Integrating Seismological and Tectonic Studies to Constrain Lithospheric Evolution at Complex Plate Boundaries

PhD Thesis Defense

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The Importance of Transient Tectonics

In regimes where plate tectonics have changed rapidly in the last few million years, the key to understanding present-day plate boundary structure and processes is dependent on how that feature has evolved through time.

Two locations that have experienced recent and rapid evolution are the plate boundaries through northern California and the southwest Pacific south of New Zealand.

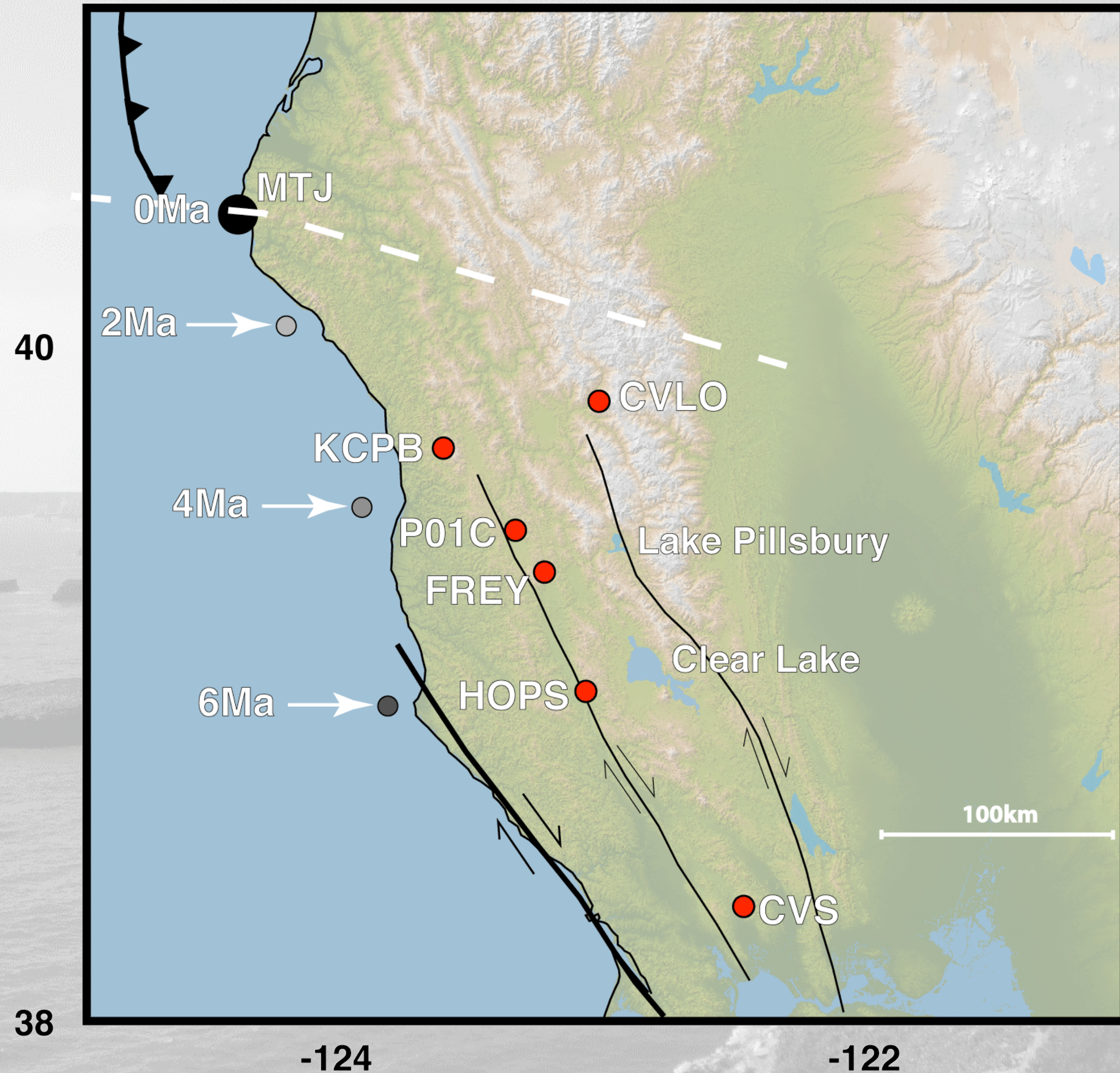
Talk Outline

- ***Evolving Boundaries*** - Recent changes in northern California and southern New Zealand.
- ***Northern California*** - The migration of the Mendocino triple junction.
- ***New Zealand*** - Reorientations in plate motions from divergence to translation.
- ***Conclusions*** - The development of two complex plate boundaries.

Northern California - Present-Day

Today, the Mendocino triple junction (MTJ) sits off Cape Mendocino.

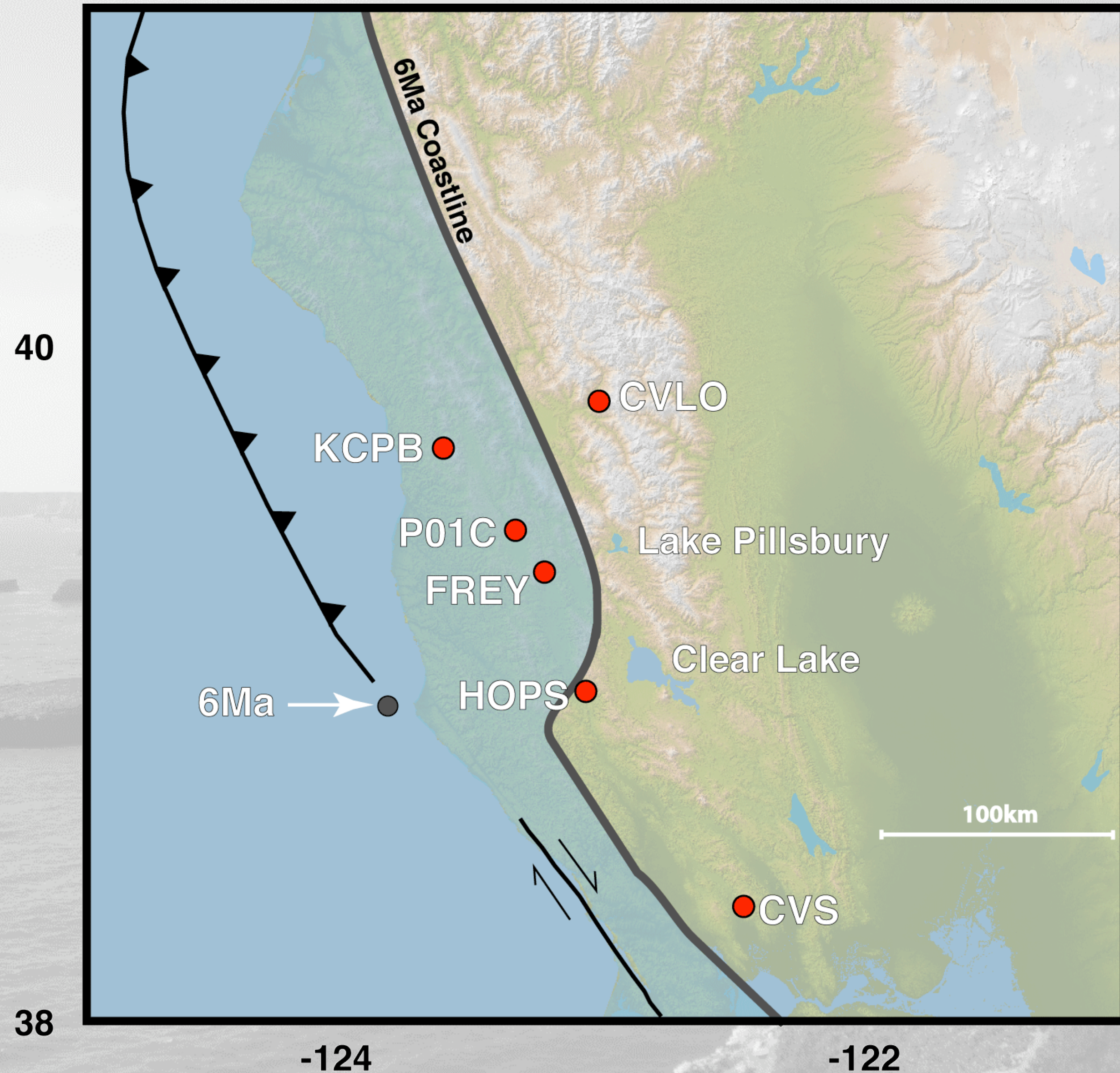
Coastal California south of the MTJ formed from accretion along the former subduction margin.



Northern California @ 6Ma

The northward migration of the MTJ has significantly modified the coastline.

At 6Ma, the triple junction was ~200km further south off Point Arena; much of the present-day Coast Ranges were below sea level and adjacent to a marine accretionary margin.

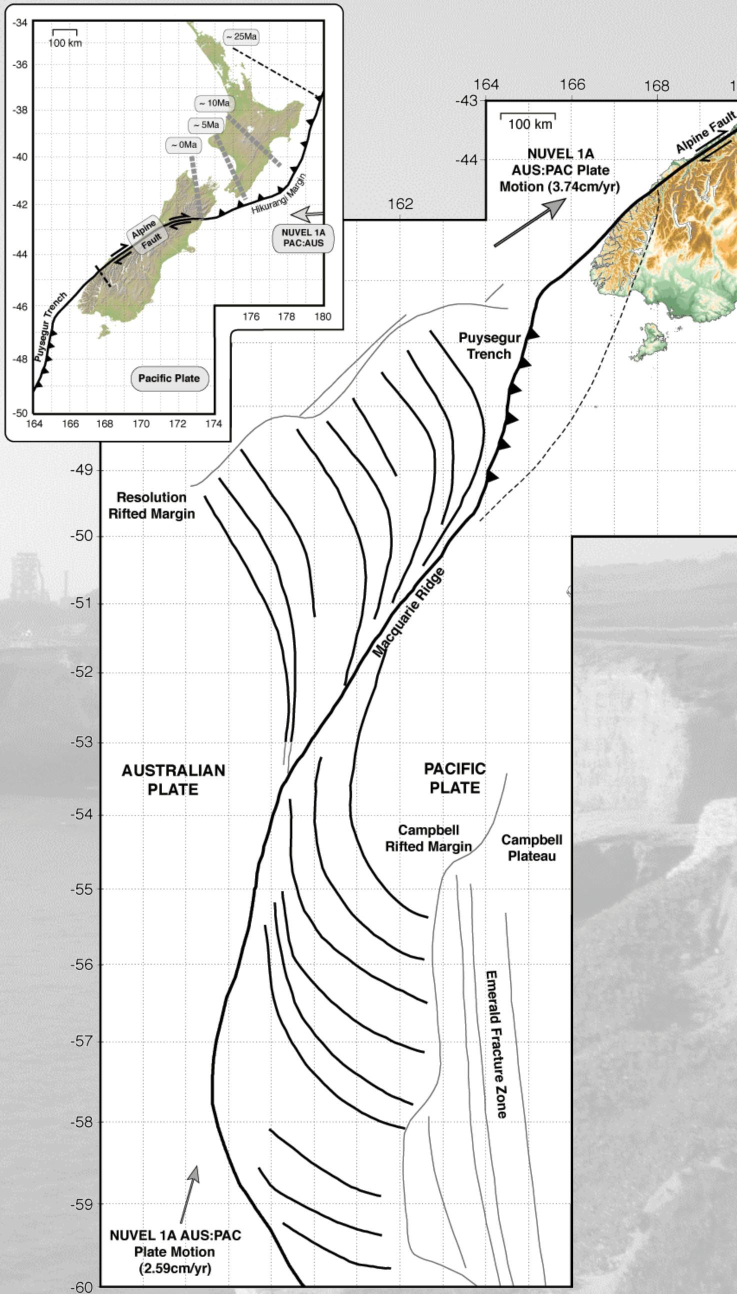


Southern New Zealand - Present-Day

The Australia:Pacific Plate boundary south of New Zealand in the southwest Pacific is located along the Macquarie Ridge Complex, currently a transform structure.

Immediately south of New Zealand, Australia subducts beneath the Pacific at the Puysegur Margin.

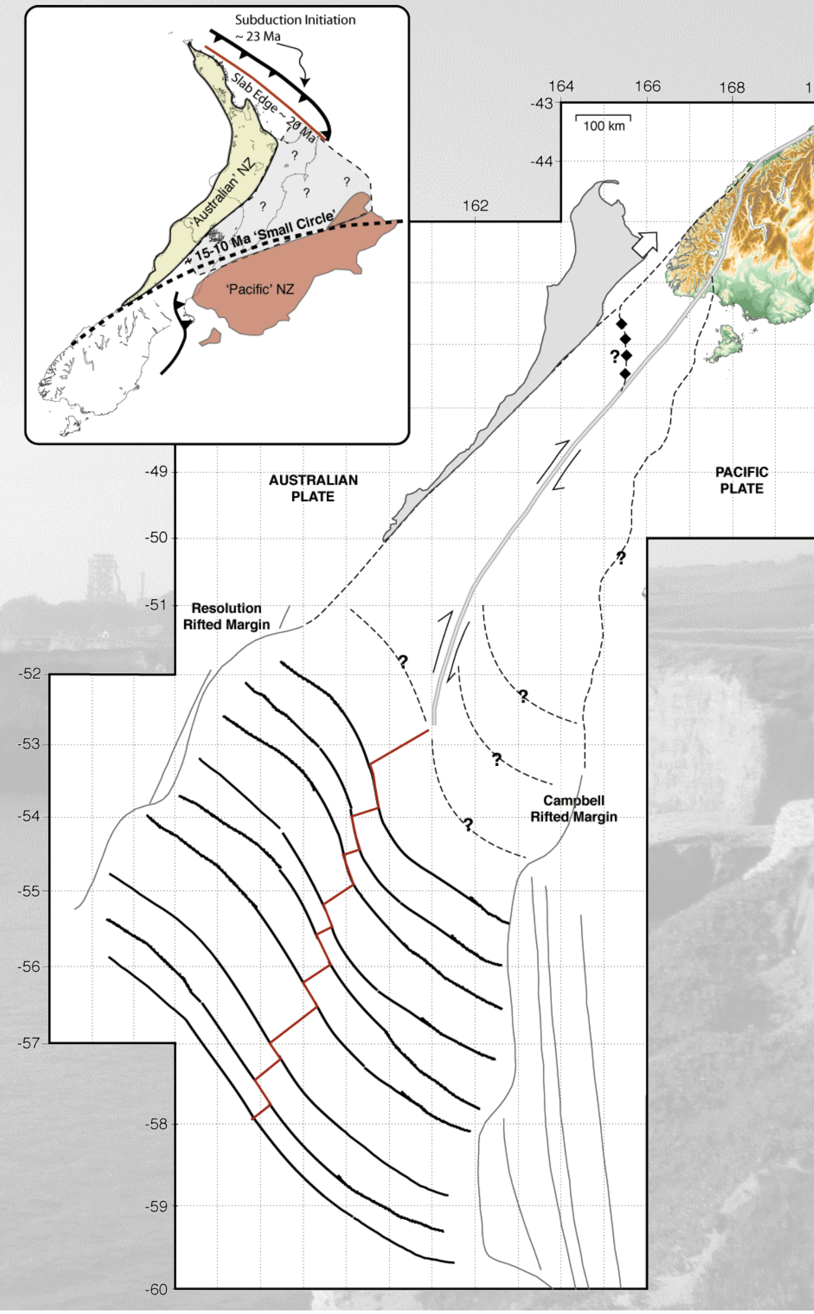
Relic fracture zones adjacent to the plate boundary reflect prior periods of plate divergence along a mid-ocean spreading ridge in approximately the same location as the current plate boundary.



Southern New Zealand @ 20Ma

Prior to 20Ma, this plate boundary was dominantly divergent; the Macquarie Ridge accommodated sea-floor spreading and fracture zones formed perpendicular to ridge segments.

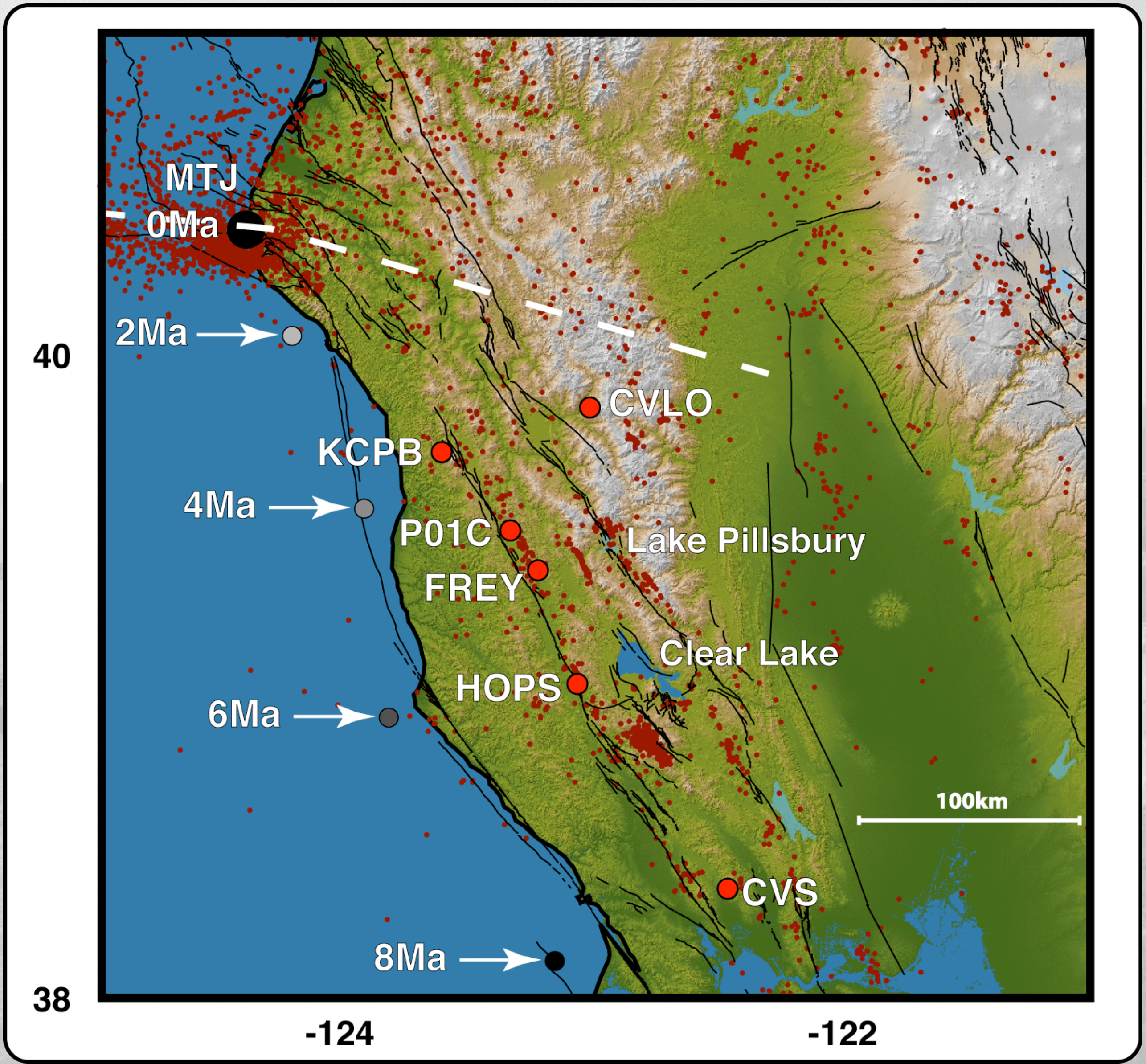
Subduction of Australia beneath Fiordland began at approximately this time.



