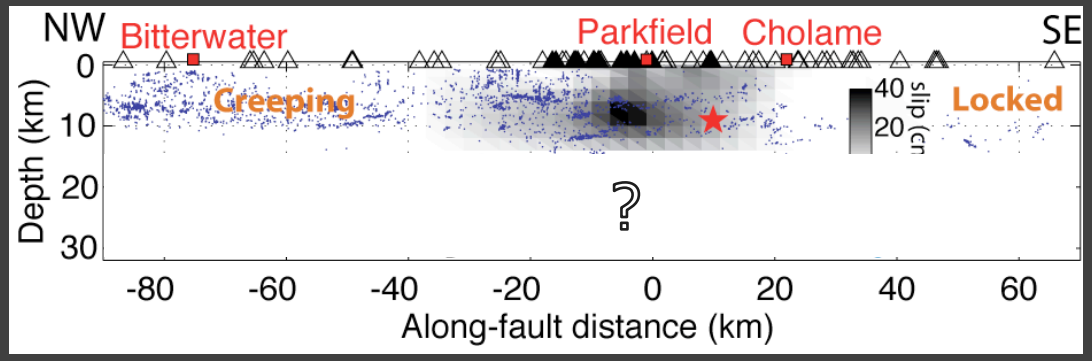
Variations in Tremor Activity and Implications for Lower Crustal Deformation Along the Central San Andreas Fault



Shelly and Hardebeck, GRL, 2010

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USGS science for a changing world

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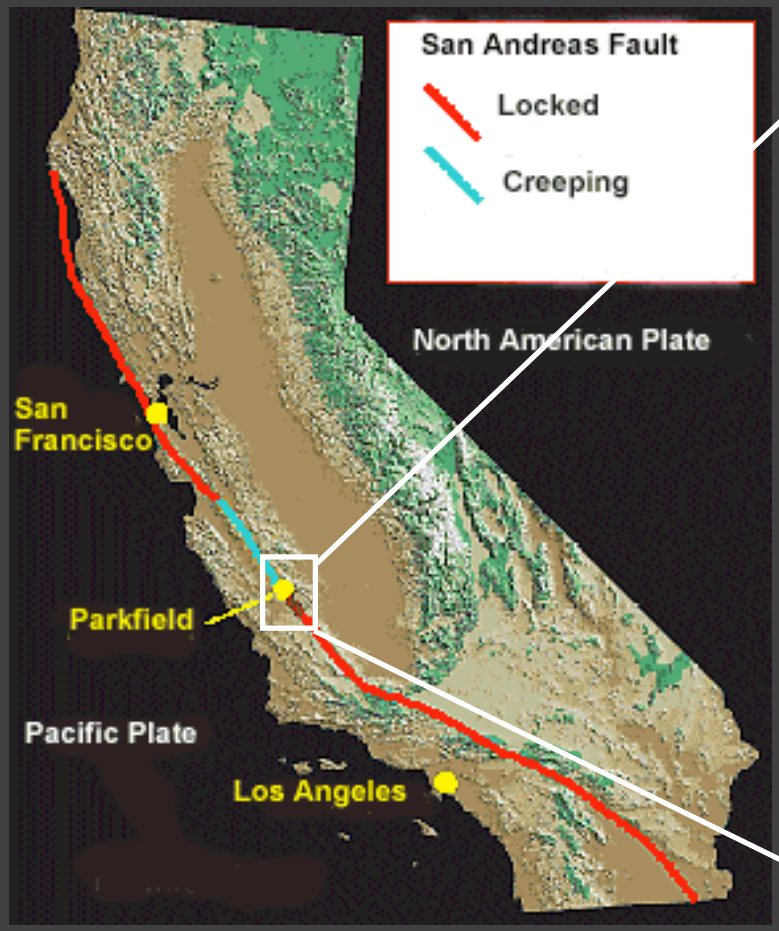
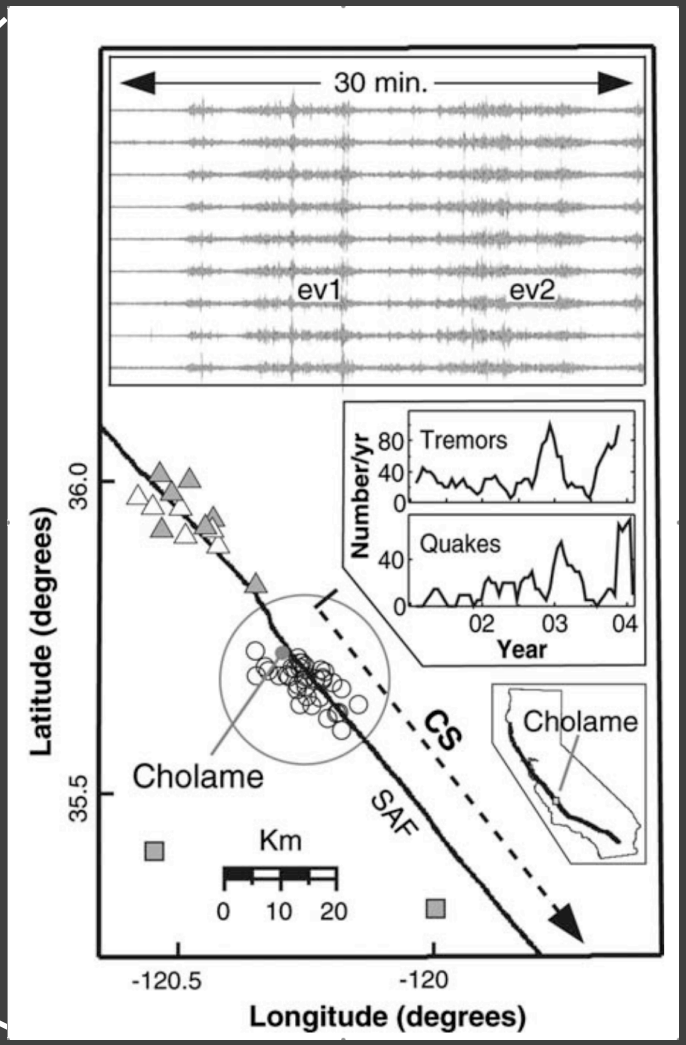
Zhigang Peng
Gary Fuis
Jessica Murray-Moraleda
Bill Ellsworth
Roland Bürgmann
Bob Nadeau
Greg Beroza

