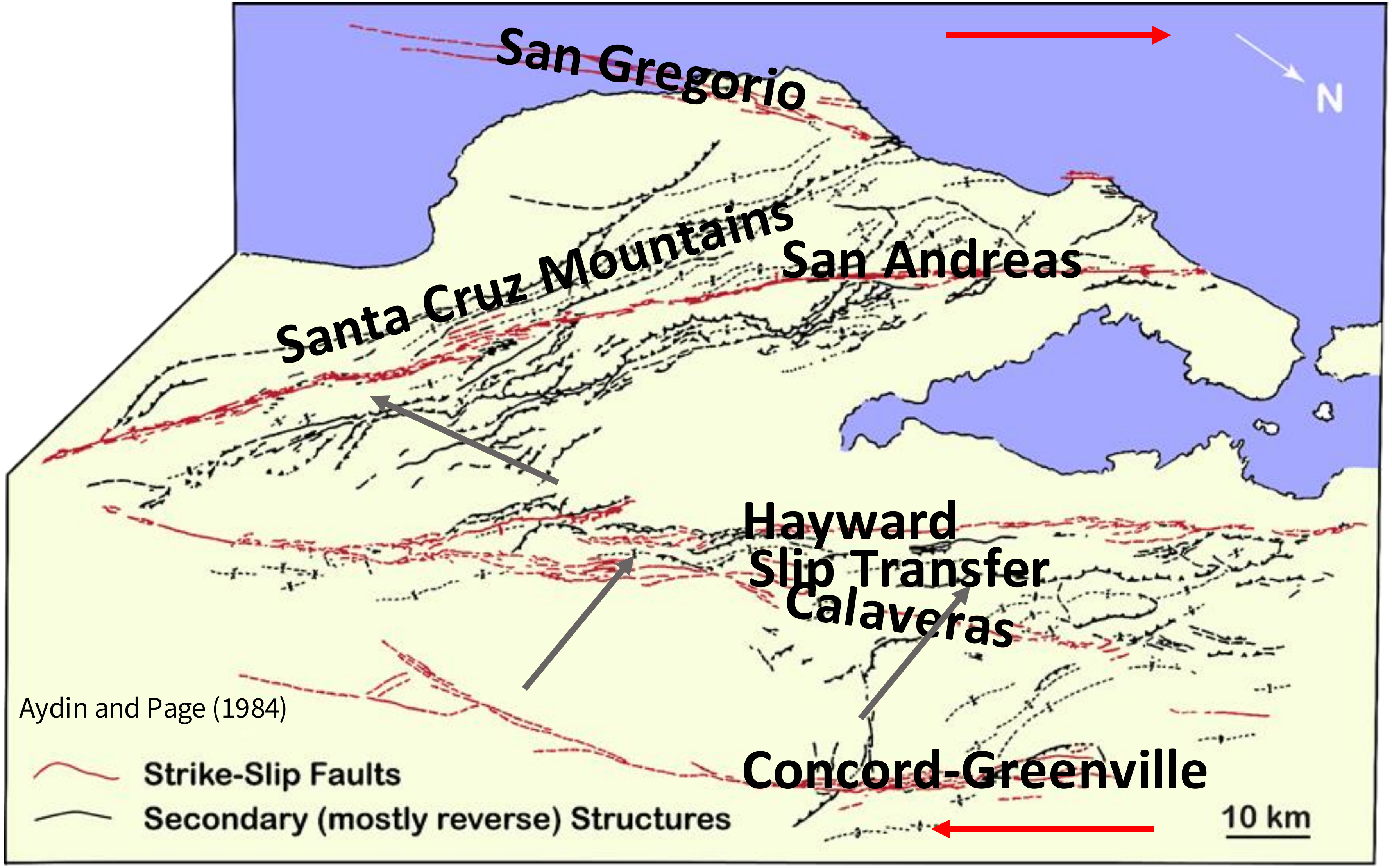
Past Work and Future Opportunities for Understanding How Strike-Slip Faults and Secondary Structures Produce Vertical Motions and Topography in the San Francisco Bay Area

HILLEY, G. E. (1), Baden, C. W. (2), and Aron, F. (3)
(1) Department of Earth and Planetary Sciences, Stanford University, (2) U. S. Geological Survey, Moffett Field, (3) Universidad de Chile, Santiago

Strike-slip and Reverse Faulting in the San Francisco Bay Area



Aydin and Page (1984)

- Geodetic data constrain total right-lateral shearing across Bay Area to be ~40 mm/yr
- This shearing is partitioned between the San Gregorio (2-4 mm/yr), San Andreas (16-18 mm/yr), Hayward-Calaveras (12-13 mm/yr), and Concord-Greenville (4-6 mm/yr) fault systems.
- Horizontal motions are converted to vertical motions by two basic causes:
  - Restraining bends in which fault strike is oblique with respect to relative plate motions.
  - Restraining steps / fault interactions in which slip transfer between different faults produces contraction.