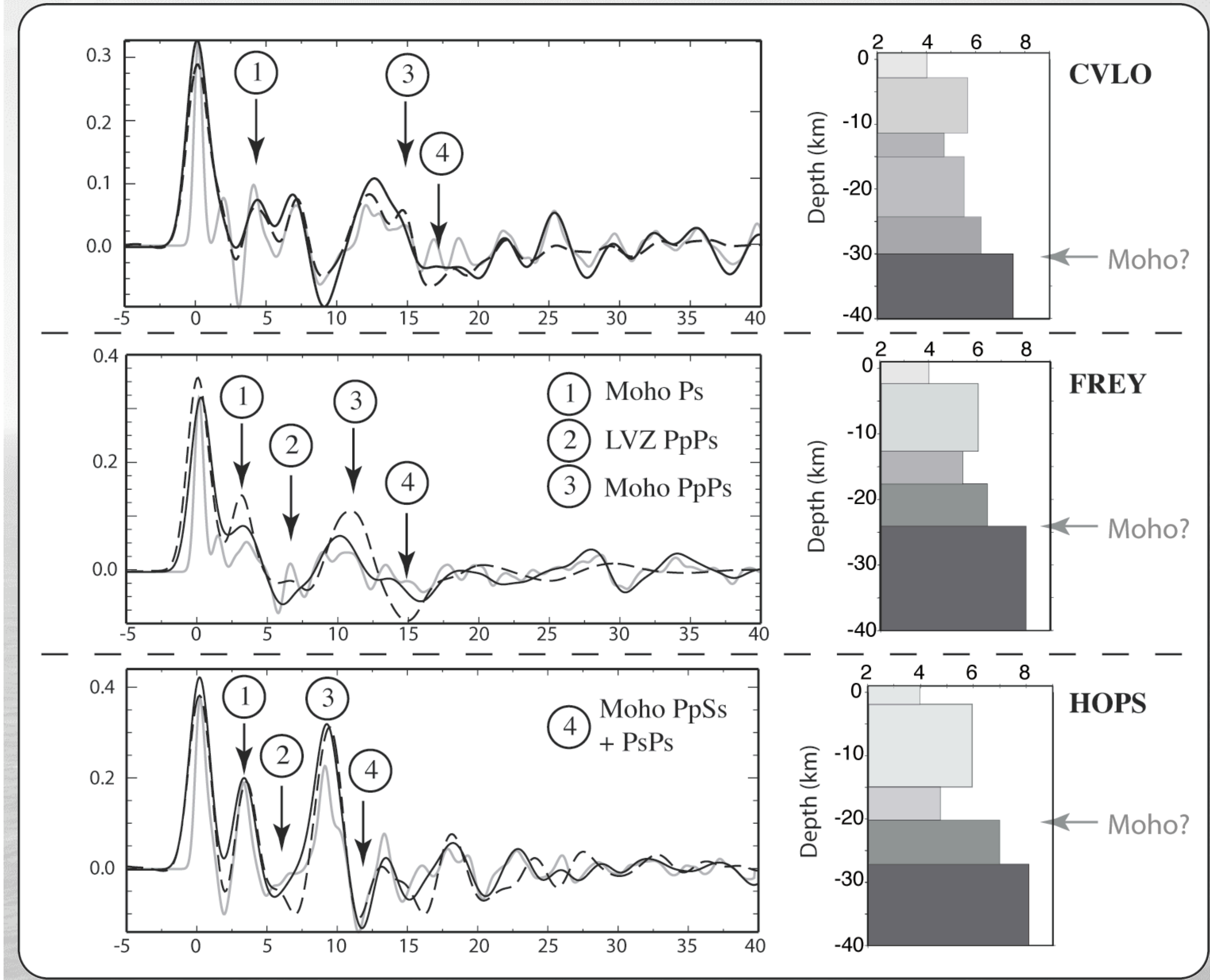
Northern California - Triple Junction Migration as a Driver for Plate Evolution

The Mendocino triple junction (MTJ) hosts the boundary between the North American, Pacific and Juan de Fuca Plates.

Northward migration of the MTJ since its formation ~30Ma has driven a thickening and thinning pattern in North American crust.

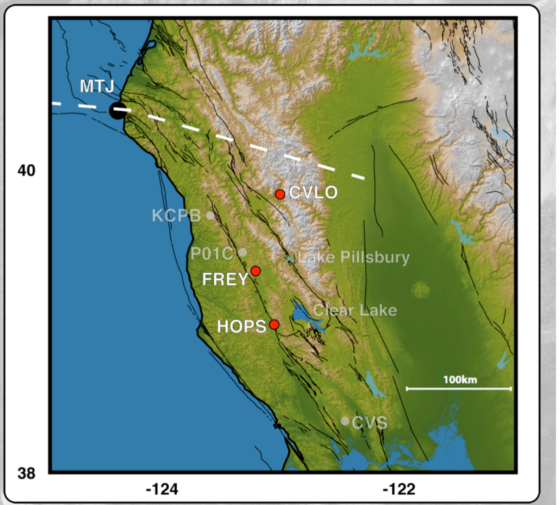


Addressing Crustal Thickness Changes With Receiver Functions



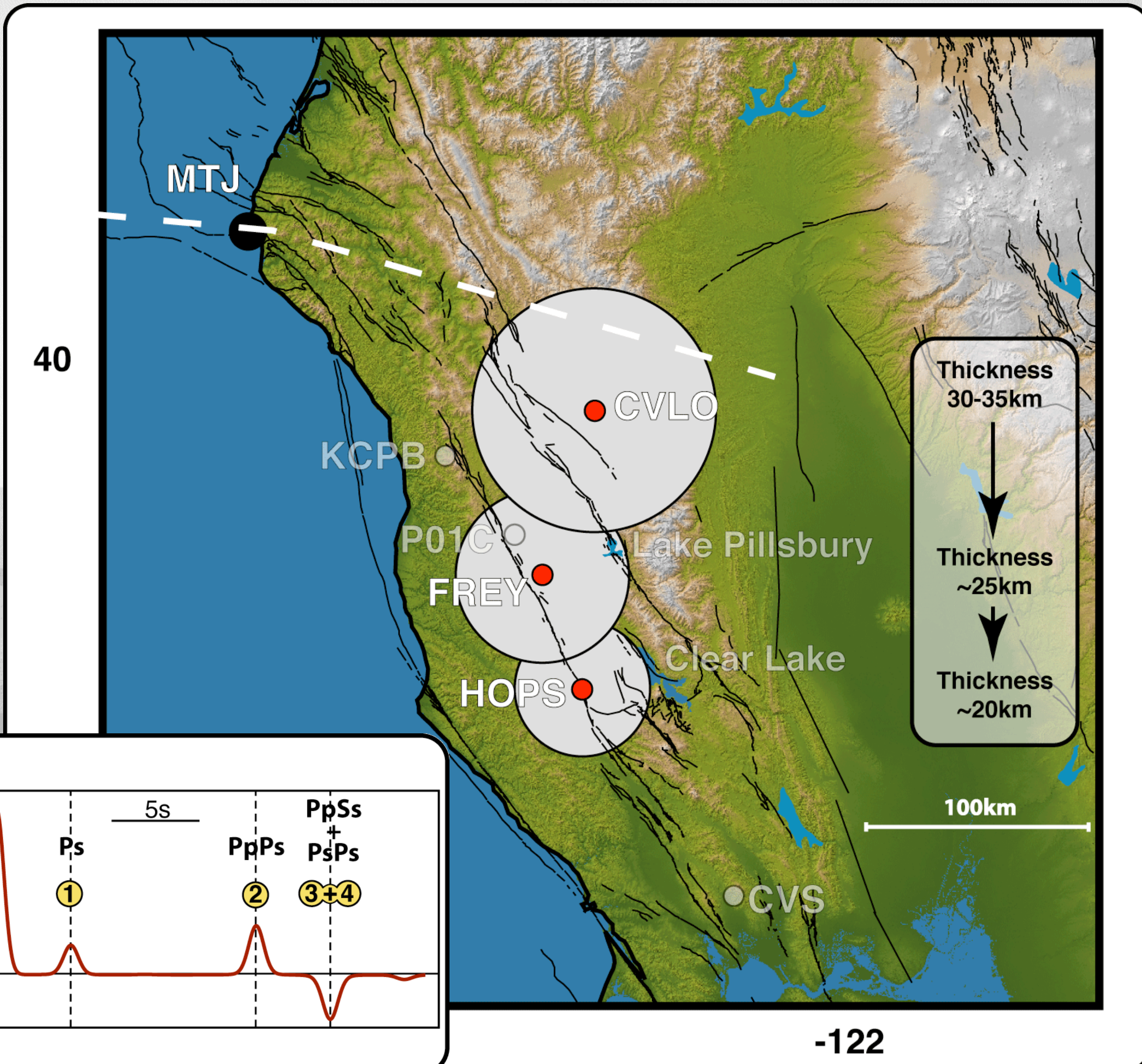
Crustal thickness can straightforwardly be assessed with receiver functions.

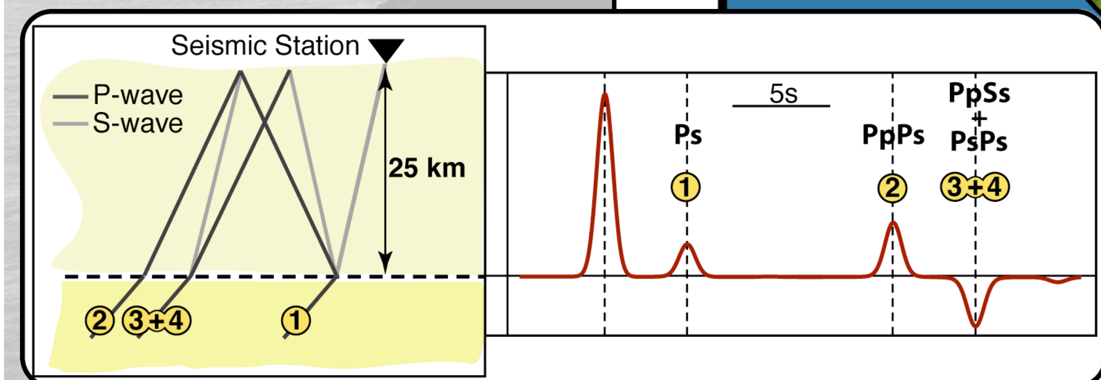
Models are consistent with previous work - thick in the north, thin in the south.



Inconsistencies in Receiver Function Forward Modeling

Assumption of planar layers is inconsistent with station spacing and sampling in northern California.



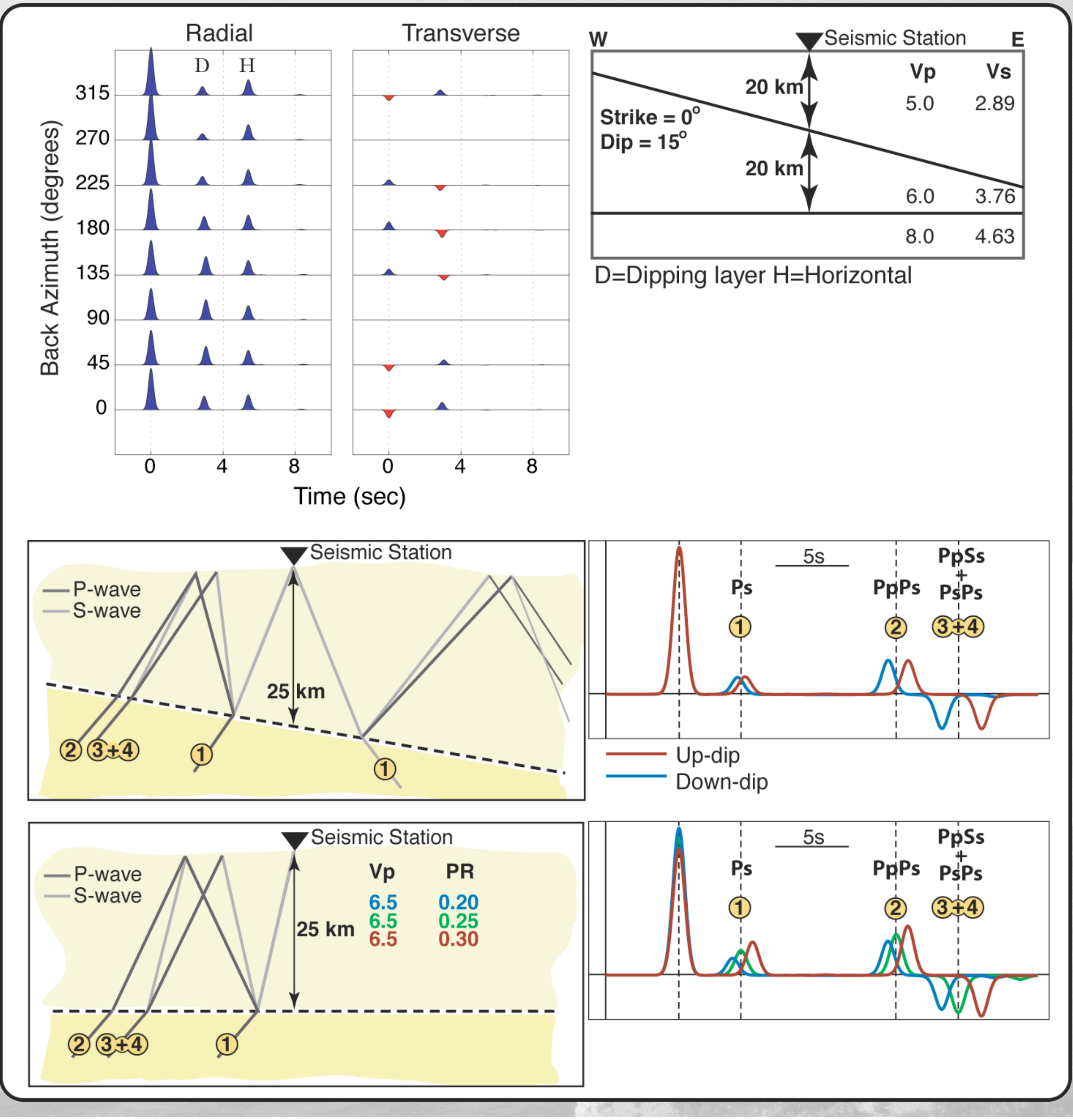


The Effects of Dipping Structure and Lateral Changes in Crustal Properties

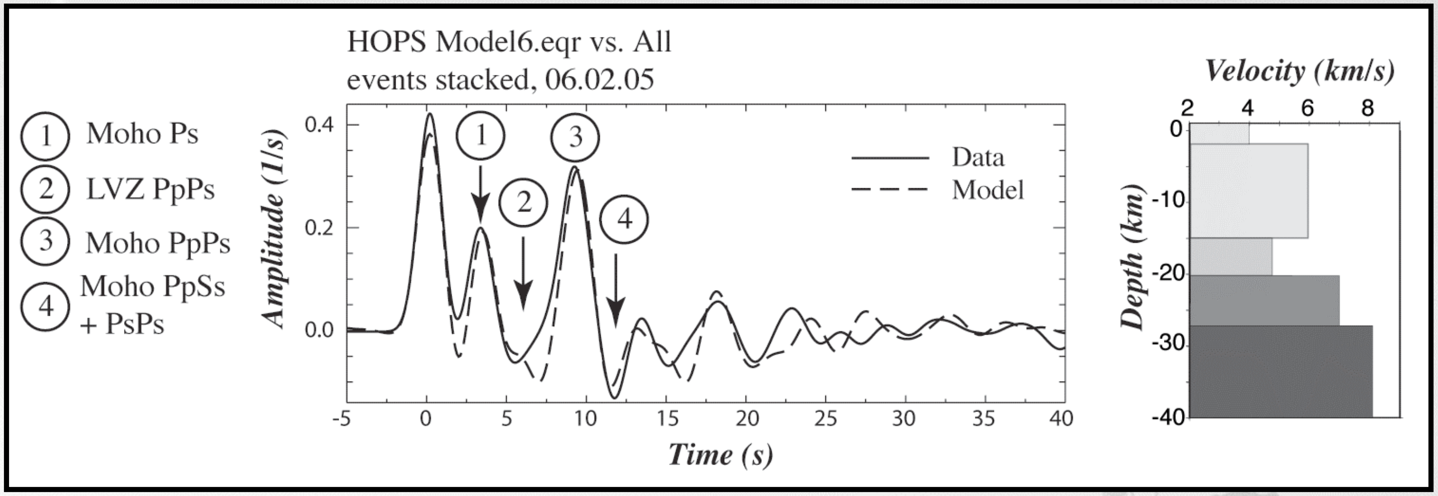
Dipping horizons cause a systematic change in the timing of receiver function conversions with back azimuth.

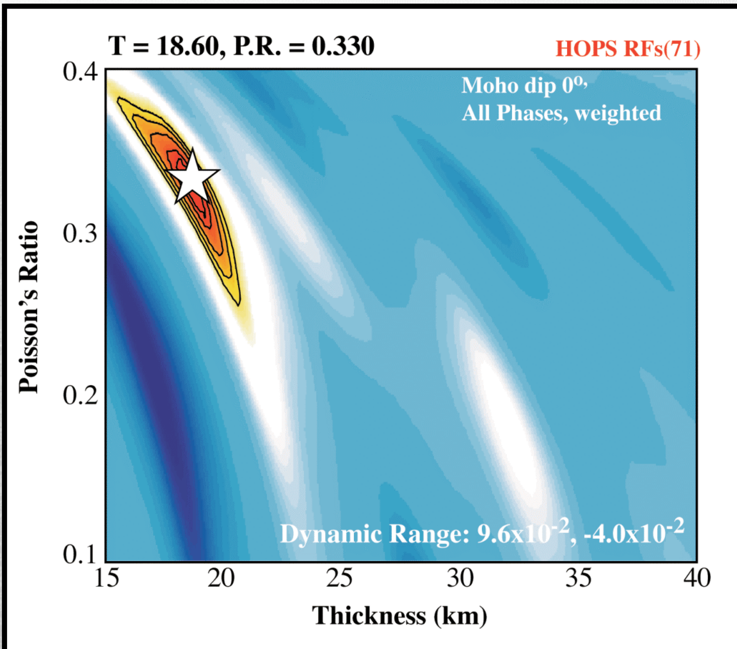
Energy on transverse component receiver function flips polarity with a 360° period.

Lateral changes in Poisson's Ratio also alters the timing of receiver function conversions.