Tremor Under the San Andreas





Nadeau and Dolenc, *Science*, 2005

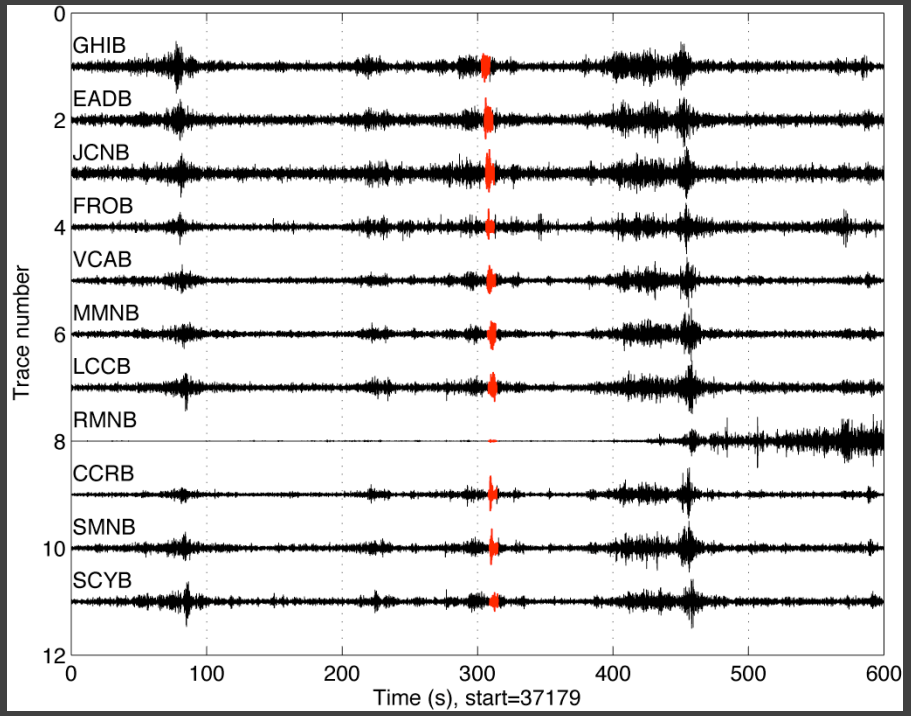
1. Tremor Locations and Migration

2 simple tecniques:

