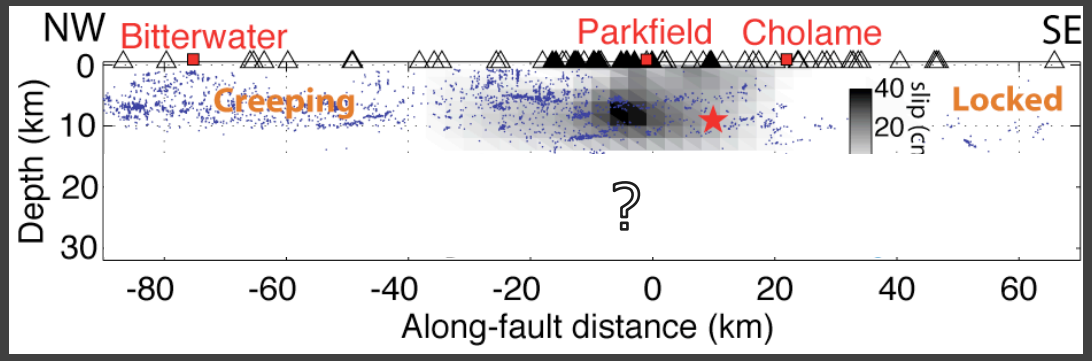
Tectonic Tremor Beneath the San Andreas Fault

Implications for lower crustal deformation



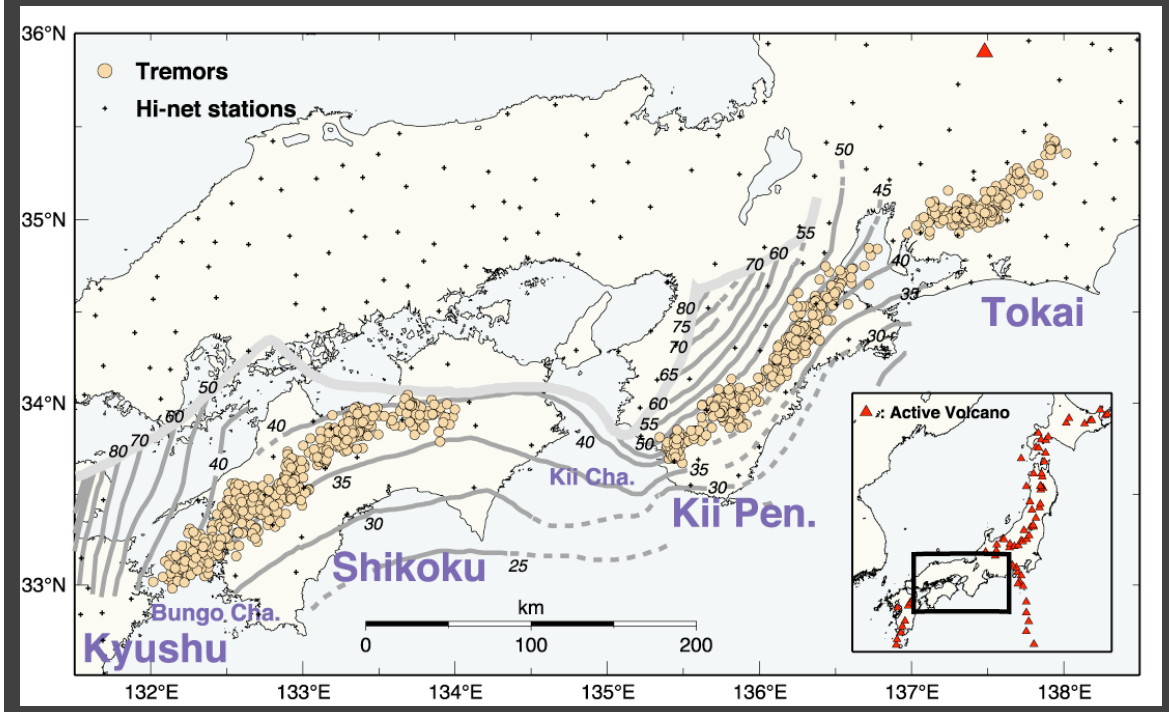
Shelly and Hardebeck, GRL, in press

David R. Shelly
USGS, Menlo Park

USGS science for a changing world

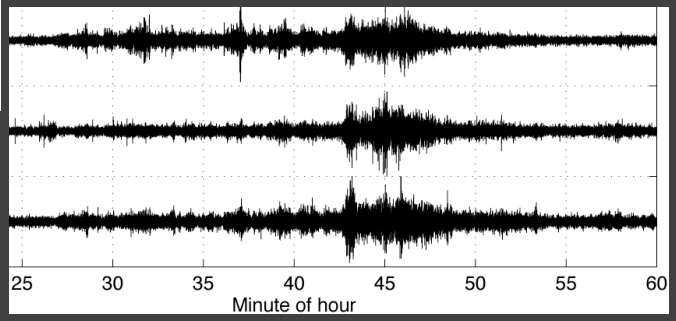
Collaborators:
Jeanne Hardebeck
Gary Fuis
Jessica Murray-Moraleda
Bill Ellsworth
Roland Bürgmann
Bob Nadeau
Greg Beroza

Deep Nonvolcanic Tremor



Obara, *Science*, 2002

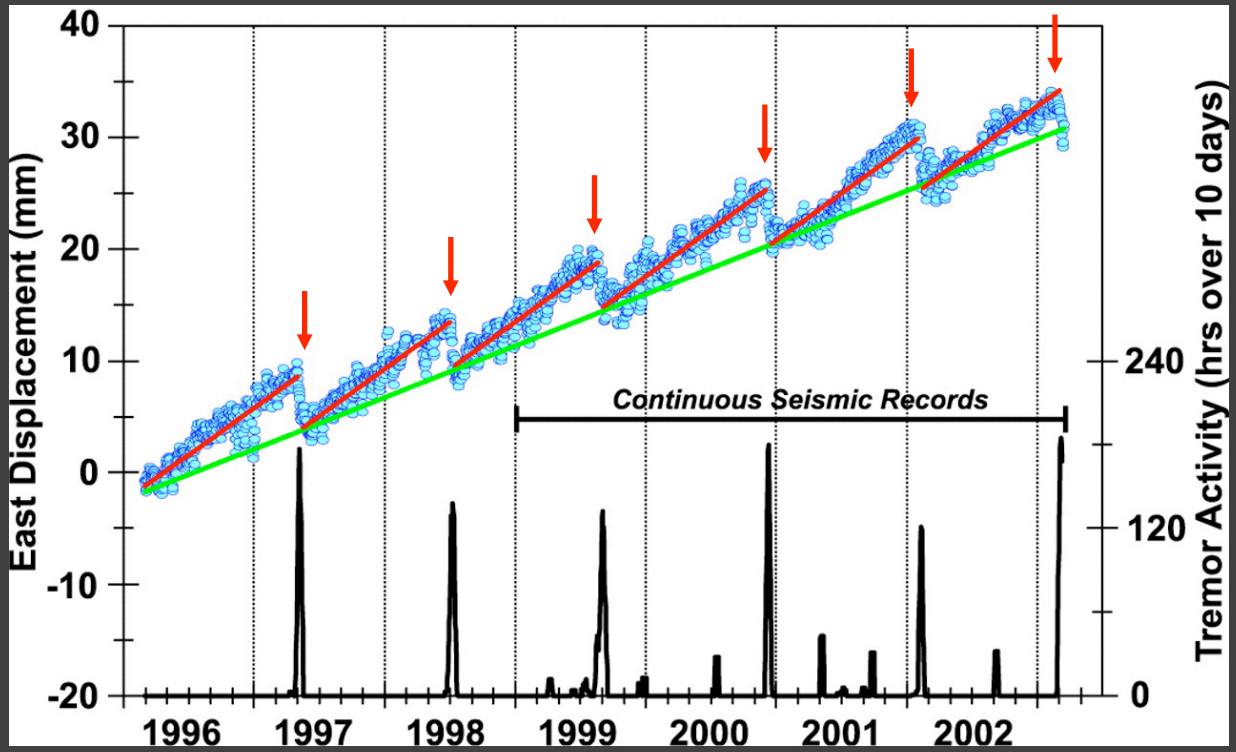
- Tremor associated with subduction
- Corresponds with ~35-40 km depth contour of subducting plate, downdip of "megathrust zone"



Rogers and Dragert, 2003

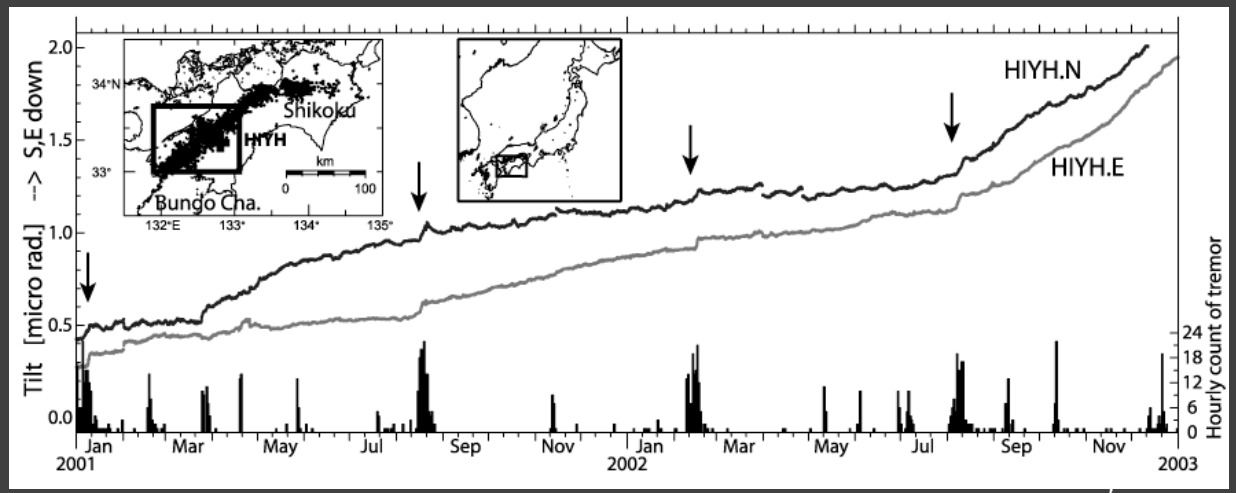
Cascadia

Episodic Tremor and Slip



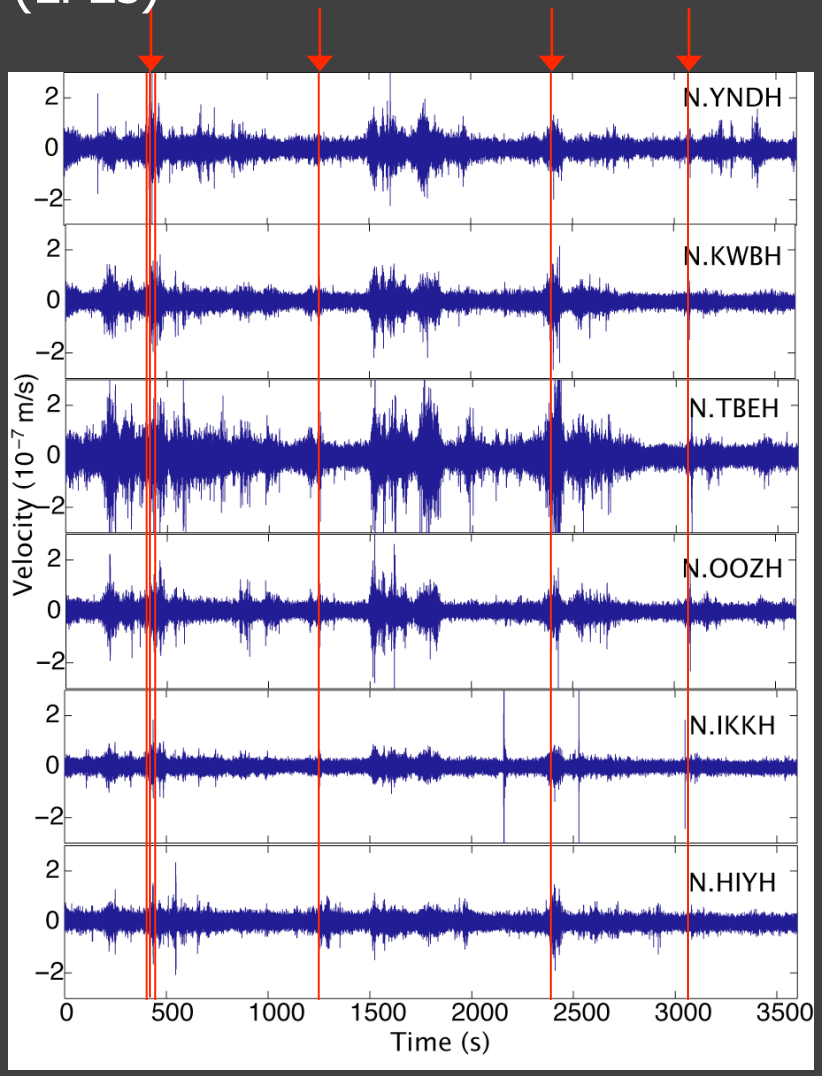
Southwest Japan

Obara *et al.*, 2004



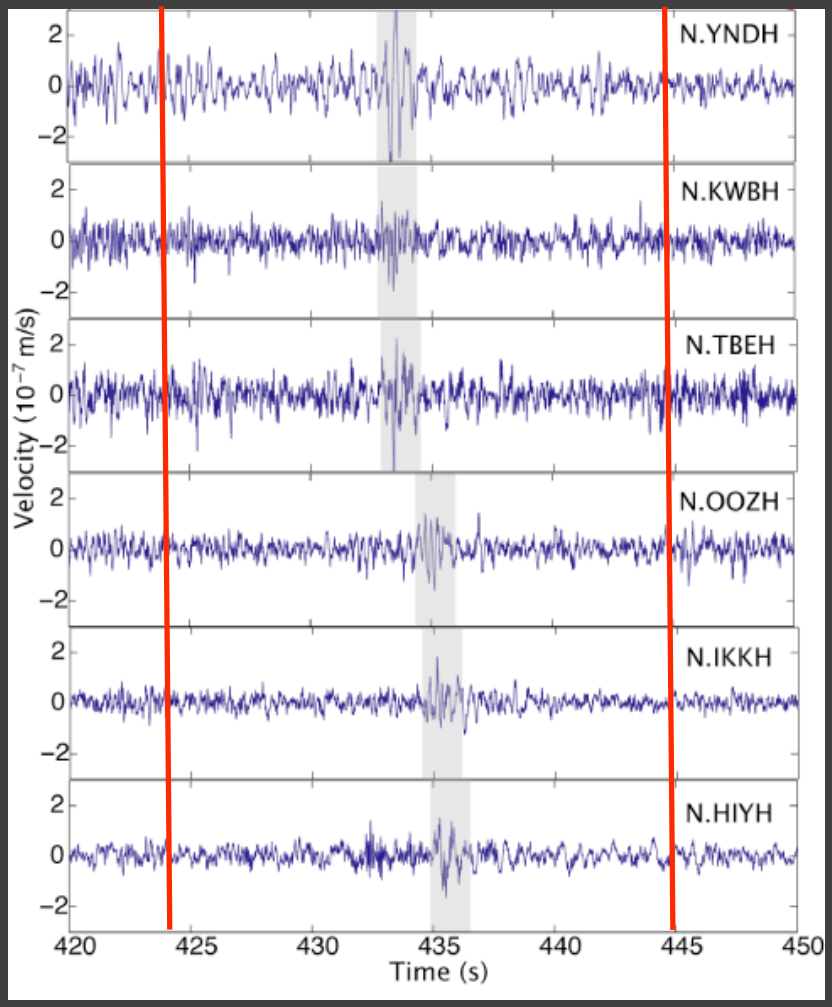
Tremor and LFEs

Low frequency earthquakes (LFEs)