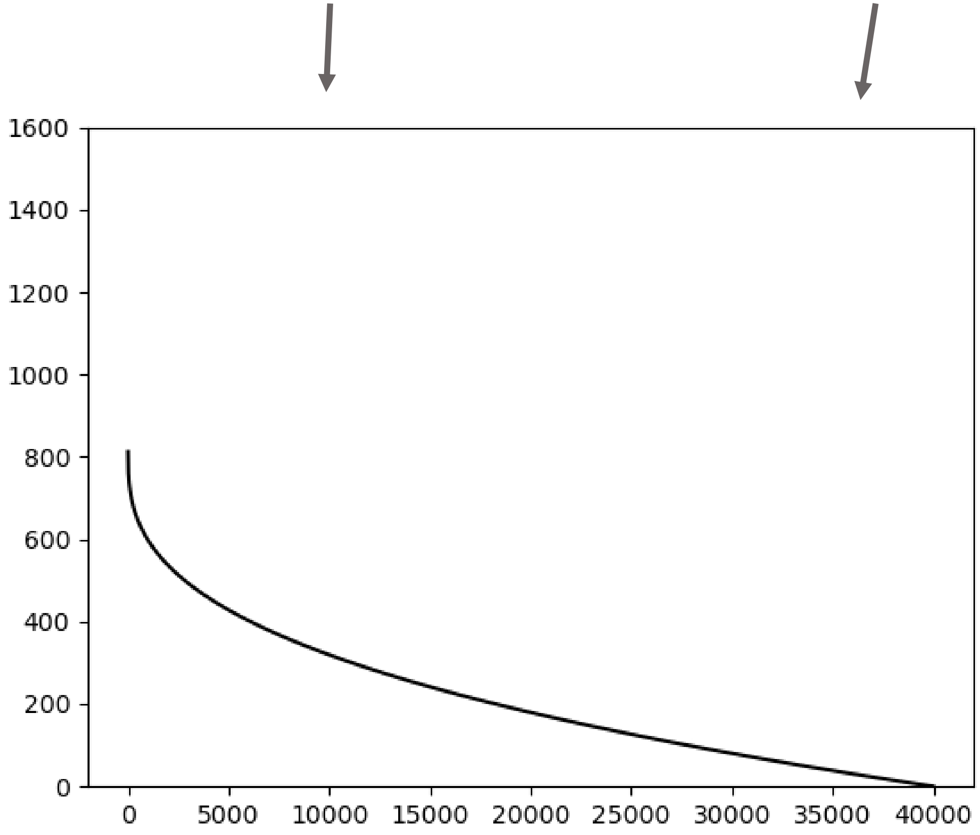
Outline

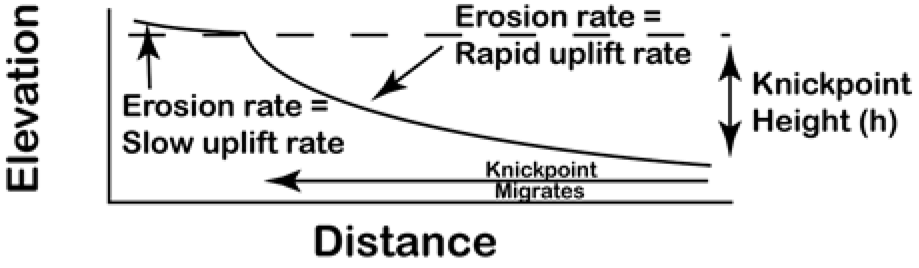
- Part 1: How do we measure vertical motions over various timescales? (e.g., decades, thousands of years, millions of years)
- Part 2: How can we use the measured vertical motions to address fundamental and applied questions for earthquake hazards and tectonics in central and northern California?
    - Example 1: Using vertical motions adjacent to strike-slip fault restraining bends to infer constitutive properties of the surrounding crust.
    - Example 2: Using topography and vertical motions to constrain the maximum seismic hazard potential of blind reverse faults.
- Part 3: Where are there opportunities to conduct future studies like these in central and northern California?

Using Topography and Erosion Rates to Constrain Vertical Motions

Old Rock Uplift = Erosion Rate Above Knickpoint

Recent Rock Uplift = Erosion Rate Below Knickpoint



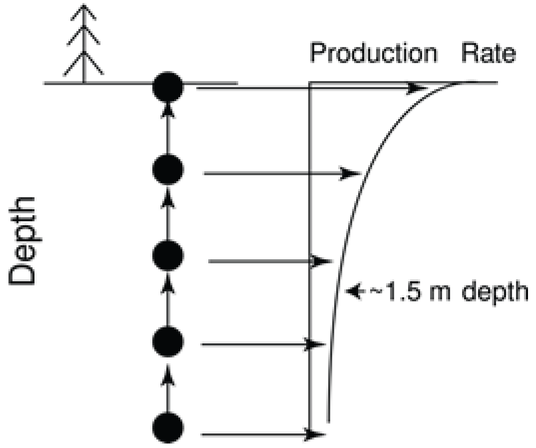


Calculate modern-day uplift rates (U_{modern}) using erosion rates from above and below river knickpoint

$$U_{modern} = \varepsilon_{below}$$

Calculate the time of the change in uplift rates (t_{change}) using erosion rates and knickpoint elevation