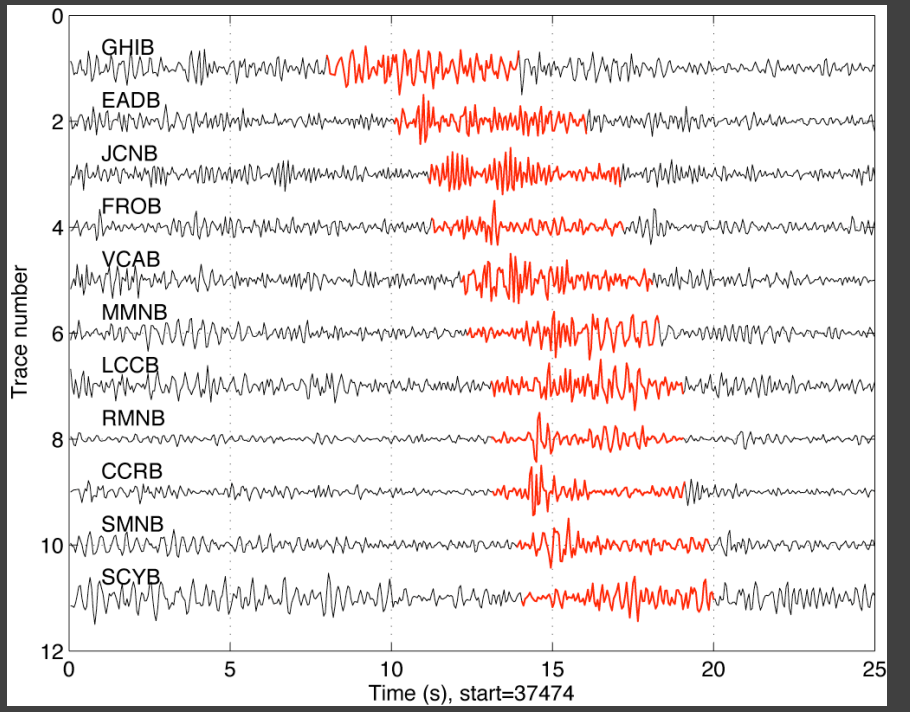
1) Cross-correlation (multiplication)

2) Stacking (addition)