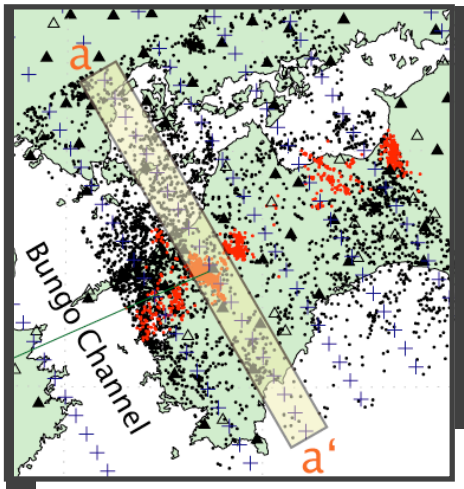
1 hour

S-wave arrival



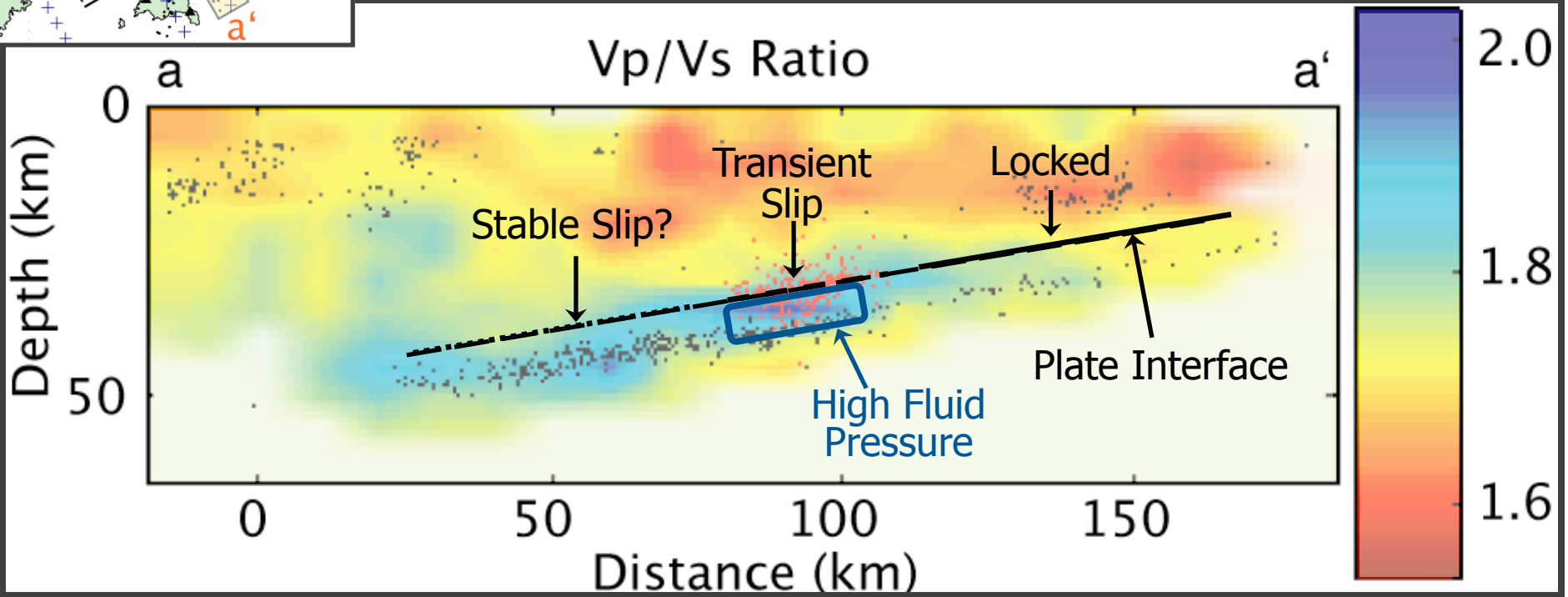
30 sec

Shelly *et al.*, Nature, 2006



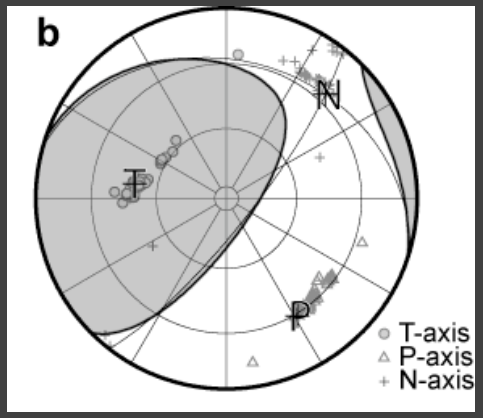
SW Japan:
Tremor located on the plate interface

Shelly *et al.*, Nature, 2006



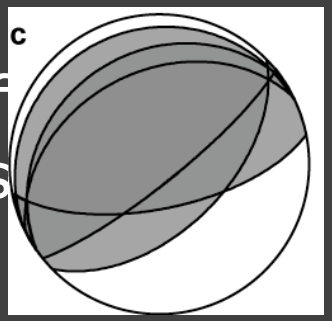
Low-Frequency Earthquake Mechanism

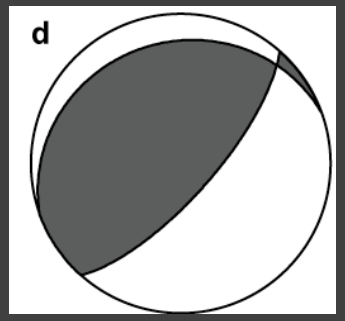
Ide, Shelly, Beroza
GRL, 2007



Empirical moment tensor solution calculated using LFE waveforms

Mechanism of slow slip events

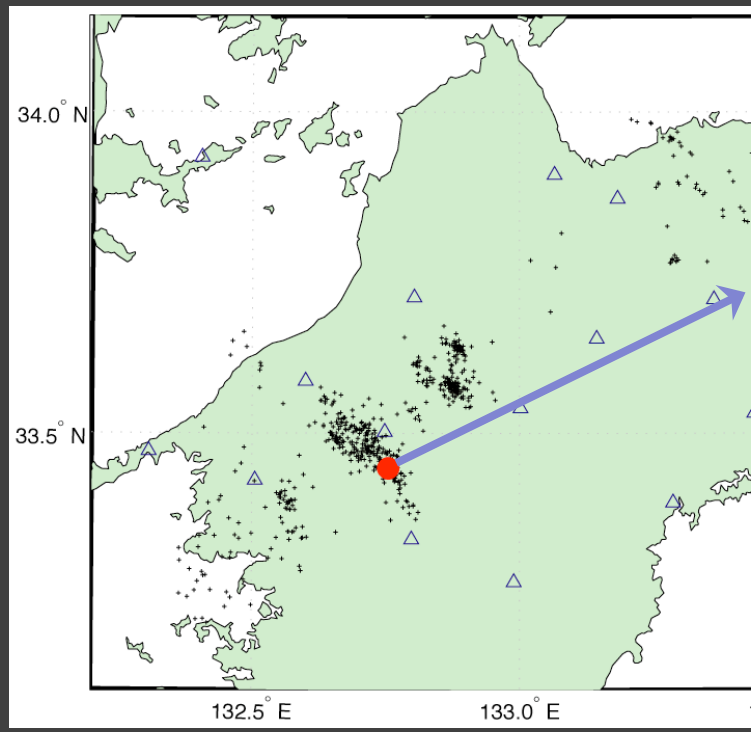


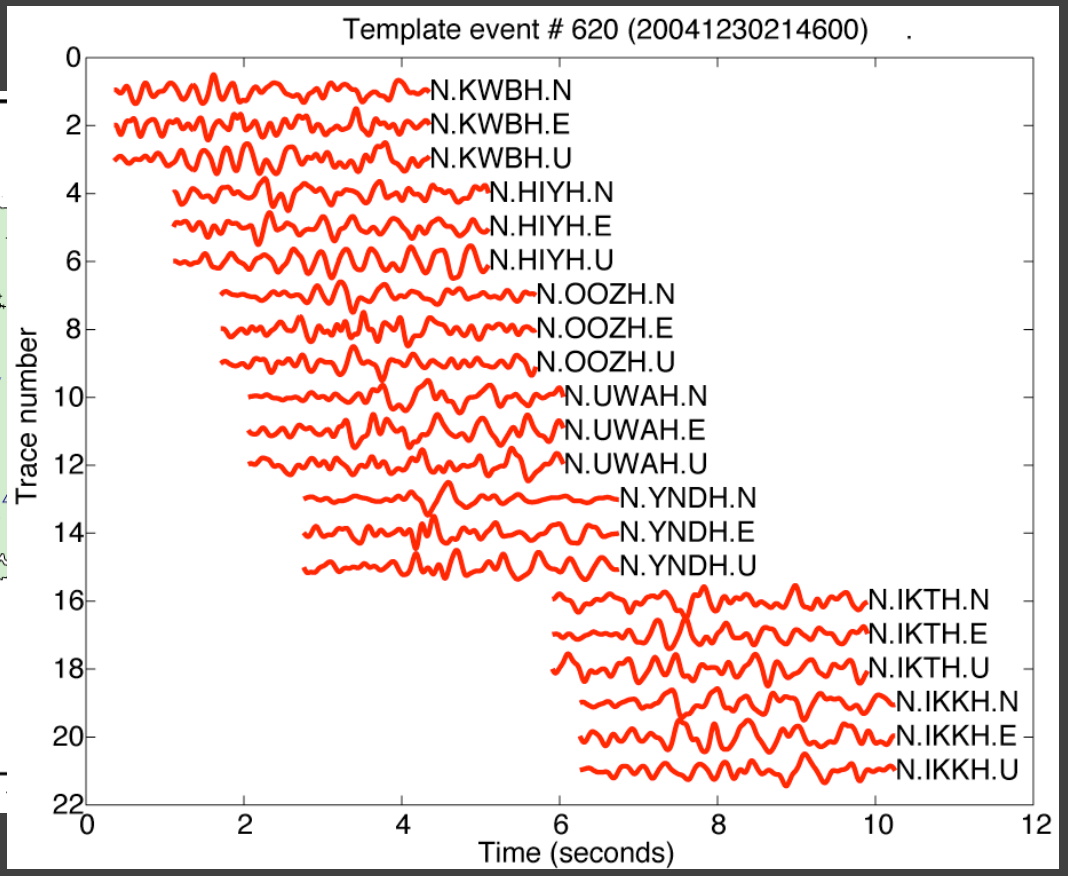


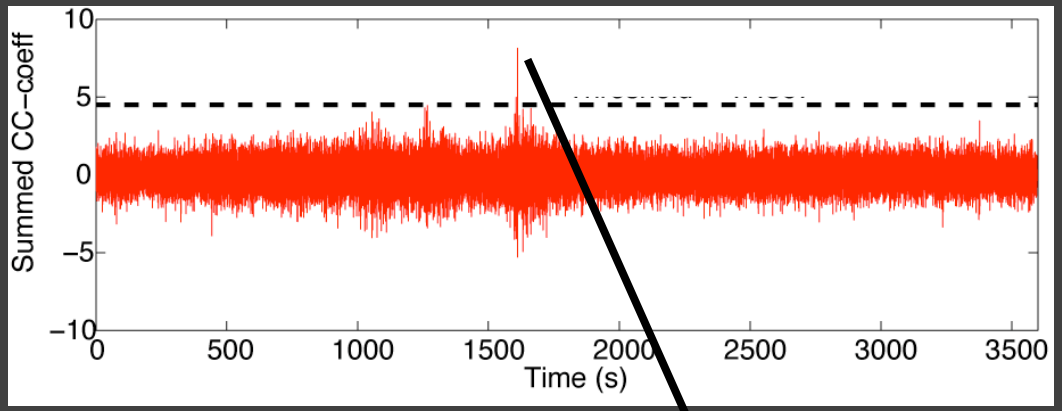
Mechanism of last large earthquake in this area, 1946 Nankai

Supports conclusion that LFEs are generated by shear slip in the plate convergence direction

