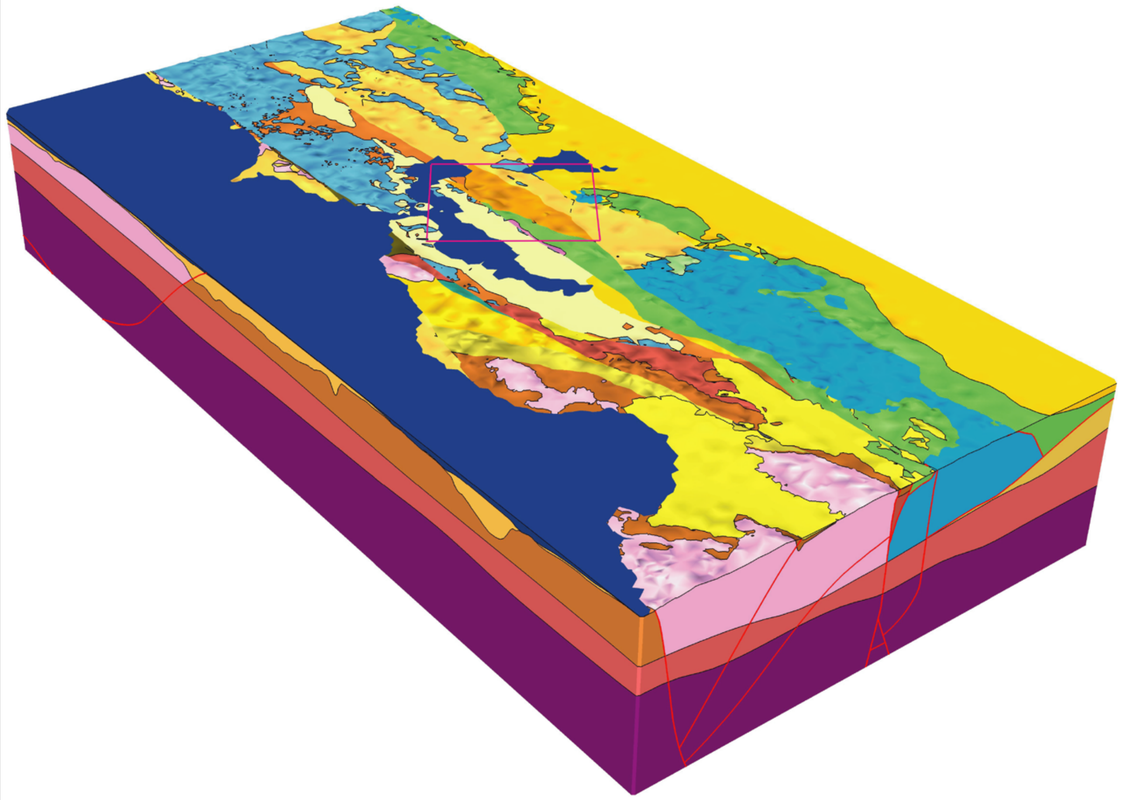
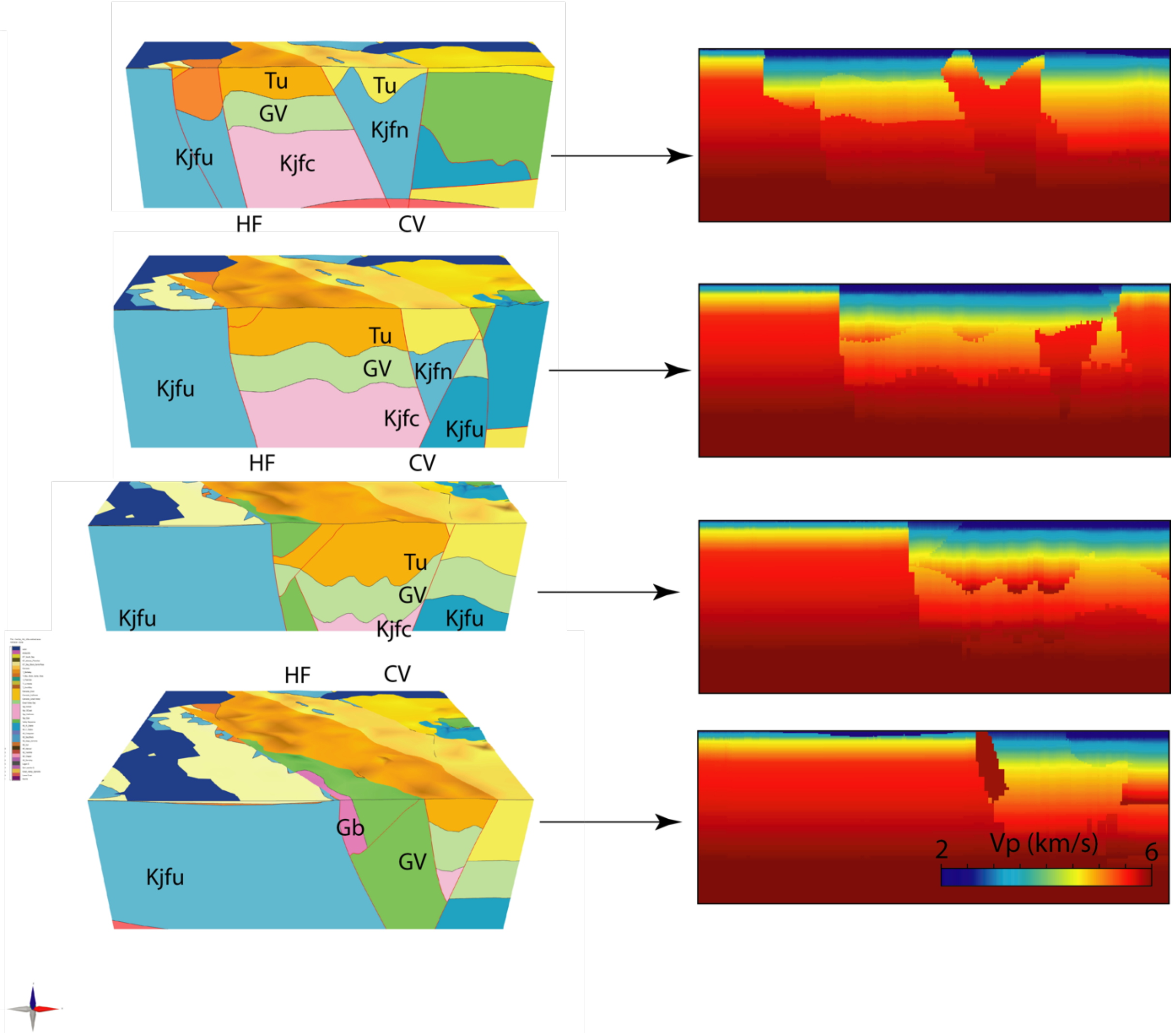
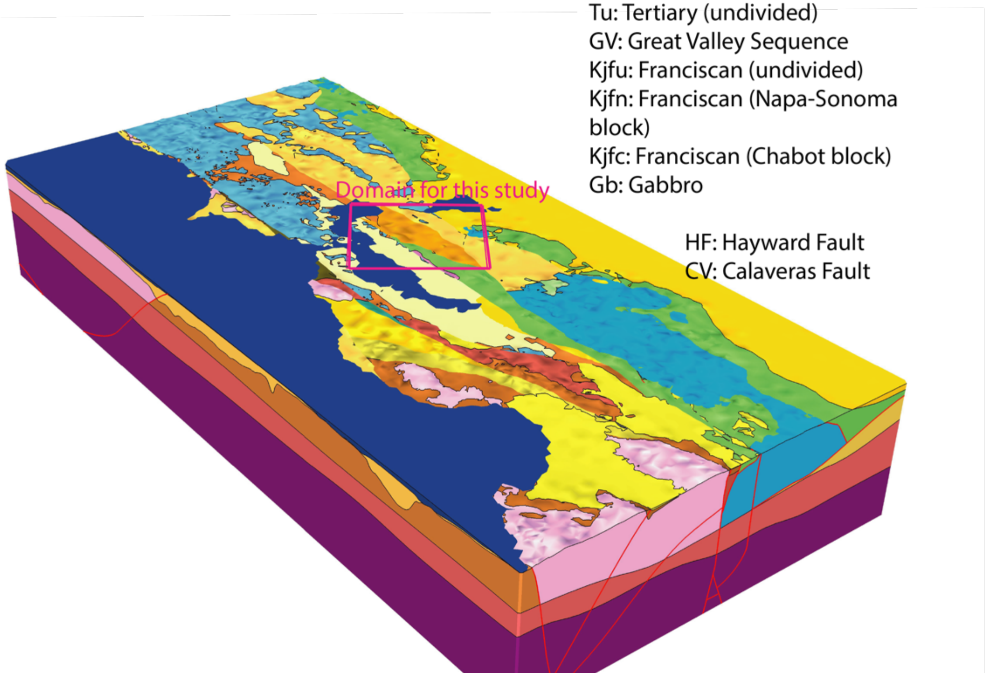
Revising the USGS Bay Area Velocity Model in the East Bay