Searching for an 'Average' Structure



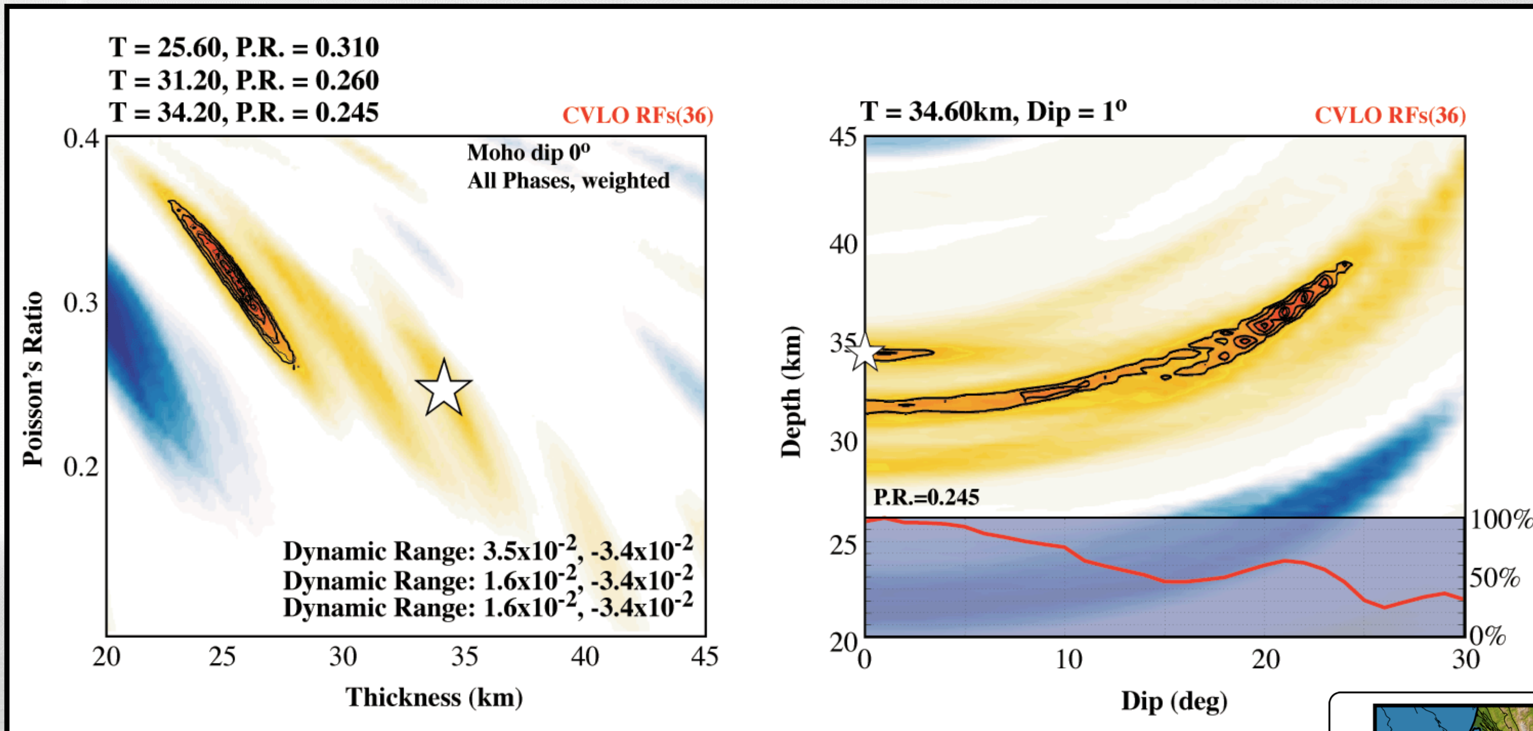


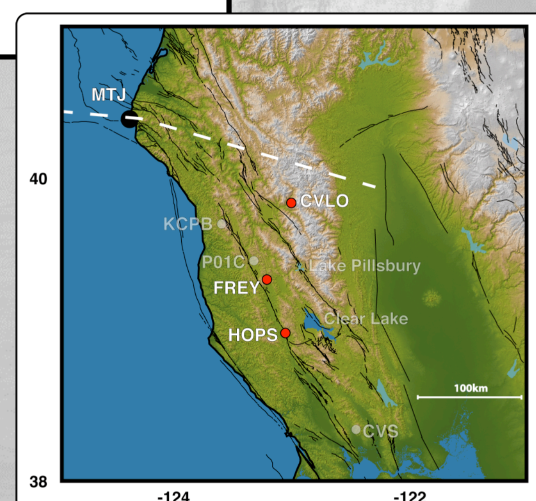
Delay times of receiver function conversions can be calculated based on conversion depth and average crustal velocities.

We can thus 'search' for the best-fitting structure by extracting amplitudes at the times predicted by a thickness and velocity combination for each conversion.

The highest amplitude (1+3+4) matches the 'correct' structure.

Results from CVLO

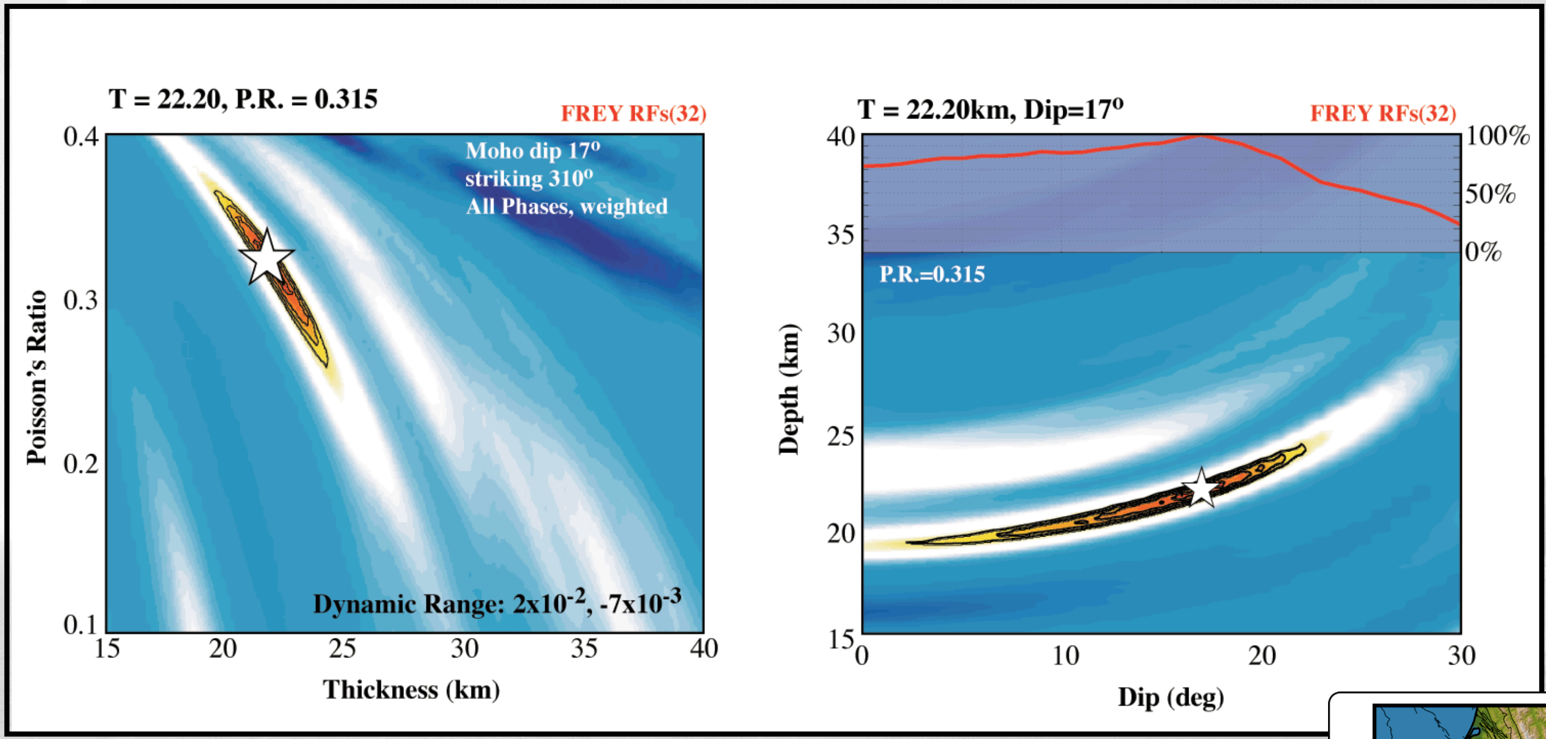


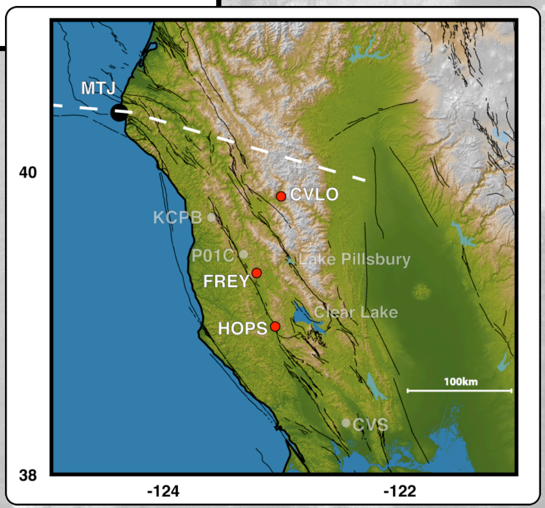


Multiple maxima seen - complex crust? Deepest maxima (35km) consistent with seismic reflection and thermal models.

Horizontal Moho associated with deepest local maxima.

Results from FREY

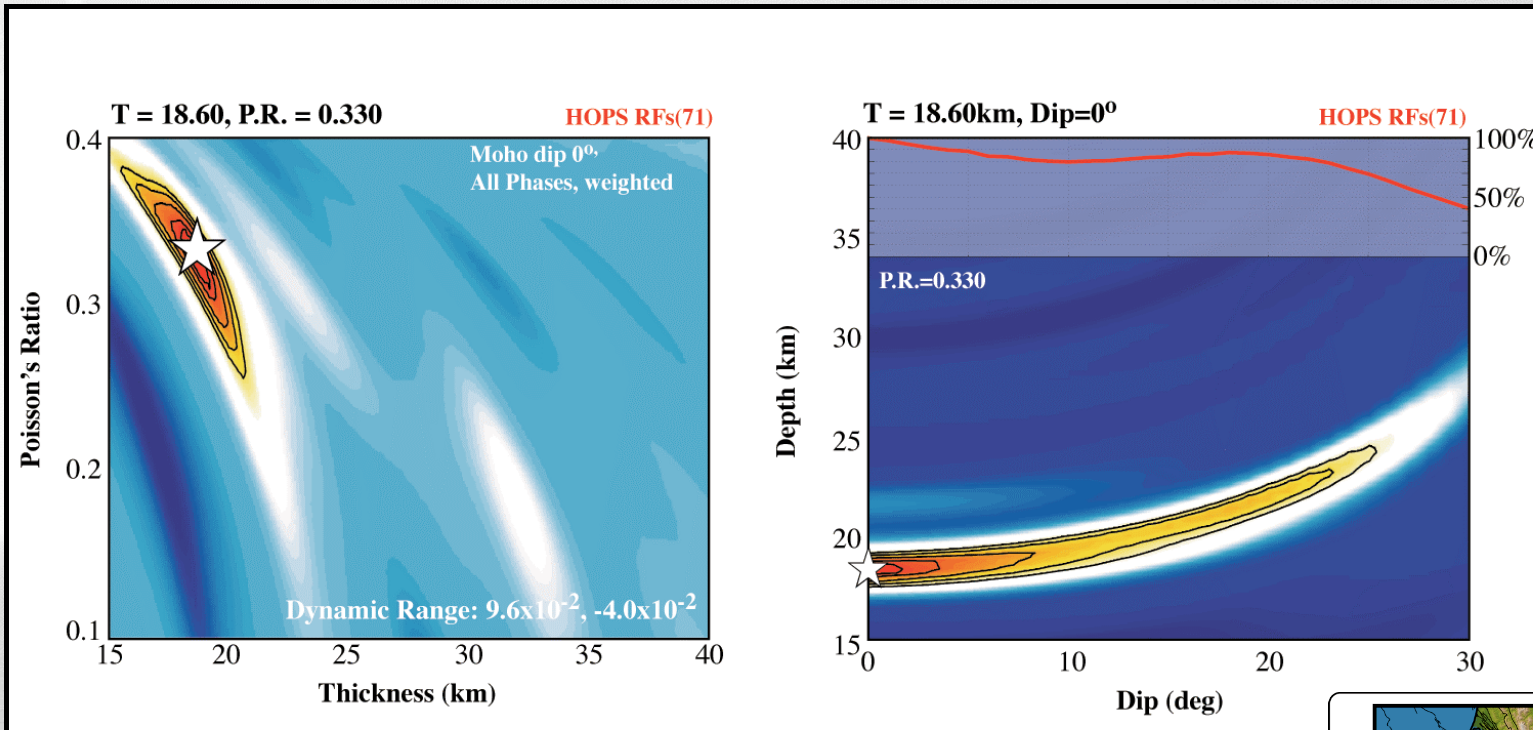


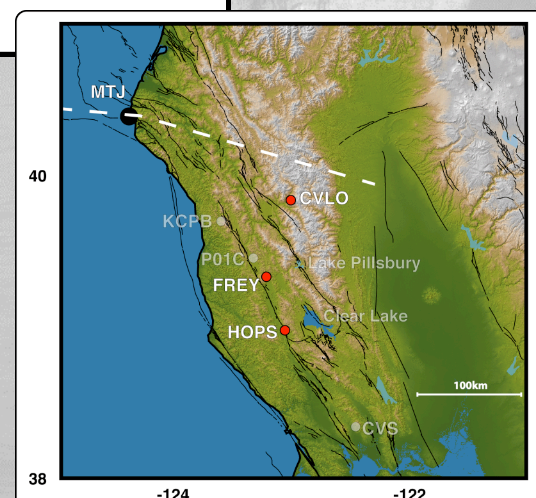


Single maxima dominates, at ~22km depth with a steeply dipping Moho.

High Poisson's Ratio suggested.

Results from HOPS





Single maxima - thinner crust, horizontal Moho.

Again, high Poisson's Ratio - adjacent to Clear Lake volcanics.

Summary of H:σ:δ Stack Results

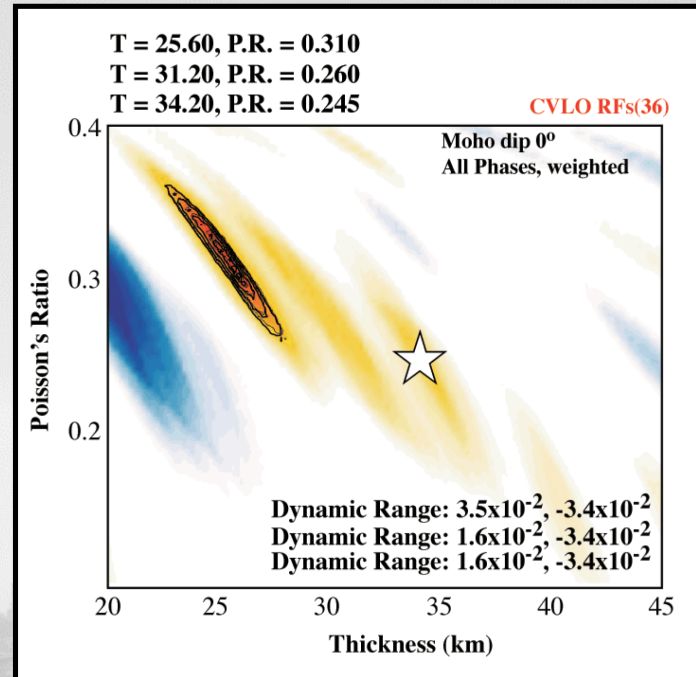
Clear peaks at FREY and HOPS.

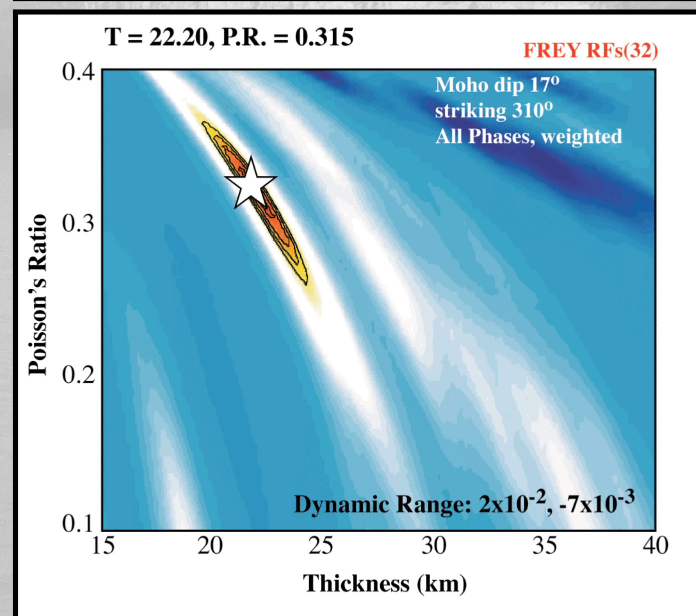
FREY best matched with a Moho dipping 17°; HOPS Moho horizontal.

High σ at both of these stations - melting in the lower crust?

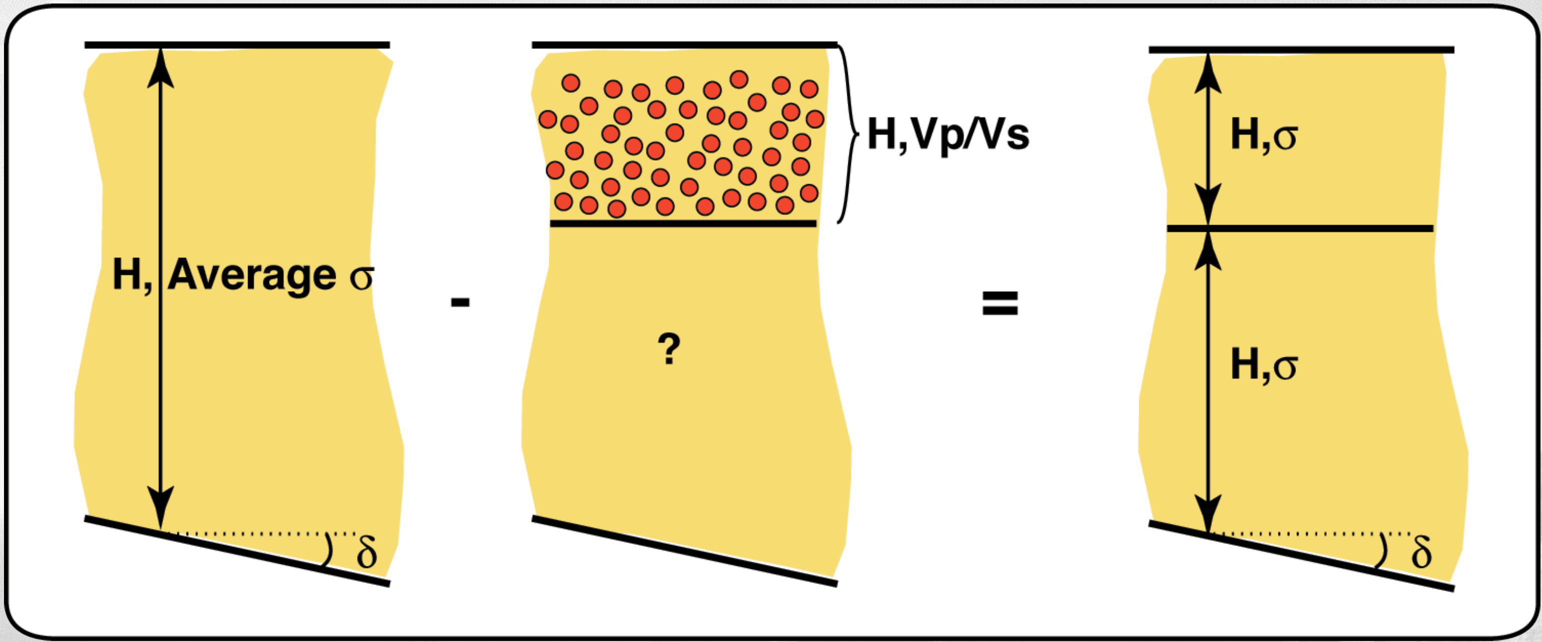
Rapid thinning in the region of FREY, not apparent just 40km south (nor 60km north at CVLO).