Template LFE Events

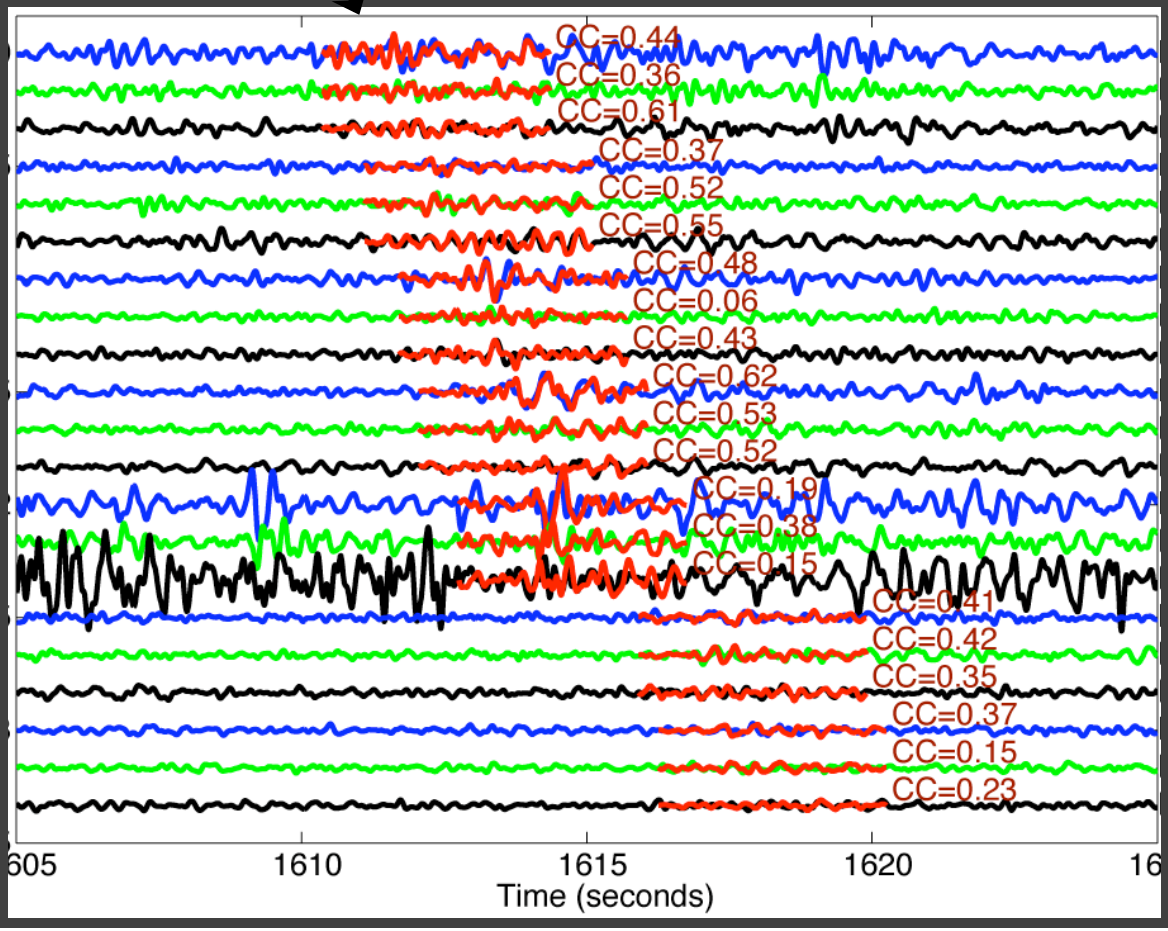




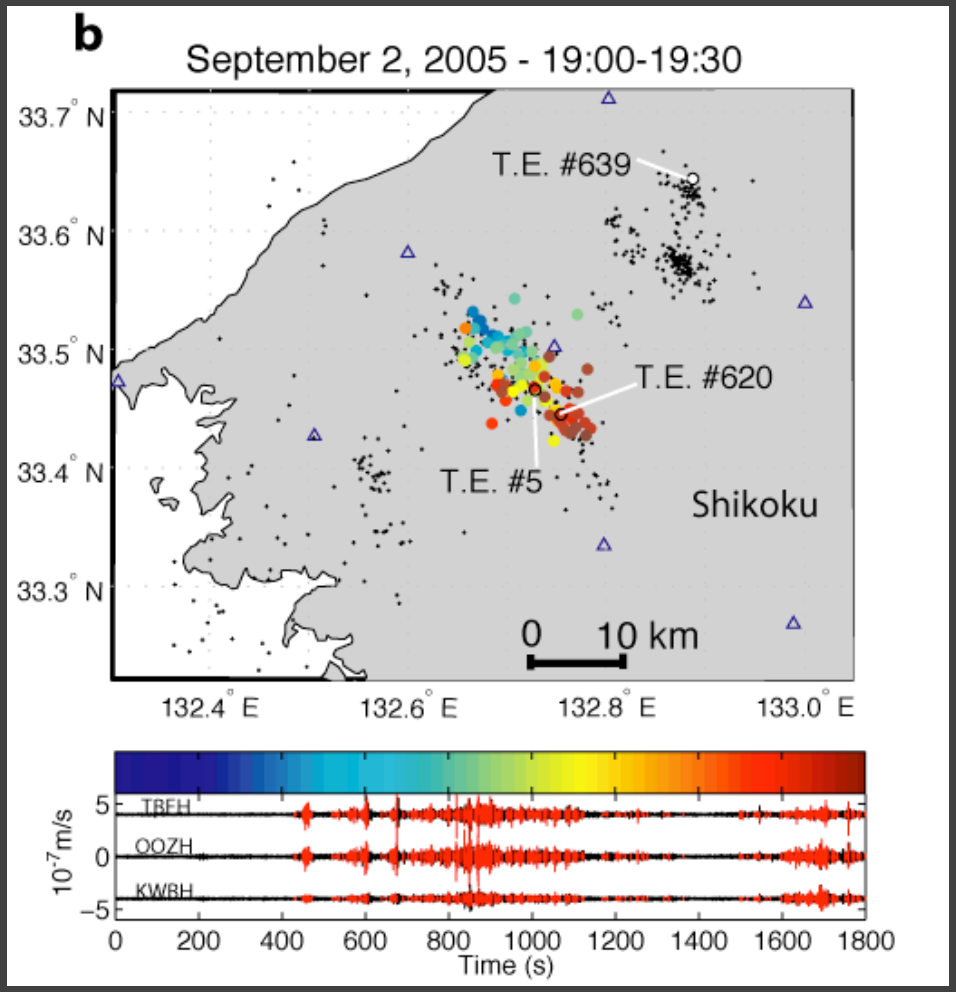


Scan template through continuous data, sum correlations

Shelly *et al.*, Nature, 2007



Tremor=LFEs

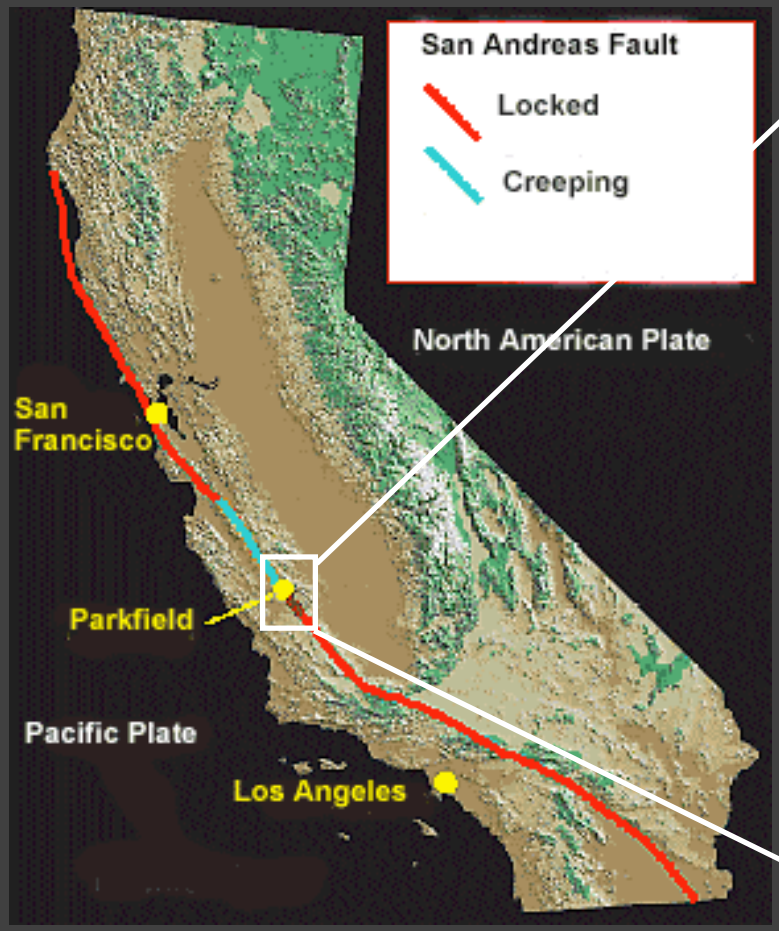


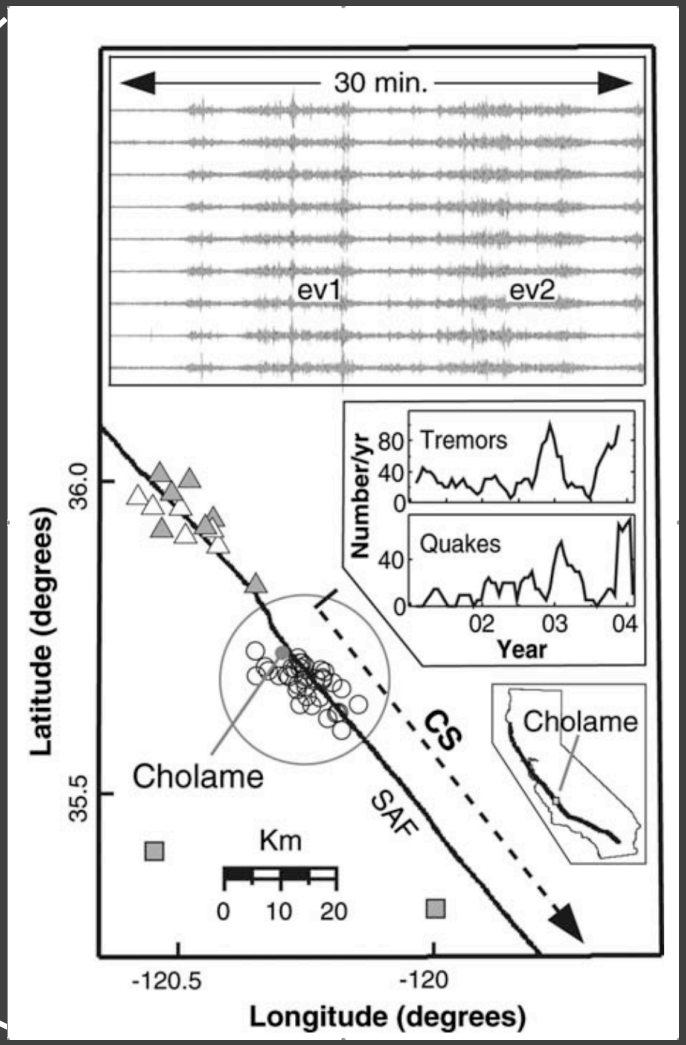
30 minutes

- Tremor can be explained as many LFEs occurring in succession
- Also provides a method for precisely locating tremor!

Shelly *et al.*, Nature, 2007

Tremor Under the San Andreas





Nadeau and Dolenc, *Science*, 2005

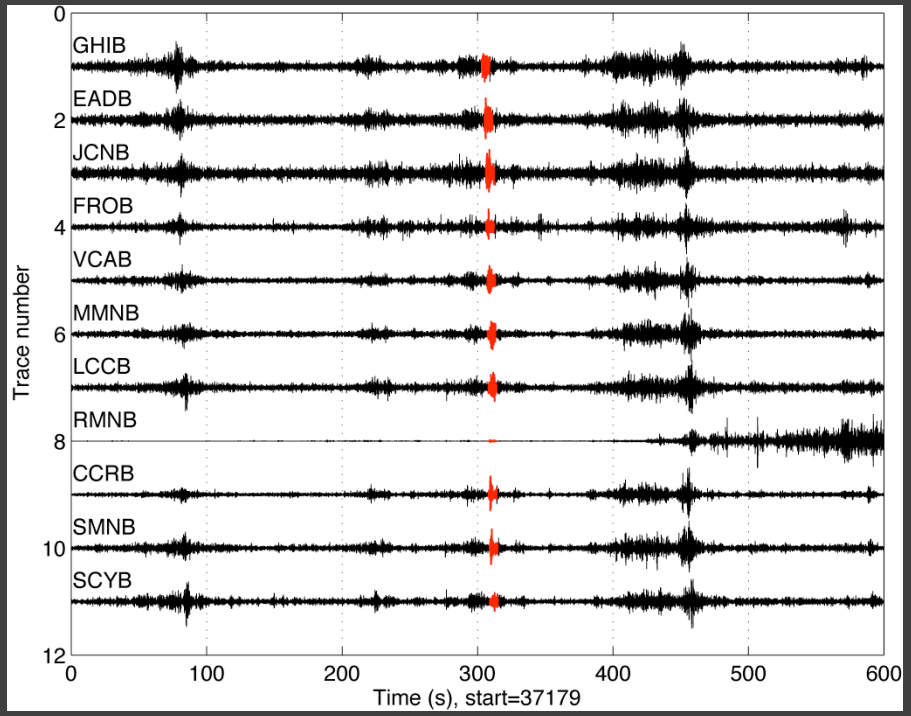
1. Tremor Locations and Migration

2 simple tecniques:

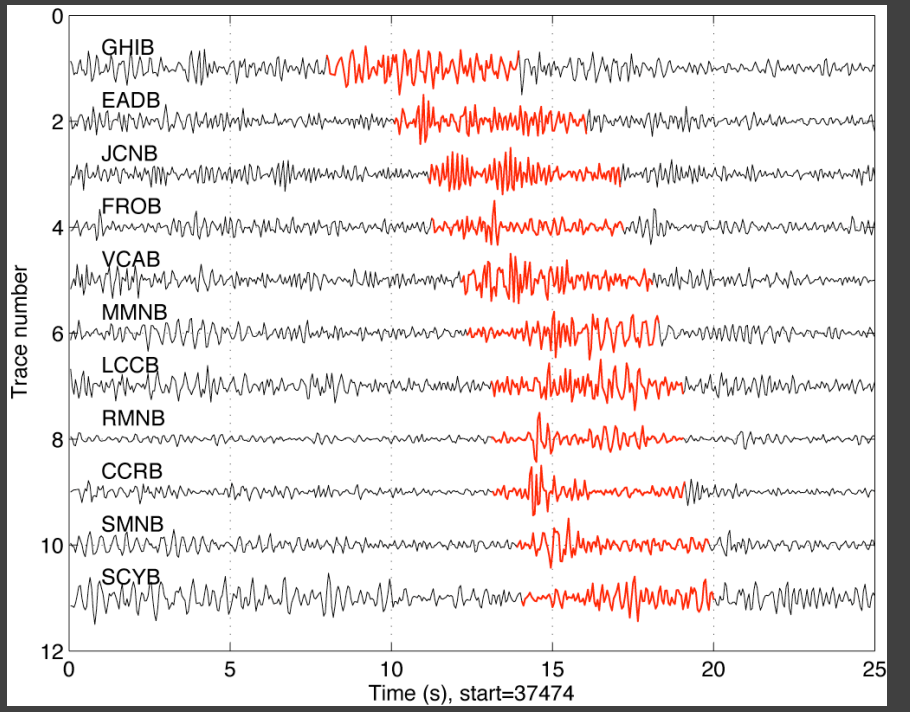
1) Cross-correlation (multiplication)

2) Stacking (addition)

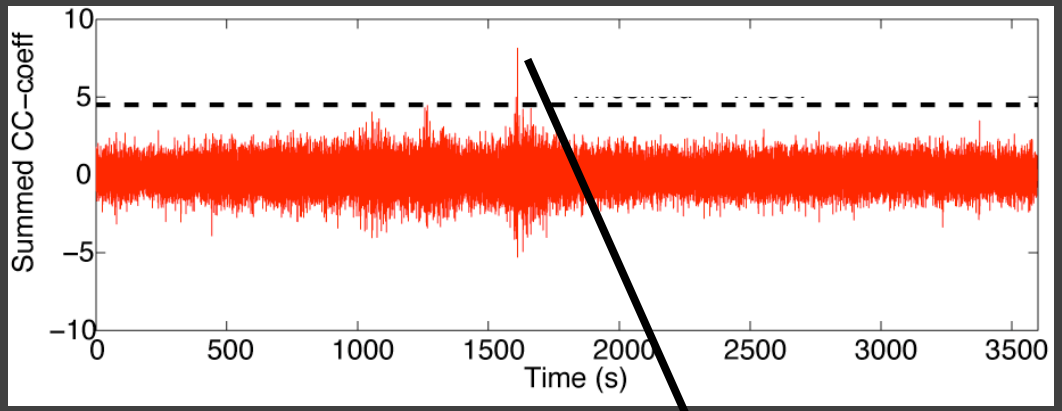
Template Waveforms



10 minutes

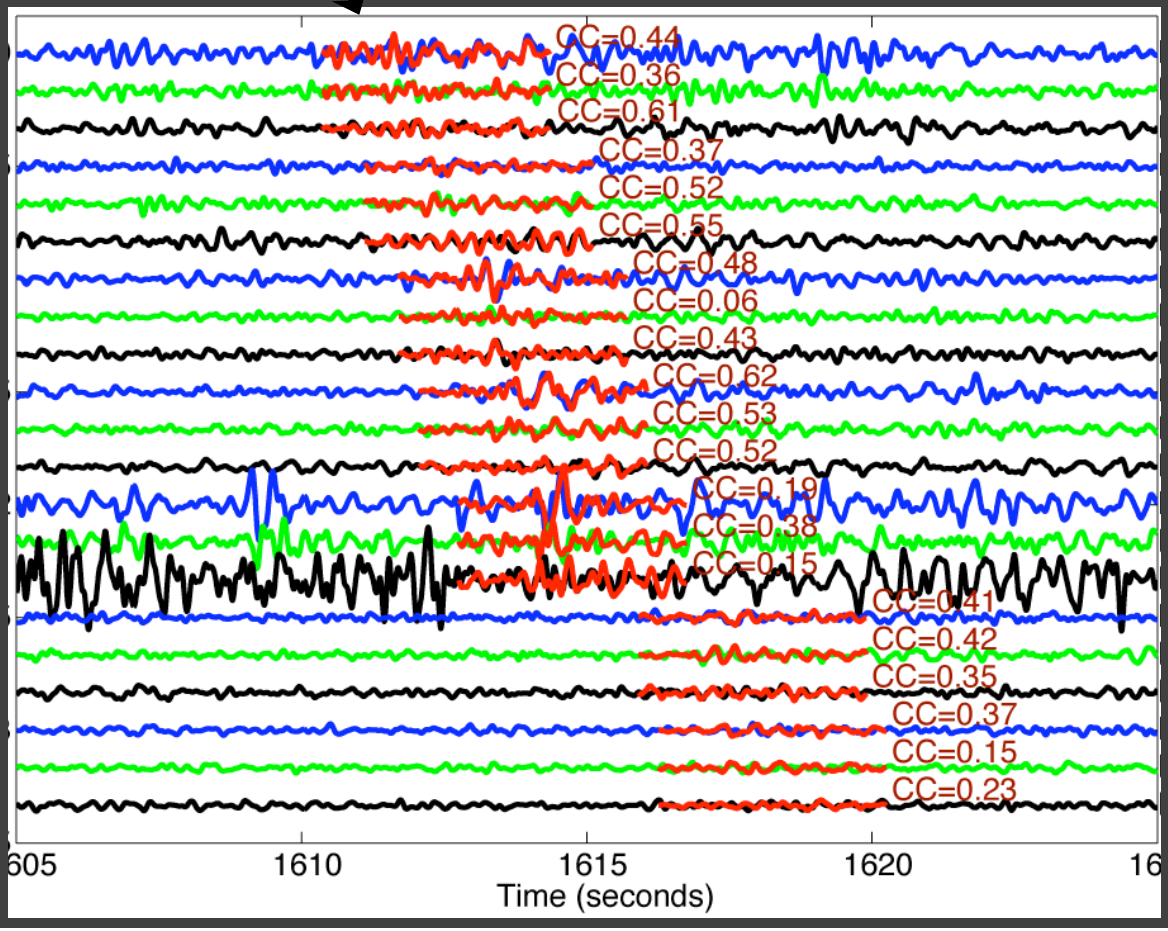


25 seconds



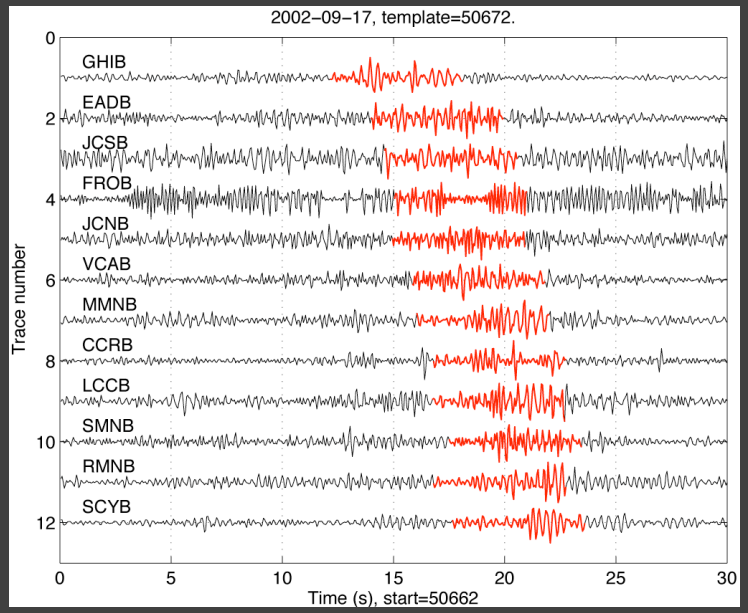
Scan template through continuous data, sum correlations