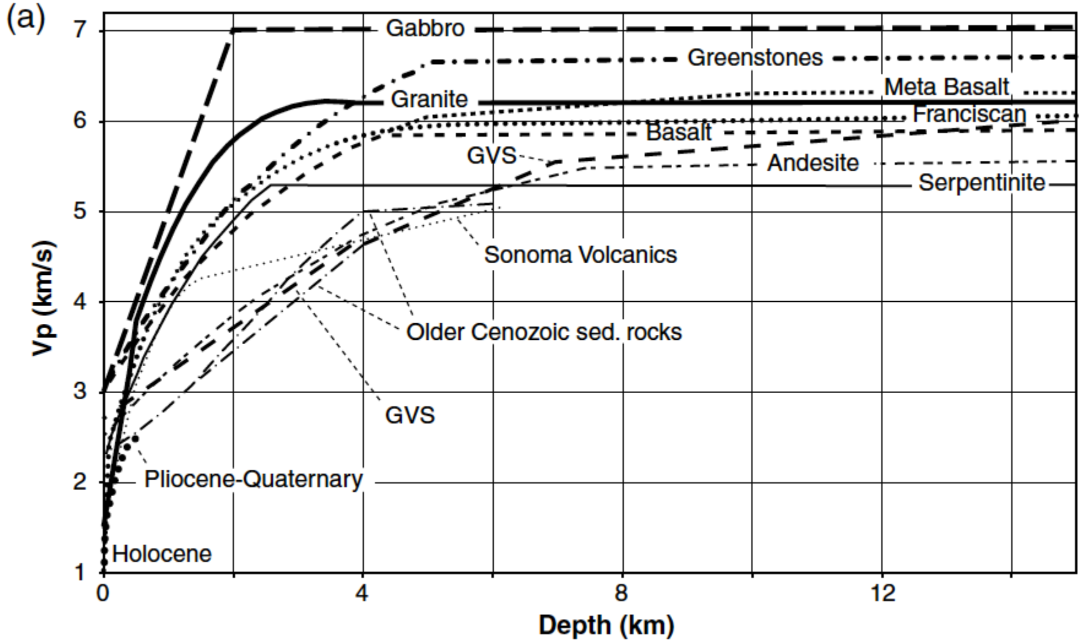
Evan Hirakawa, USGS Menlo Park



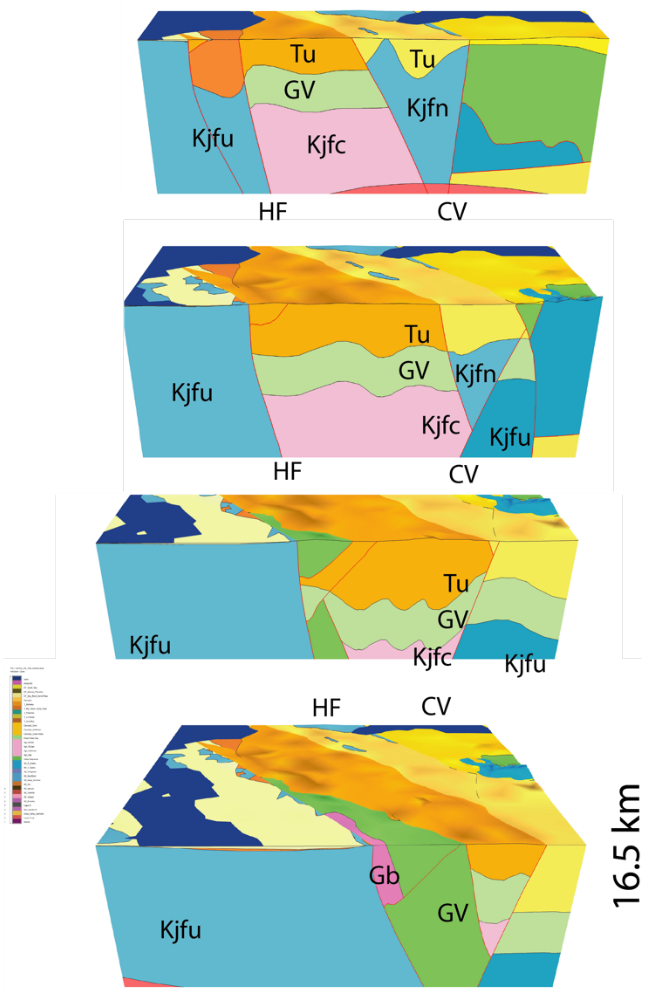


Velocities assigned to geologic units by Brocher's (2008) rules

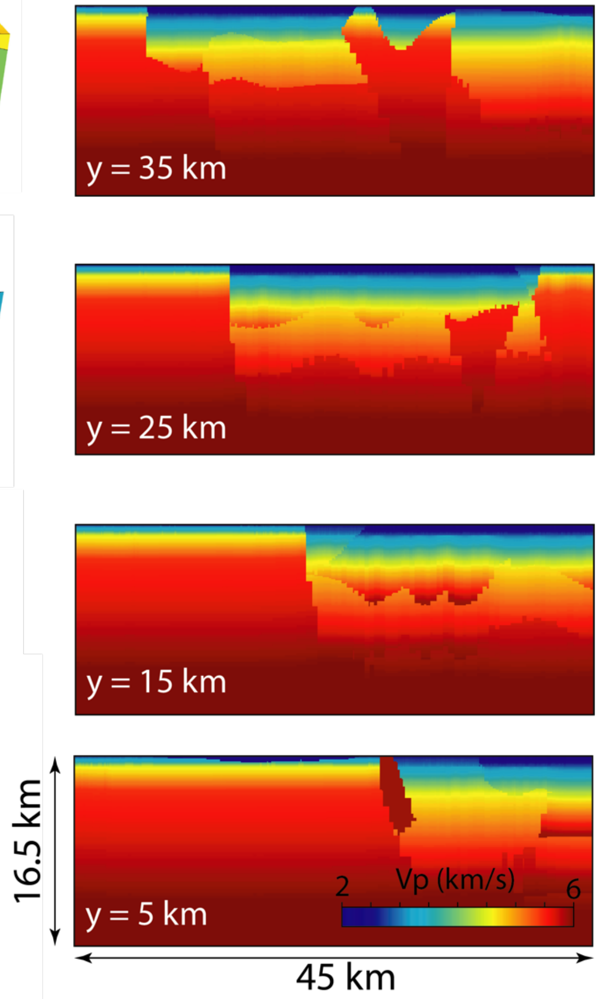




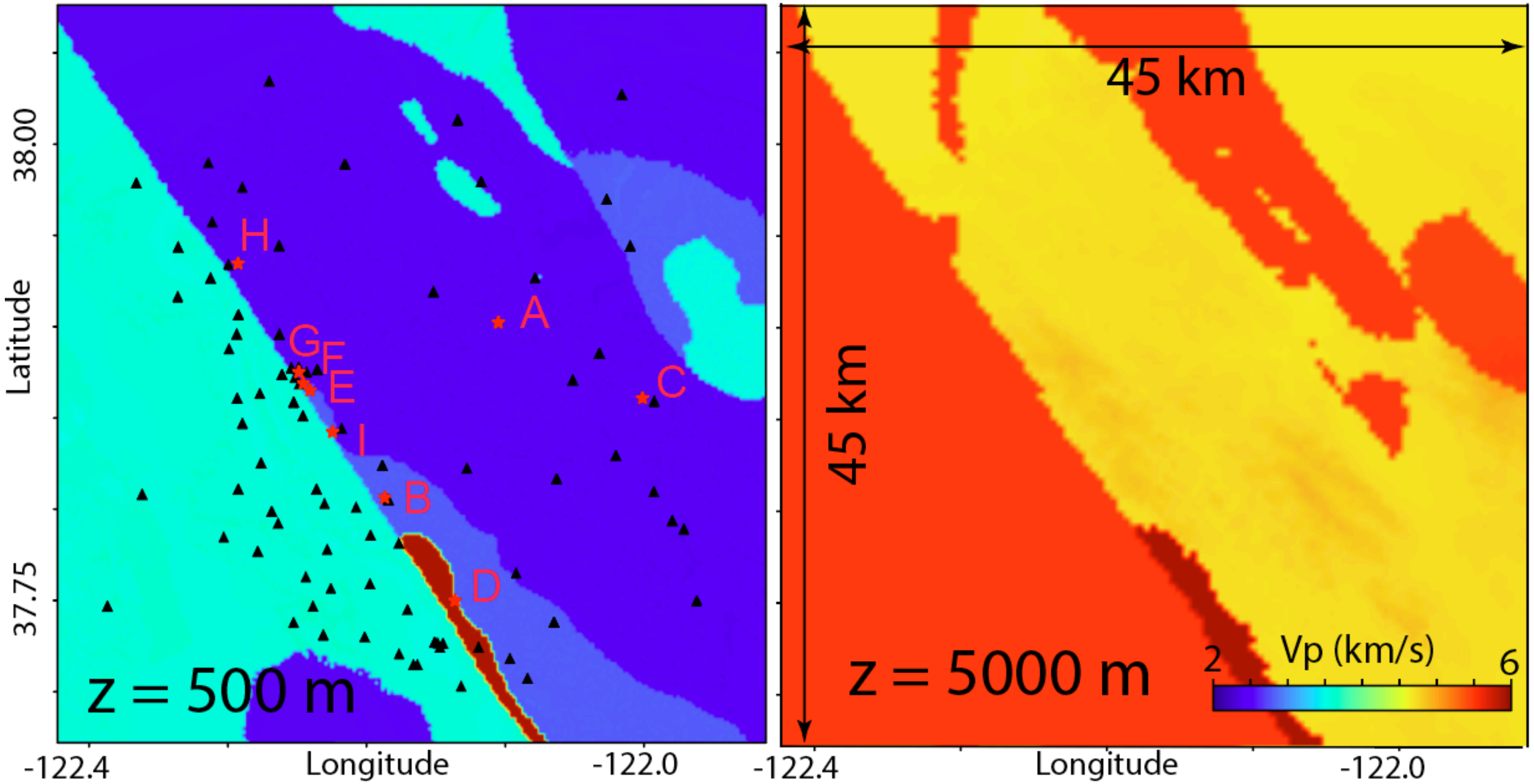
Geologic Model



Velocity Model

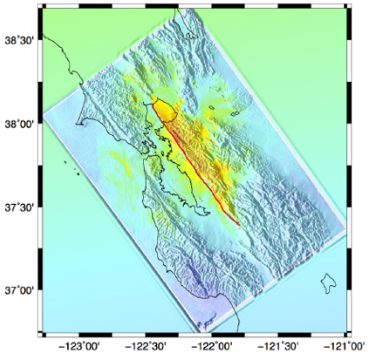


Velocity Model Evaluation with Numerical Simulations



- Simulation of moderate events with SW4 – 4th order anelastic wave propagation code
- Focus on East Bay, Hayward fault area; 45 km^2 domain, 17 km deep
- No topography (squashing)
- Minimum Vs is 500 m/s
- Data from BK, NC, NP, GS stations
- Filtered at 7 - 2 seconds

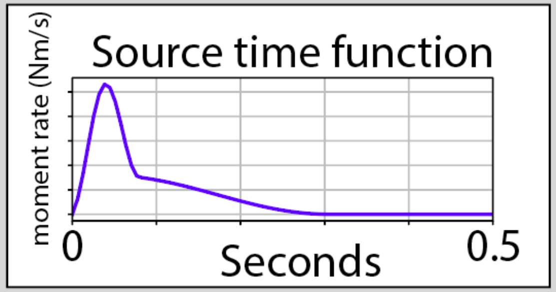
SW4



LLNL, Petersson, Sjogreen

Simulated events

	Date	Mw	depth (km)
A	03/02/07	4.23	14.3
B	07/20/07	4.20	4.1
C	09/06/08	4.10	13.2
D	08/24/11	3.60	7.8
E	10/20/11	3.95	8.5
F	10/21/11	3.84	8.2
G	10/27/11	3.62	7.9
H	03/05/12	4.00	8.0
I	08/17/15	4.01	4.6

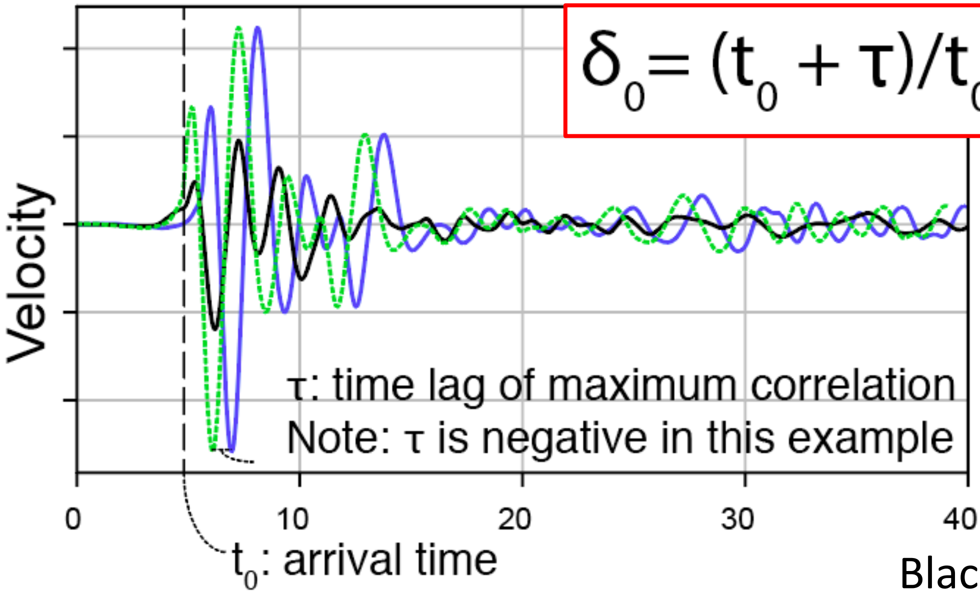


Liu (2006) source time function

Performance Metrics

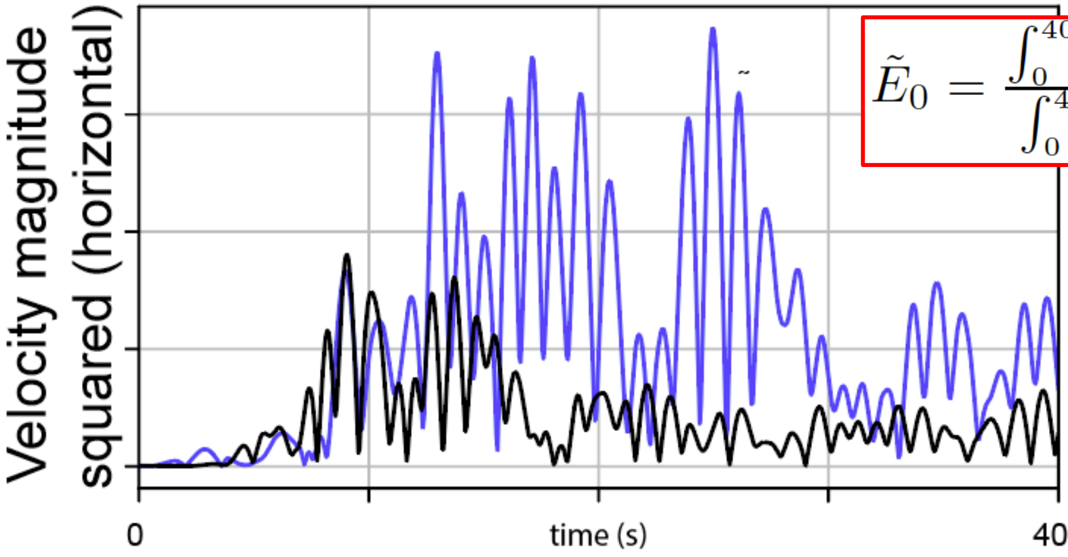
Normalized travel time residual (or velocity ratio)

$$\delta_0 = (t_0 + \tau)/t_0$$



Relative Energy

$$\tilde{E}_0 = \frac{\int_0^{40} V_{H,model}^2(t)}{\int_0^{40} V_{H,data}^2(t)} dt$$