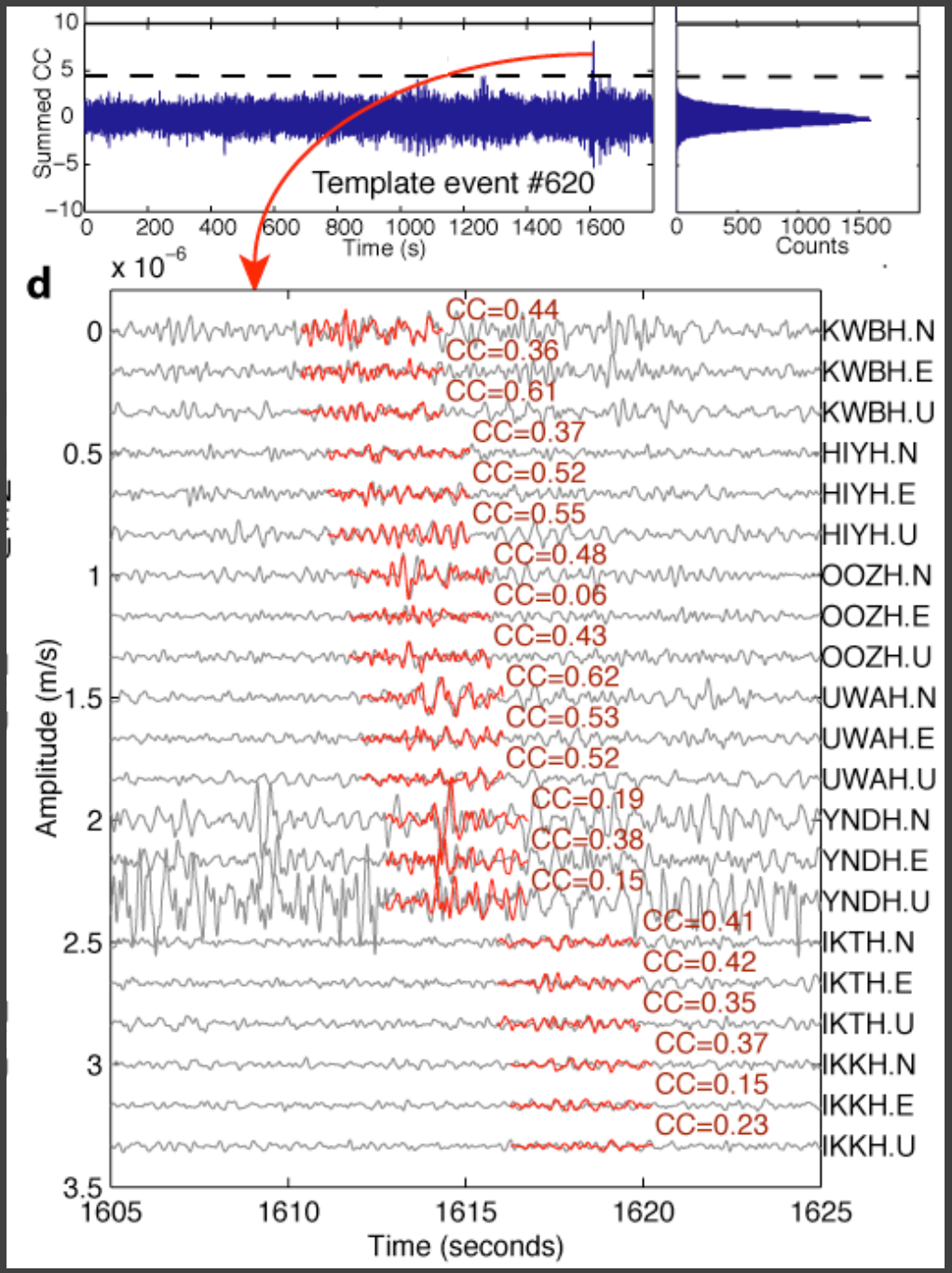
Template Waveforms



10 minutes



25 seconds

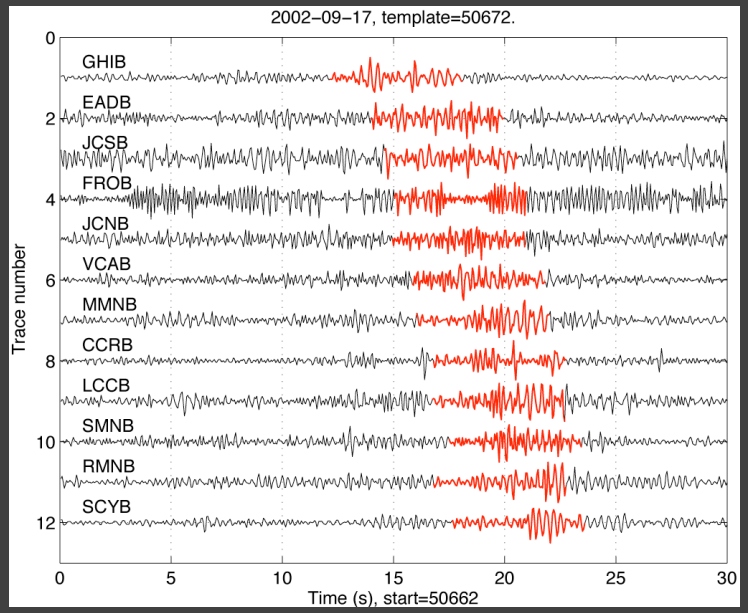


Scan template through continuous data, sum correlations