Multiple maxima with very high σ at some stations suggest complications - requires additional constraints.





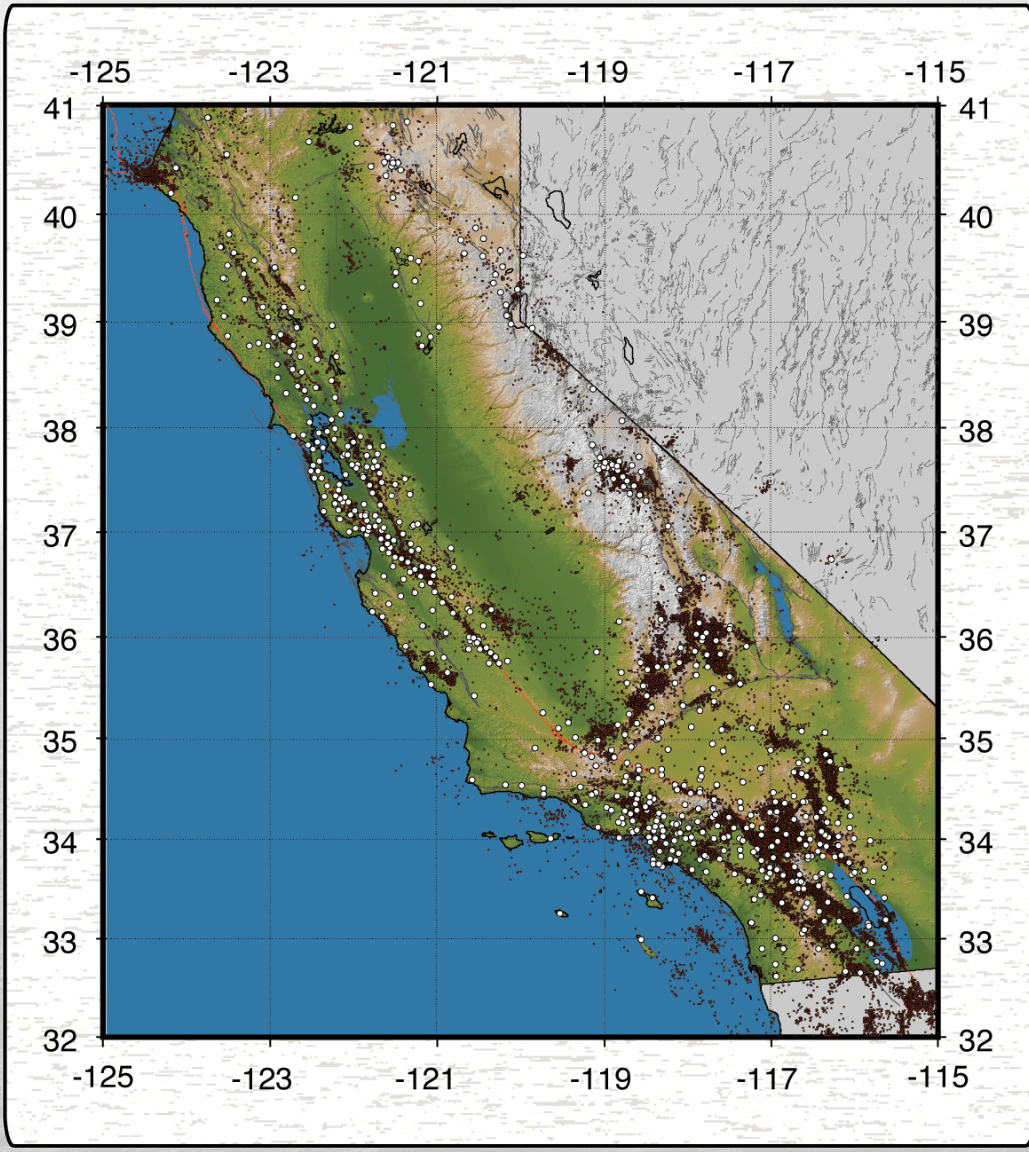
Resolving Crustal Components from Bulk H:σ:δ Estimates

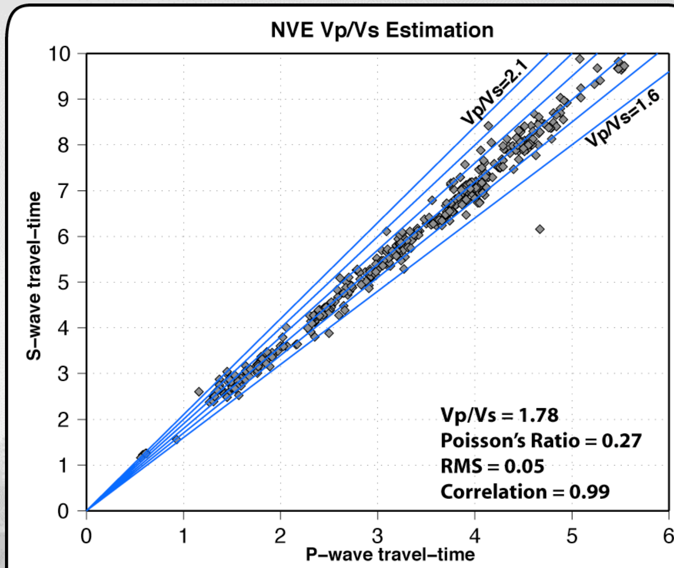


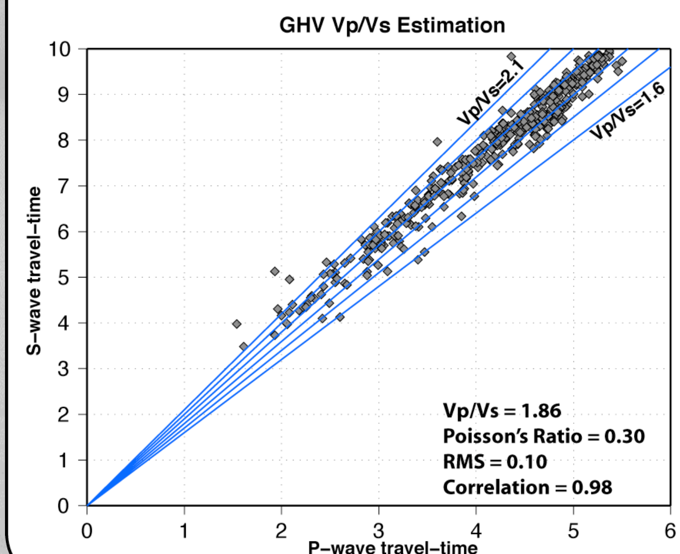
To constrain the cause of multiple maxima in the *H:σ:δ* stack, we require independent estimates of crustal Poisson's Ratio.

We can exploit the seismicity record (restricted to the upper, brittley deforming crust) to estimate upper crustal velocity structure (directly related to Poisson's Ratio).

Calculating Upper Crustal VpVs - California Dataset





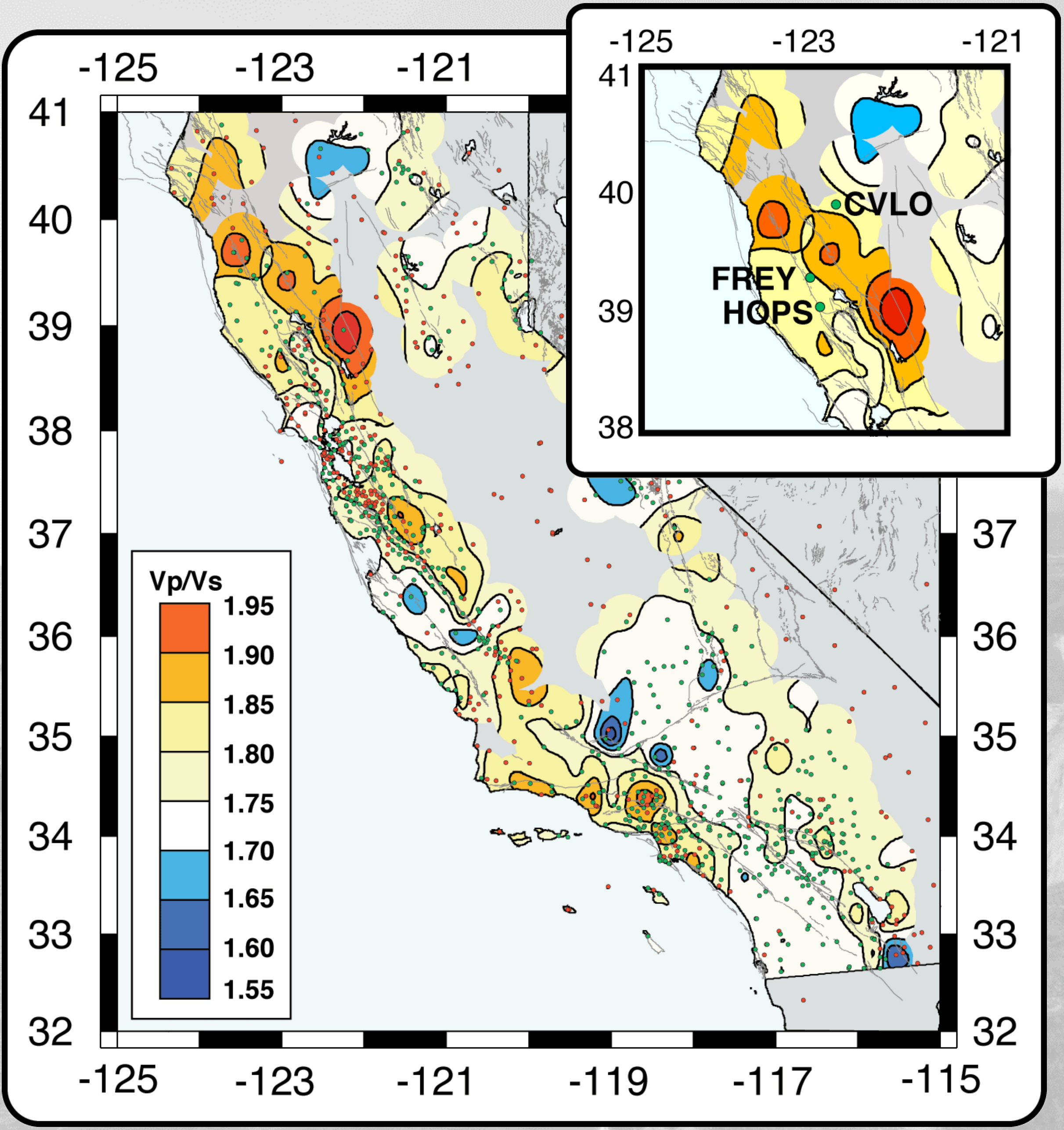


Upper Crustal Velocity Ratio of California

Valid over entire upper crust, to the depth limit of seismicity.

Allows us to resolve bulk crustal parameter estimates from receiver functions into upper and lower crustal components.

This approach has many other uses, investigated further as part of this thesis.



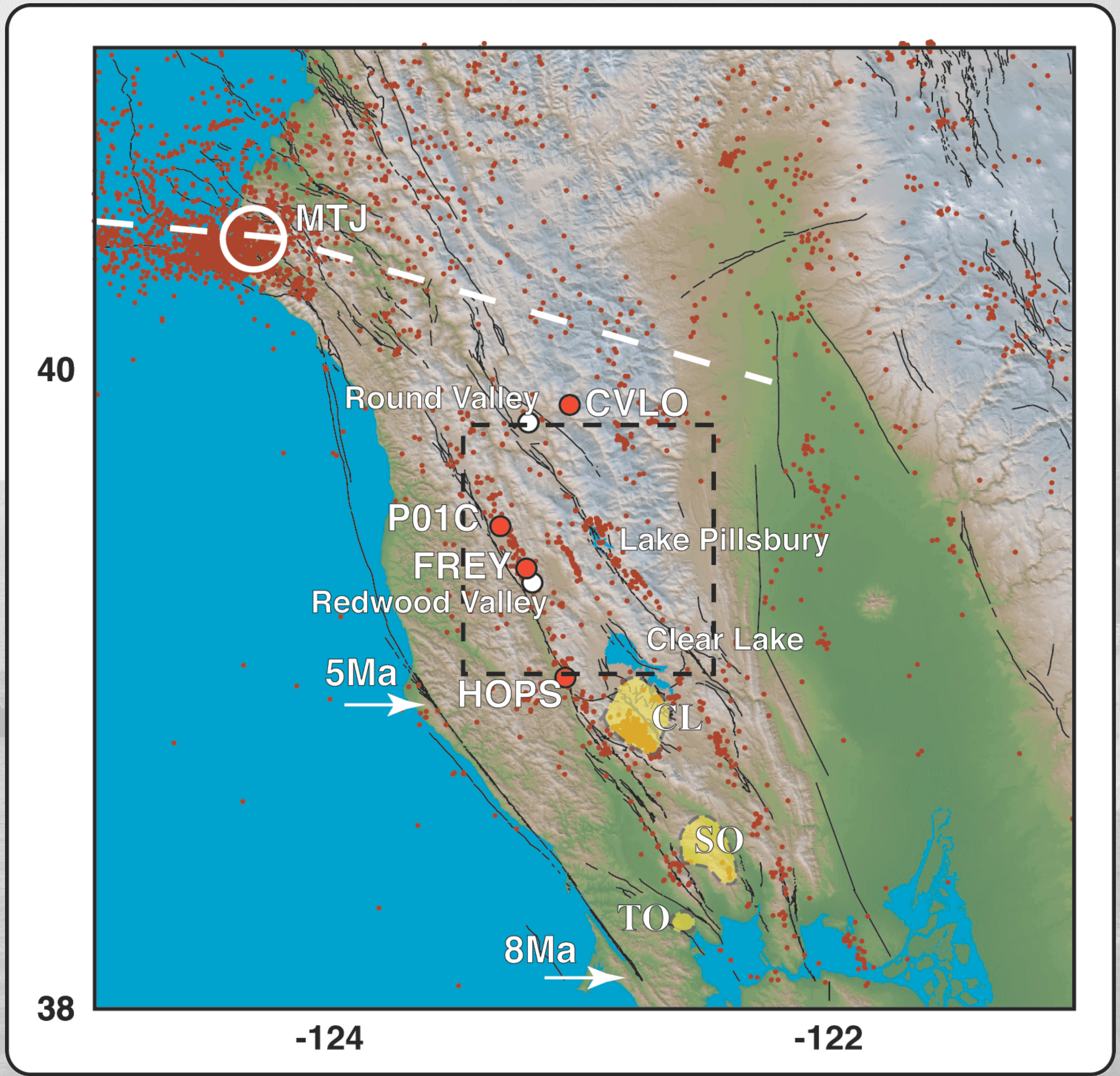
Crustal Manifestations of MTJ Evolution - Part I

Crustal Seismicity

Cenozoic volcanism migrates northwards in the wake of the triple junction.

Last surface volcanism at Clear Lake, initiating ~2Ma. MTJ has since migrated a further ~100km north - volcanism expected north of Clear Lake in the future.

Associated with lower crustal melts in RF analysis?

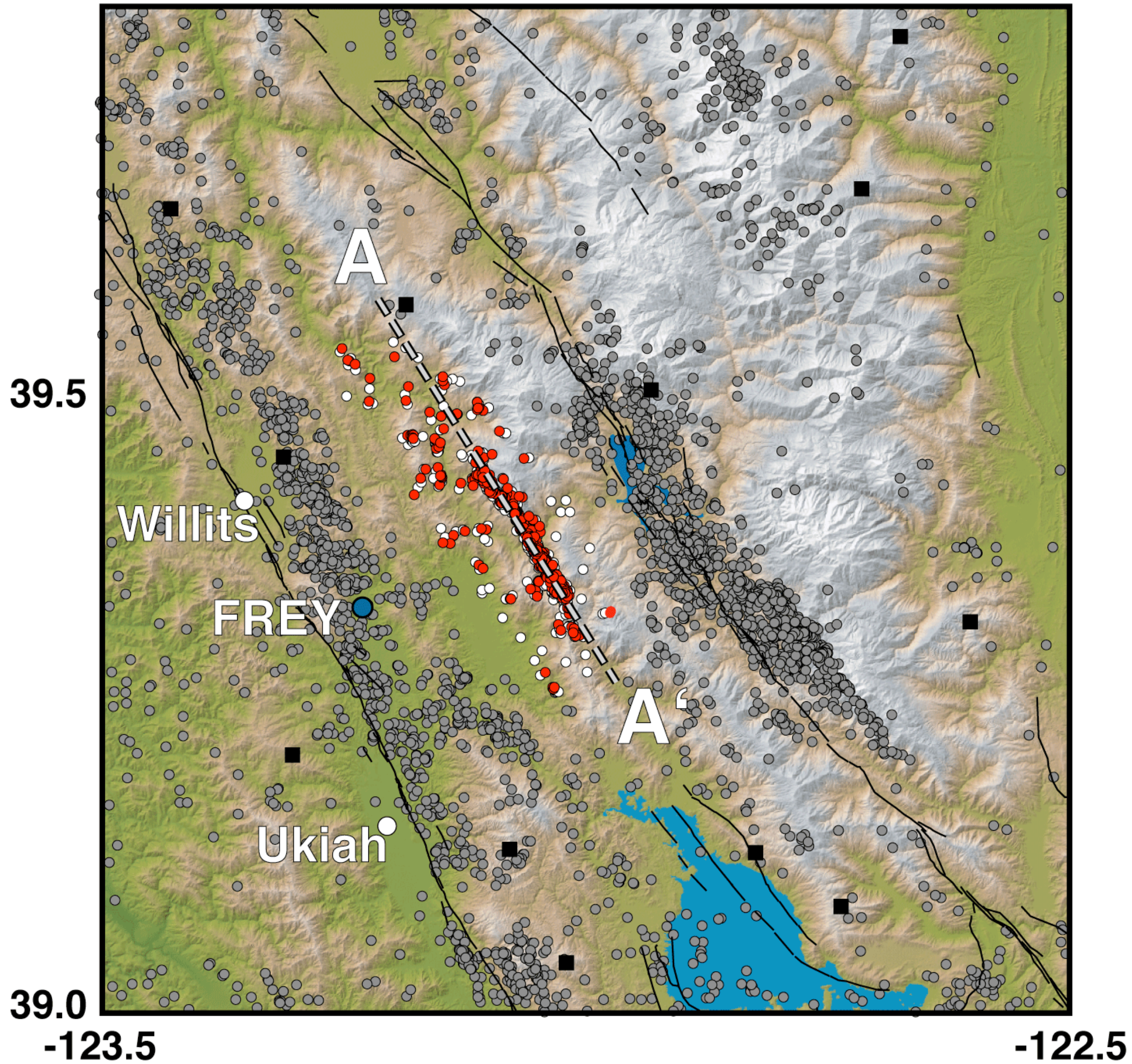


Pillsbury Earthquake Sequence

Enigmatic seismicity in the upper crust coincident with area of rapid thinning.