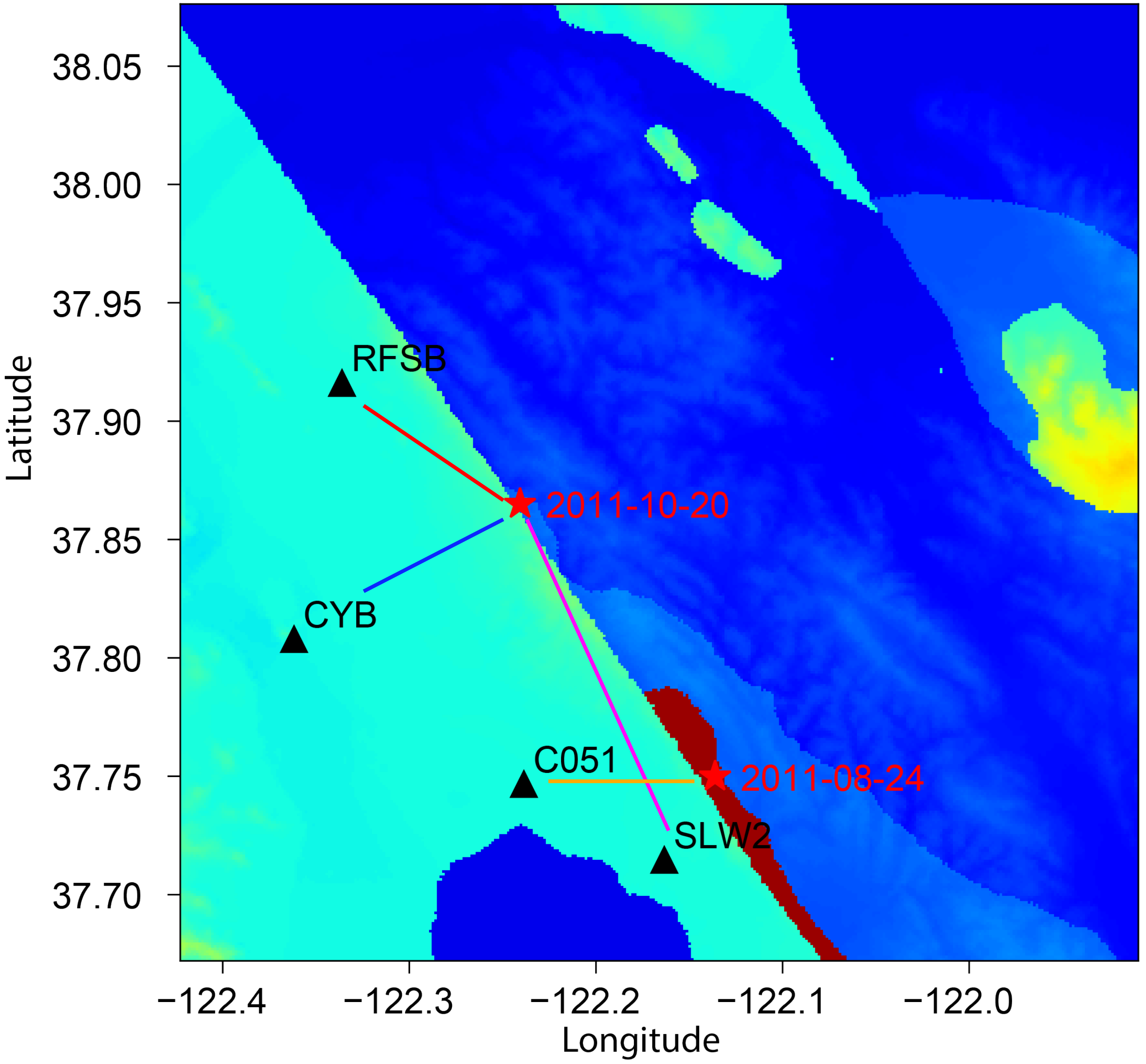


Black: data; blue: synthetics; dashed green: time shifted synthetic

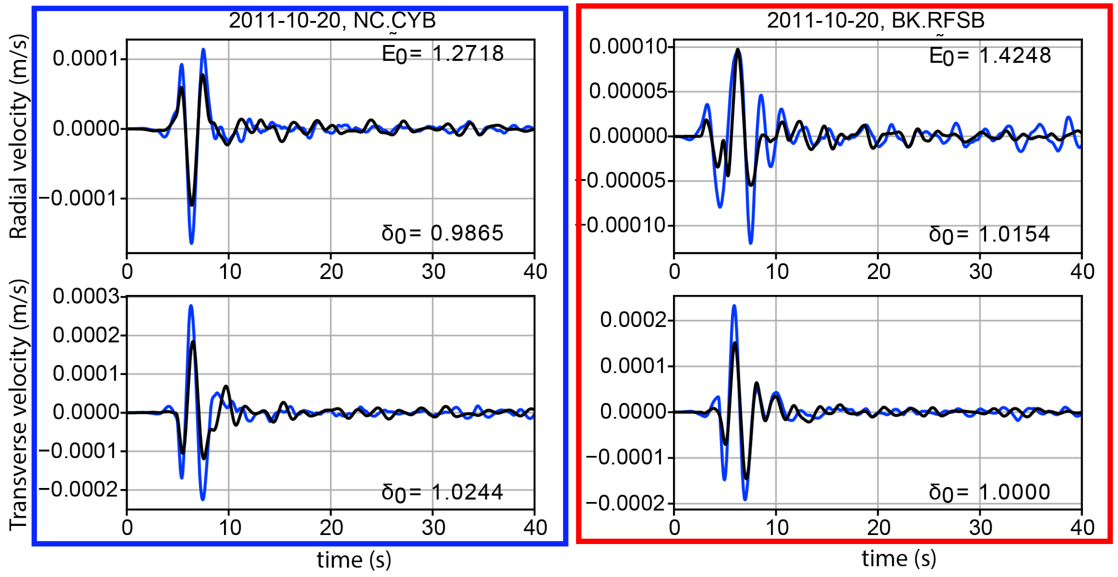
- Note that $r/(t_0+tau) = V_{obs}$; $r/t_0 = V_{synthetic}$ (where r is source-station distance)
- So $delta_0 = (t_0+tau)/t_0 = V_{synthetic}/V_{obs}$, is a measure of "velocity error"
- For example, $delta_0 = 0.9$ implies the velocity of the synthetic is 90% of apparent true velocity

- Ratio of integrals of squared horizontal velocities (synthetic/data)
- For example $E_0 = 0.9$ means the model underestimates kinetic energy by 10%
- Note that for now this does not distinguish between main arrival and coda