Shelly *et al.*, Nature, 2007



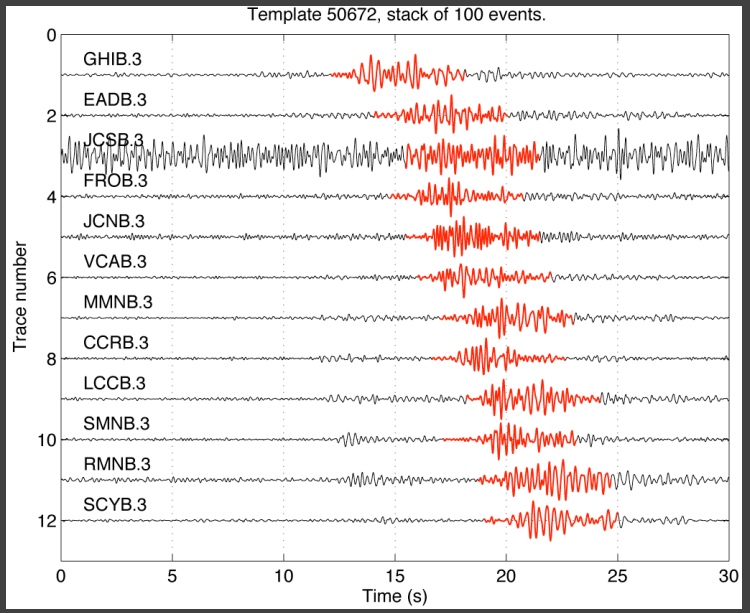
Stacked LFE Templates

Single LFE template

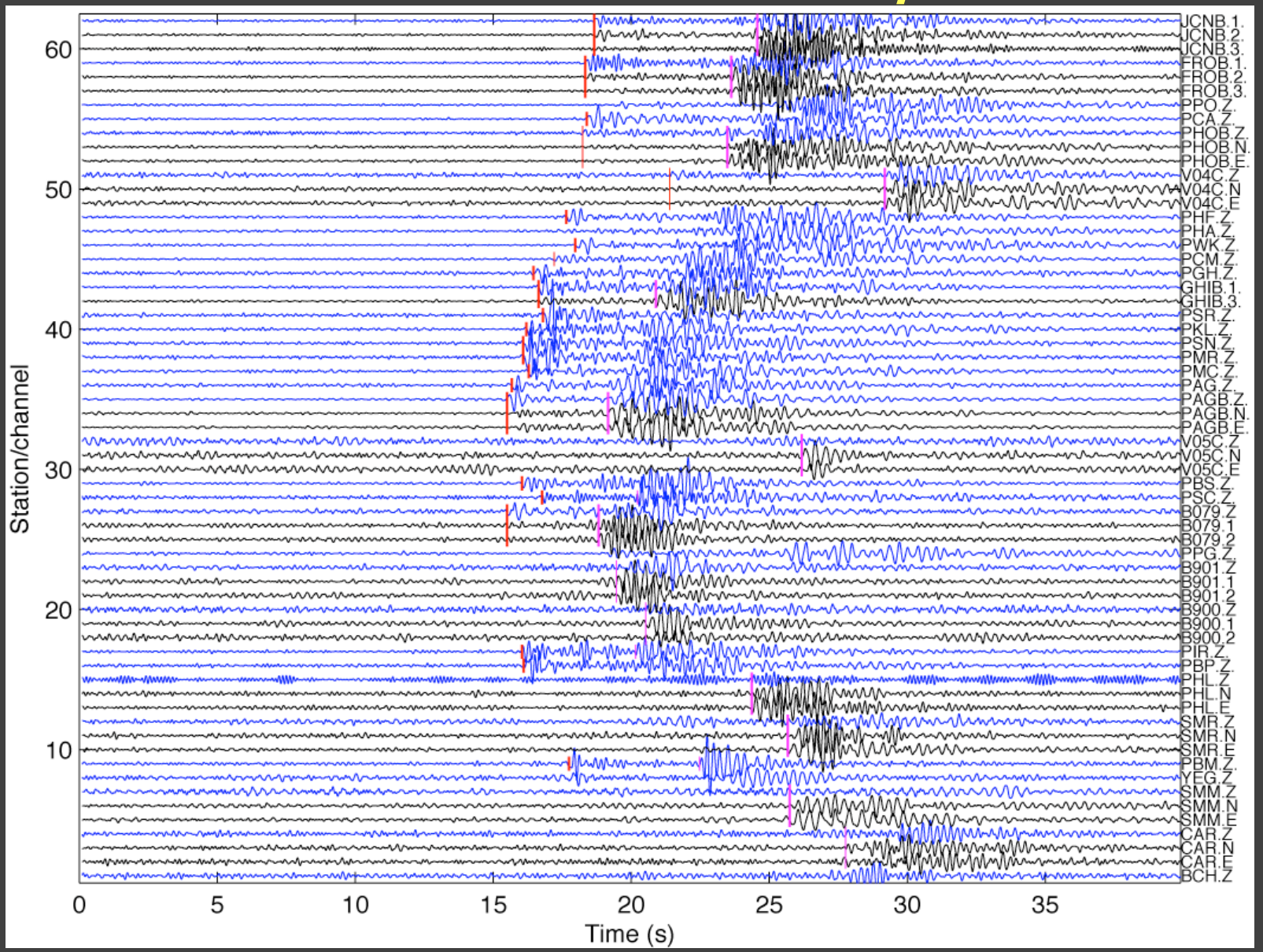


stacking

100 LFE stack template

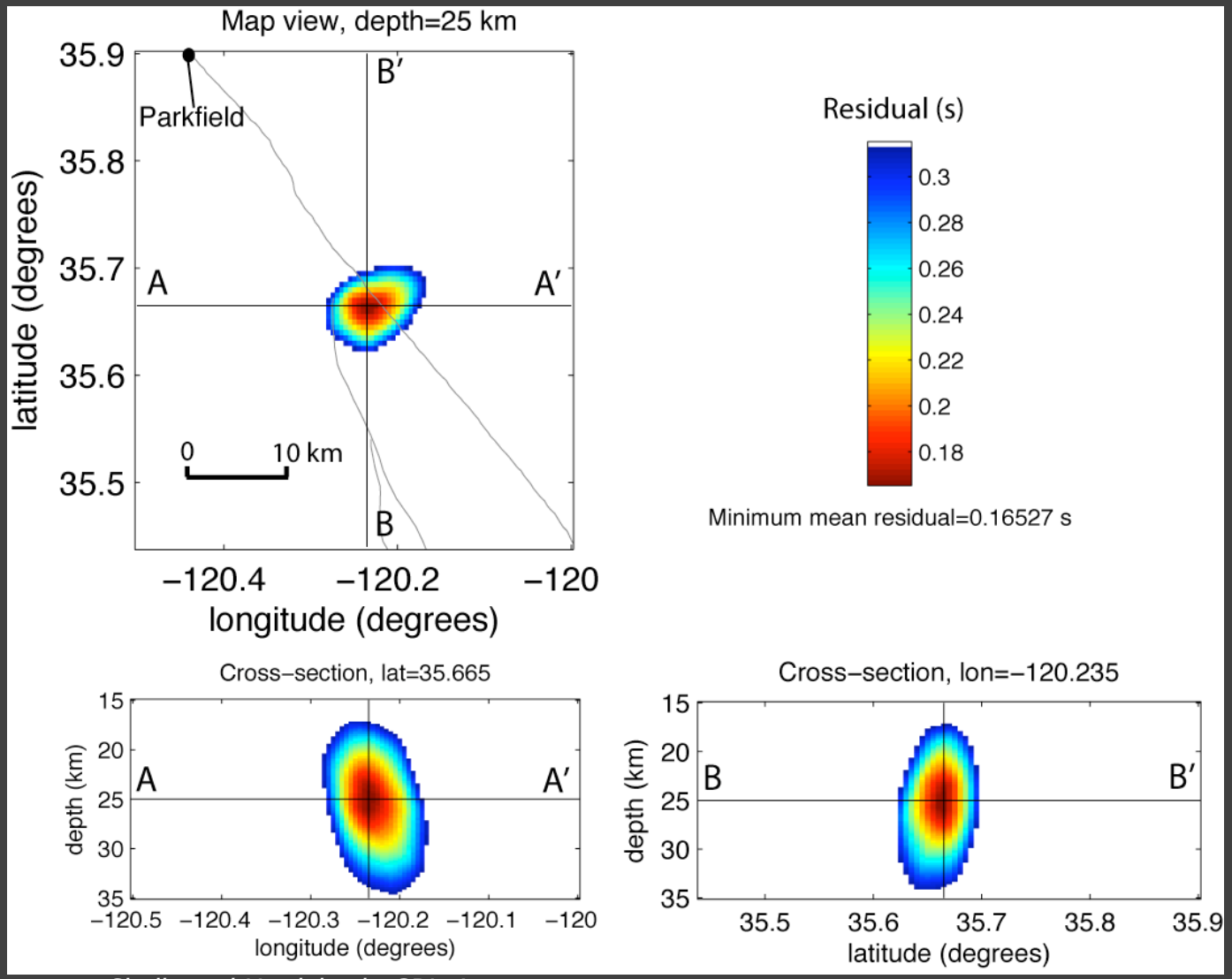


Stacked Waveforms/Picks



Shelly and Hardebeck, GRL, in press

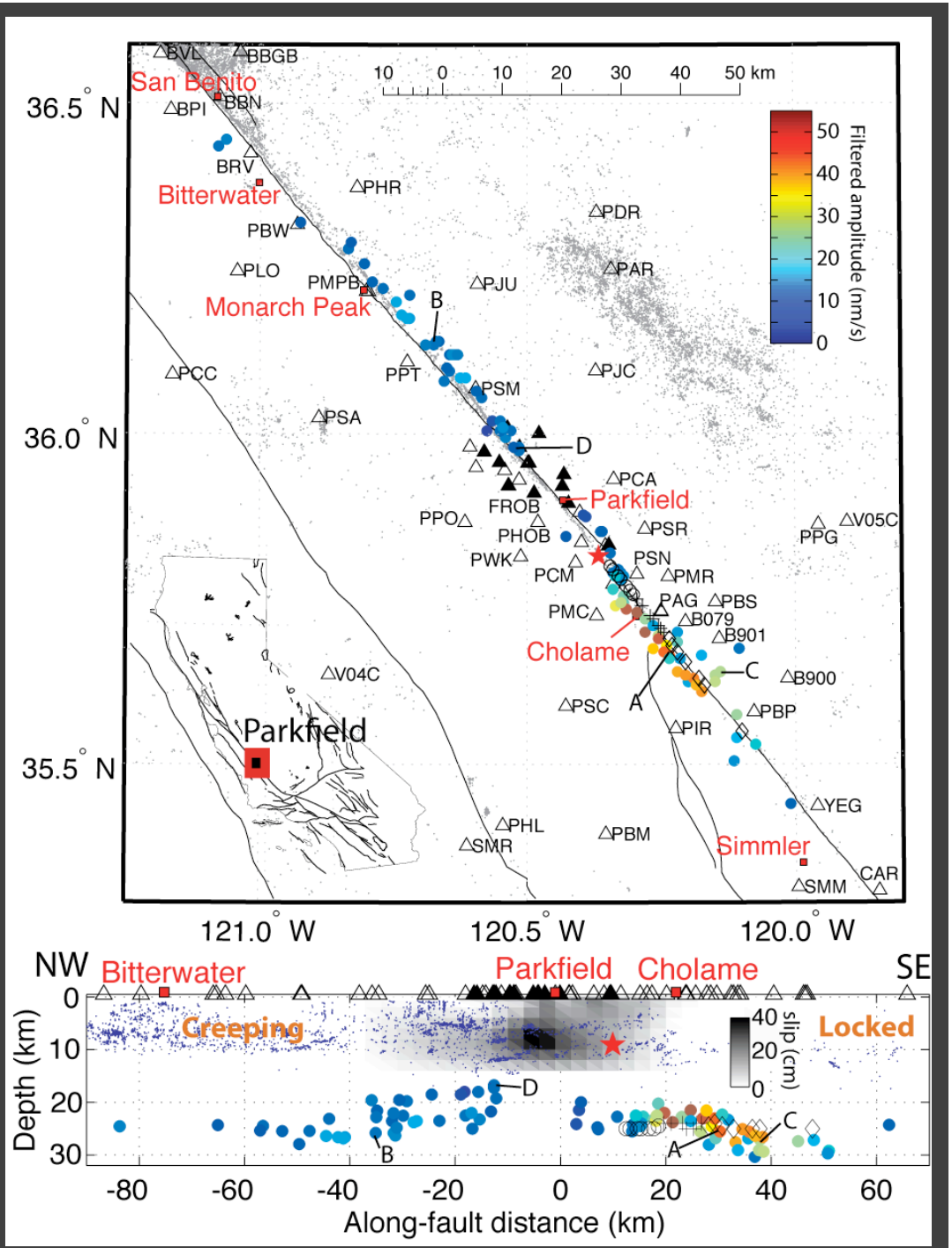
Grid Search Location (3D)



Shelly and Hardebeck, GRL, in press

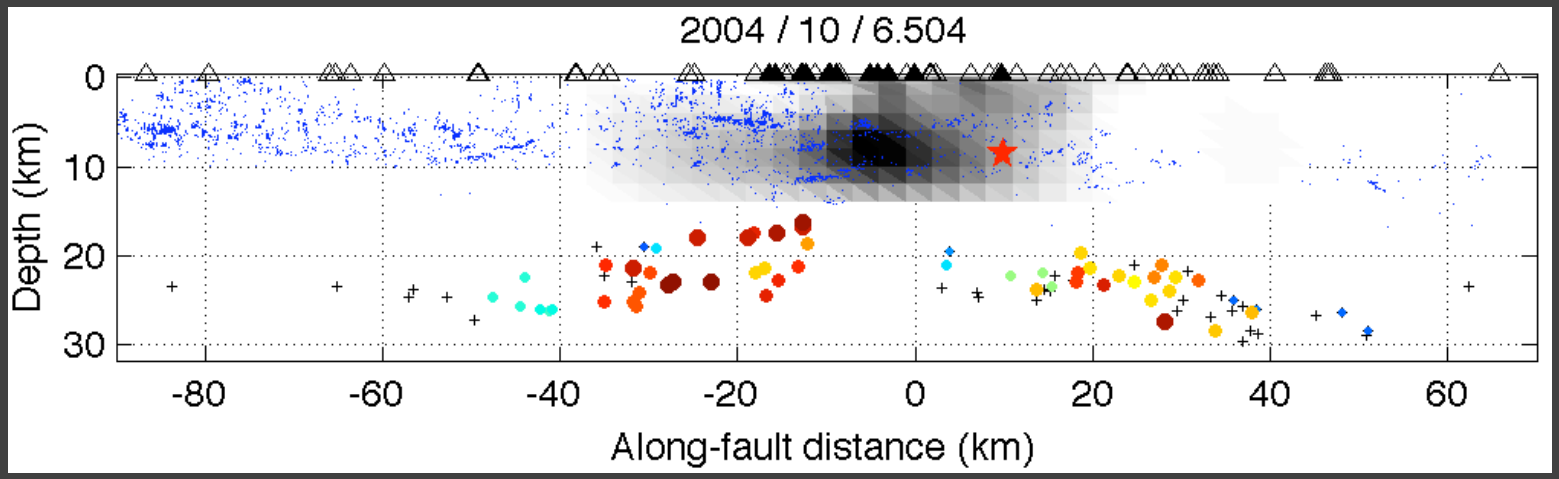
Parkfield Tremor Locations

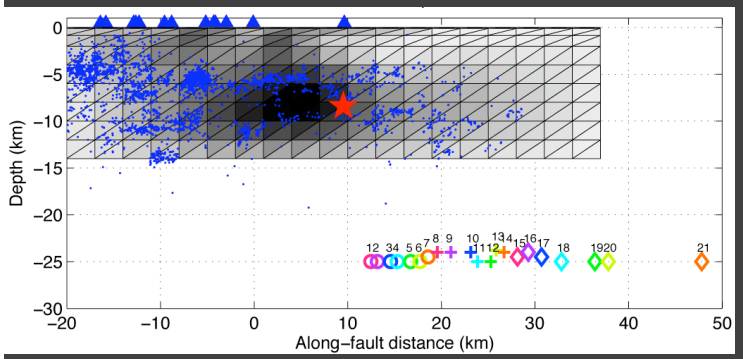
- 88 stacked LFE templates
- Located by P and S arrivals on stacked waveforms, using a 3D velocity model.
- Sources extend 75 km both NE and SW of Parkfield



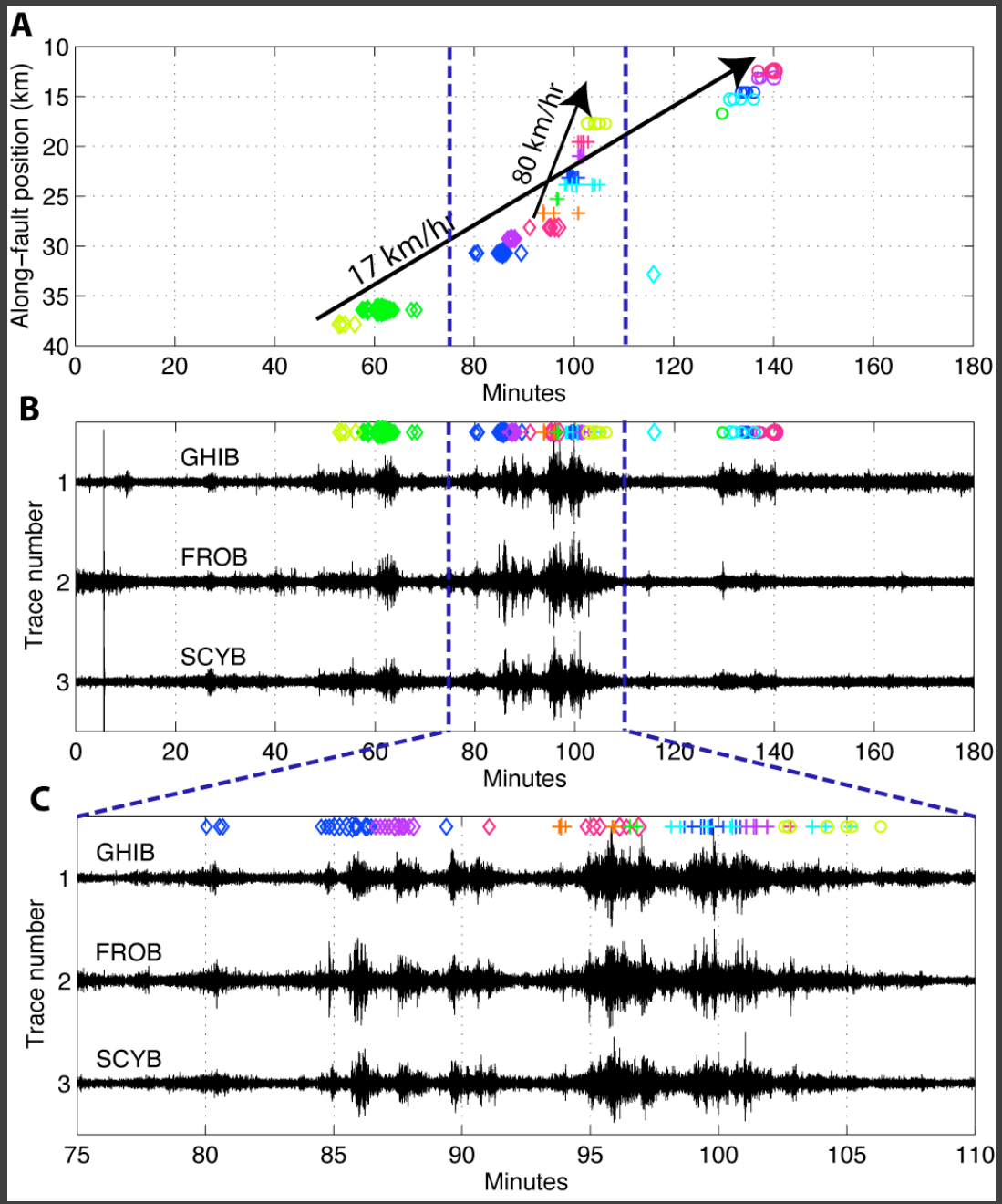
Shelly and Hardebeck, GRL, in press

Parkfield Tremor – Animation





Tremor Migration



Shelly, Nature, 2010

What does it mean? (1)