Not associated with any known surface faulting.

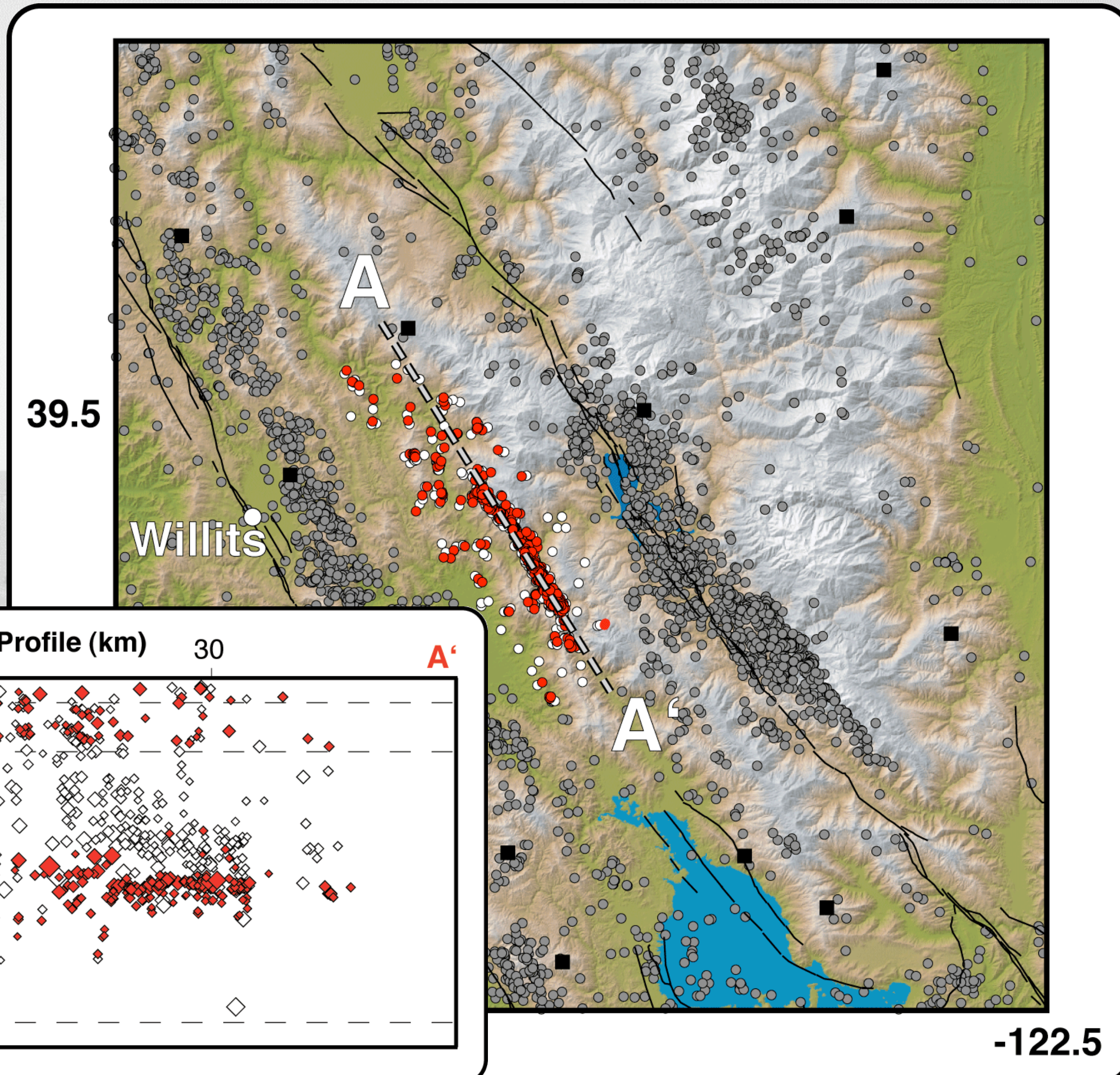
> 250 events of M>1.5 between April and September 2000; 3x the number of events in the preceding 15 years.

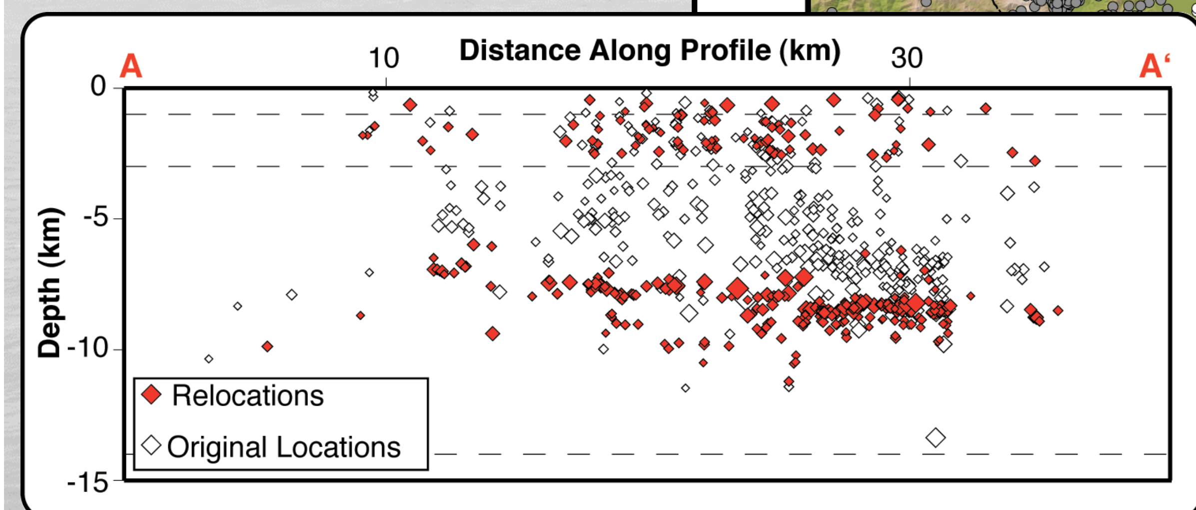


Pillsbury Earthquake Sequence

Earthquake relocations (via waveform cross-correlation) show seismicity is restricted to a streak at ~8km depth.

Largely aseismic mid-crust.



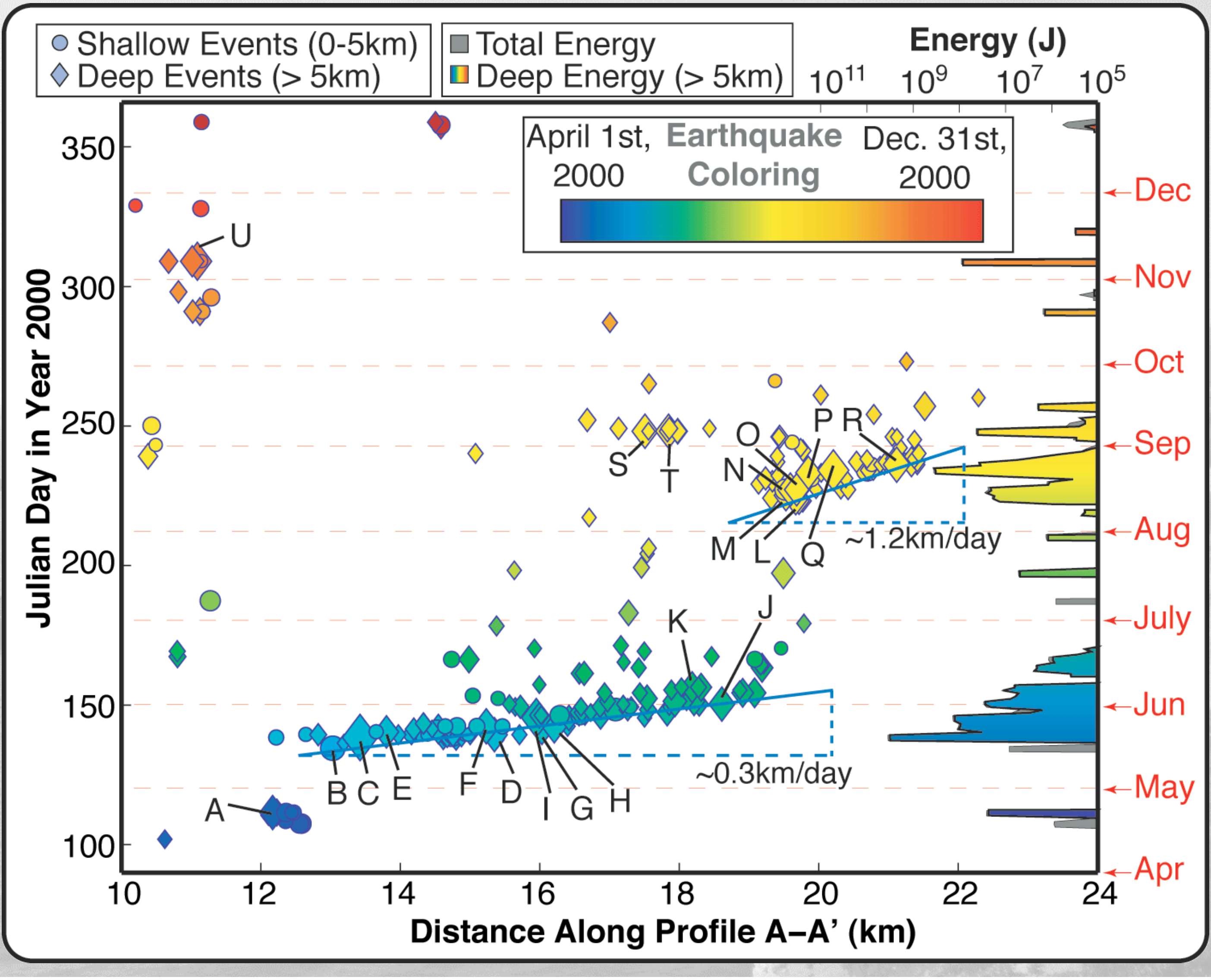


Temporal Evolution of Seismicity

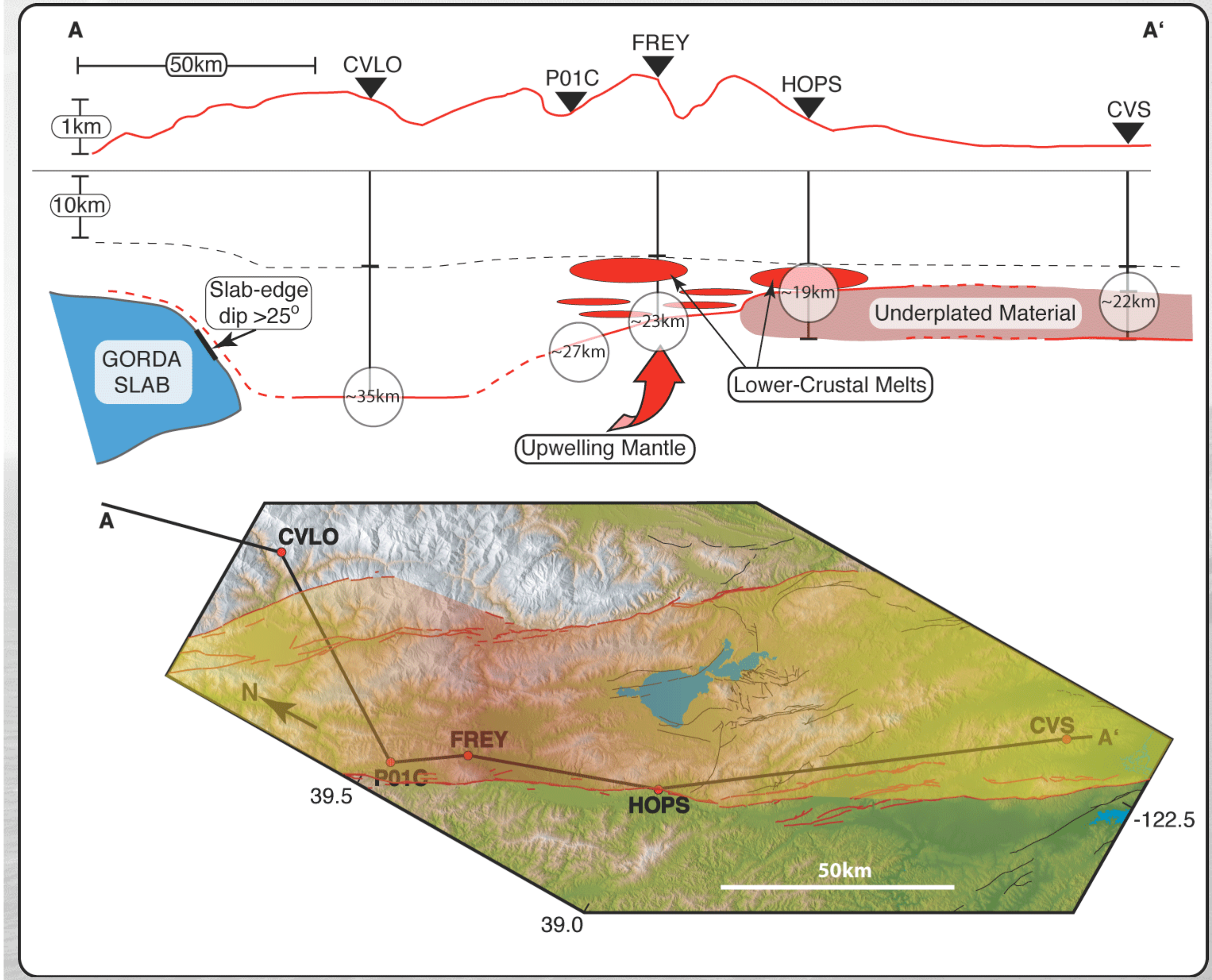
Two pulses of activity, clear southward migration.

>95% of sequence energy release in these two pulses.

Associated with dike injection related to migrating volcanics?



Implications for the Evolution of Northern California



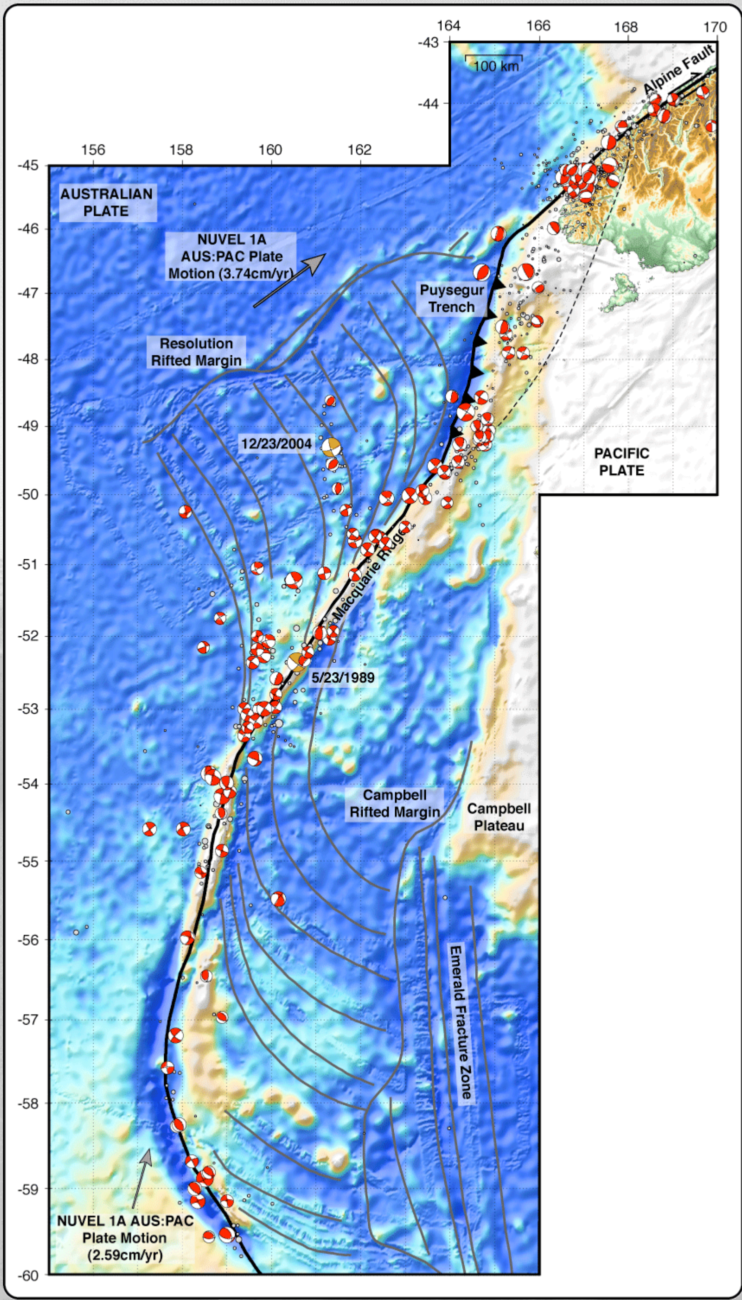
- Abrupt changes in crustal thickness.
- Coincident steeply dipping (~17°) Moho.
- Coincident high Poisson's Ratio (>0.30) isolated to the lower crust.
- Uniform thickness upper crust (~12km).
- Shallow seismicity consistent with triggering by dike injections.

New Zealand - Euler Pole Migration as a Driver for Plate Evolution

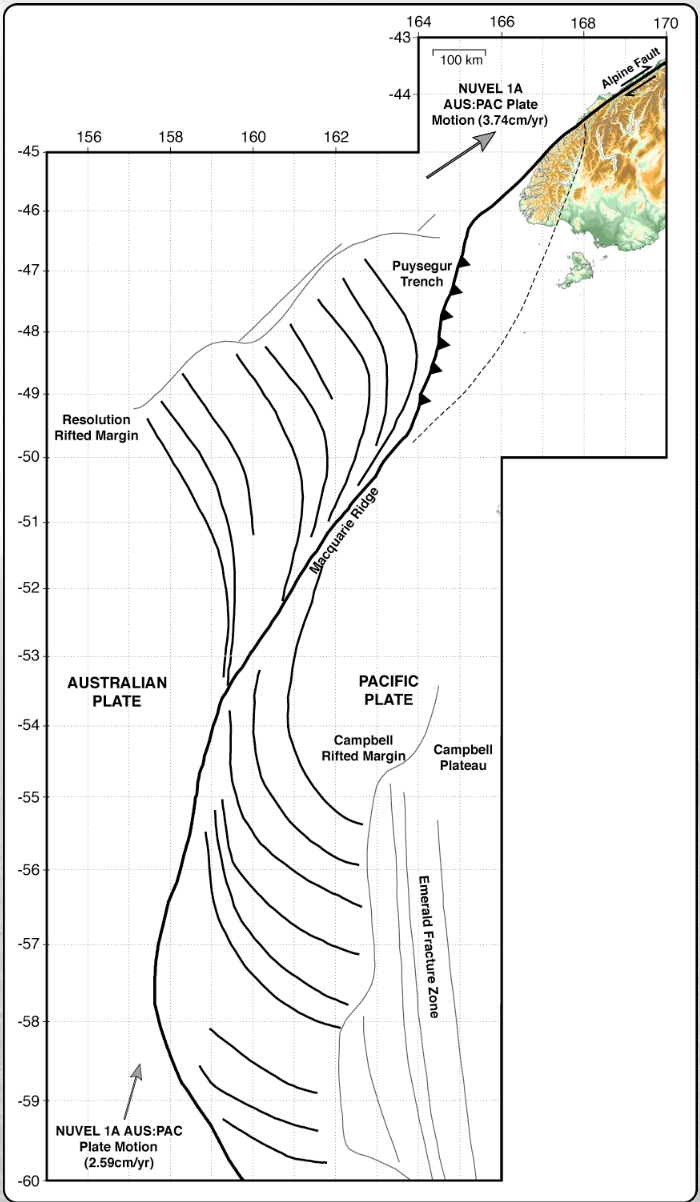
Migration of the Pacific:Australia Euler pole (describing the rotation of one plate w.r.t the other) during the Eocene-Oligocene caused a transition from plate divergence (prior to ~25Ma) to the translation seen today.