Simulation Results

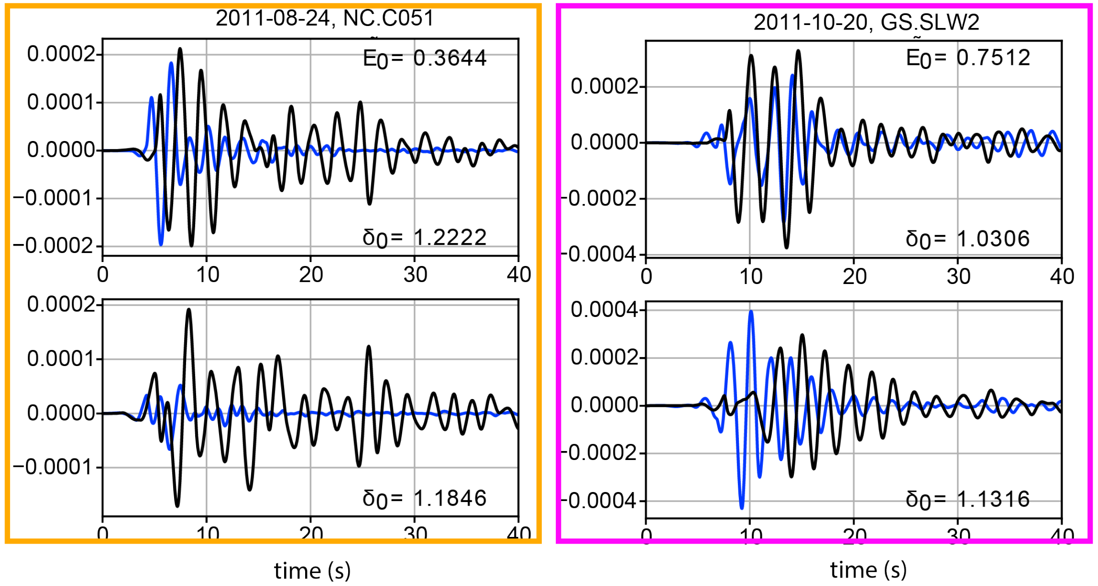


Synthetics fit data well

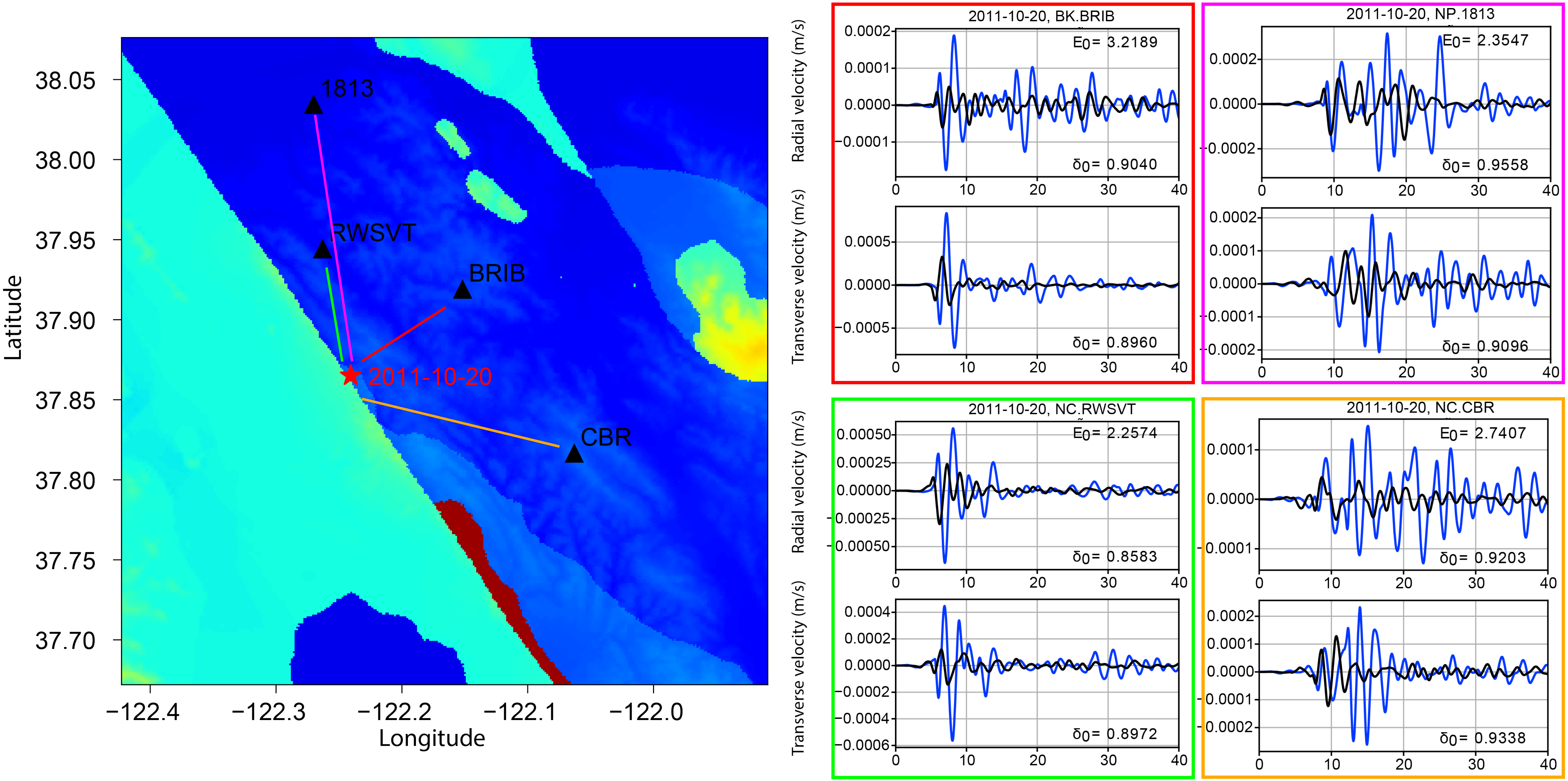


Black: data; blue: synthetics

Synthetics are too fast, missing coda motions

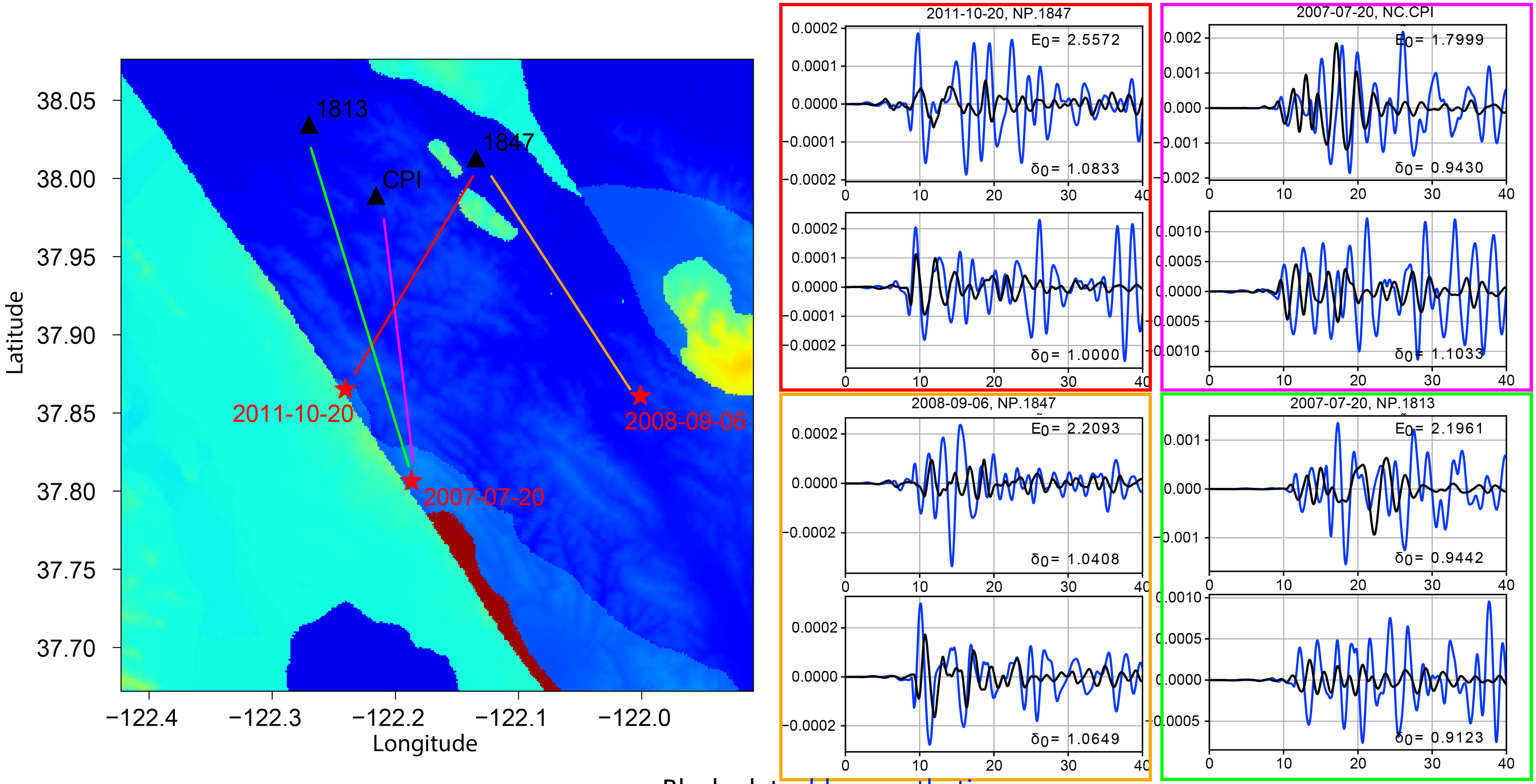


Synthetics are too slow (δ_0<1)

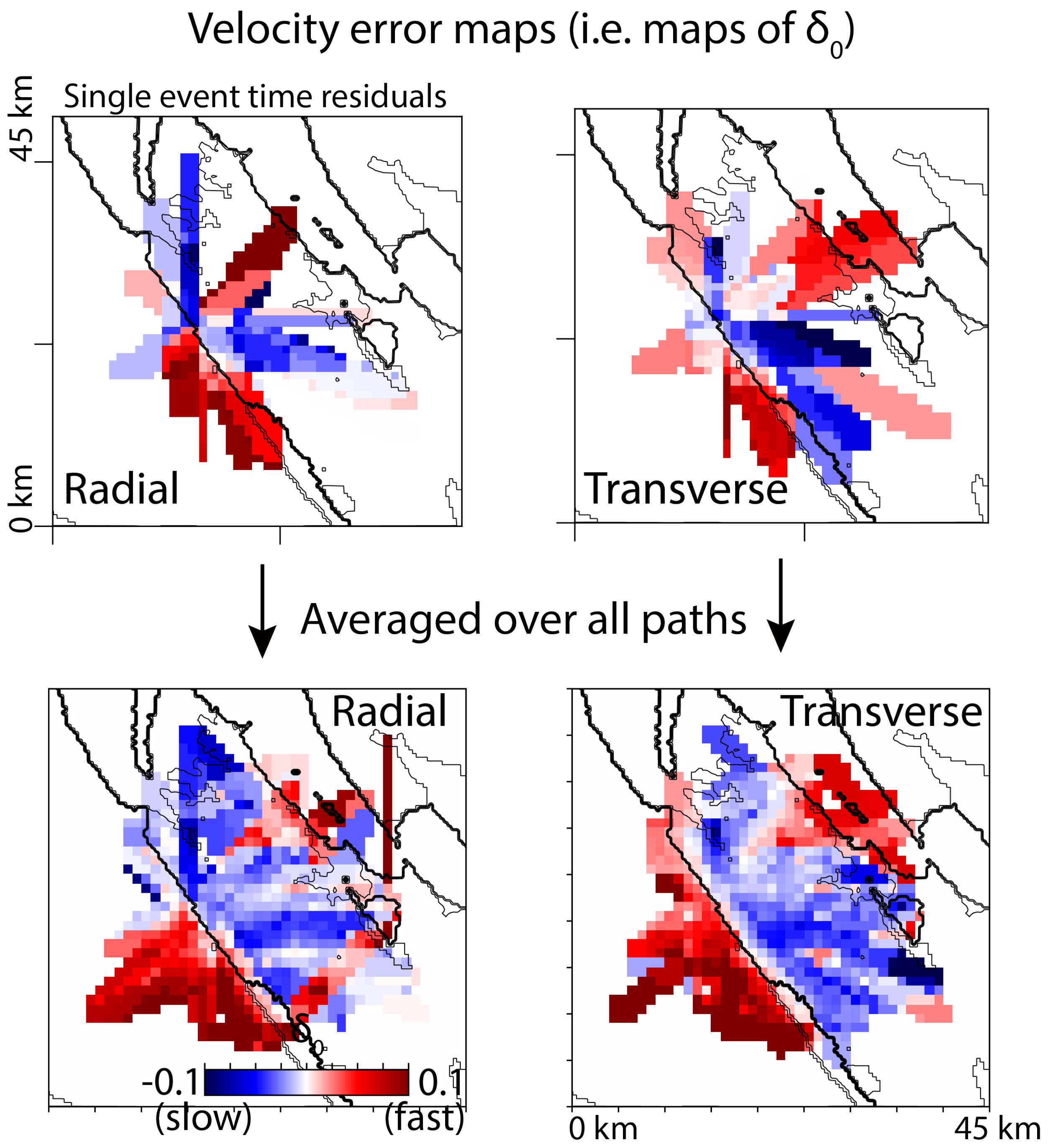


Black: data; blue: synthetics

Synthetics overestimate reverberations ($E_0 > 1$)



Black: data; blue: synthetics

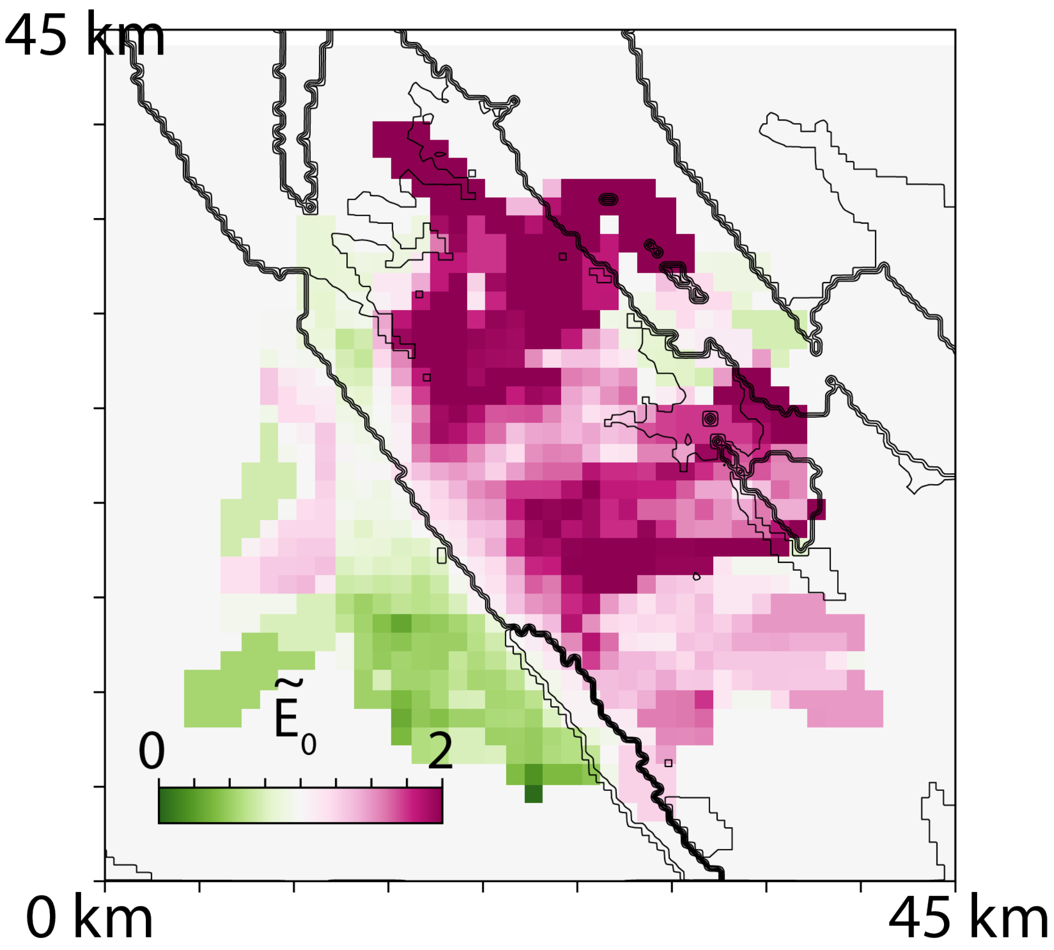


Summarize results over all paths

- Create relatively coarse grid (1 km cells)
- Does source-station path go through cell?
- Color that cell with value of delta0
- Average over all source-station paths