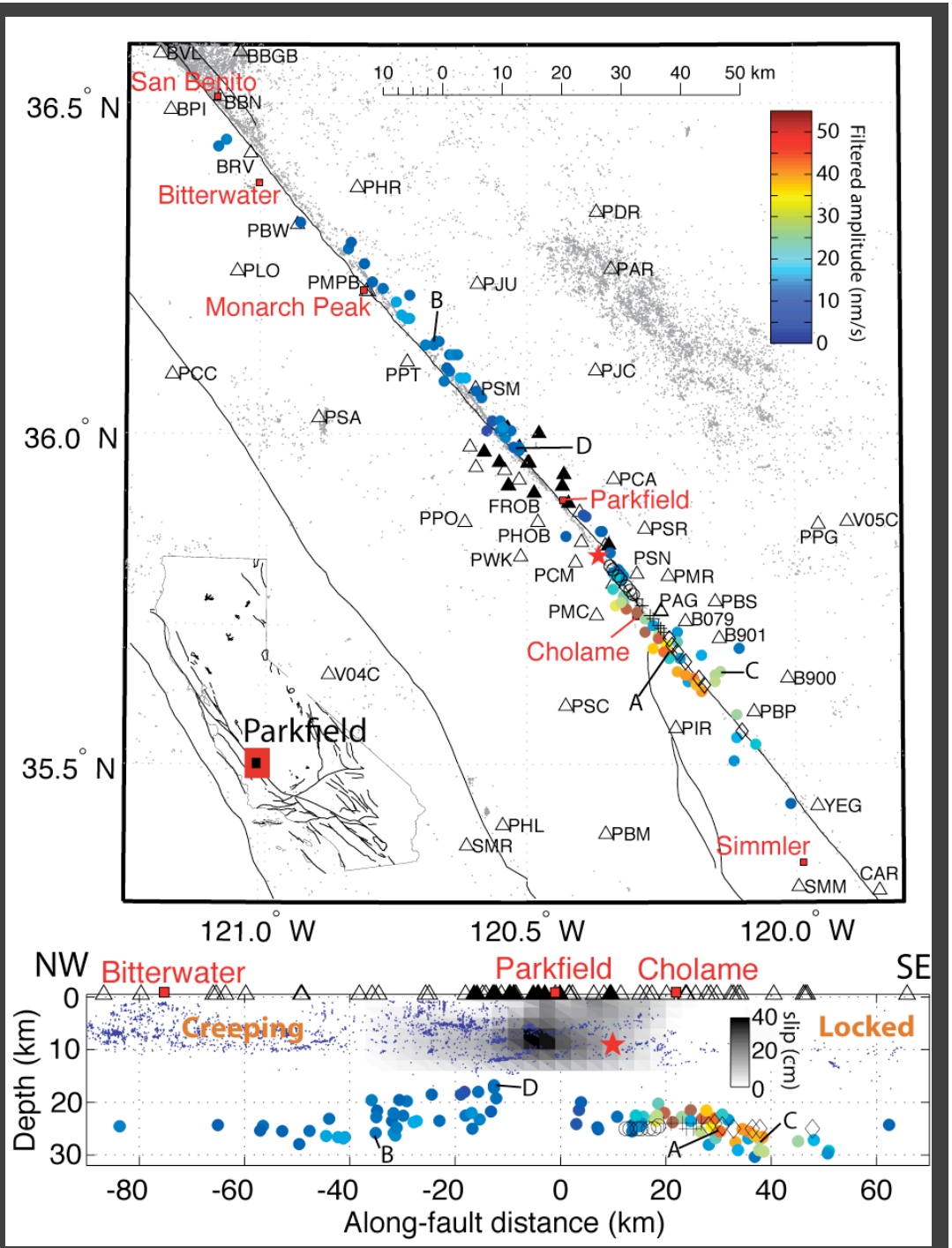
Conclusion 1.1: The San Andreas fault does not end at the base of the "seismogenic zone." Tremor sources are located on the deep extension of the fault, in the lower crust. Migration suggests the fault exists as a through-going structure at this depth.

Conclusion 1.2: At least some portions of the deep fault deform brittlely. Tremor contains seismic waves of 30+ Hz even with temperatures ~500-600C

Parkfield Tremor Catalog

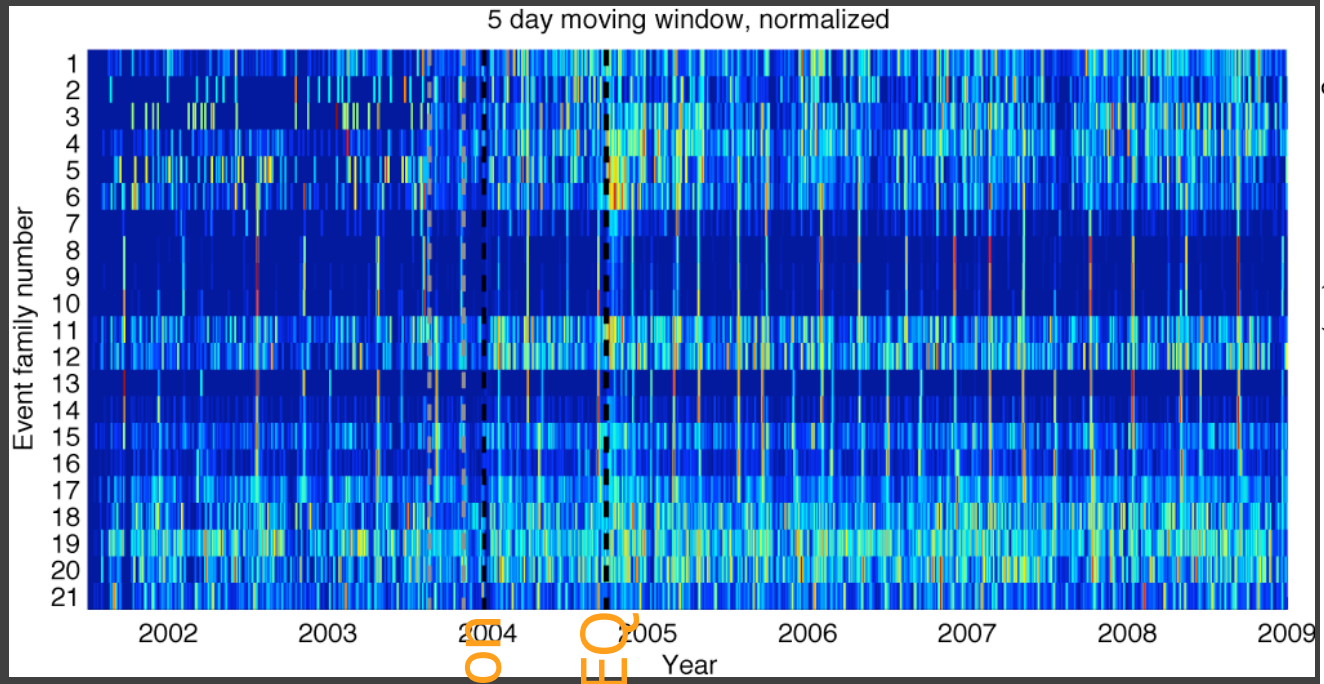
- 9 years of data
- ~36 trillion cross-correlation measurements
- ~550,000 events detected since mid-2001 (2000-20,000 per family)
- Detectible tremor activity in some area every day

Shelly and Hardebeck, GRL, in press



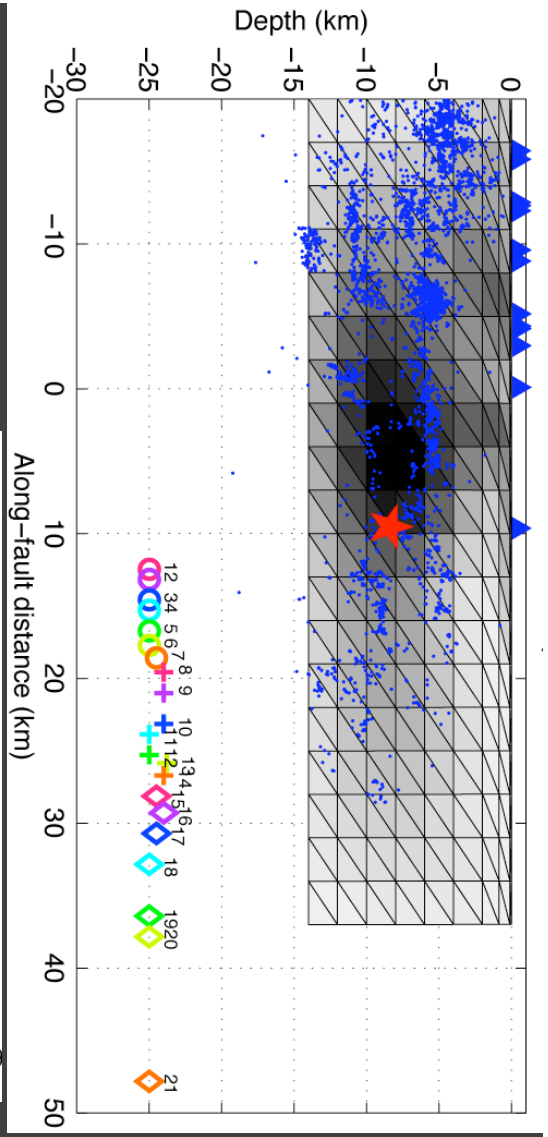
2. Variations in recurrence patterns and amplitudes among tremor families