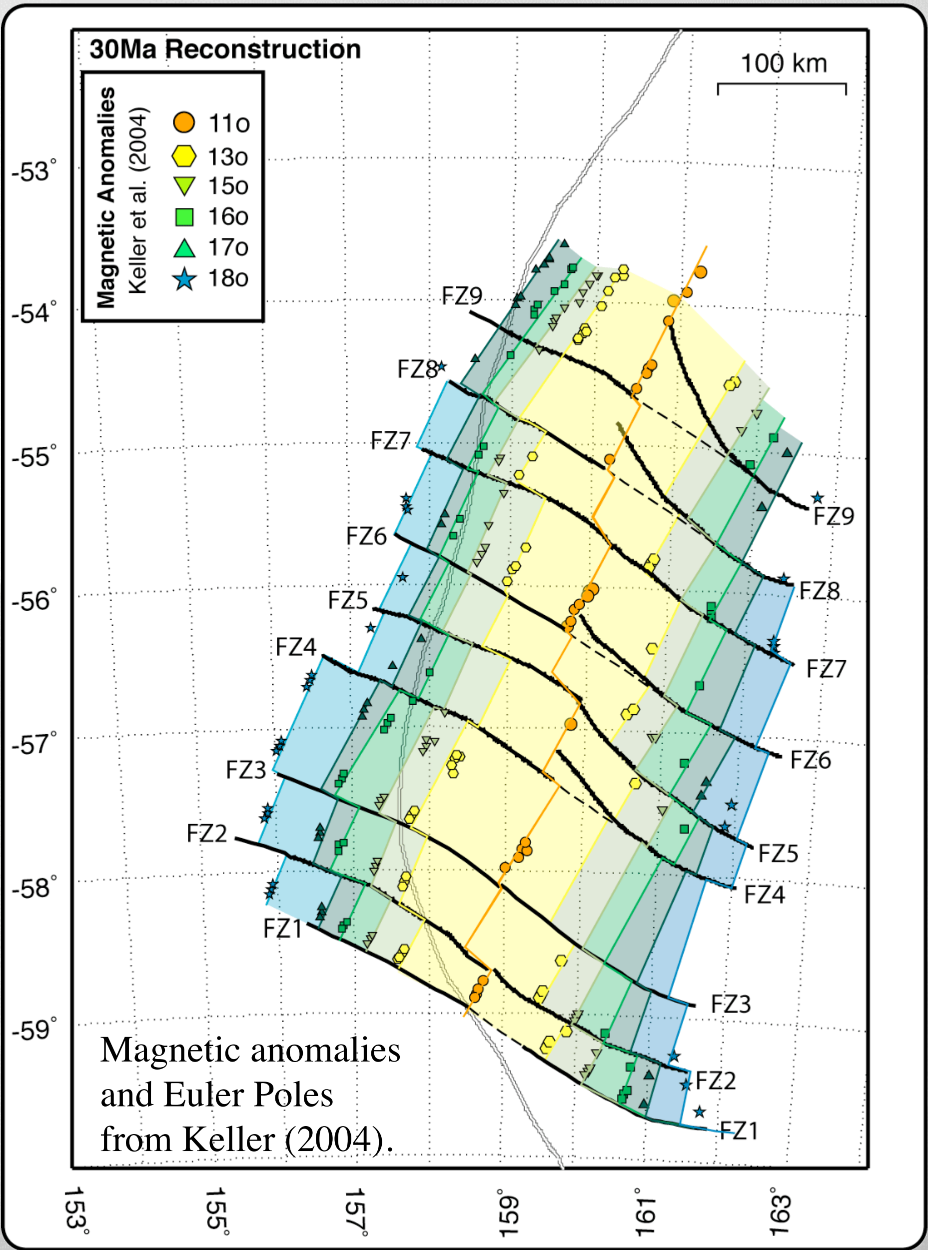
Region demonstrates high levels of seismicity, including two M8+ events in the past 20 years.

Modern earthquake locations and relic fracture zones formed during the period of divergence may record the history of plate deformation since this transition.



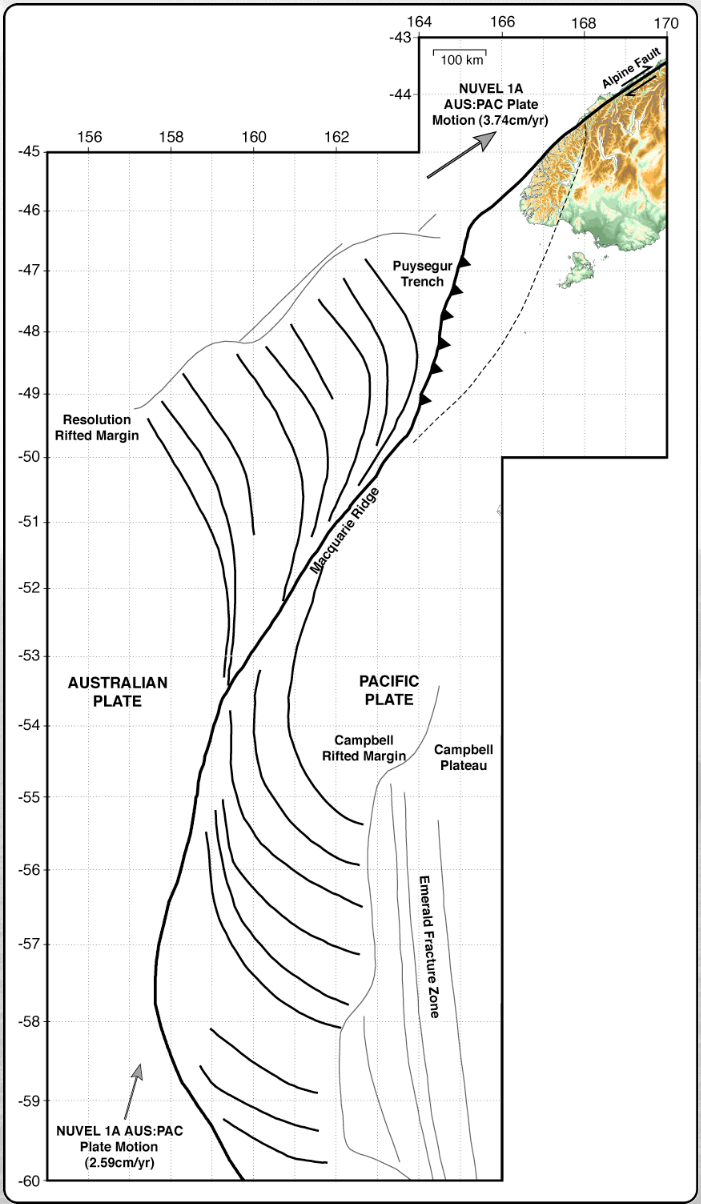
Macquarie Plate Reconstructions

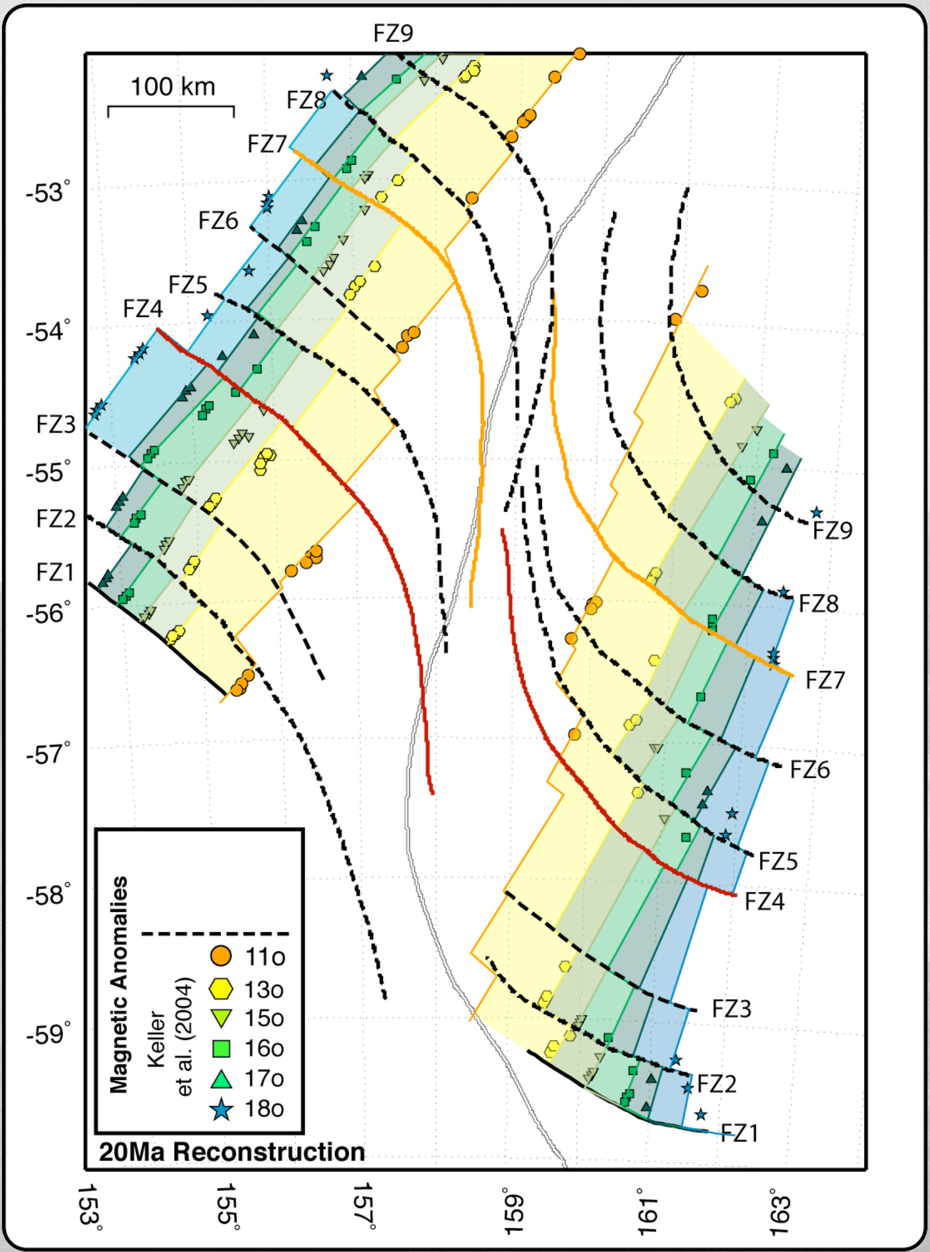




Magnetic anomalies and Euler Poles from Keller (2004).

Macquarie Plate Reconstructions

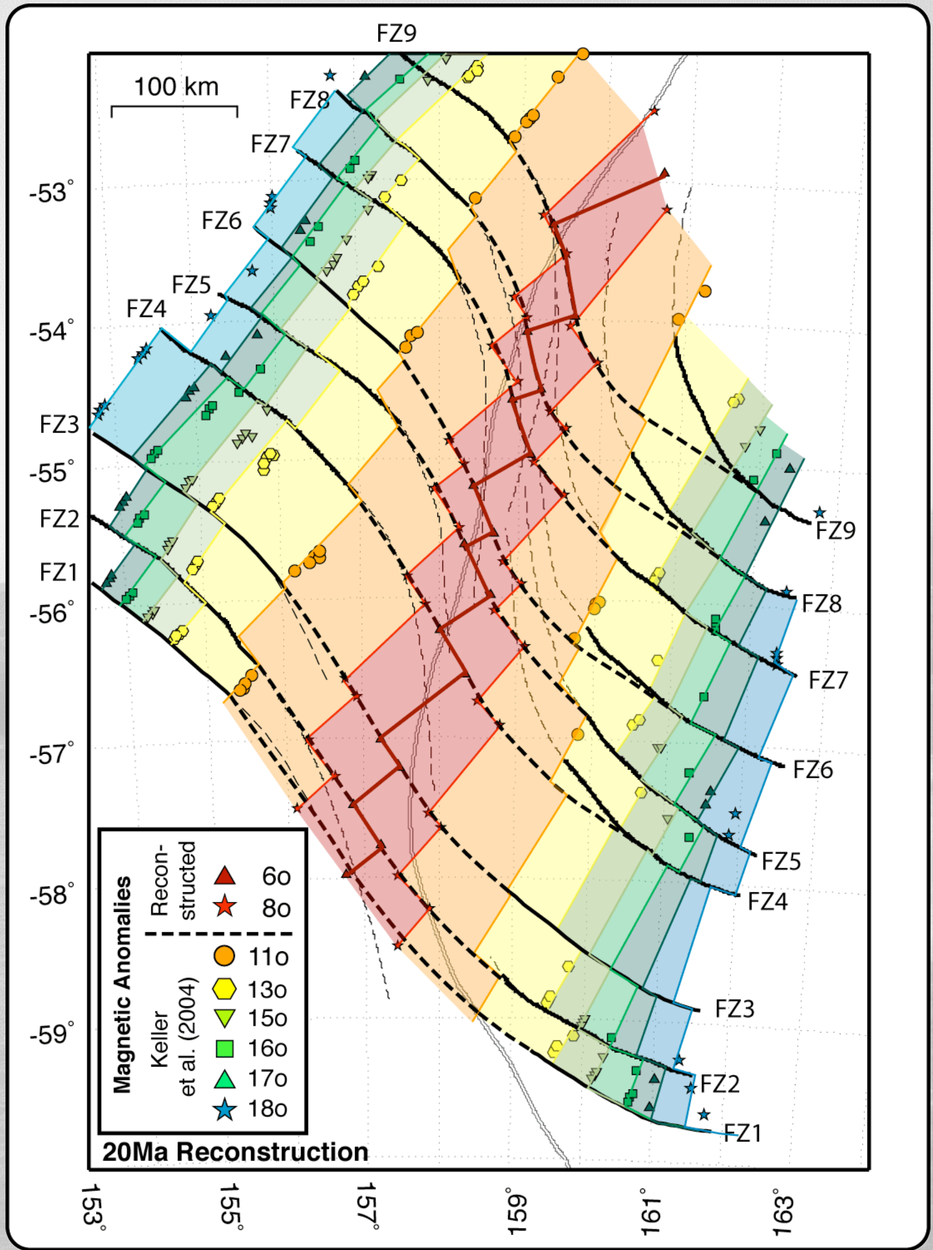




Macquarie Plate Reconstructions

We can use these plate reconstructions to restore the fracture zones to their approximate true positions at the time of formation.

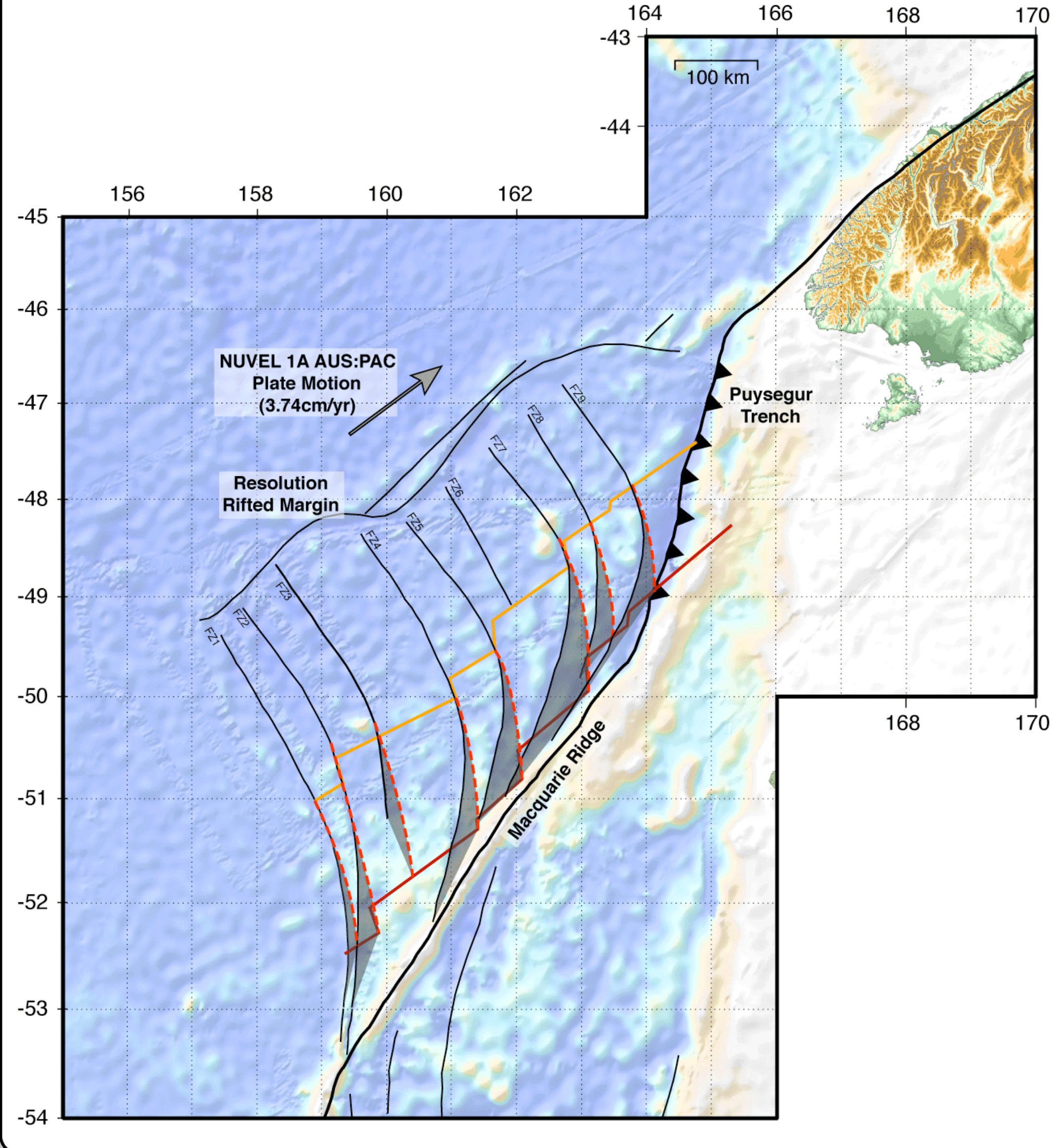
By comparing these restored features to their present-day appearance, we can therefore approximate the deformation that has occurred in the Australian Plate since ~20Ma



Deformation Recorded in Australian Plate Fracture Zones

This comparison reveals that current fracture zone positions are deflected significantly to the south with respect to the reconstructed 20Ma fracture zones.