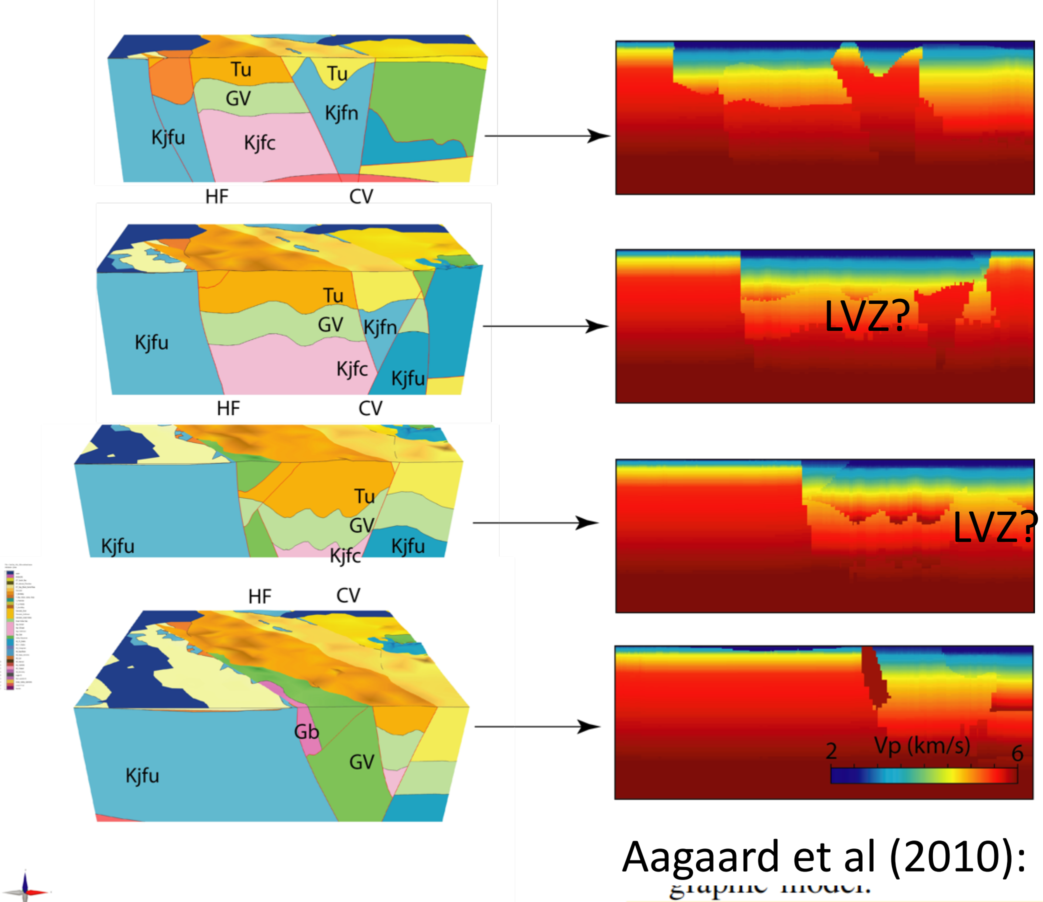
- High velocities in Franciscan west of Hayward fault, specifically in southern portion of simulation domain (near San Leandro)
- Velocities too high near Franciscan wedge (Napa-Sonoma unit)
- Velocities too low in Berkeley Hills, immediately east of Hayward Fault

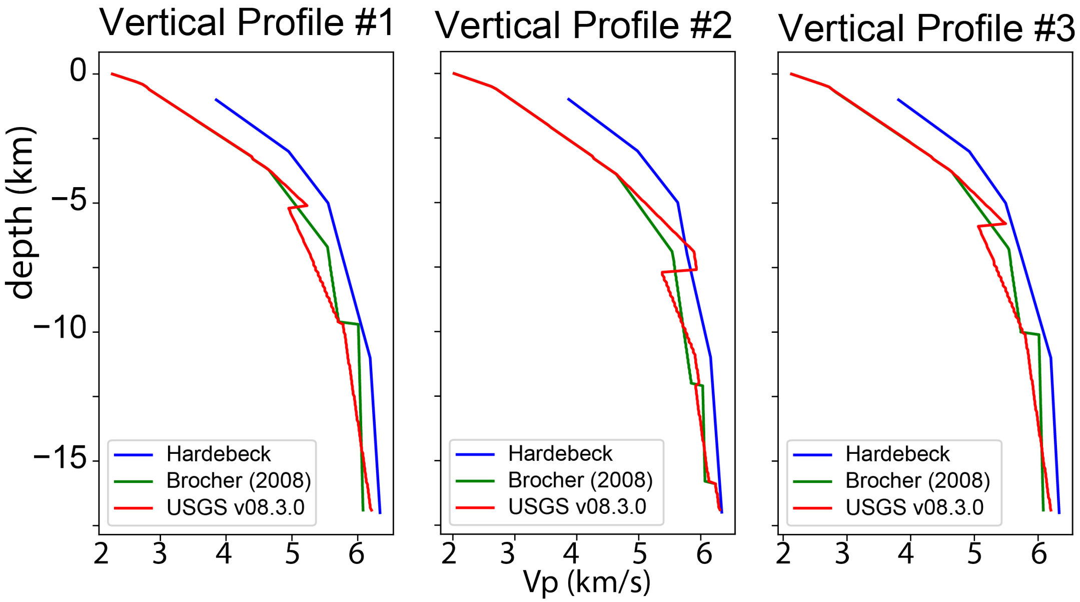
Similar map of energy ratio (E0)



- Remember that E0 > 1.0 (pink on the map) indicates that synthetics have too much kinetic energy, E0 < 1.0 (green) means not enough
- E0 is large between N. Hayward Fault, Franciscan wedge (Napa-Sonoma unit)
- E0 is small west of Hayward Fault (near San Leandro)

Closer look at current USGS velocity model





Brocher (2008):

sonic velocities than their Cenozoic counterparts. For depths between 0.05 and 4 km, I propose that a higher Vp be used for the rocks in the Great Valley Sequence:

$$Vp(\text{km/sec}) = 2.75 + 0.4725z. \qquad (12)$$

Misfits predicted by equation 7 for these well log data have a standard deviation of 0.44 km/sec. Equations 8 and 9 should be used to calculate the Vp of Great Valley Sequence rocks located at depths greater than 4 km. These equations were

Aagaard et al (2010):

graphic model.

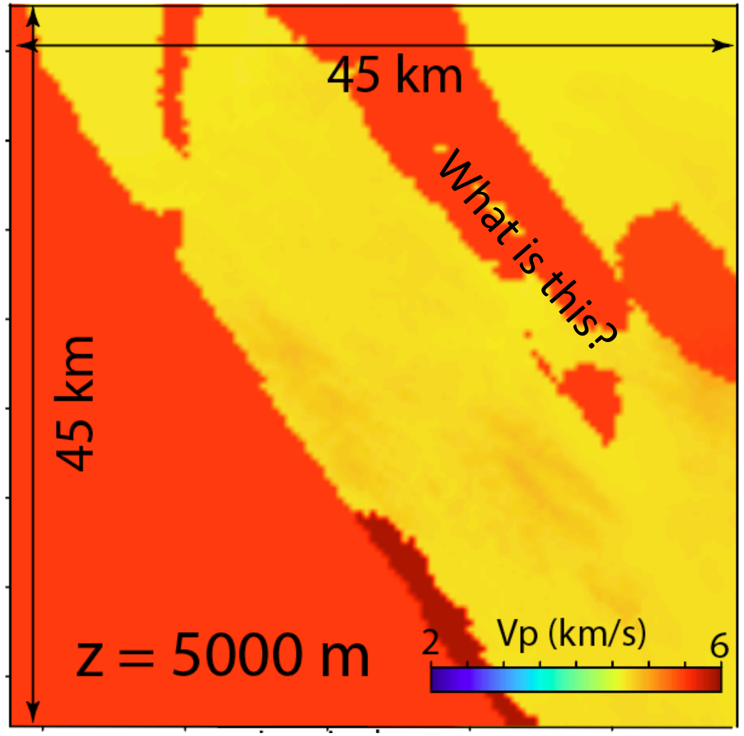
5. For Great Valley sequence units below 3 km, the velocities honor the Thurber *et al.* (2007) tomographic model.
6. For Tertiary-Cenozoic sedimentary units at depths above 750 m, we attempted to honor the V_P relation of Hartzell *et al.* (2006) for the Cupertino basin; otherwise, above 4 km depth, the wave speeds honor the sonic well log data (Brocher, 2005), which are considered more reliable than tomography at these depths; below 4 km the wave speeds honor the Thurber *et al.* (2007) tomography model.

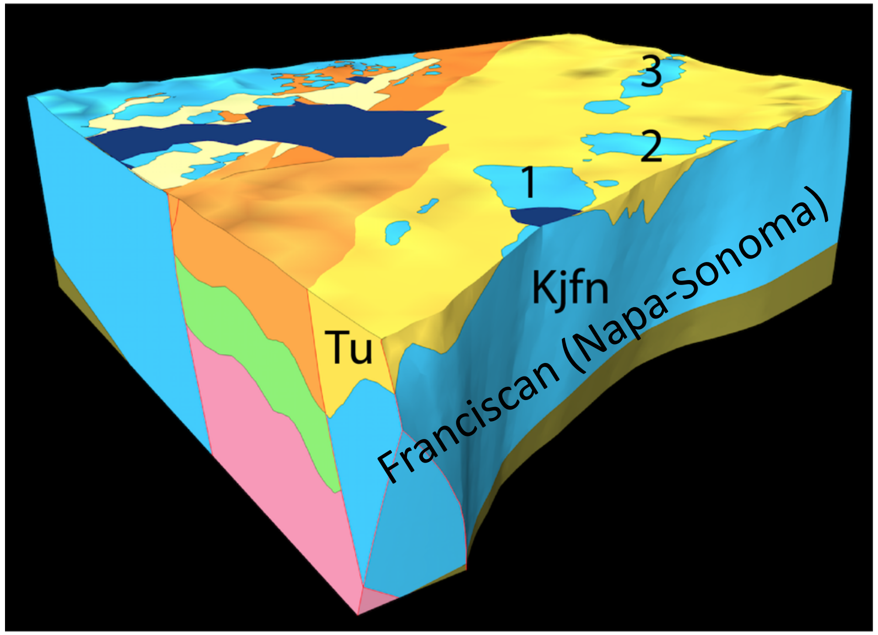
Hartzell et al (2016):

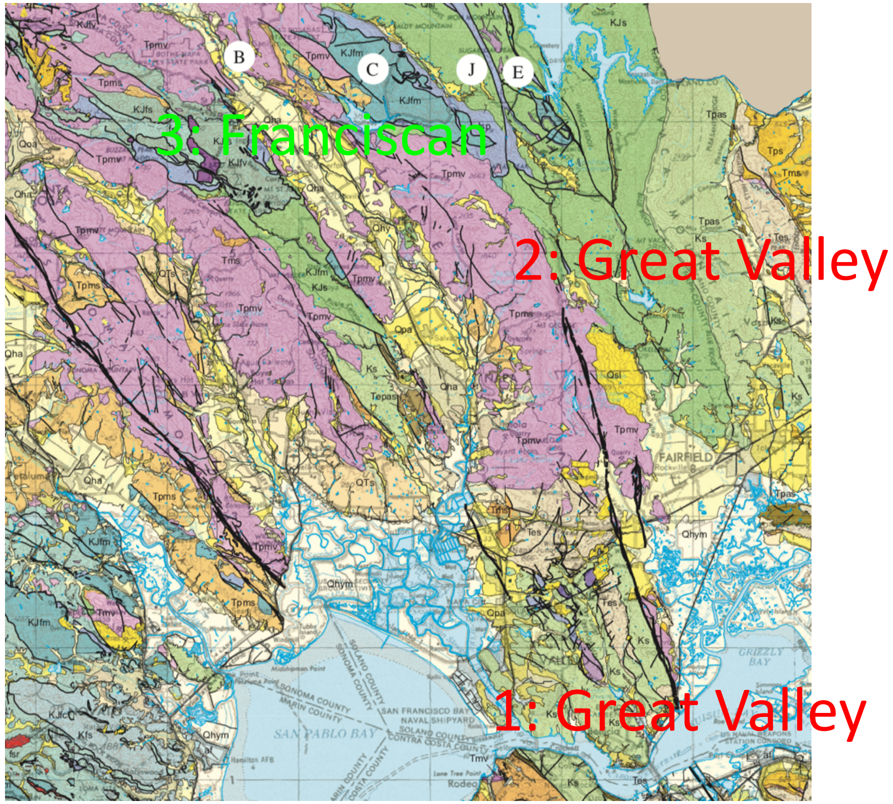
and upper-mantle units in the latest version of the model, v.08.3.0. We use this velocity model with two modifications. First, by examining velocity profiles, we discovered that the velocities of the Great Valley sequence, filling the lower Livermore basin, did not follow the functional relationship of Brocher (2008) for depths greater than 4 km. As a result, there was an unrealistic low-velocity zone below the Livermore basin fill. Replacing with the correct Great Valley sequence velocity profiles corrected this error. Second, we

- Low velocity layer does not show up in tomographic model
- In version 08.3.0, are the rules correctly applied?
- What about previous version (v05)?