Event Recurrence Patterns



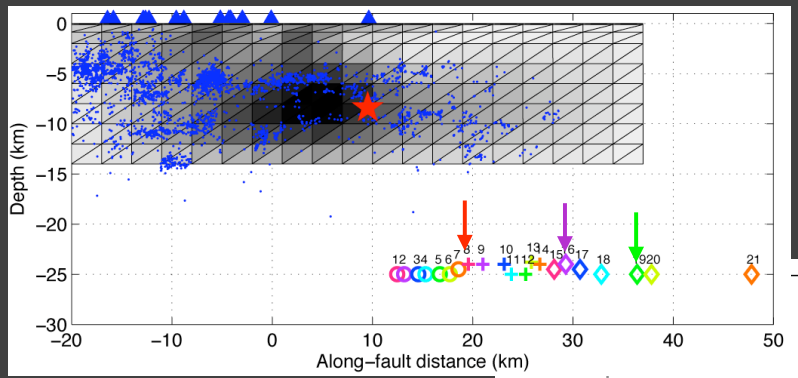
San Simeon

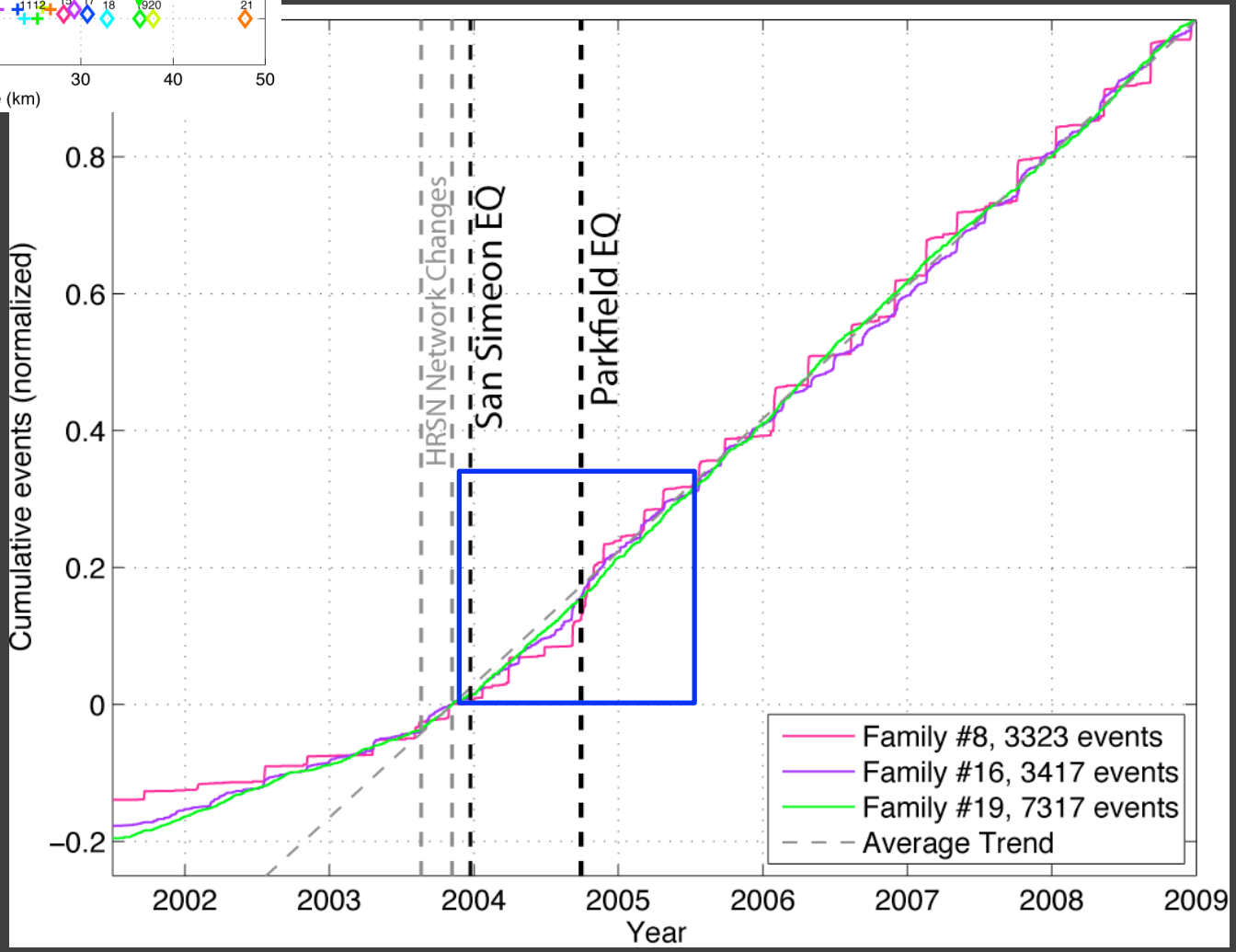
Parkfield EQ



Shelly, Nature, 2010

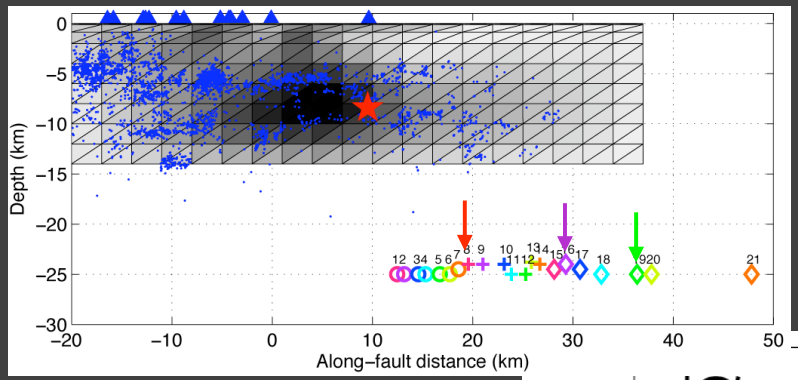
Cumulative Events

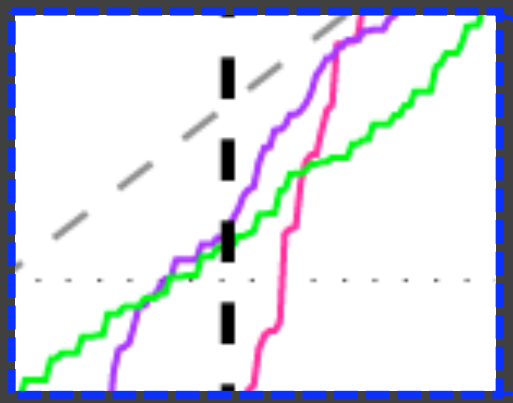


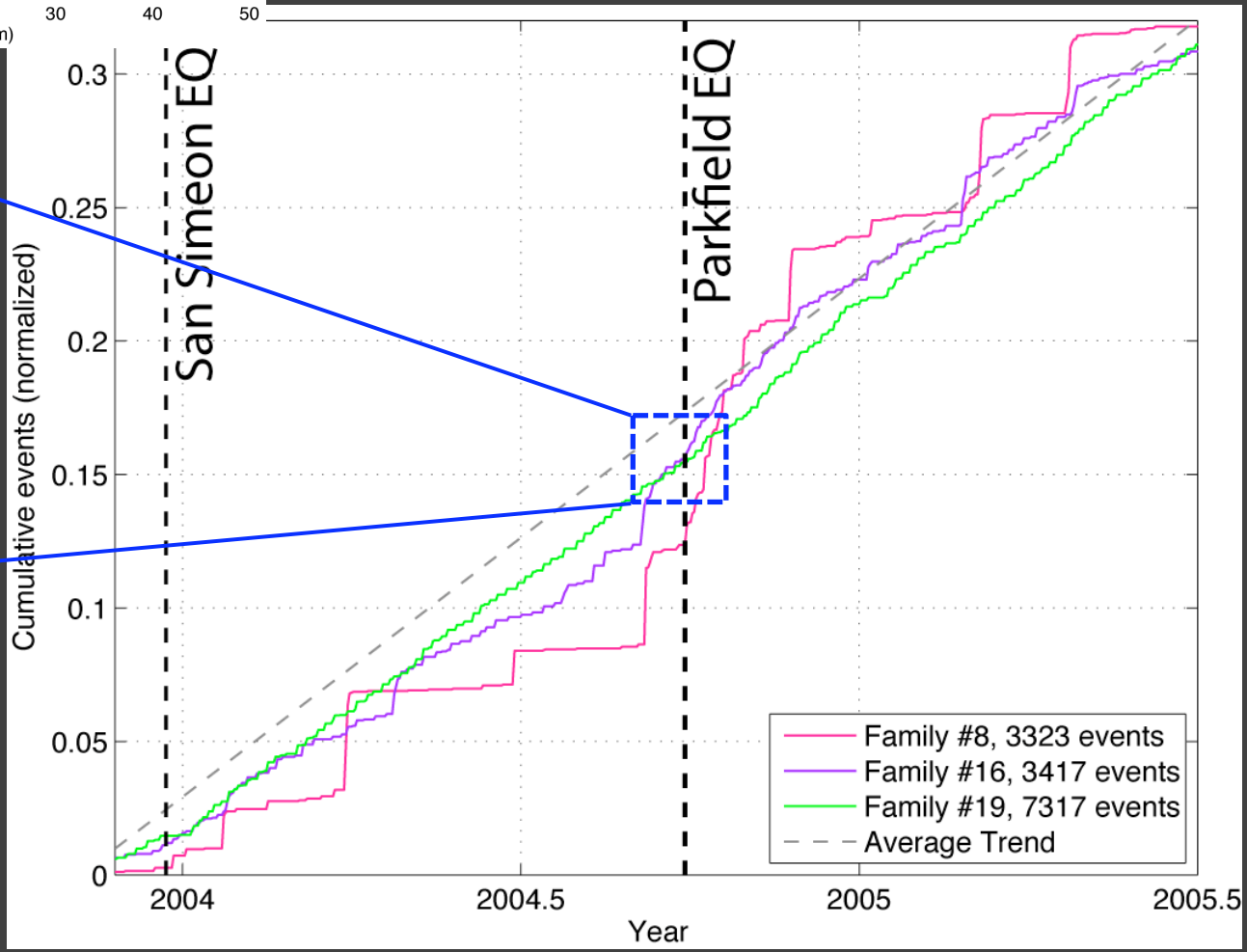


Shelly, Nature, 2010

Cumulative Events

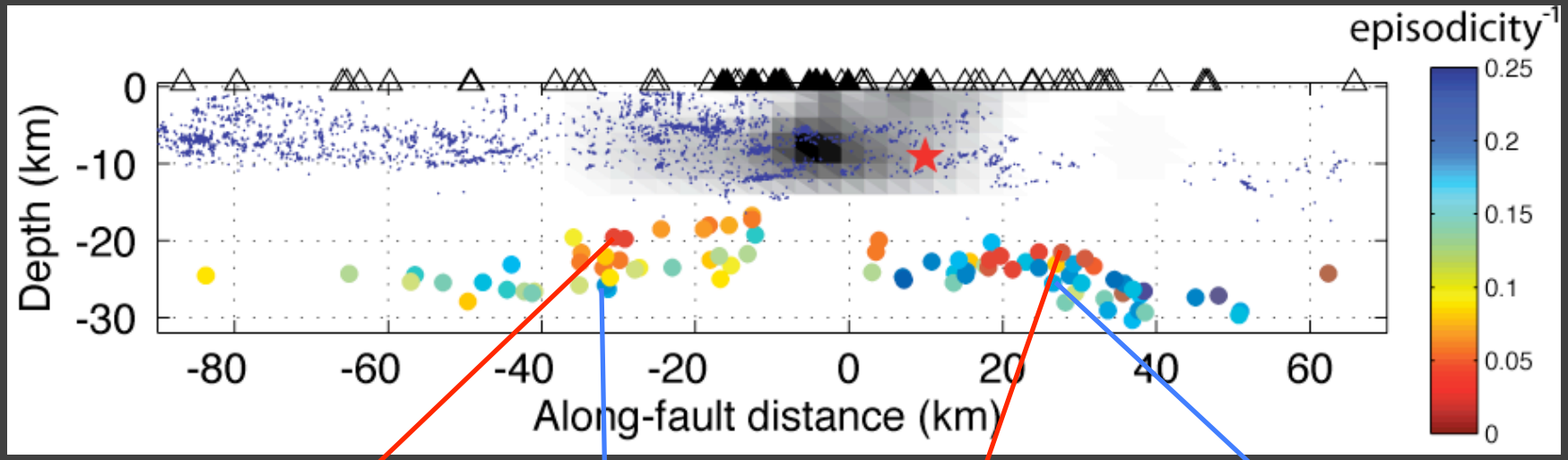


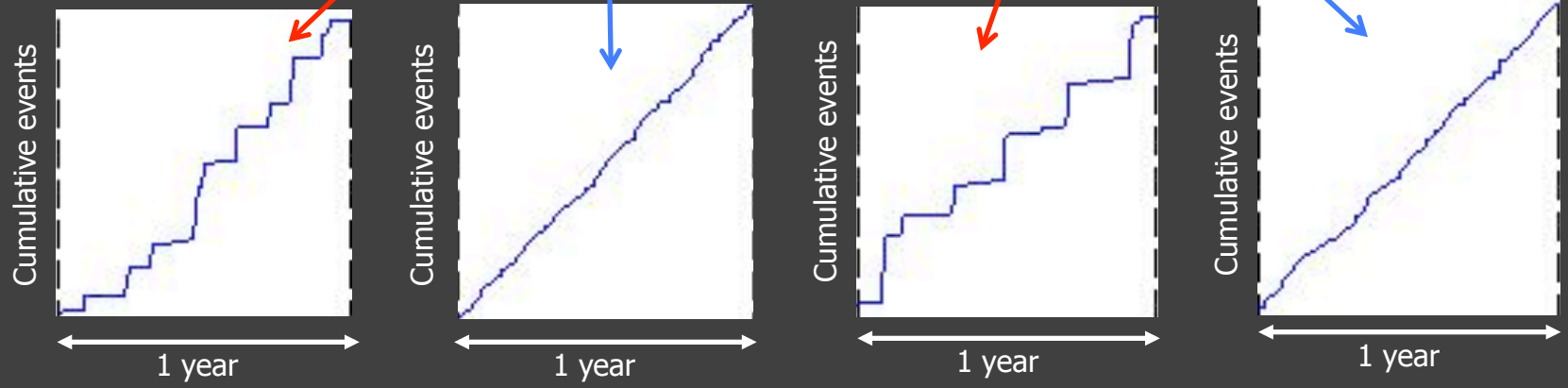




Shelly, Nature, 2010

Shallower sources have larger, less frequent bursts



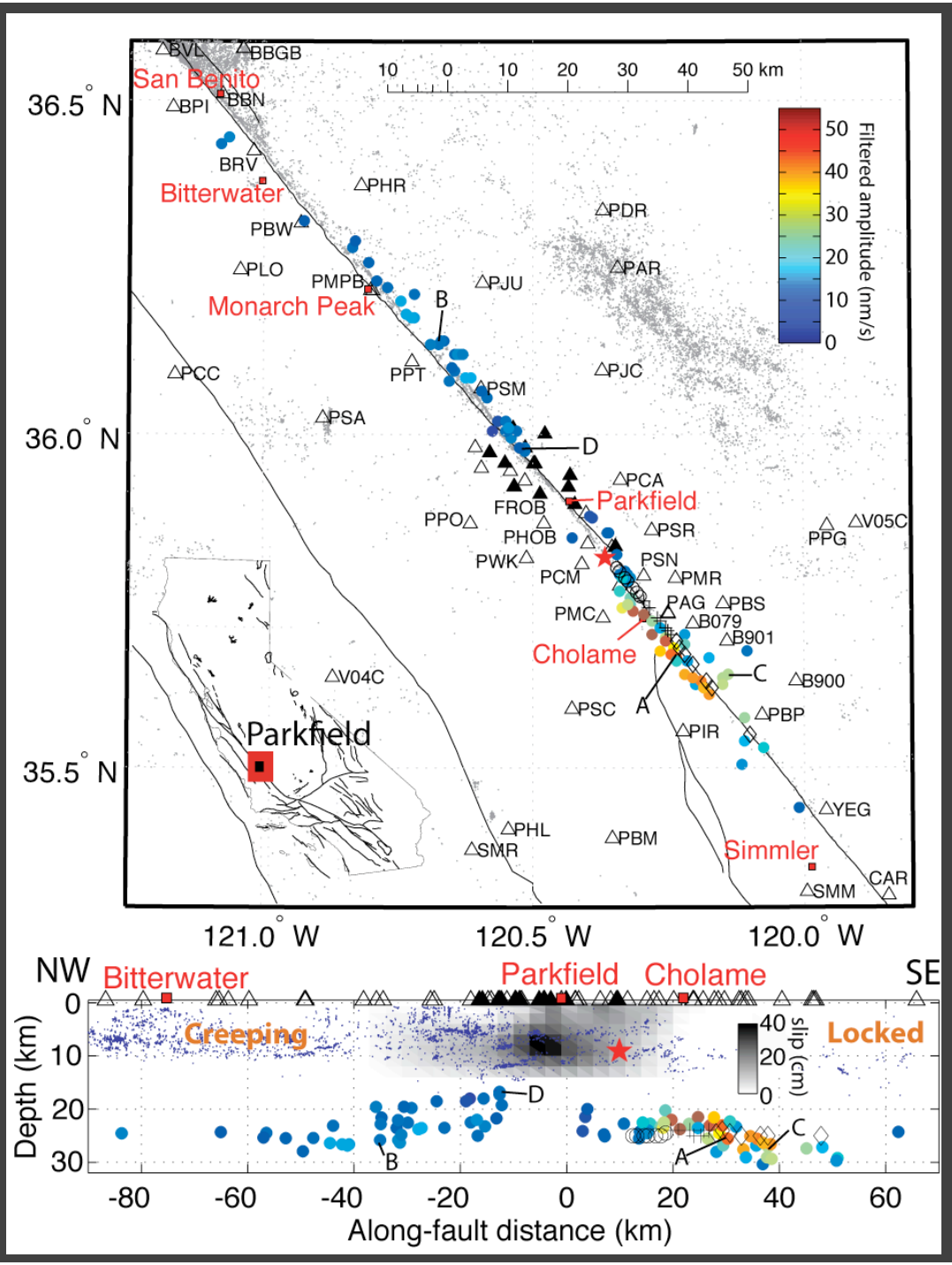


Shelly, in prep.

Amplitude potential

- Characterize source amplitude as peak ground velocity of 20th largest event during 2001-2010.
- Avoids bias from large amplitude outliers (EQs/ noise) and large number of small amplitude events

Shelly and Hardebeck, in press



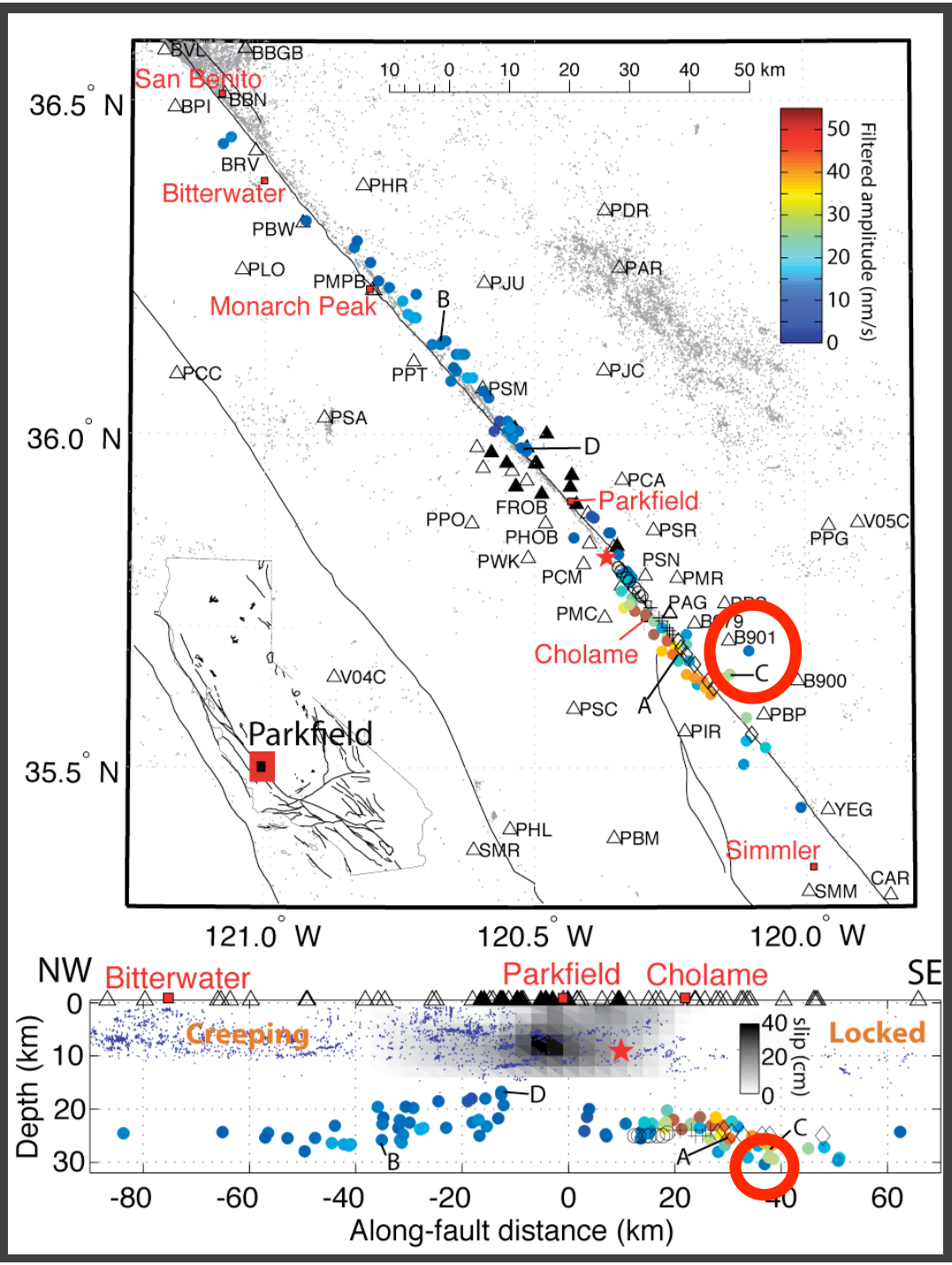
What does it mean? (2)

Conclusion 2.1: The strength of the lower crust appears to vary with depth. Shallower tremor sources have larger, less frequent episodes compared to deeper sources. (But what's happening from 13-20 km depth?)

Conclusion 2.2: Tremor amplitude varies coherently along strike. This implies a corresponding variation in geology (fluids???). Gap beneath Parkfield may reflect further amplitude variation.