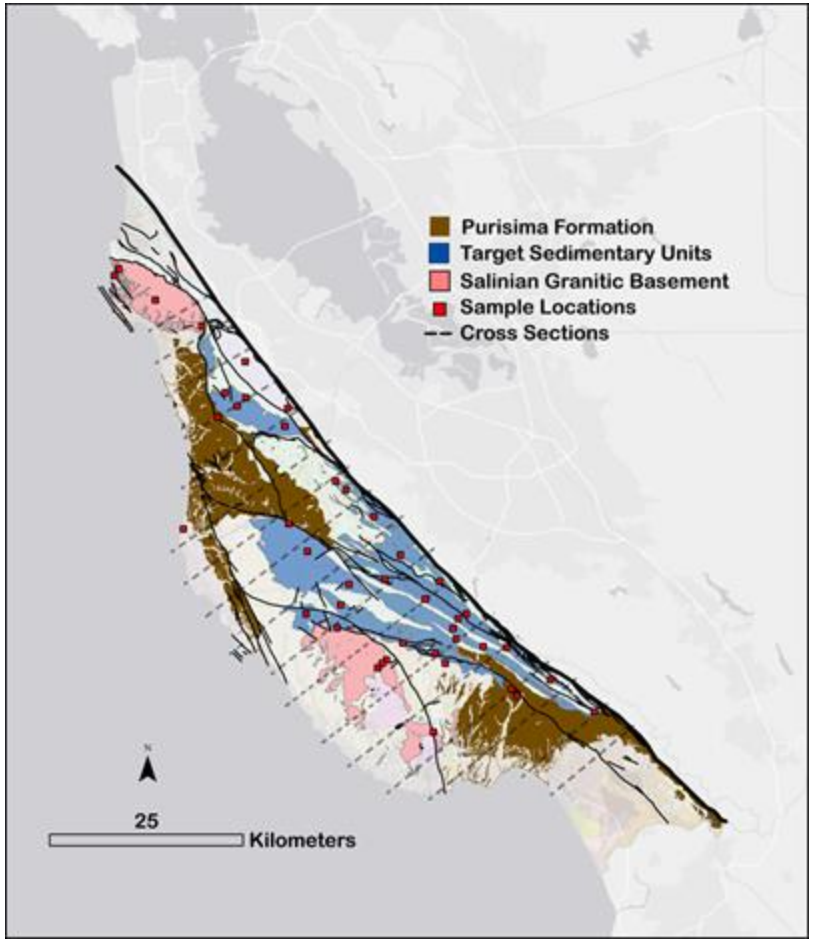
$$t_{change} = \frac{h}{\varepsilon_{below} - \varepsilon_{above}}$$



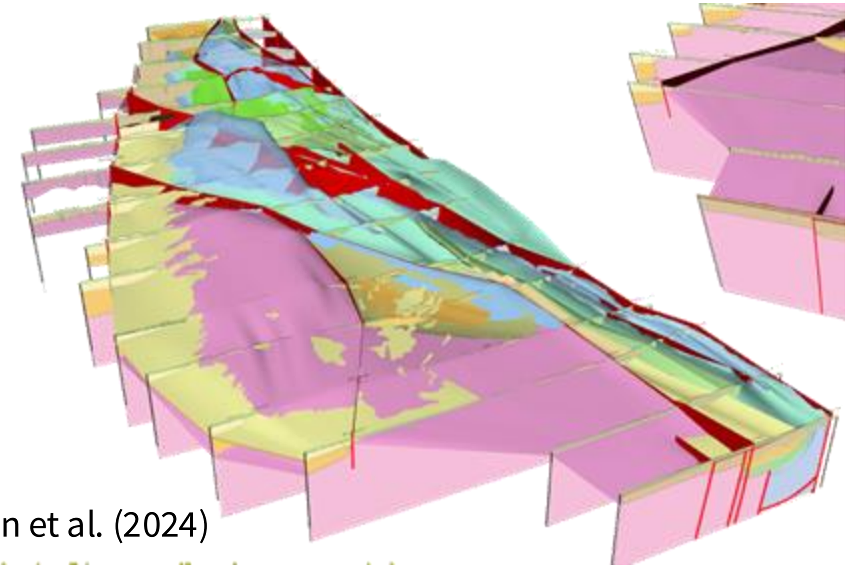
- Rapid erosion reduces exposure near surface and abundance of 10-Be in quartz.
- Slow erosion increases exposure near surface and abundance of 10-Be in quartz.

Using Geology and Thermochronology to Constrain Vertical Motions

Geologic Mapping and Well Control

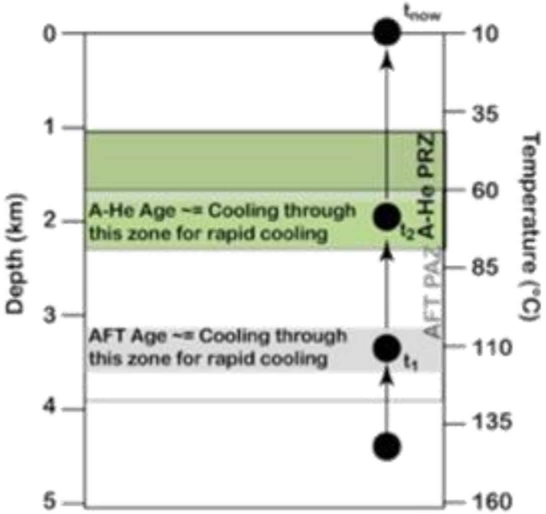


Create Retro-Deformable Geologic Volume



Baden et al. (2024)