Looking at geologic maps







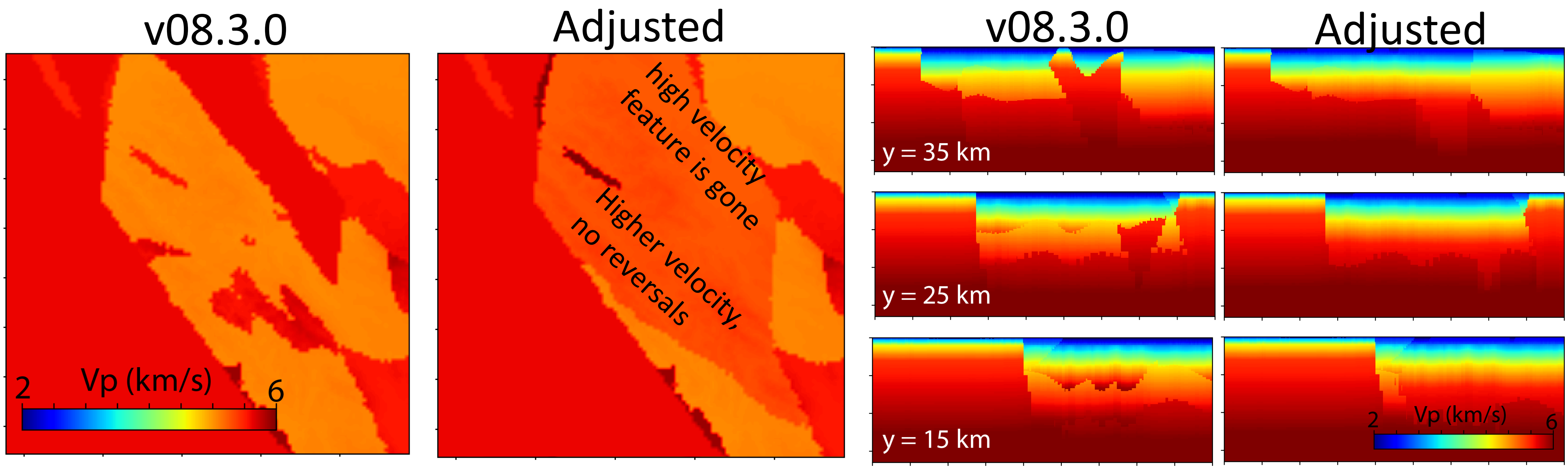
- Are large reflections and reverberations in synthetics due to high velocity tabular feature?

- This feature is the Franciscan unit of the Napa-Sonoma block.

- There are some surface exposures of this unit in the geologic model, are they on the map?

- Some of the surface exposures of Napa Franciscan appear to actually be Great Valley sequence on geologic map (Graymer et al 2006). Franciscan rocks outcrop further north.

Model Adjustments



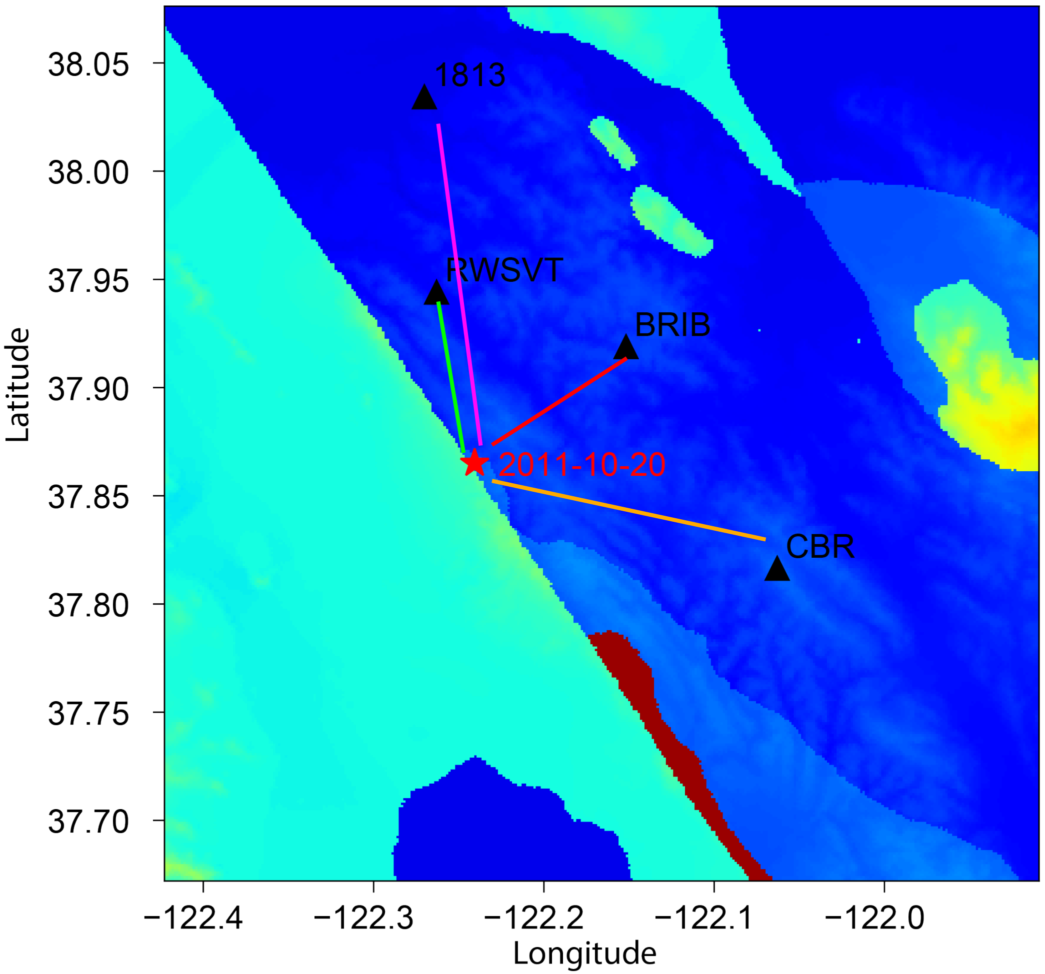
Adjustment 1: Removal of low velocity layer

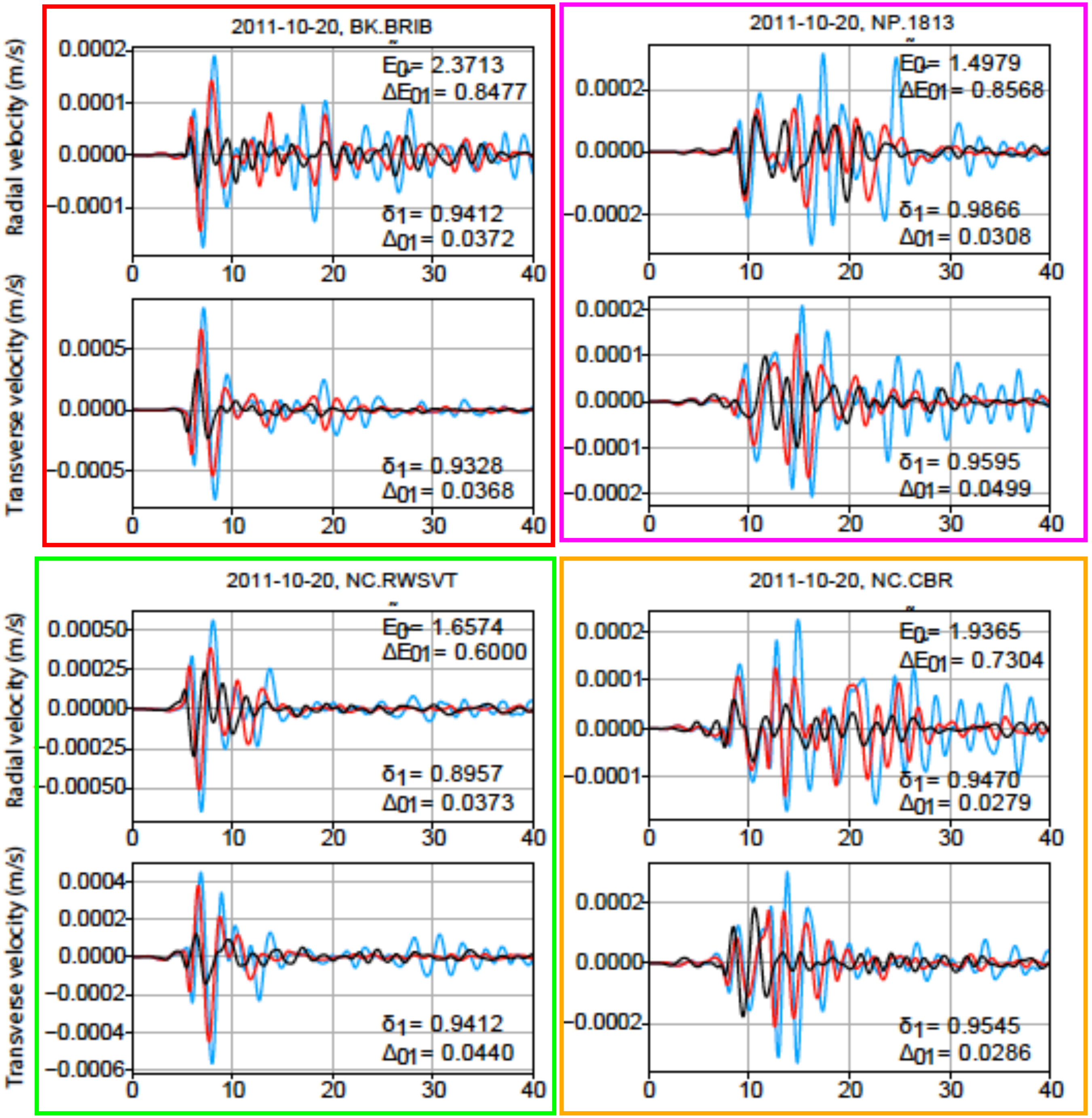
- Use Brocher (2008) rules (equations 8 and 9) for both Cenozoic and Great Valley Sequence below 4 km.
- This rule uses the same equation for both rocks, gives a constant gradient

Adjustment 2: Removal of high velocity feature

- Guess that Franciscan (Napa-Sonoma) is actually Cenozoic or Great Valley Sequence in this domain
- Apply equations 8 and 9 from Brocher (2008)