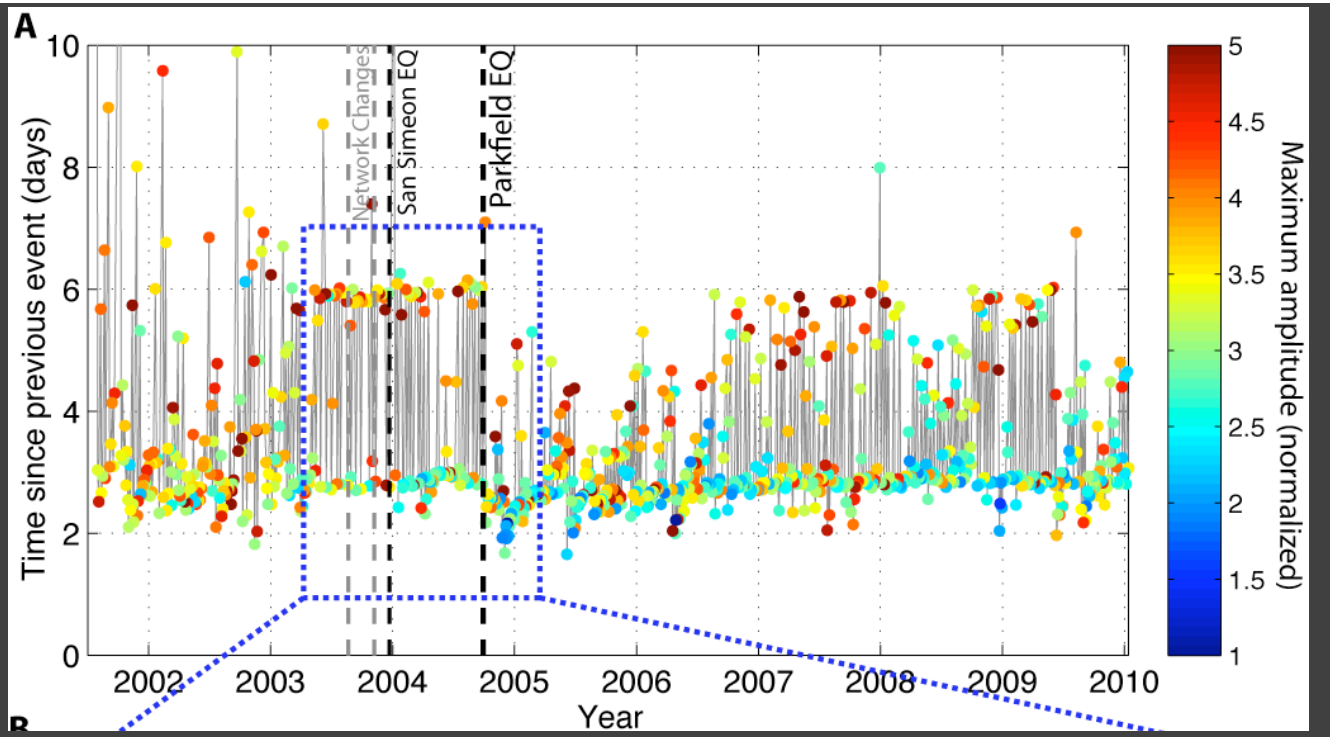
3. Periodic, chaotic, and doubled recurrence intervals in one event family

Family Location

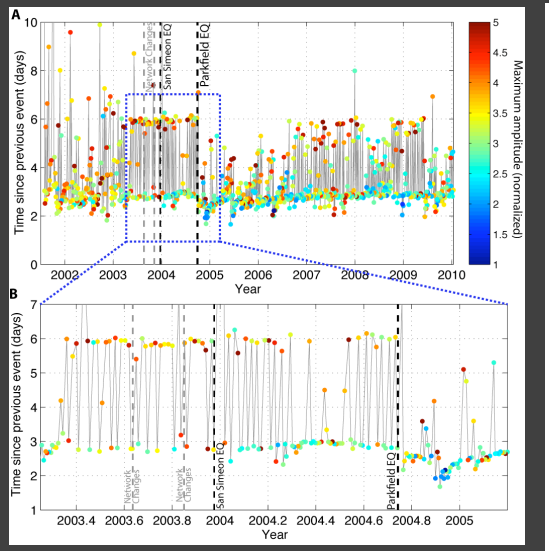


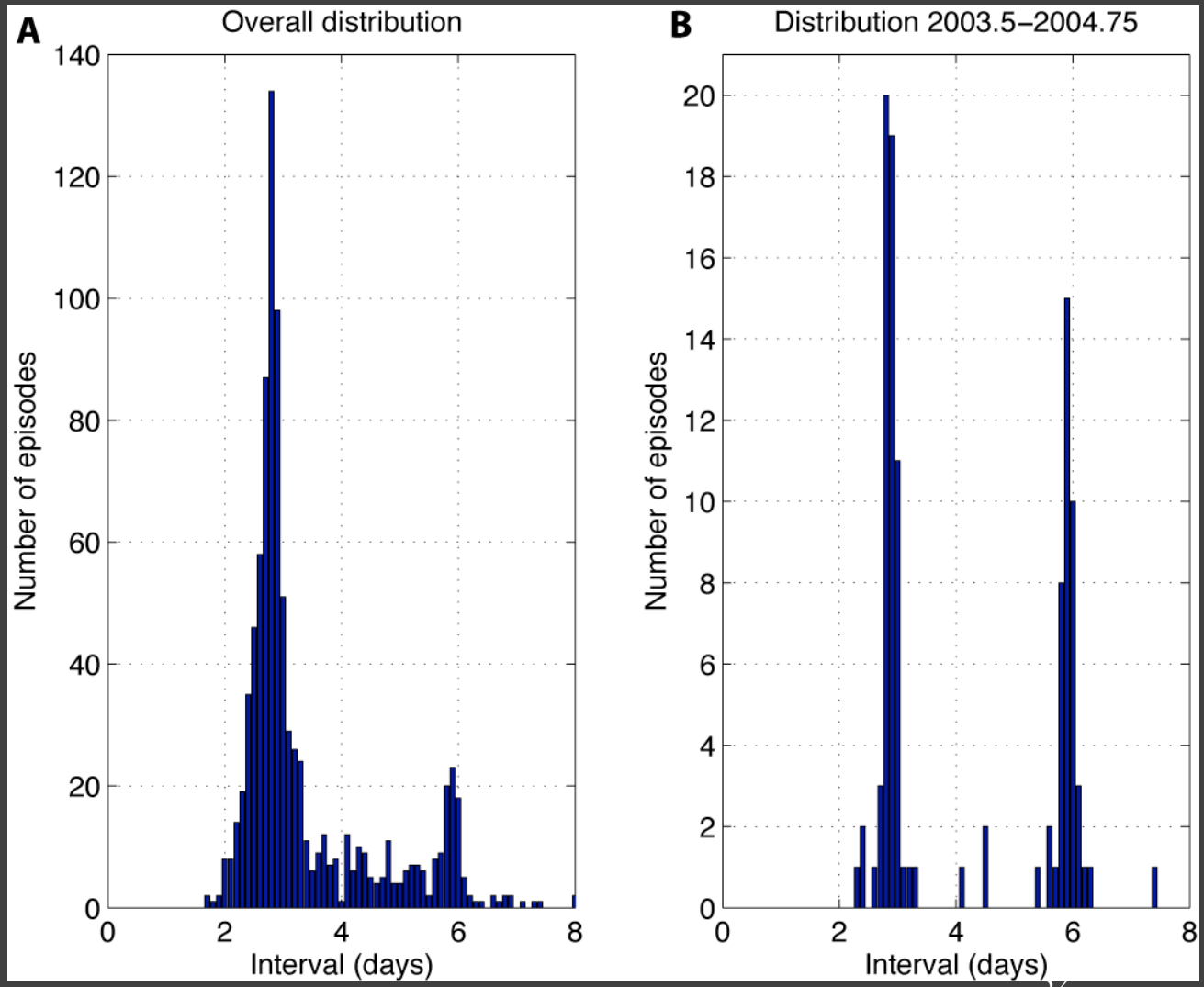
Shelly, Science, 2010

Complex recurrence patterns



Bi-Modal Recurrence

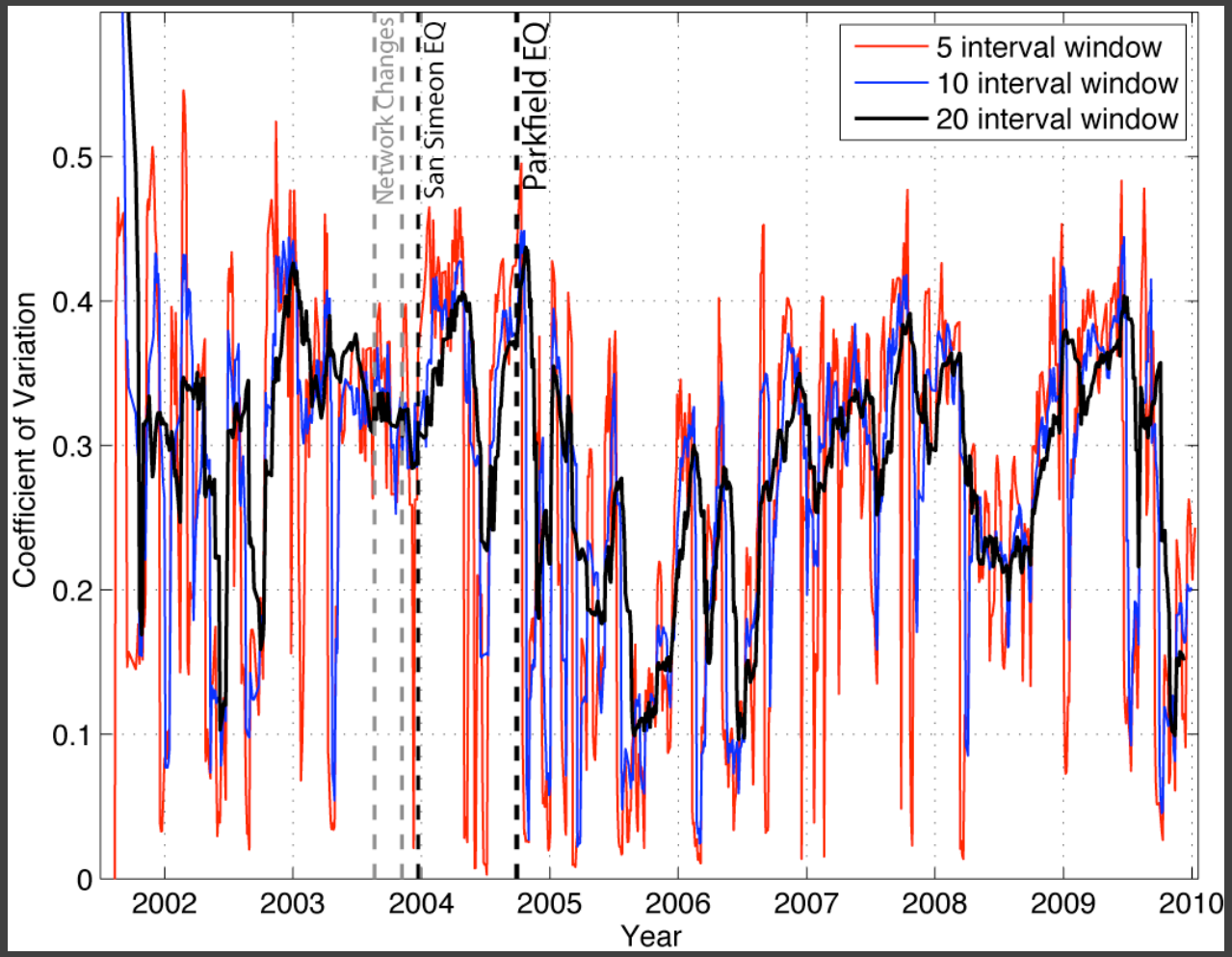


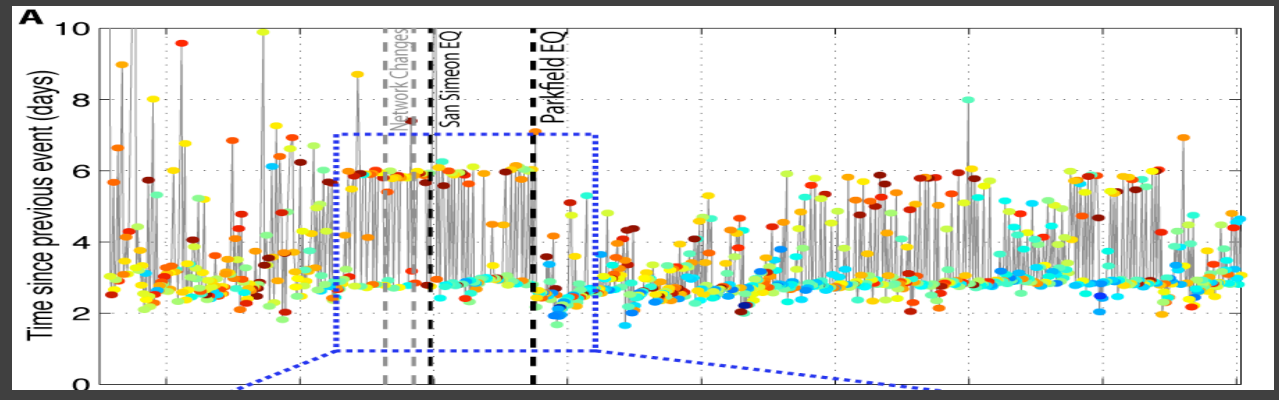


Shelly, Science, 2010

Shelly, Science, 2010

Variations in regularity





What does it mean? (3)

Conclusion 3.1: Evidence for complexity in earthquake recurrence. Similar to effects seen in laboratory/numerical models. Small perturbations to the system can produce large changes in behavior.

Conclusion 3.2: Limitations to using short historical (or paleoseismic) earthquake sequences to predict timing of future events?

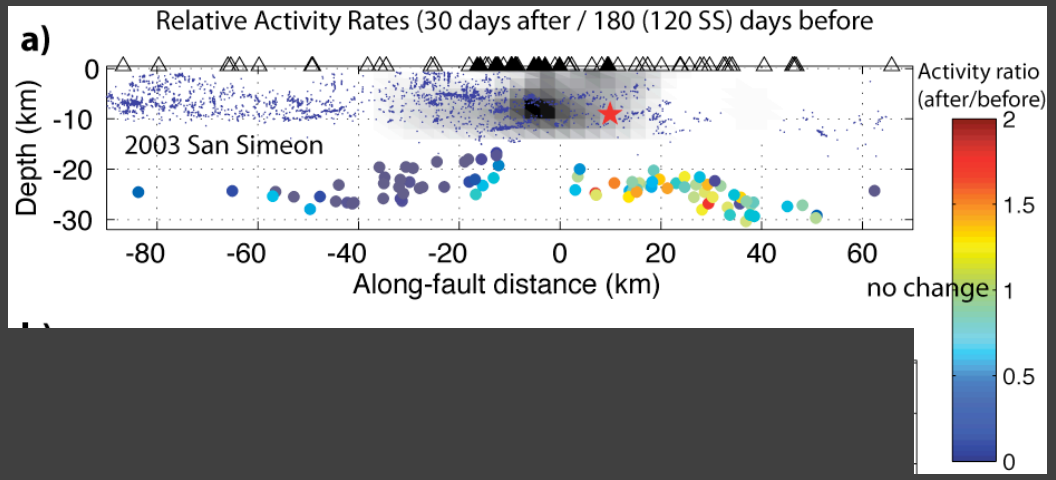
4. Tremor response to nearby earthquakes

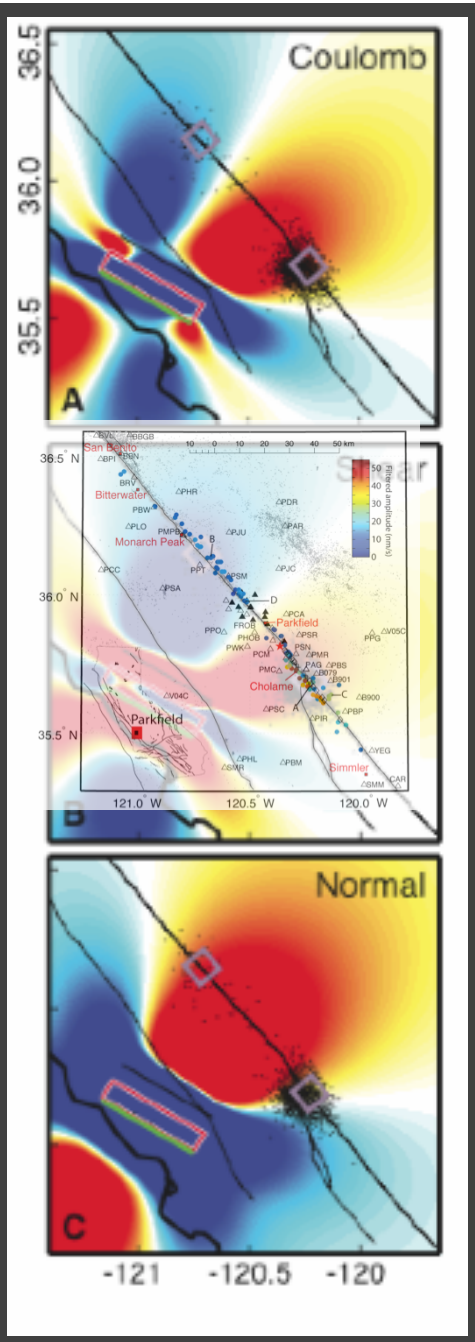
1) 2003 San Simeon (M 6.5)

2) 2004 Parkfield (M 6.0)

