Plate Boundary: Constraints From the Crustal Architecture of Northern California. *Tectonics*, *43*(6), e2023TC007963.

Govers, R., Furlong, K. P., van de Wiel, L., Herman, M. W., & Broerse, T. (2018). The Geodetic Signature of the Earthquake Cycle at Subduction Zones: Model Constraints on the Deep Processes: Megathrust Earthquake Cycle From GNSS. *Reviews of Geophysics*, *56*(1), 6–49.

Lawson, A. C. (1908). The California earthquake of April 18, 1906. In *Report of the State Earthquake Investigation Commission* (1969th ed., Vol. 1).

McCulloch, D. S. (1989). Evolution of the offshore central California margin. In E. L. Winterer, D. M. Hussong, & R. W. Decker (Eds.), *The Eastern Pacific Ocean and Hawaii*. Geological Society of America.

Prentice, C. S., Merritts, D. J., Beutner, E. C., Bodin, P., Schill, A., & Muller, J. R. (1999). Northern San Andreas fault near Shelter Cove, California. *Geological Society of America Bulletin*, *111*(4), 512–523.

Savage, J. C., & Burford, R. O. (1973). Geodetic determination of relative plate motion in central California. *Journal of Geophysical Research*, *78*(5), 832–845.

Song, S. G., Beroza, G. C., & Segall, P. (2008). A Unified Source Model for the 1906 San Francisco Earthquake. *Bulletin of the Seismological Society of America*, *98*(2), 823–831.

Worden, C. B., Hearne, M., and Thompson, E. M. (2018). ShakeMap v4 Software, *USGS Software Release*.