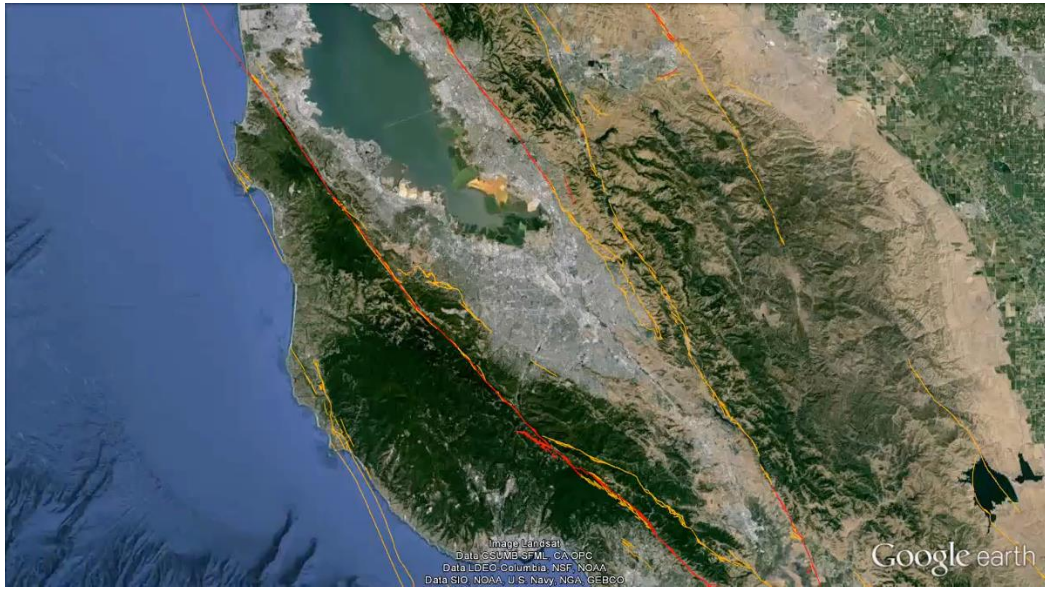
Use Thermochronology to Constrain Rates

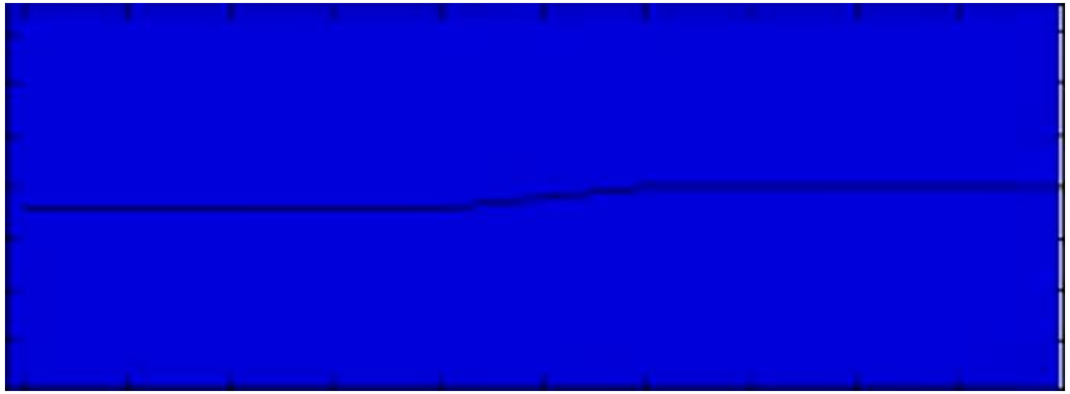


- Geologic information provides total finite deformations sustained by rock mass.
- Thermochronologic methods allow the time at which rock samples cooled below a particular temperature to be estimated:
  - Some methods use lattice damage created during fission events (i.e., fission tracks) to determine the time since rocks cooled below the temperature at which tracks cease to heal.
  - Other methods use the fission products (e.g,. Helium) to determine the time at which rocks cooled below a temperature at which gas diffusion through the crystal lattice was no longer possible.

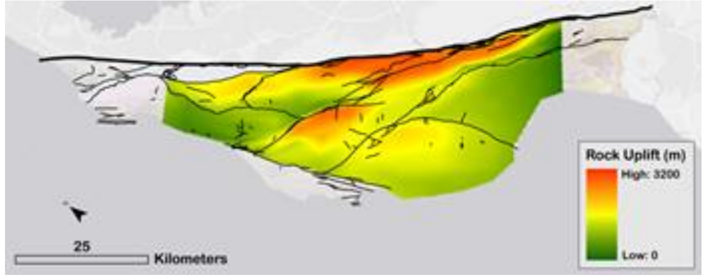
What Can Vertical Motions Tell Us About the Constitutive Properties of the Crust?

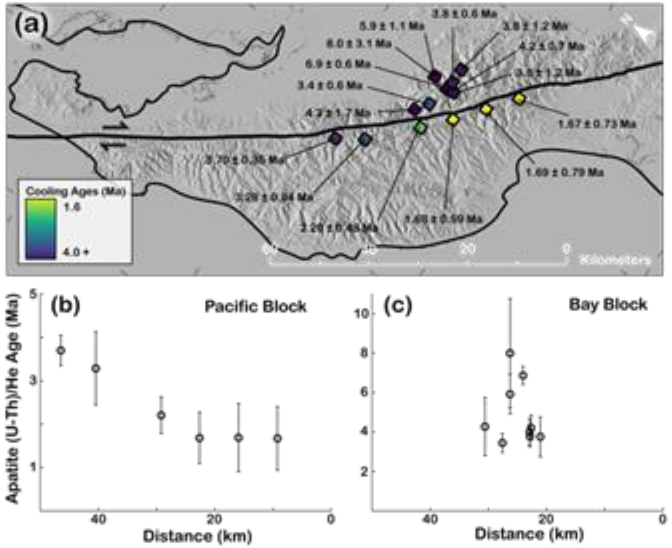
Study Area: The Santa Cruz Mountains Restraining Bend