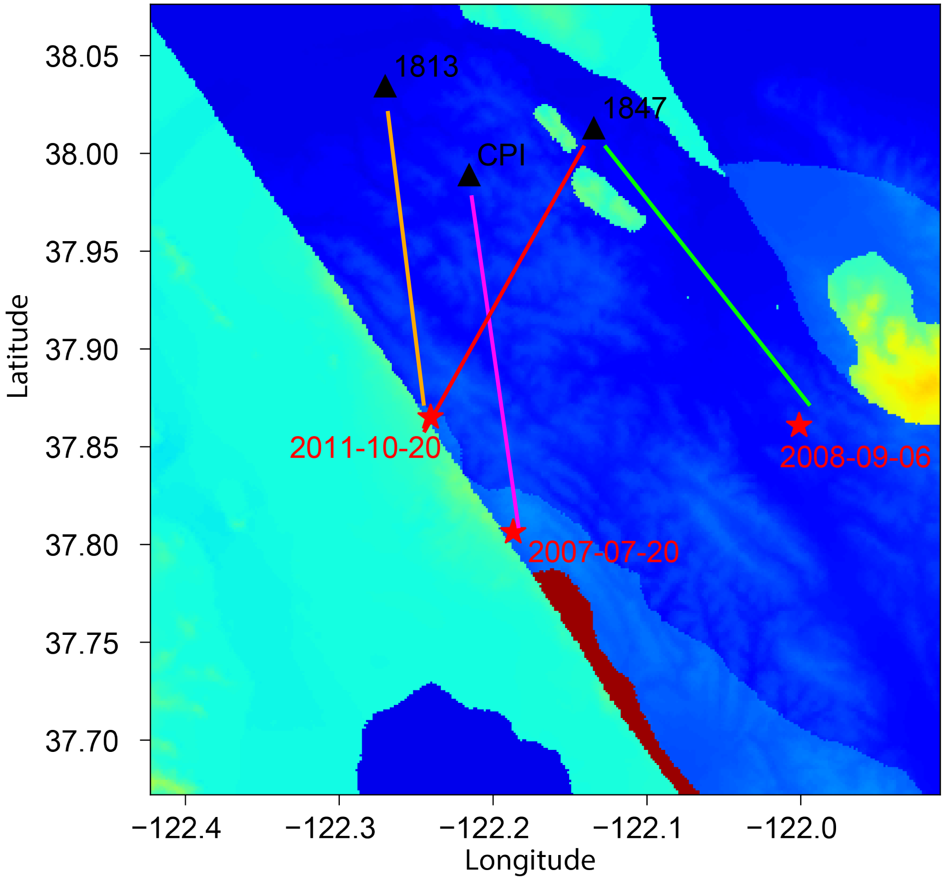
Some improvements in arrival time

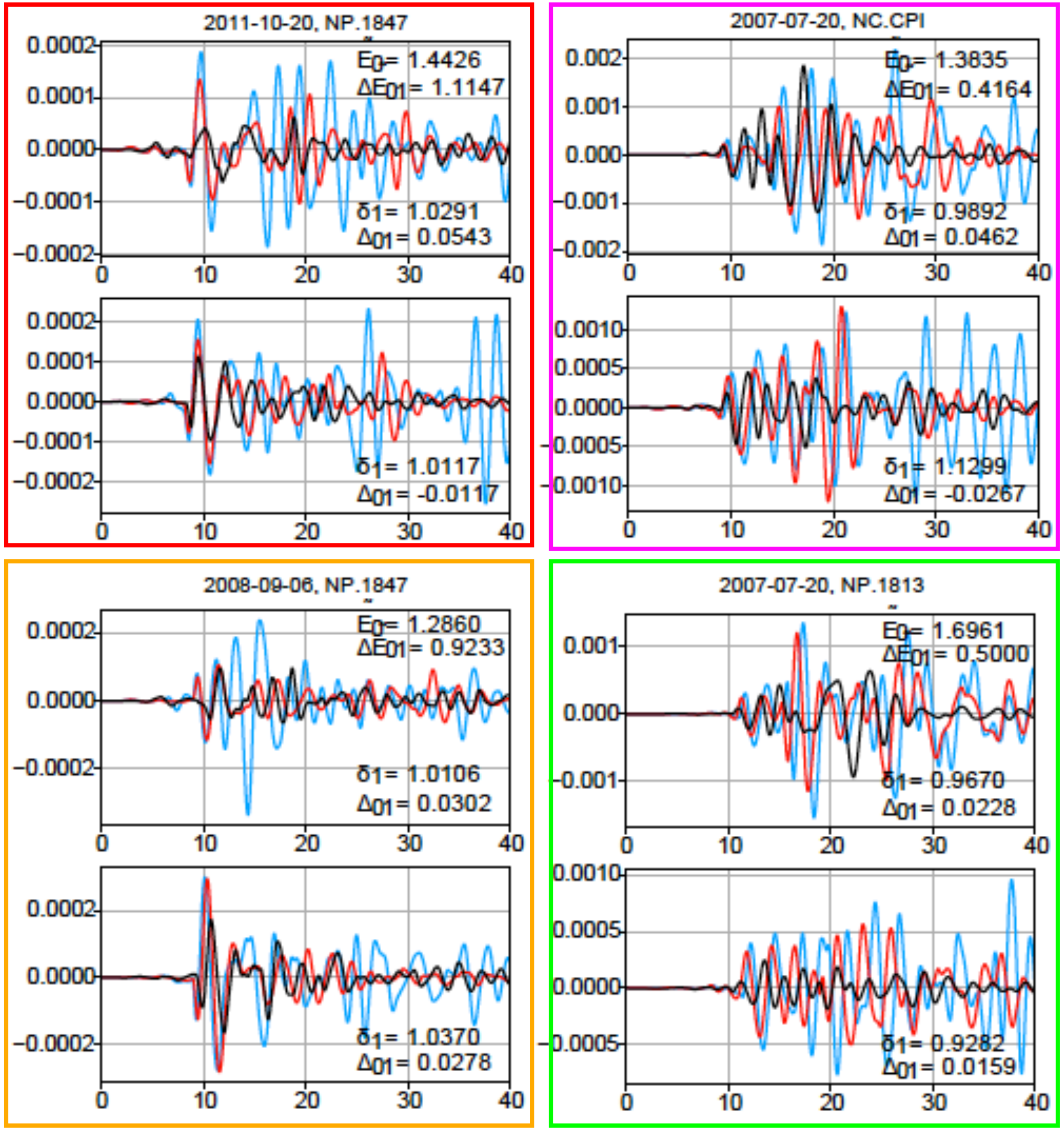




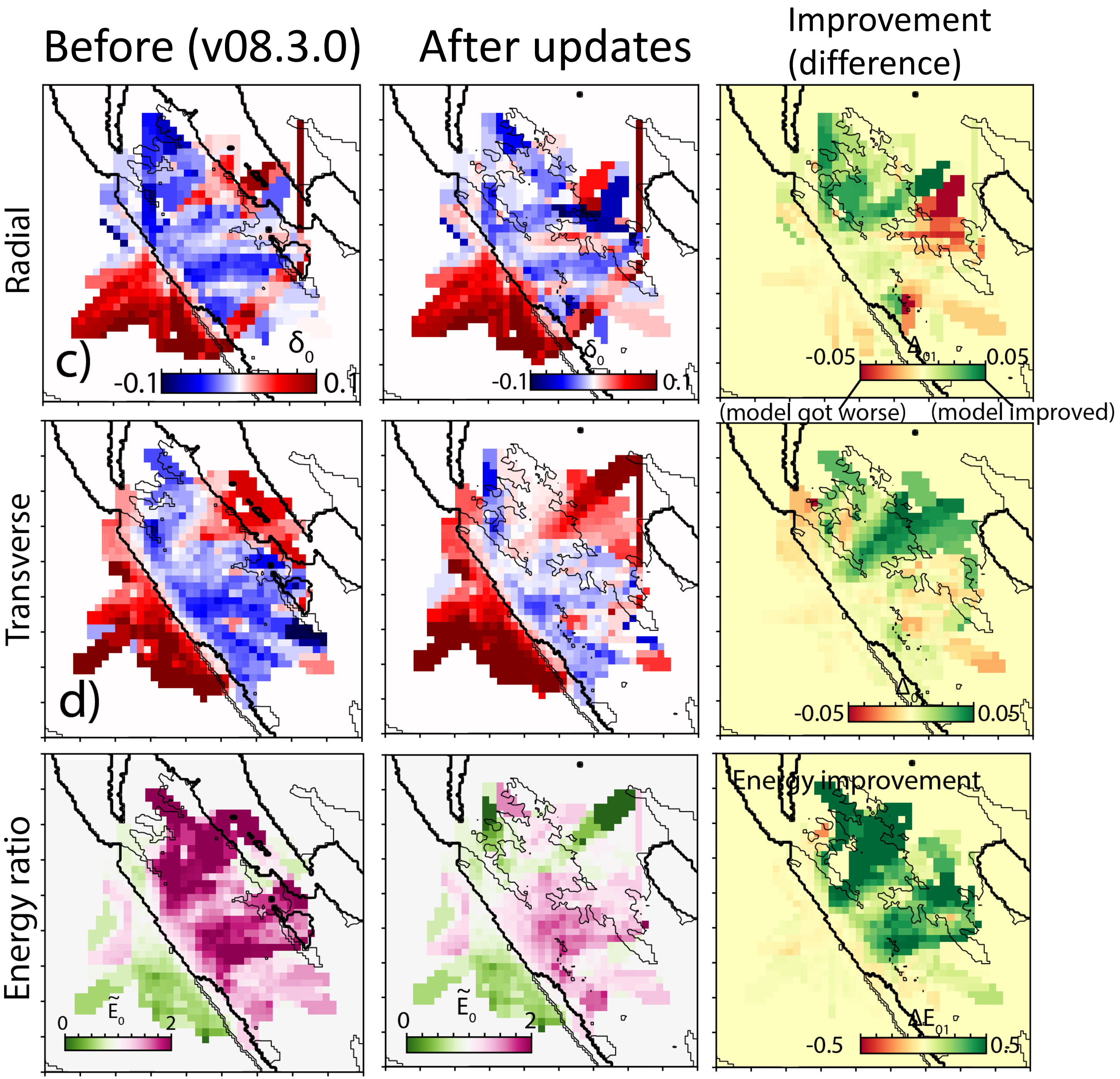
Black: data; blue: synthetics (v08.3.0)
Red: new model synthetics

Significant reduction in coda motions





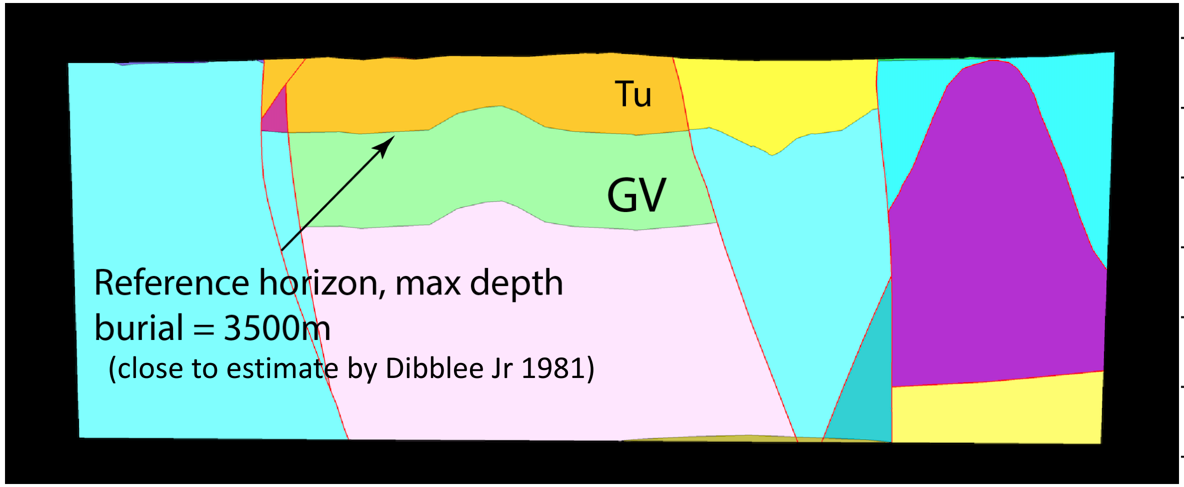
Black: data; blue: synthetics (v08.3.0)
Red: new model synthetics



How did we do overall?

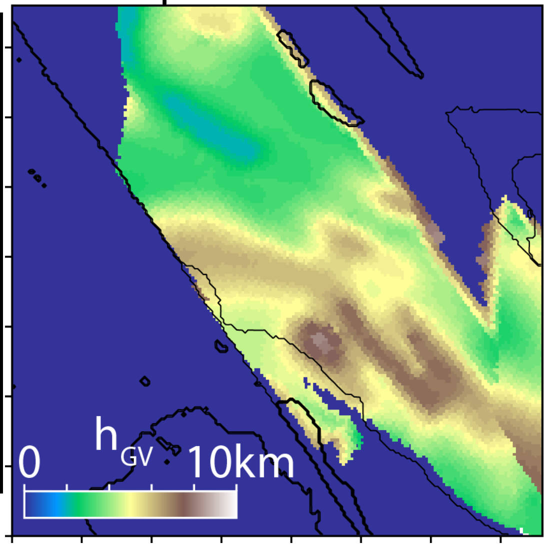
- Velocities (arrival times) improved in some areas to the east of the Hayward fault
- Some areas (colored red on improvement maps) got worse; poor path coverage, bad correlations?
- Energy estimate greatly improved due to removal of high velocity feature

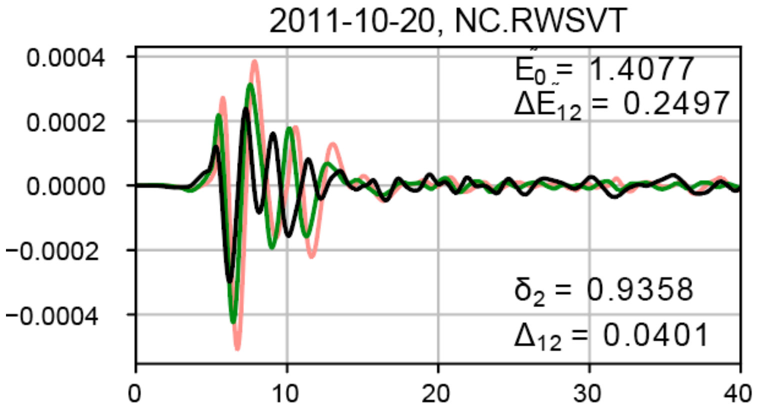
Other ideas: Material that was once deeper may have higher velocities than those calculated with current depths

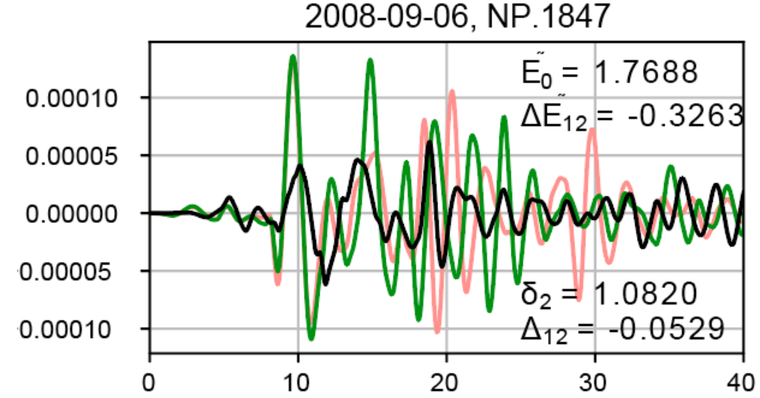


New effective depth for Brocher's rules is maximum depth of burial, assumed from distance to reference horizon