Shelly *et al.*, Nature, 2007

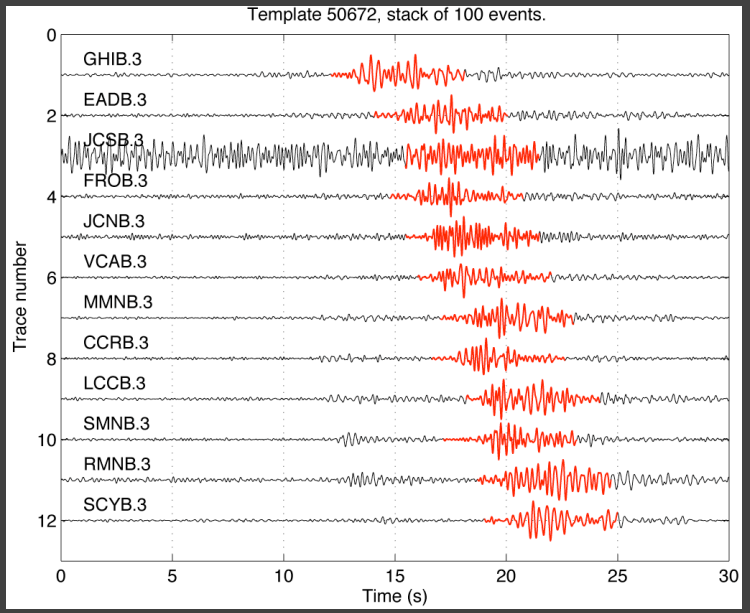
Stacked LFE Templates

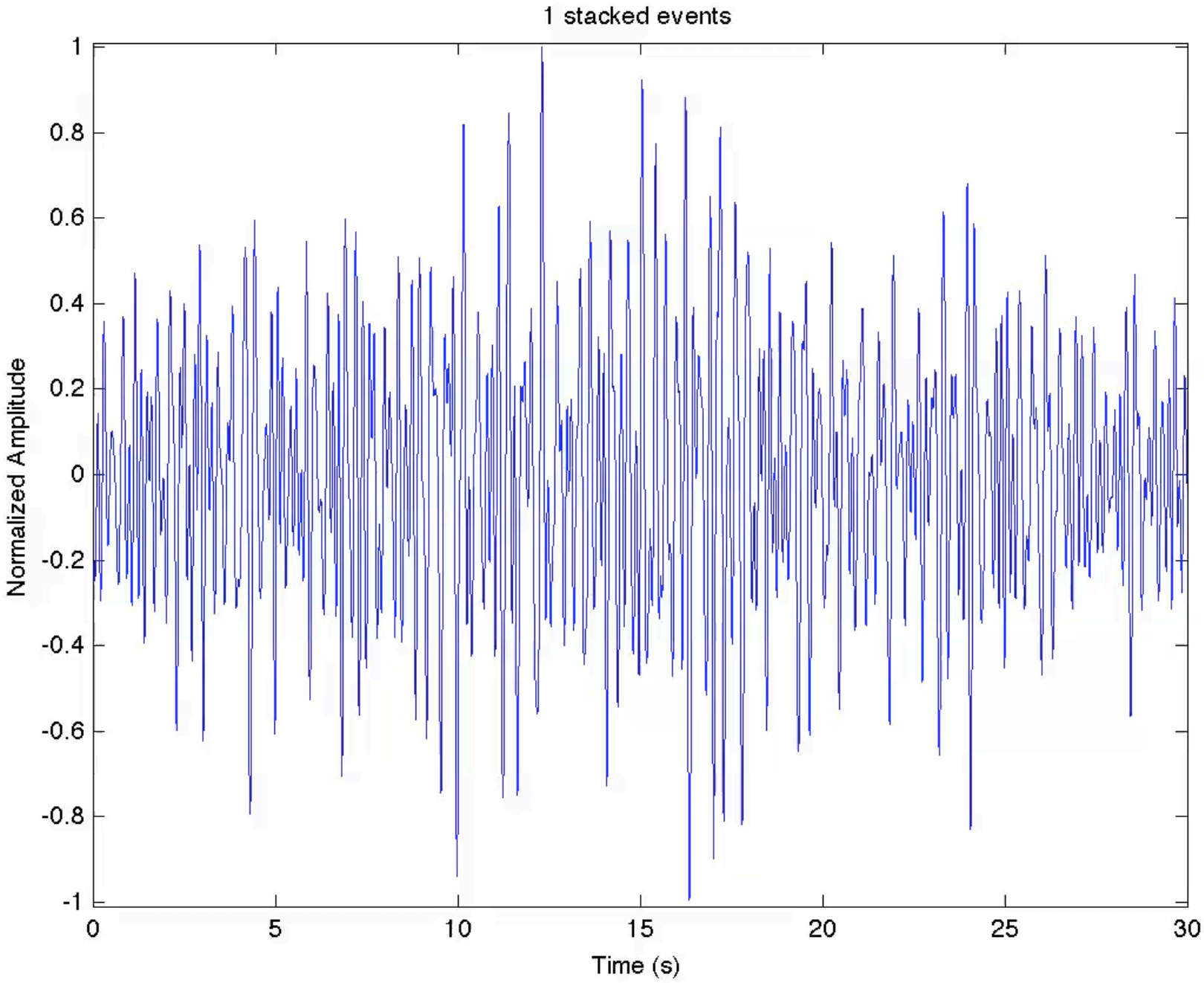