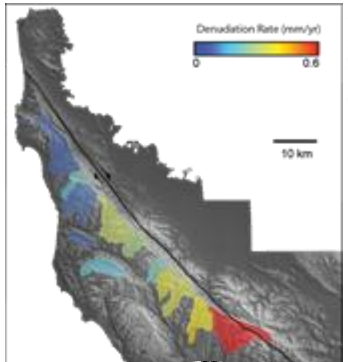


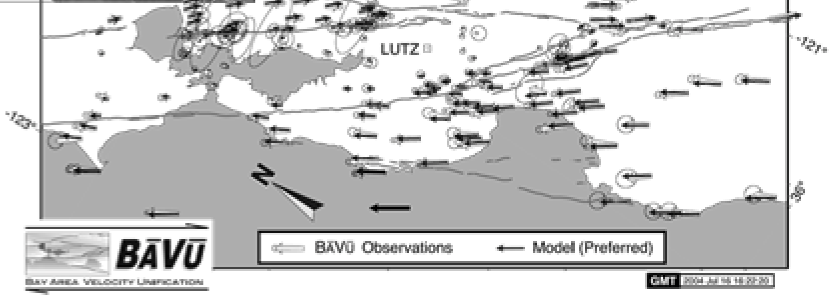


Data About Vertical Motions Span Geologic to Geodetic Timescales



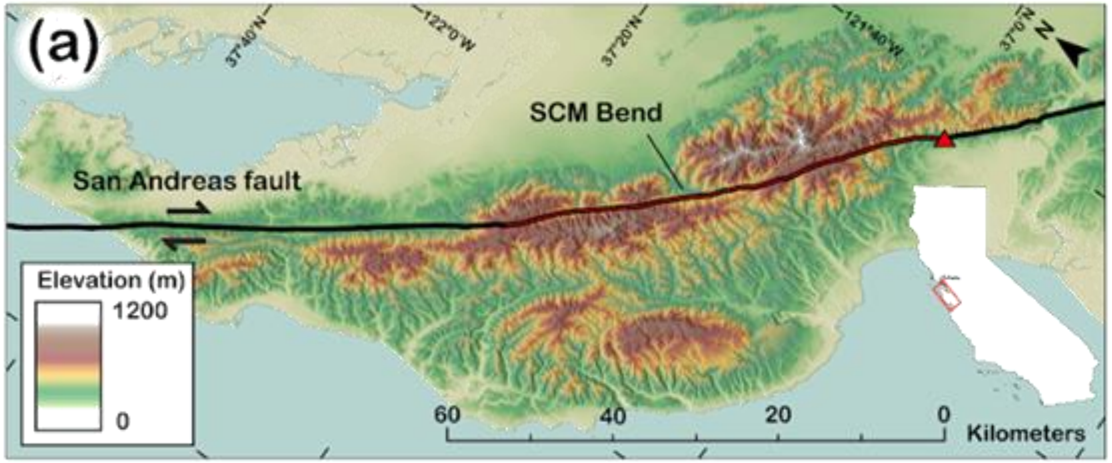






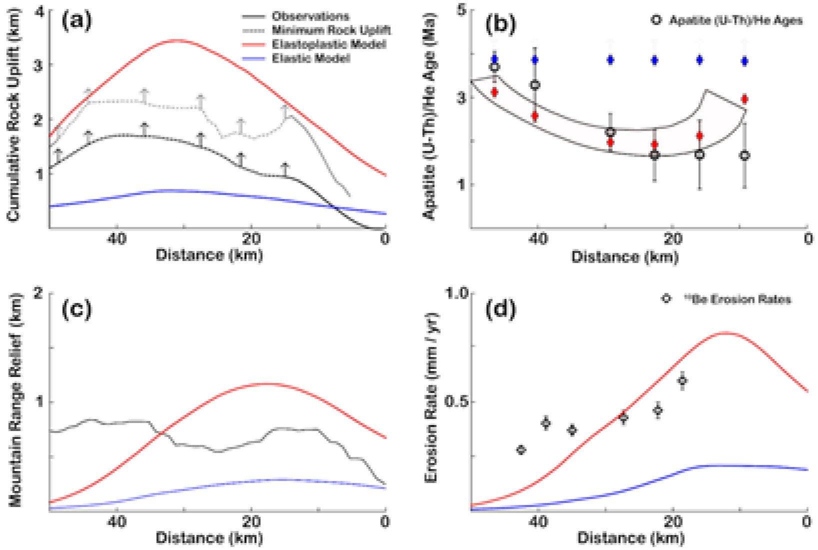
Baden et al. (2022, 2024);
D'Alesio et al. (2005)

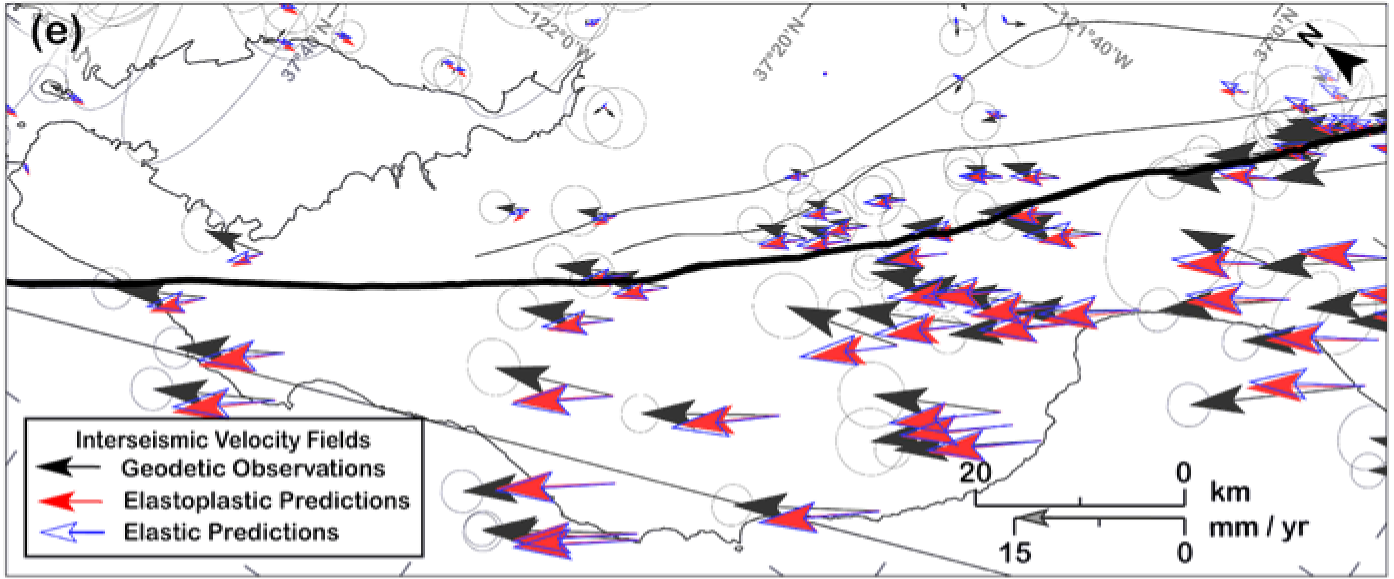
What Can Vertical Motions Tell Us About the Constitutive Properties of the Crust?