Coseismic Stresses

2003 M 6.5 San Simeon

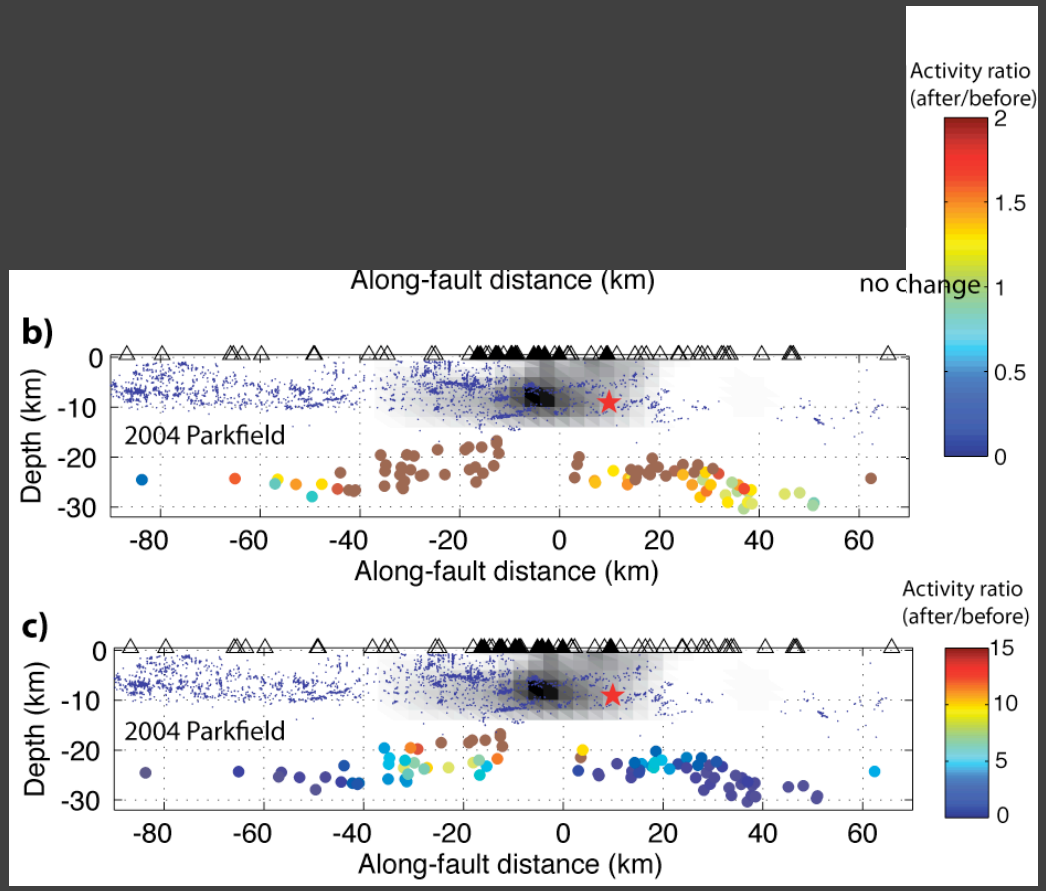


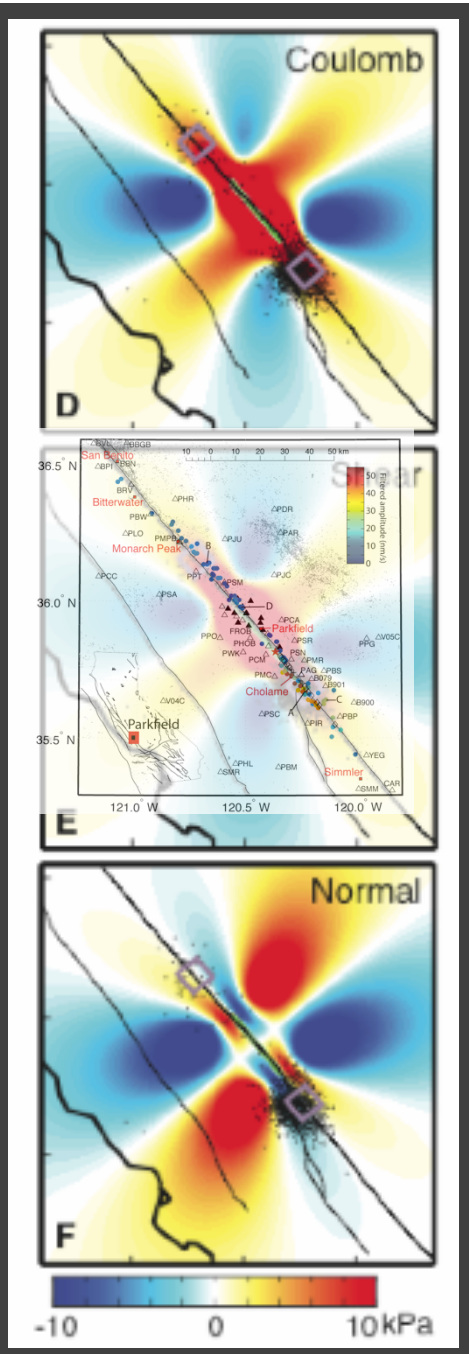


Nadeau and Guilhem, Science, 2009

Coseismic Stresses

2004 M 6.0 Parkfield





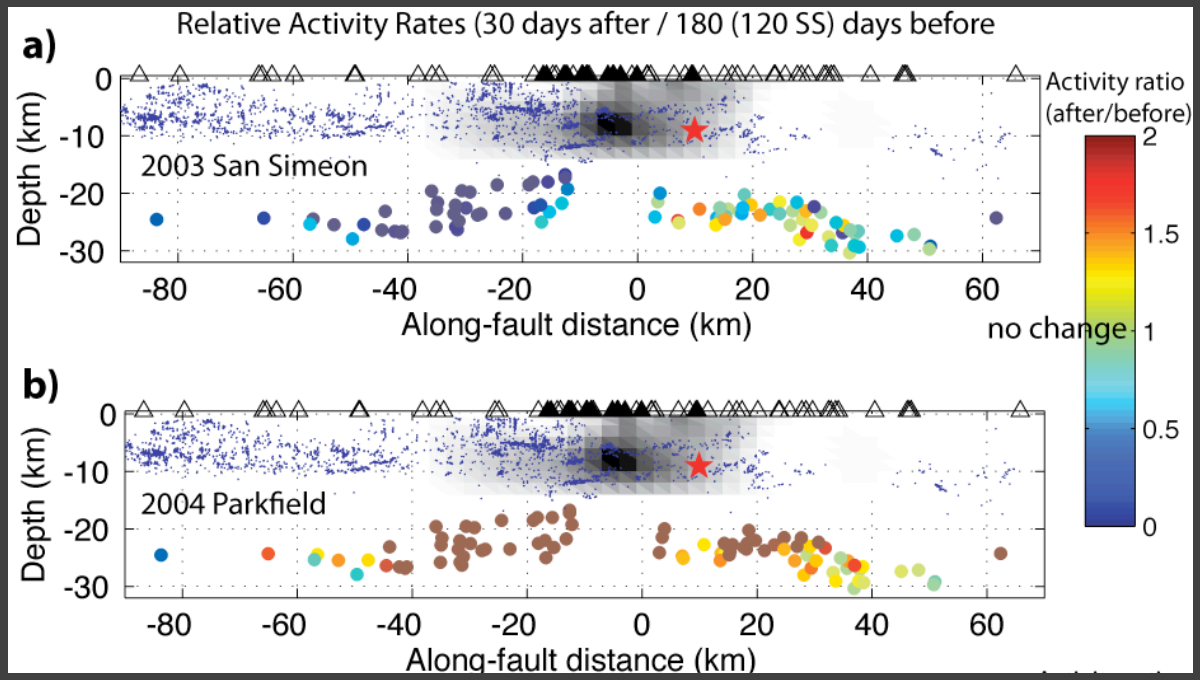
Nadeau and Guilhem, Science, 2009

Response to 2003 San Simeon and 2004 Parkfield Earthquakes

2003 San Simeon

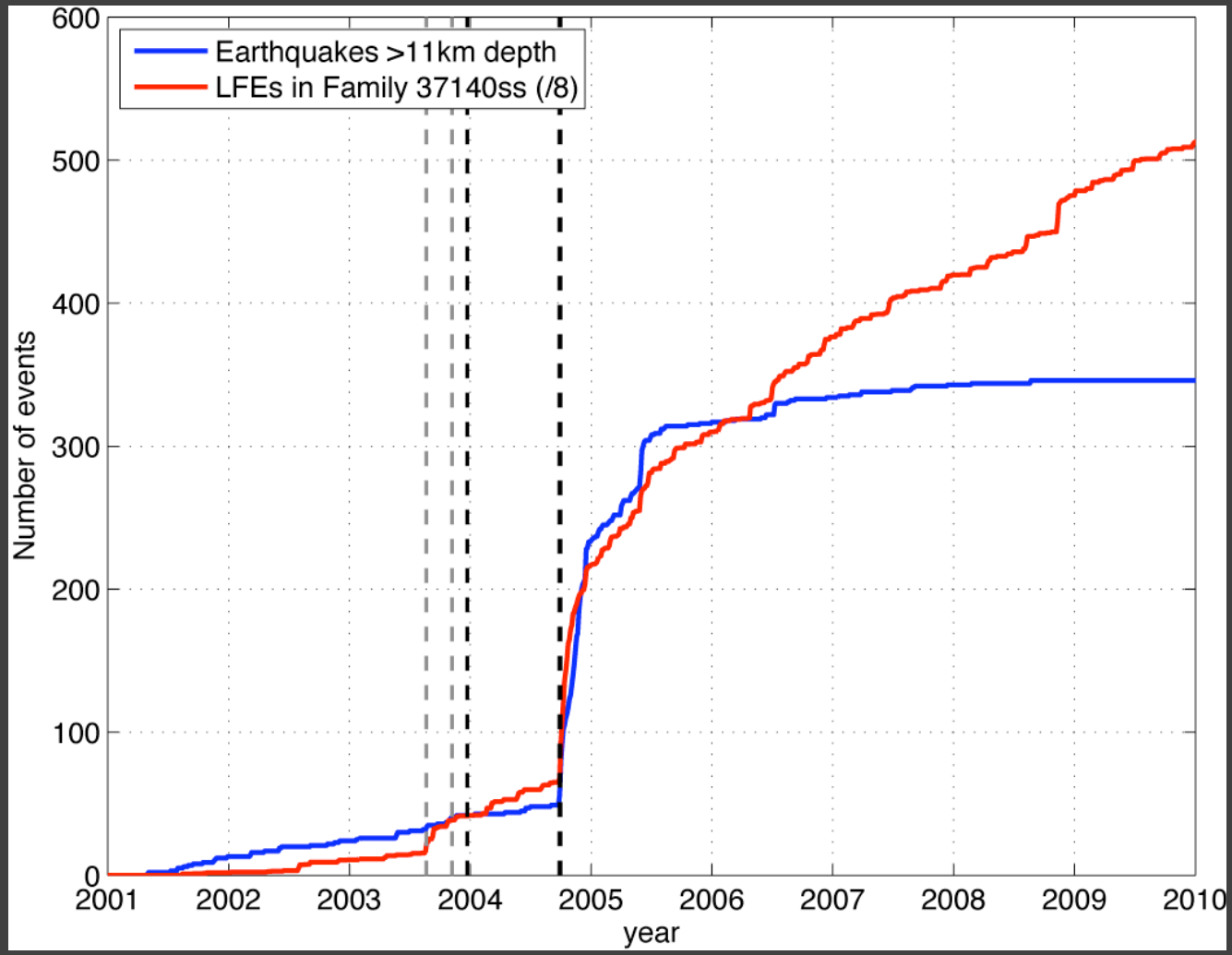
2004 Parkfield

2004 Parkfield (rescaled)



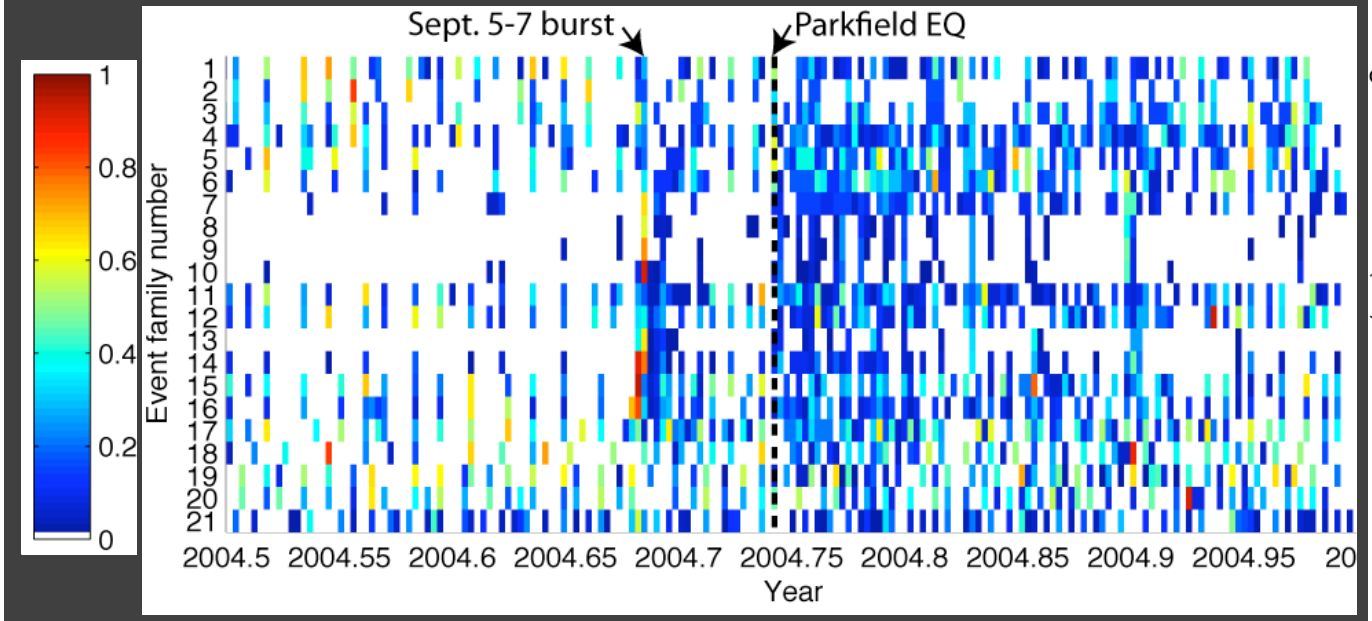
Shelly, in prep.

Comparison of Tremor and EQ response

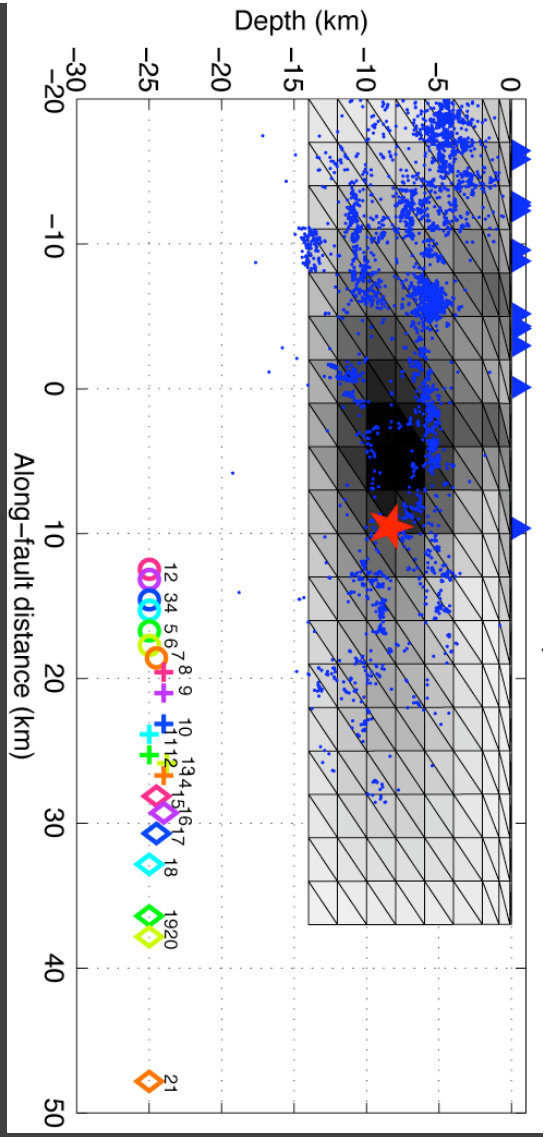


Shelly, in prep.

Event Periodicity Changes with Parkfield EQ



1.5 years



Shelly, Nature, 2010

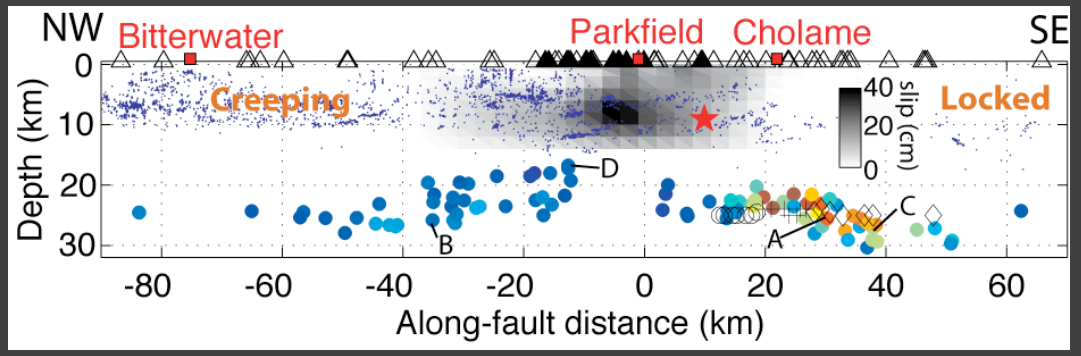
What does it mean? (4)

Conclusion 4.1: Postseismic deformation extends into the lower crust, probably as deep afterslip. Response is asymmetric, with a greater effect beneath creeping section NW of Parkfield.

Conclusion 4.2: At greater distances, periodicity changes without changing overall event rate – effect of dynamic (rather than static) stress?

Remaining Questions (Lots!)

1. How do you get brittle deformation at 600ºC? *(Extreme weakening of the fault???)*
2. Why does the deep fault slip in lots of little tiny events rather than a single larger event? What controls the migration velocities? *(Interplay between brittle and ductile deformation???)*
3. What's happening in places between earthquakes and tremors (~13-20 km depth)? Does this zone slip every few months along with shallow tremor bursts?? Only in big (1857-type) earthquakes???
4. Many more…



Parkfield Tremor – Animation