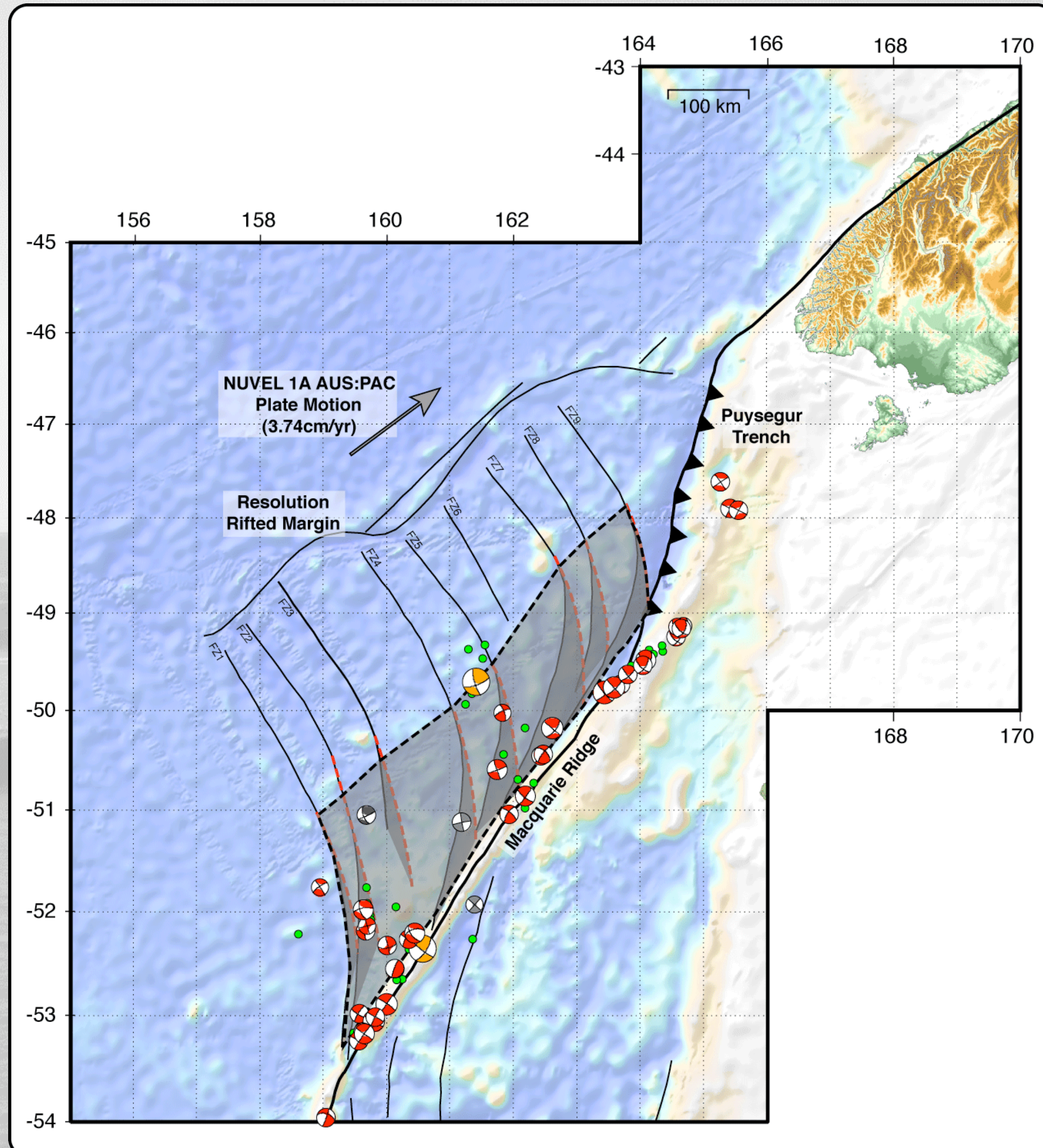
⇒ broad region of deformation bounded by the 30Ma (orange) and 20Ma (maroon) isochrones that reflects the deformation of fracture zones of the Australian Plate.



Deformation Recorded by Modern Seismicity

Earthquake relocations of all Macquarie Ridge events since 1/1/1989 confirms high levels of seismicity internal to the Macquarie Block, limited to an area within ~150km of the plate boundary.

This seismicity includes probable activity on relic fracture zones, notably with a M_w8.1 earthquake in December 2004.

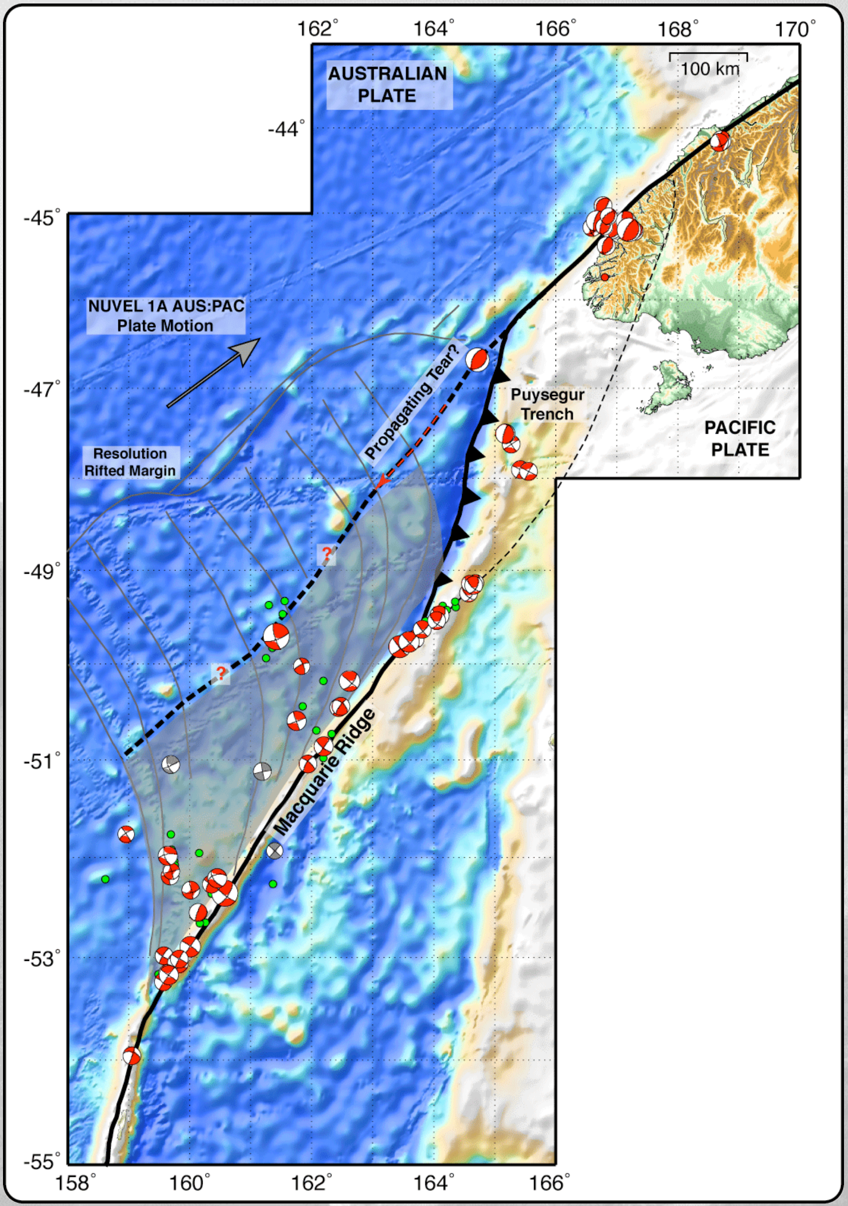


Intraplate Deformation Related to Inhibited Subduction?

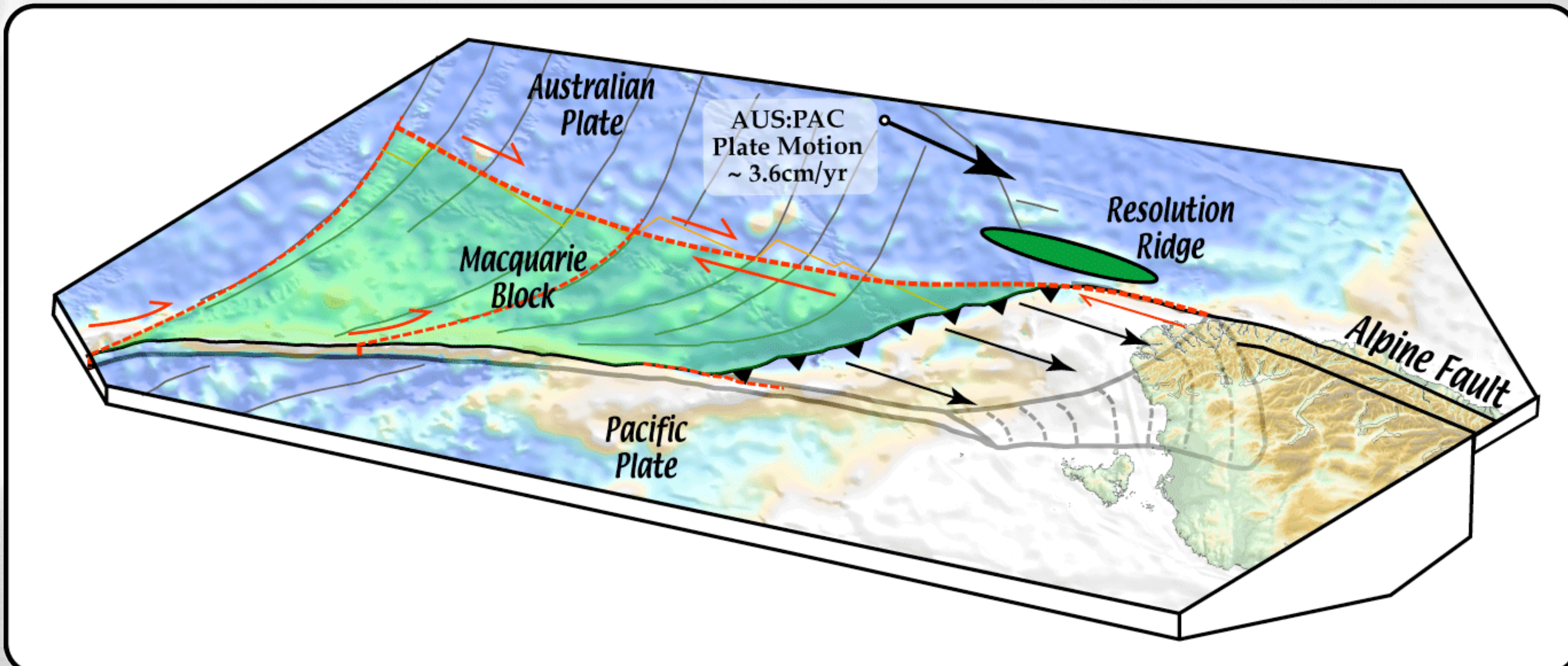
Two independent measures of deformation coincide in location and extent:

⇒ deformation evident in the fracture zones has occurred since translational motion began at ~20Ma, and continues at present as expressed by high levels of seismicity.

Deformation a consequence of the impingement of the subducting Australian Plate on the thickened lithosphere of New Zealand? This buttress may act as a resisting force to subduction, transferring stresses south through the Australian Plate.



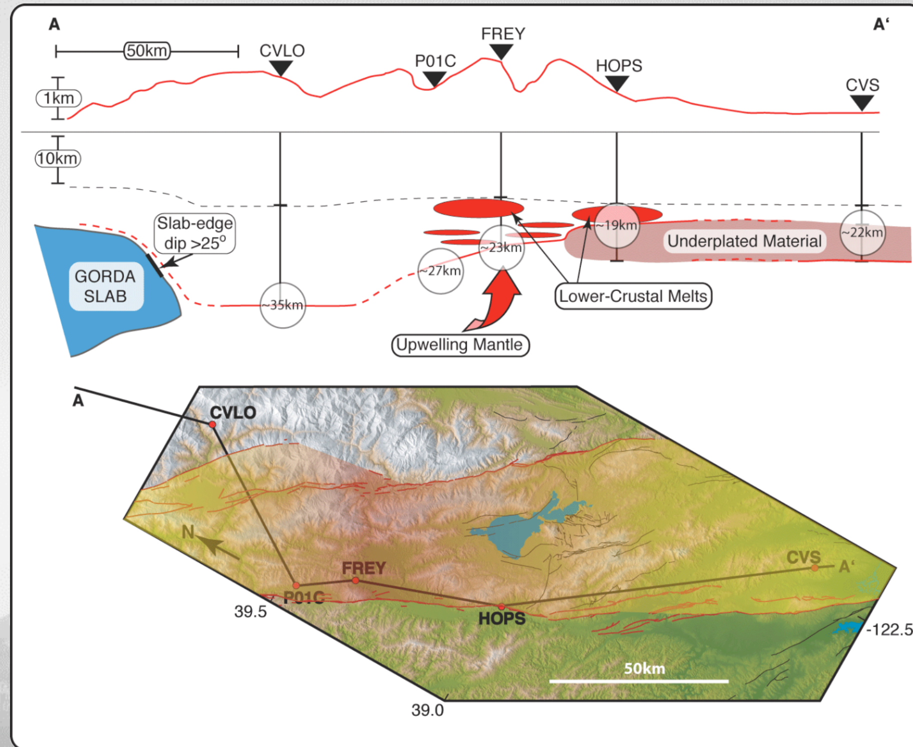
A Model for an Evolving Plate Boundary



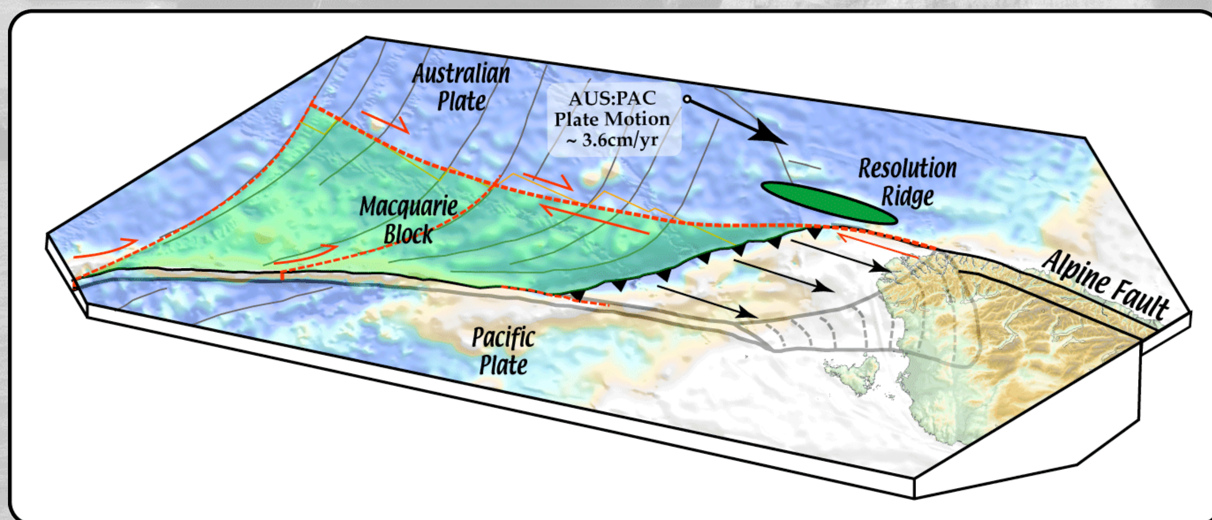
Over time, if the resistance forces responsible for this deformation continue, prolonged motion along the Macquarie Block fractures may lead to a southward jump of the subduction zone and a capturing of the Macquarie Block onto the Pacific Plate

The Evolution of Two Complex Plate Boundaries

These works describe the detailed manifestations of lithospheric evolution in response to recent and rapid changes in plate boundary structure in northern California and the southwest Pacific.



The integration of seismological tools within a tectonic framework facilitates the address of fundamental questions concerning plate boundary evolution.



The Evolution of Two Complex Plate Boundaries

In addressing these problems, I have further developed existing methodology in receiver function analysis to provide three-dimensional resolution of crustal structure variations.

In conjunction with this advance, I have also introduced a method to calculate the velocity ratio of the upper crust using P- and S-wave travel times from local seismicity recorded at dense local seismometer networks.

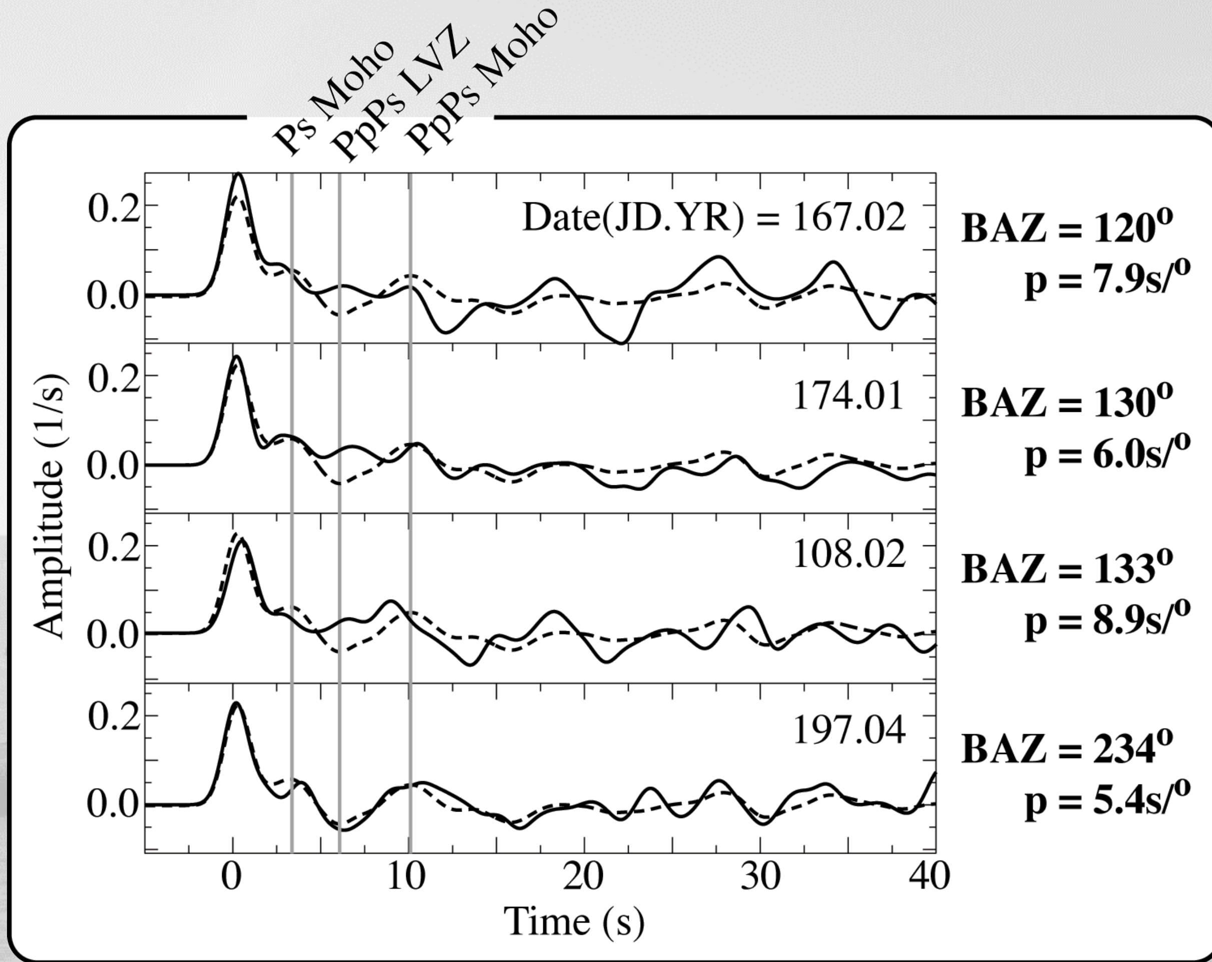
The development of these methods provide useful new techniques for the seismologists toolbox.