Main Conclusions

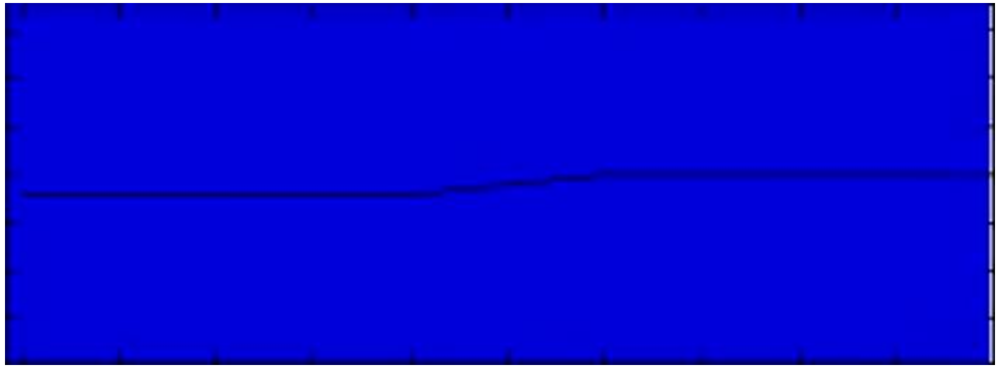
- Geodetic observations can be fit with a simple linear-elastic rheology, but geologic observations cannot.
- Elastic models produced lower total vertical motions than geological observations require, and stresses are well above the yield stress for crustal materials.
- Elasto-plastic models can reconcile both the observed interseismic, geomorphic, and geologic deformations observed around the SAF.
- Only by considering a broad range of time-scales can the appropriate constitutive model of crust near the plate boundary be revealed.

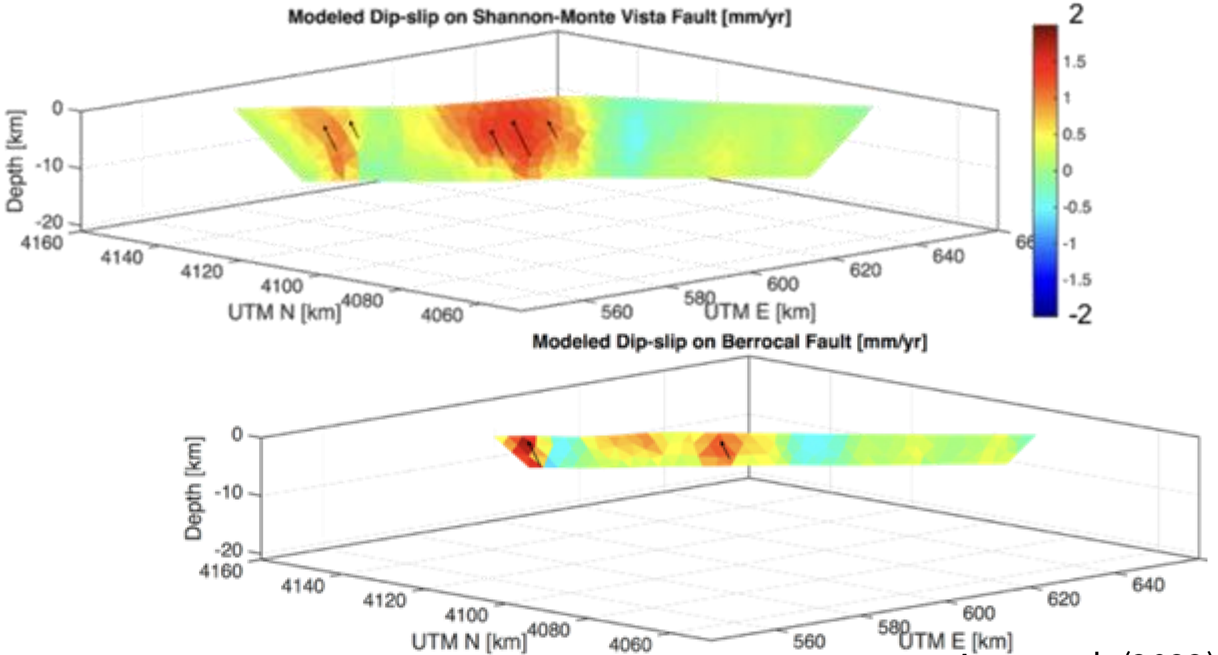




Baden et al. (2022)

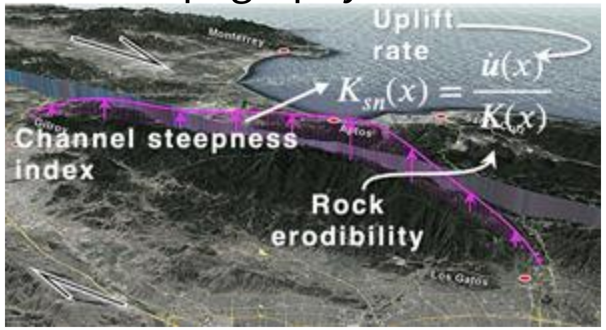
How Can We Use Topography and Vertical Motions to Improve Seismic Hazard Assessment?