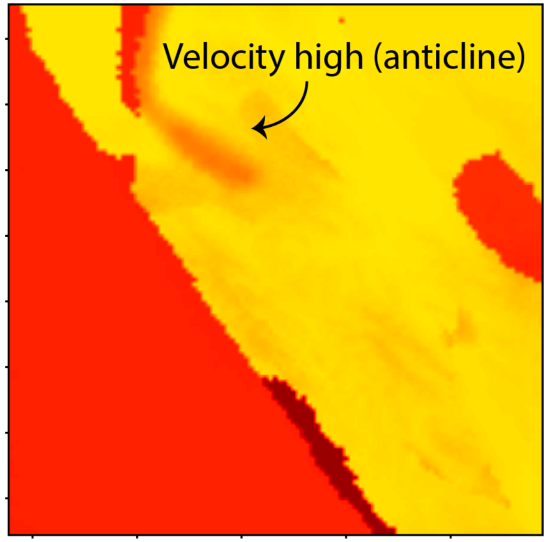
Depth to Horizon

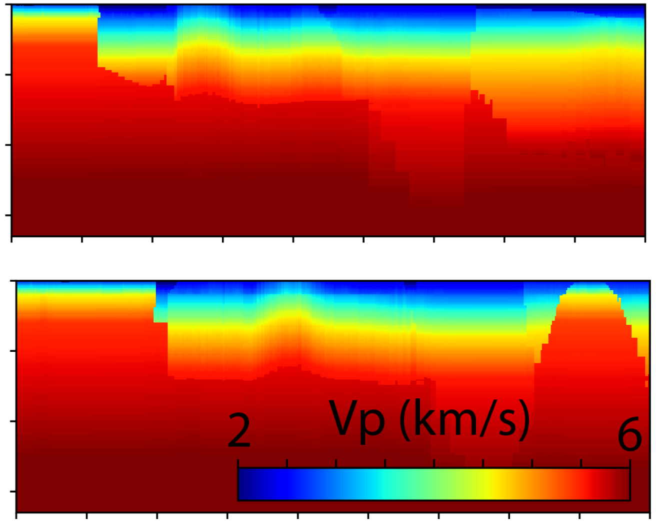




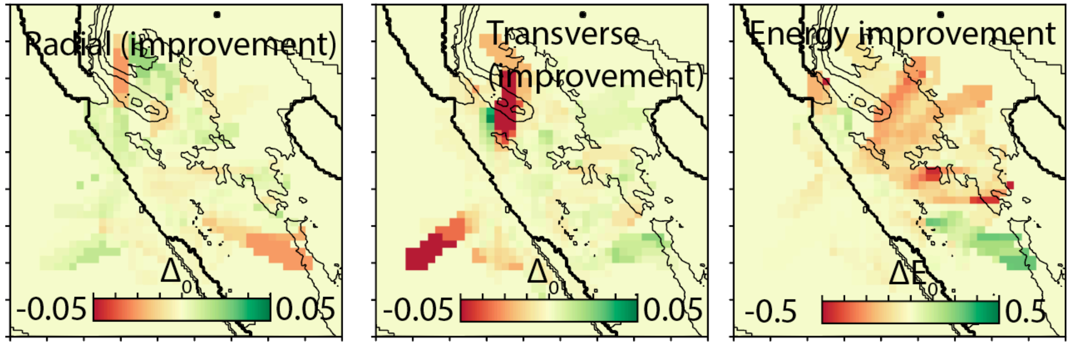


Black: data;
red: synthetics (updated model 1)
green: synthetics (updated model 2)

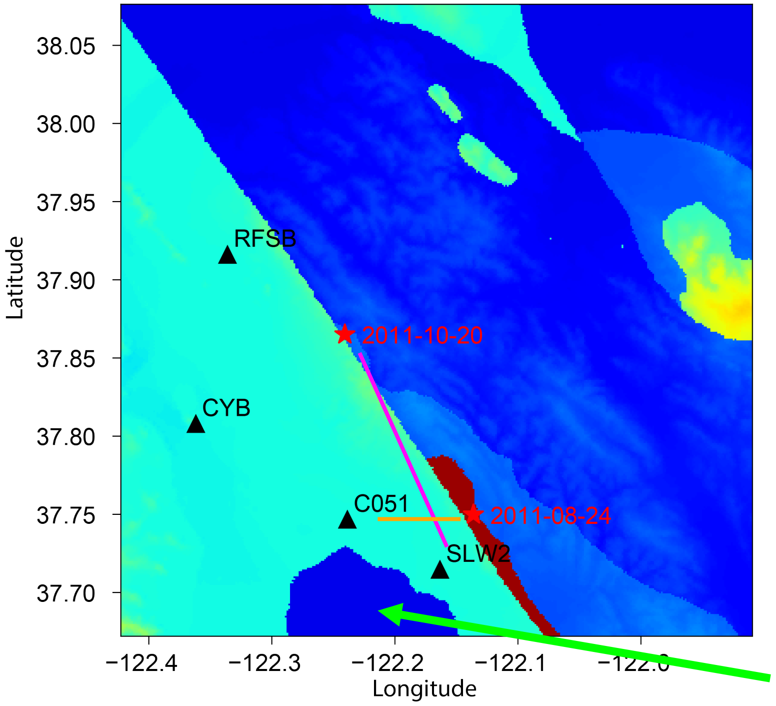




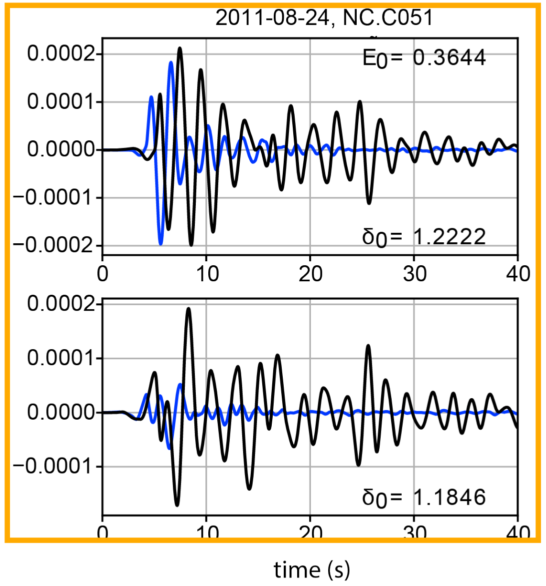
Mixed results so far (some good, some bad)

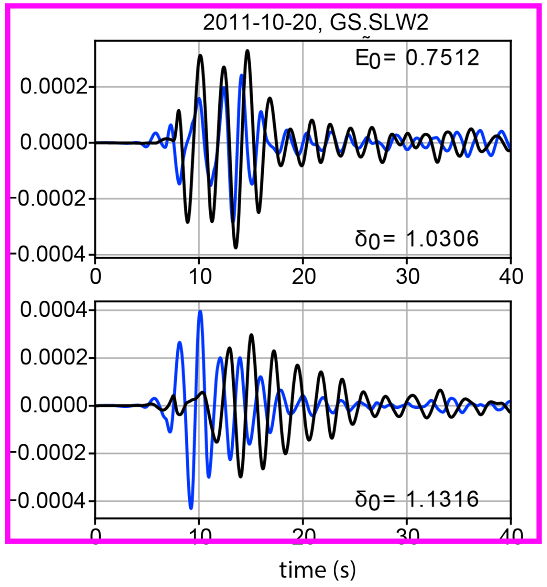


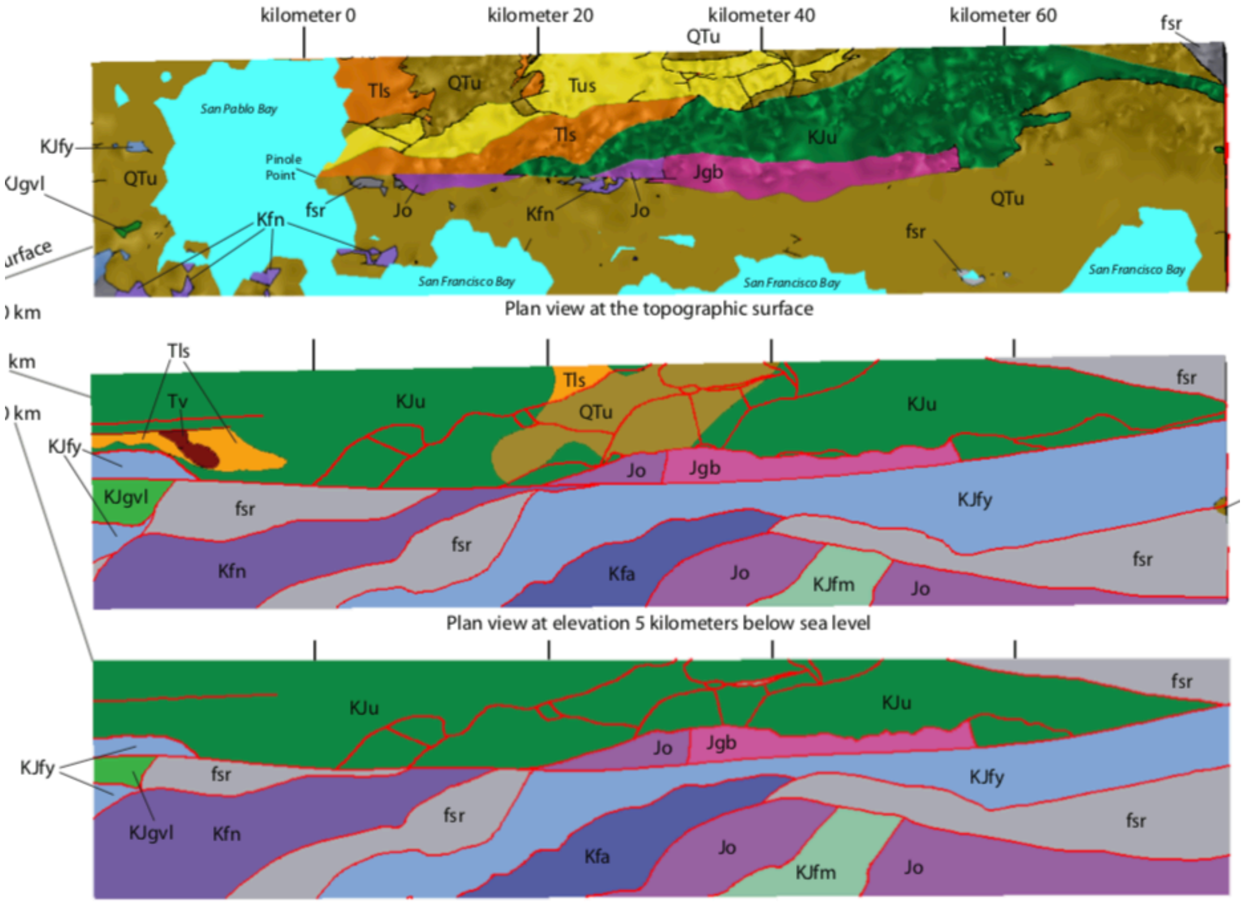
Add more geology, refine geologic model?



Can't ignore San Leandro basin, low velocity sediments (<500 m/s)







Three-Dimensional Geologic Map of the Hayward Fault Zone, San Francisco Bay Region, California

By

G.A. Phelps, R.W. Graymer, R.C. Jachens, D.A. Ponce, R.W. Simpson, and C.M. Wentworth

2008

Summary, Discussion

- Simulation of moderate earthquakes in the East Bay reveal areas where the velocity model needs improvement.
- In some places, velocity rules may have been applied incorrectly (e.g. the low velocity Great Valley Sequence layer), and/or geologic units are possibly mislabeled (e.g. Franciscan Napa-Sonoma block).
- Adjustments to velocities in these units led to noticeable improvements in arrival times and coda duration/energy.

Going Forward…

- We need to more thoroughly document changes between model versions, and what rules were applied where.
- More careful consideration of where to apply velocity rules and where to draw on tomography (e.g. Thurber 2007; Hardebeck 2007).
- More realistic and/or detailed geologic model could help the velocity model.