End of Talk - Thank You!

Inconsistencies in Receiver Function Forward Modeling

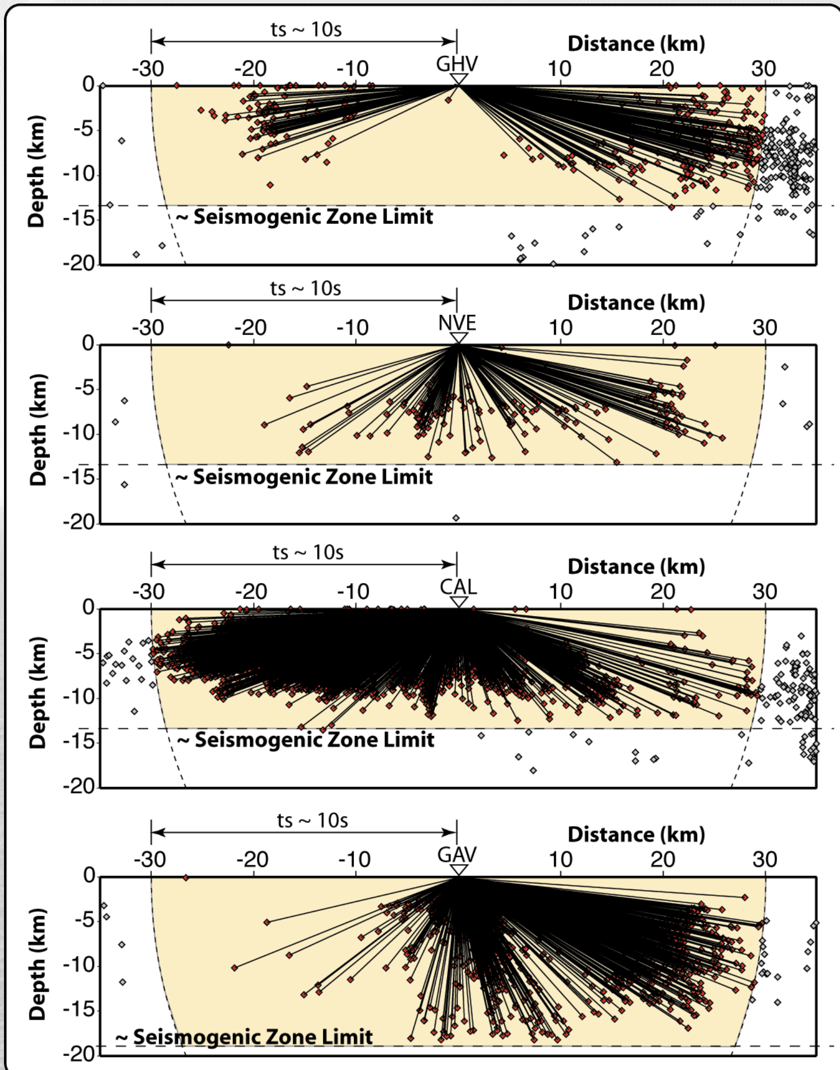
Forward modeling generally stacks over broad azimuthal ranges and assumes planar layers with invariant crustal properties.

Any variation in structure over the area sampled (up to a radius of ~40km around a station in NCal) is thus unaccounted for through stacking.

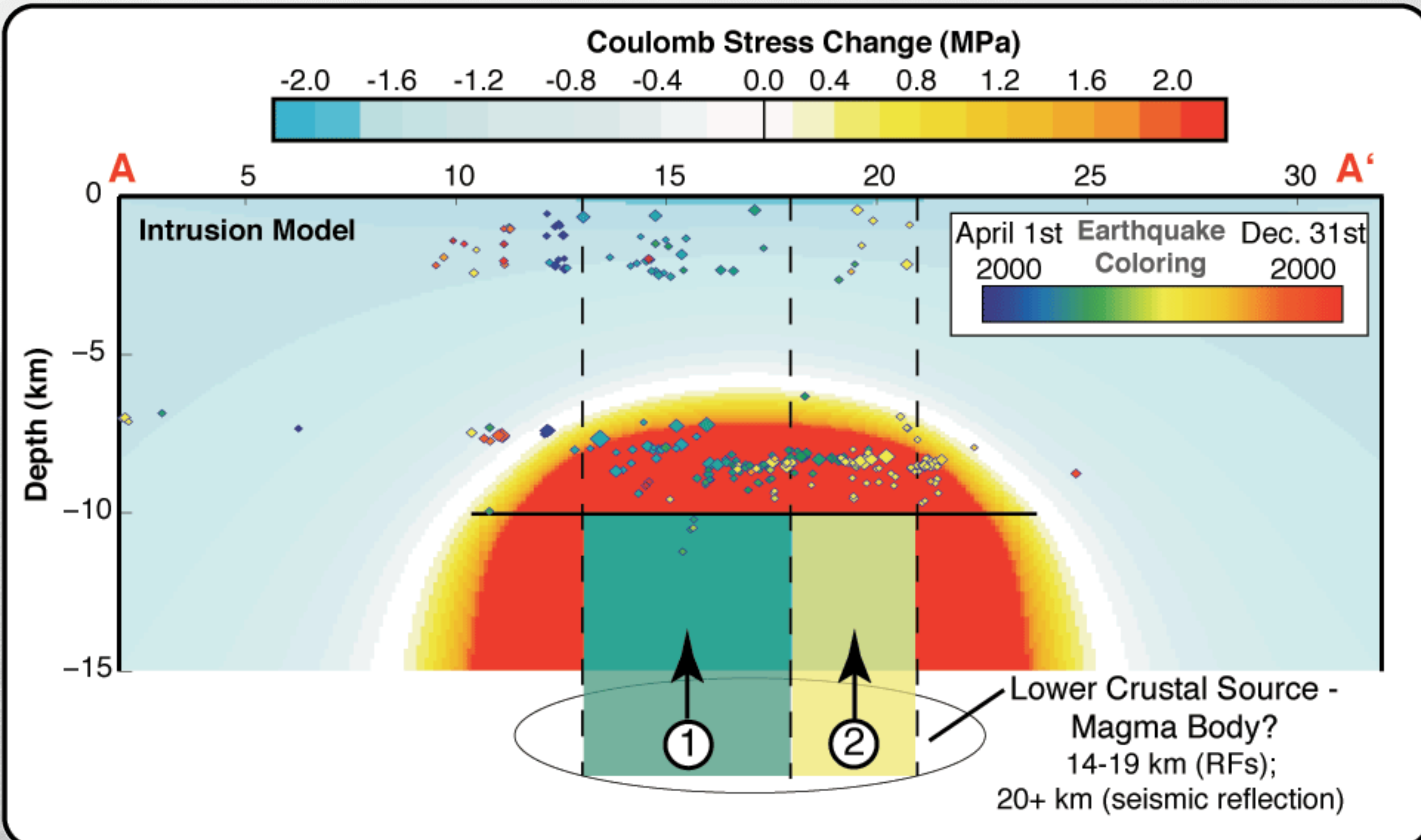


⇒ Models not representative of all receiver functions.

Calculating VpVs - Individual Stations Cross-sections



Evidence for Shallow Crustal Dike Injections?



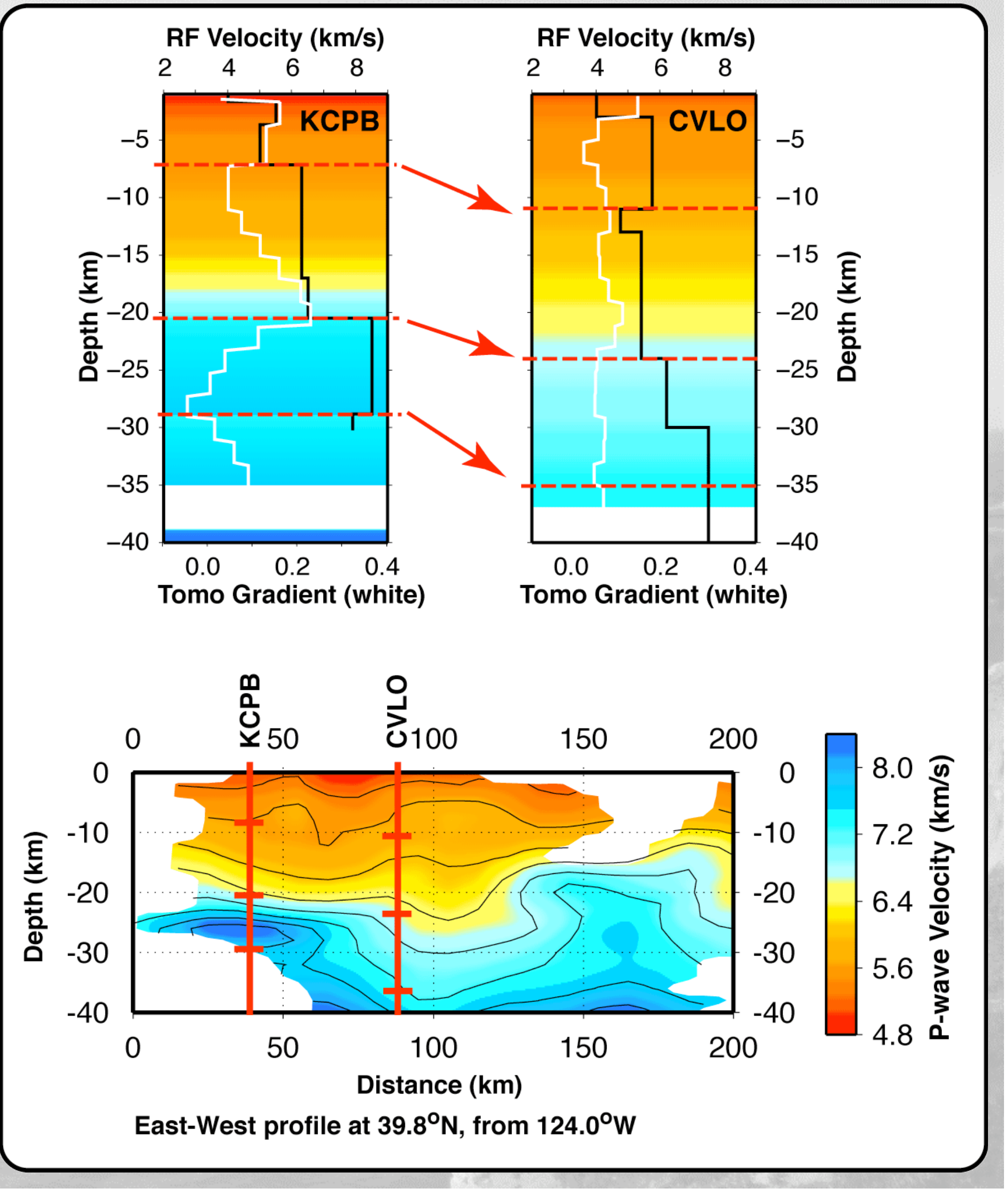
Crustal Manifestations of MTJ Evolution - Part II

Integrating Data Sets

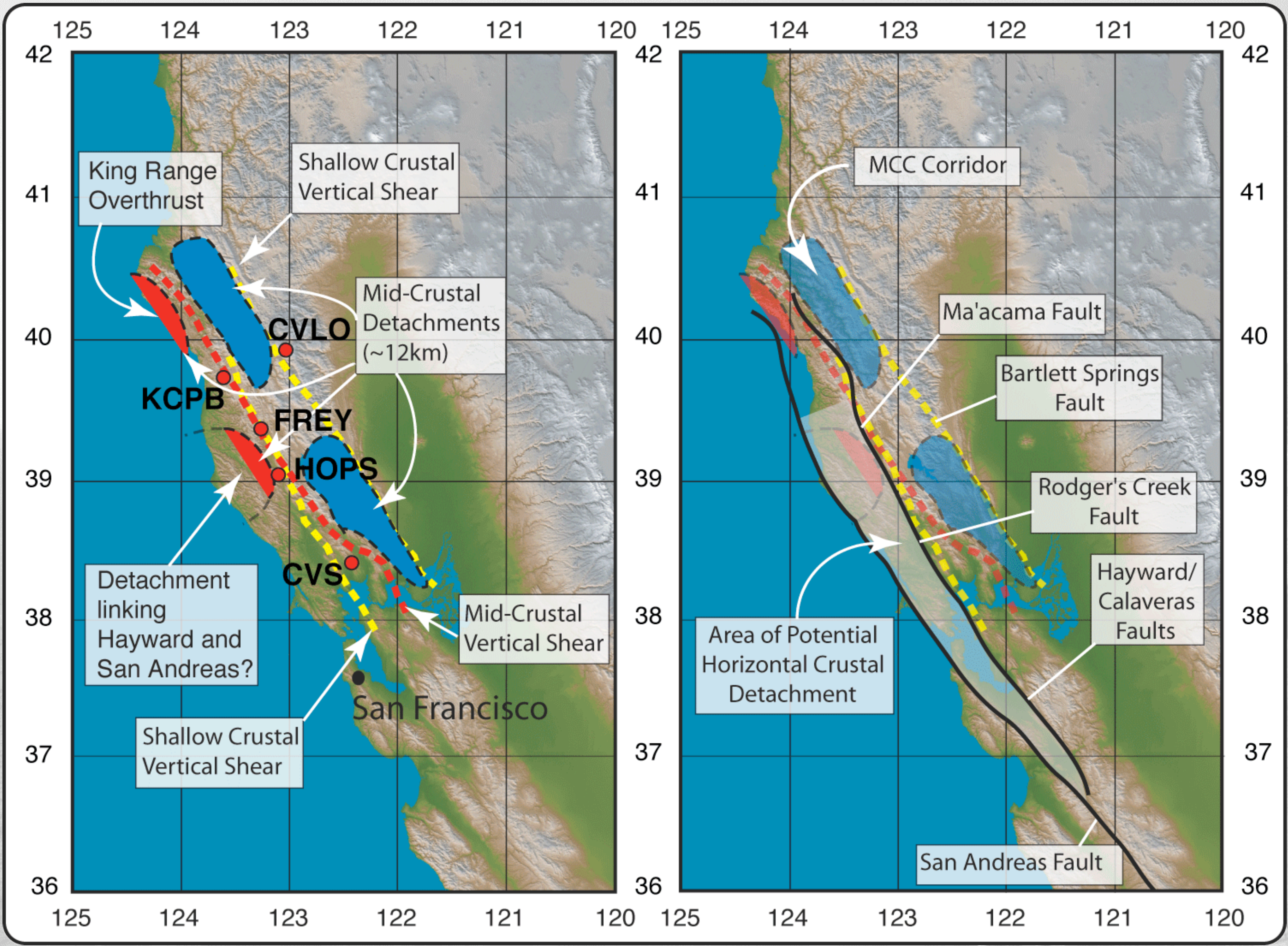
Implications of localized crustal thinning can be tested via the integration of additional seismological data sets with the receiver function analysis.

I make use of a seismic tomography data set of northern California (Villasenor et al., 1998) to extend horizons evident in the receiver functions across the entire Coast Ranges.

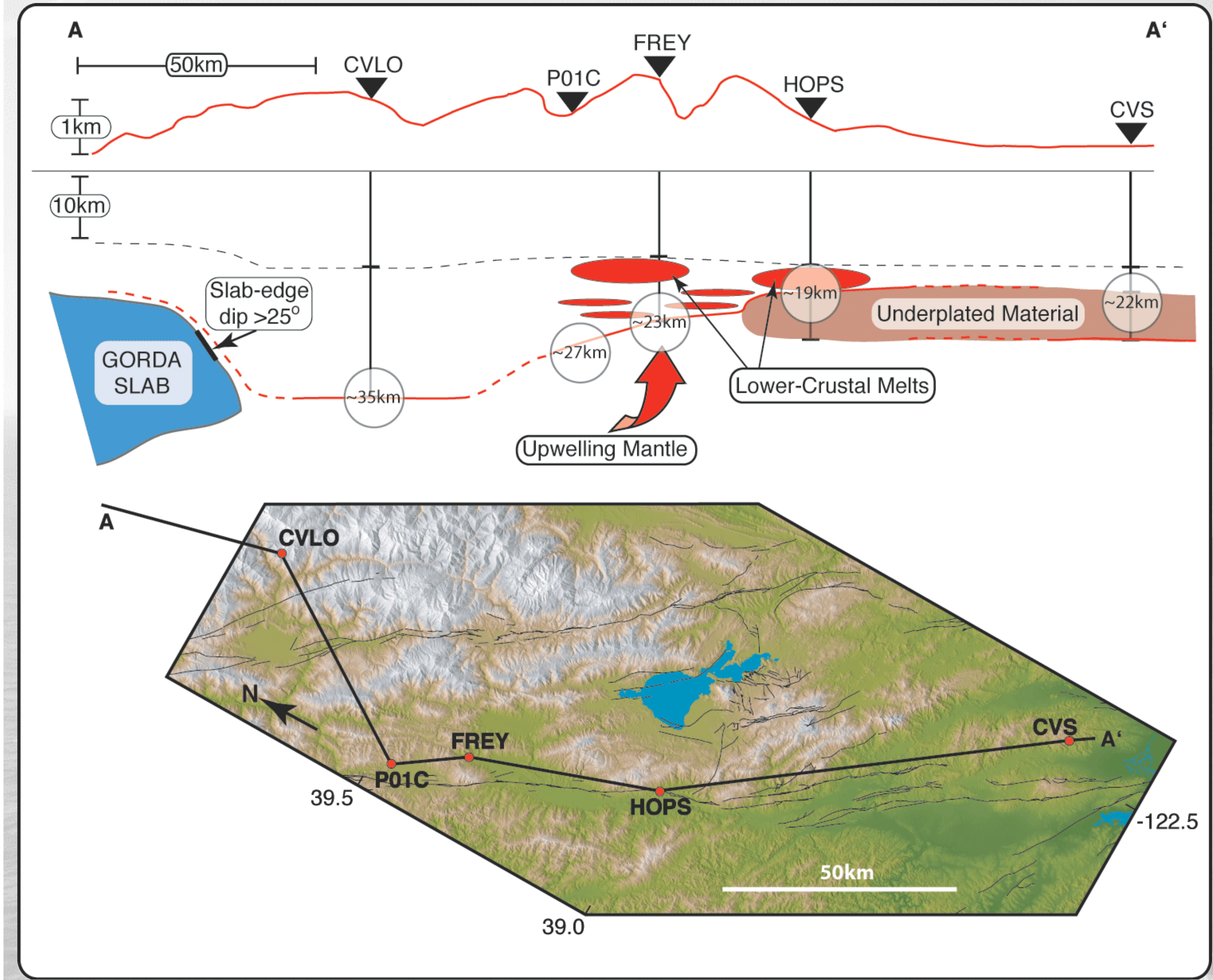
Leads to a 3D strain model of the northern California crust.



Northern California Shear Zone Formation



The Evolution of North American Crust



Combining results shows abrupt variation in crustal thickness.

Thinning localized to crust around FREY, where the Moho dips ~17°NE.

High Poisson's Ratio in the lower crust at FREY and HOPS imply areas of melt.