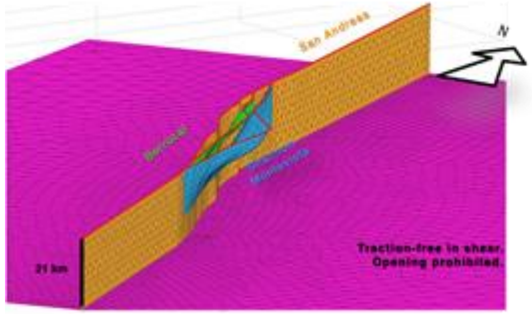


Aron et al. (2022)

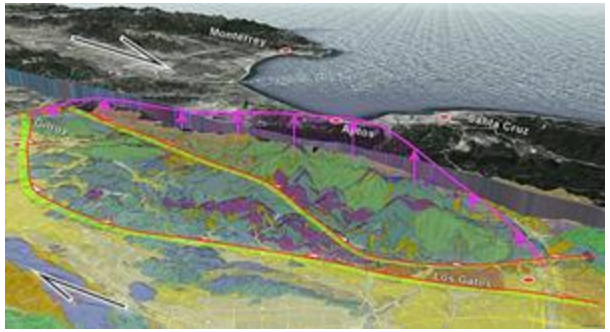
Topography



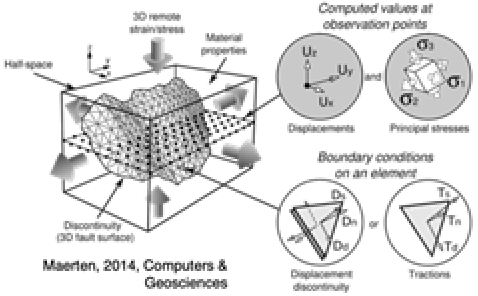
Fault Geometry



Geology



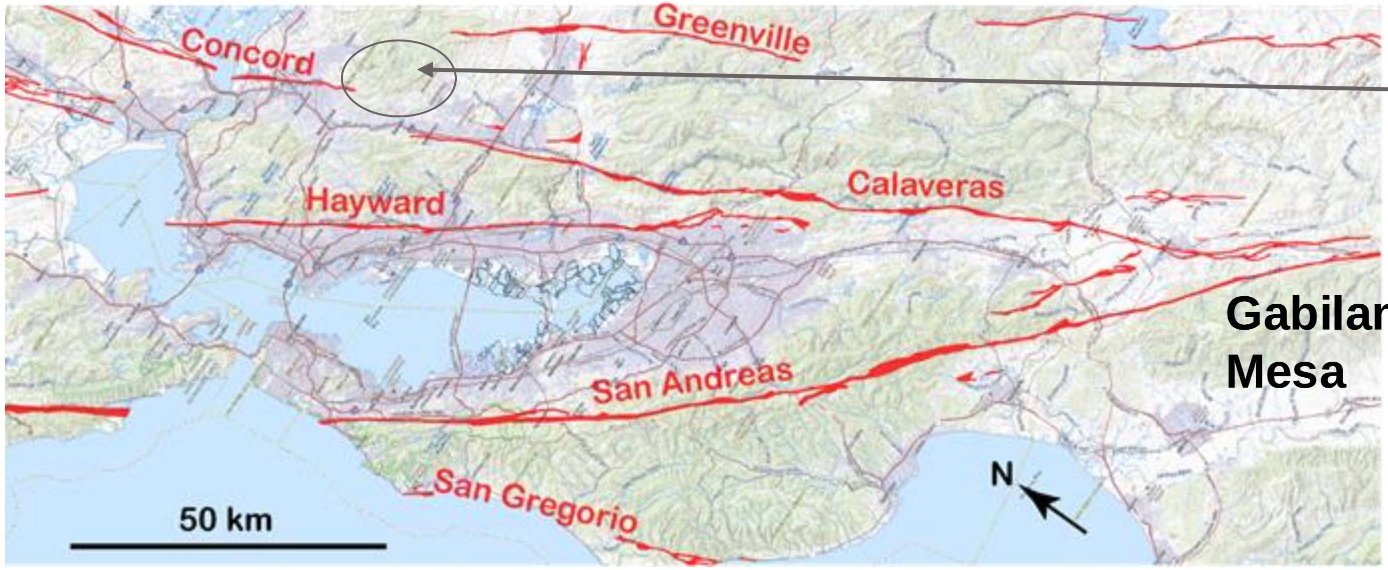
Mechanical Model

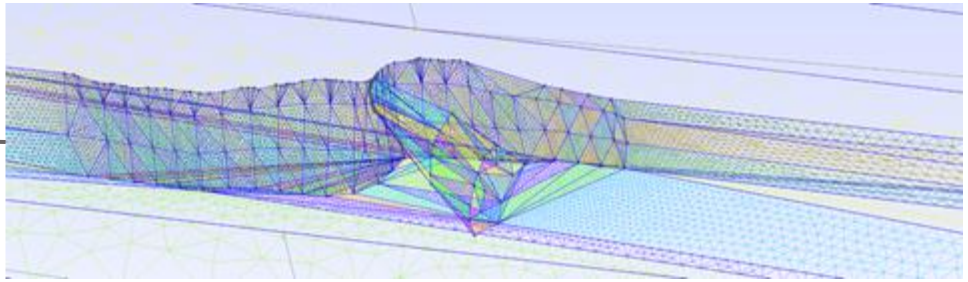


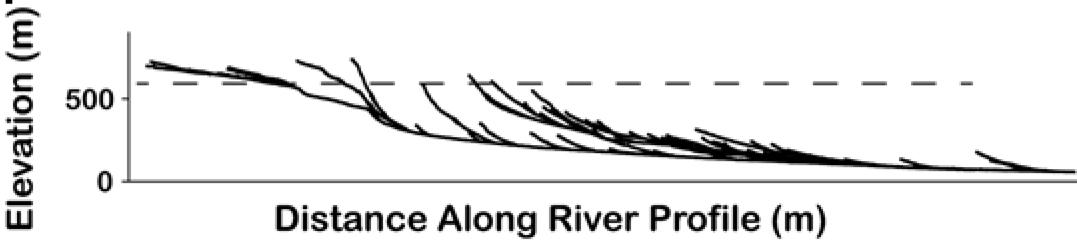
Main Conclusions

- Rate of motion along the San Andreas that is required to produce the topography and vertical motions is ~16 mm/yr, consistent with geodetic estimates.
- Interseismic velocity field produced by modeling fits observed GPS velocity field.
- Long-term slip along the reverse faults is capable of producing a Mw=6.9 earthquake every 300 years.

Future Opportunities for Using Vertical Motions to Understand Faulting Processes and Earthquake Hazards







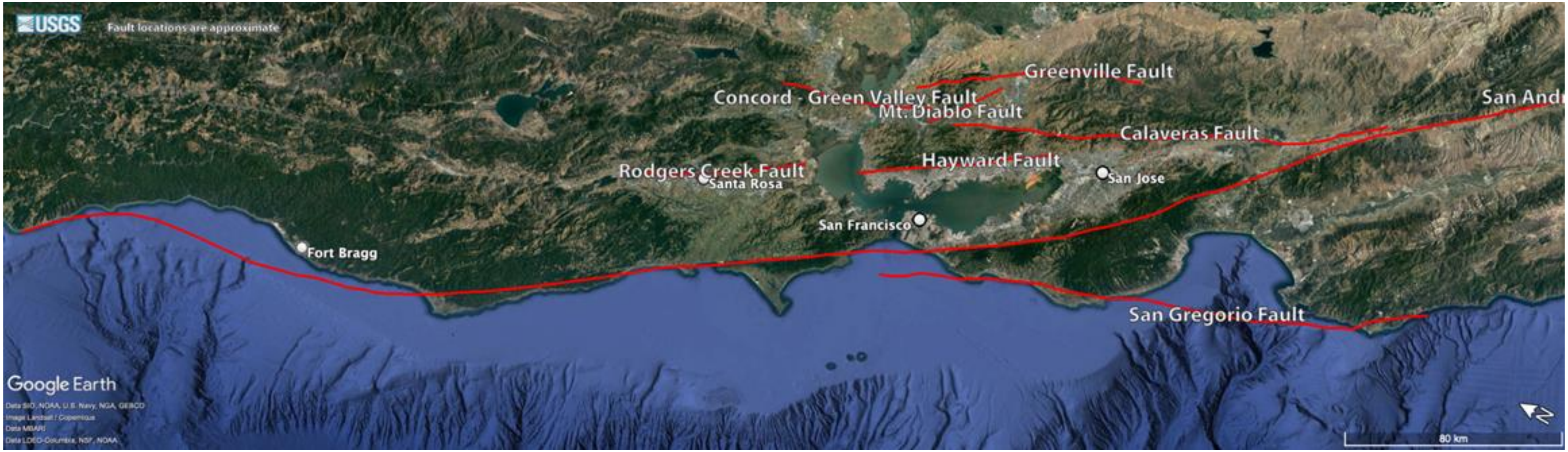
Potential Priority Targets:

- The **Gabilan Mesa** geomorphology shows a clear signature of a change in rock uplift rates. Estimating current and past rates, as well as the timing of this transition could shed light on the timing and mechanisms of formation of the restraining bend, as well as provide information about seismic hazards in this area.
- The **Concord-Greenville fault step** hosts the Mount Diablo thrust. Deploying inversion methods developed in the Santa Cruz Mountains could better constrain the seismic hazard and rates of the thrust, and strike-slip faults.

Secondary Targets:

- Mission Hills and East Bay Hills are extremely important for slip transfer between the Hayward and Calaveras. Materials may be ornery to analyze.

Future Opportunities for Using Vertical Motions to Understand Faulting Processes and Earthquake Hazards



Other Northern California Targets:

- There are a number of faults that extend into northern California, including the Green Valley, Napa, Rodgers Creek, San Andreas, and Maacama Faults. These faults presumably interact with one another, which could be revealed by the vertical motions encoded in the erosion and topography of the area.
- It is unclear how the slip along each of the different fault systems is routed into the Mendocino Triple Junction. The vertical motions may provide some information about how slip from faults to the northeast of the triple junction is transferred across the Coastal Ranges in northern California.

Some Thoughts on Future Opportunities of the Statewide California Earthquake Center

- Plate tectonics, though foundational to Earth Sciences, is too idealized for real systems; along strike-slip boundaries, motion is partitioned among evolving micro-blocks and fault strands, which shape fault locations, crustal properties, and earthquake hazards.
- The evolution of these complex boundaries over time determines current seismic risks through the long-term juxtaposition of crustal fragments and accumulated stresses from thousands of years of tectonic activity.
- There have been no studies that strive to understand, in an integrated way, how these complex systems have evolved into their current states, and how this determines the hazards posed by earthquakes from triple-junction to triple-junction of a strike-slip plate boundary.

The new Statewide California Earthquake Center now spans the entire Pacific-North American Plate boundary from triple-junction to triple-junction, which allows us to revisit the basic concepts of plate tectonics, to understand the evolution and geodynamics of this margin (and perhaps others), and to study how these factors conspire to create the earthquake hazards that result from the interactions between the faults along the margin.