Single LFE template



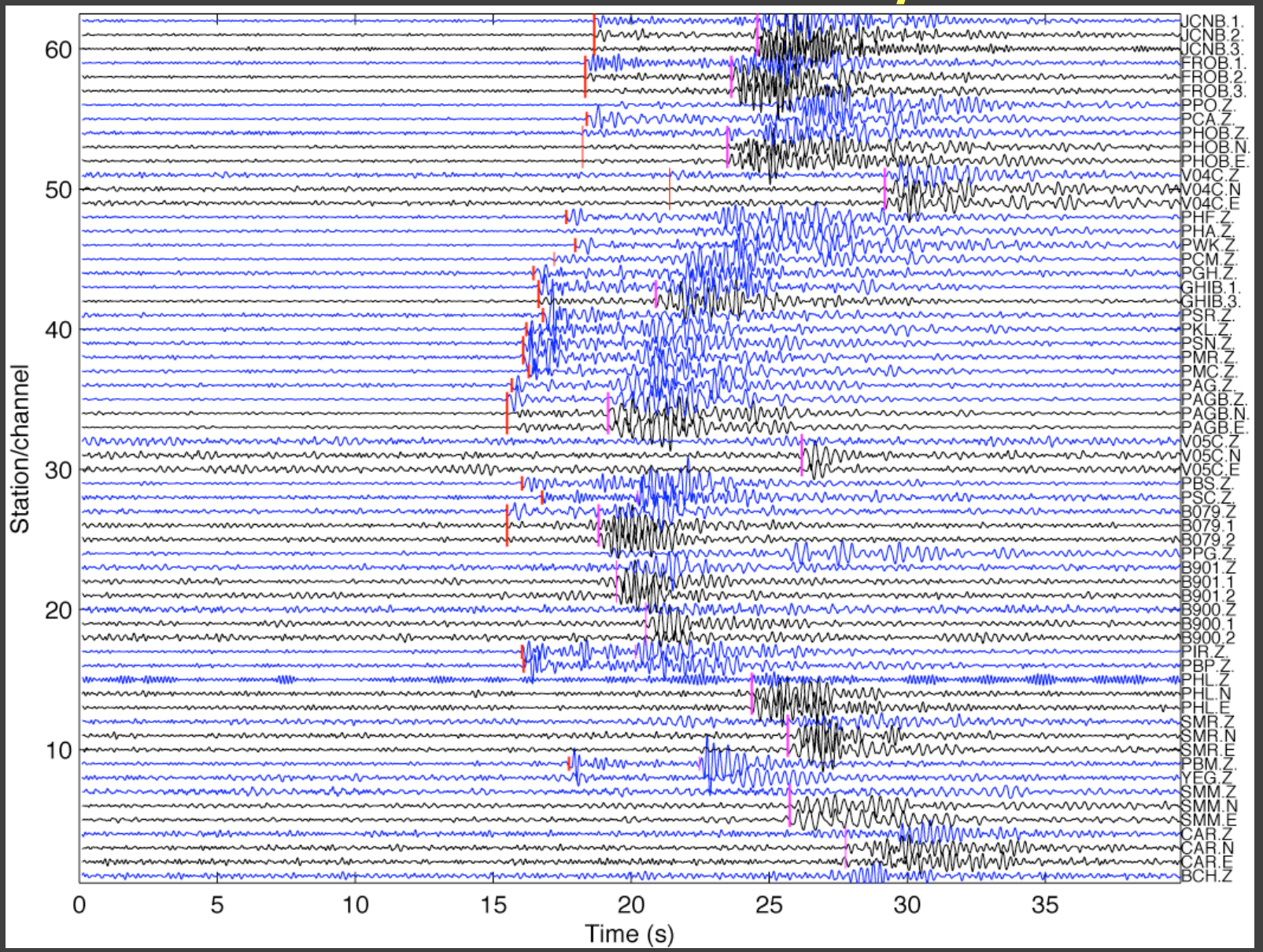
stacking

100 LFE stack template



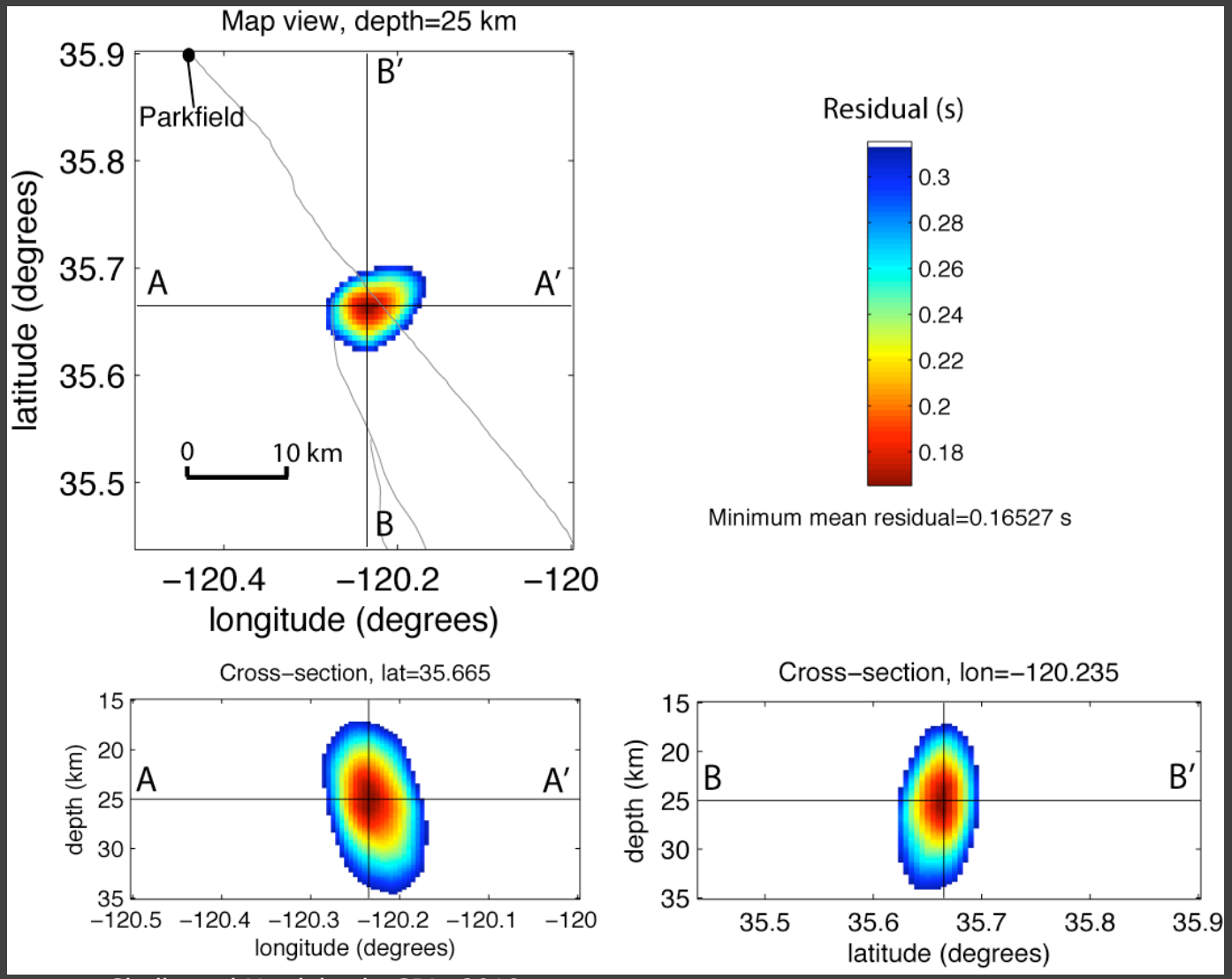

1 stacked events
Normalized Amplitude
Time (s)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
5
10
15
20
25
30

Stacked Waveforms/Picks



Shelly and Hardebeck, GRL, 2010

Grid Search Location (3D)

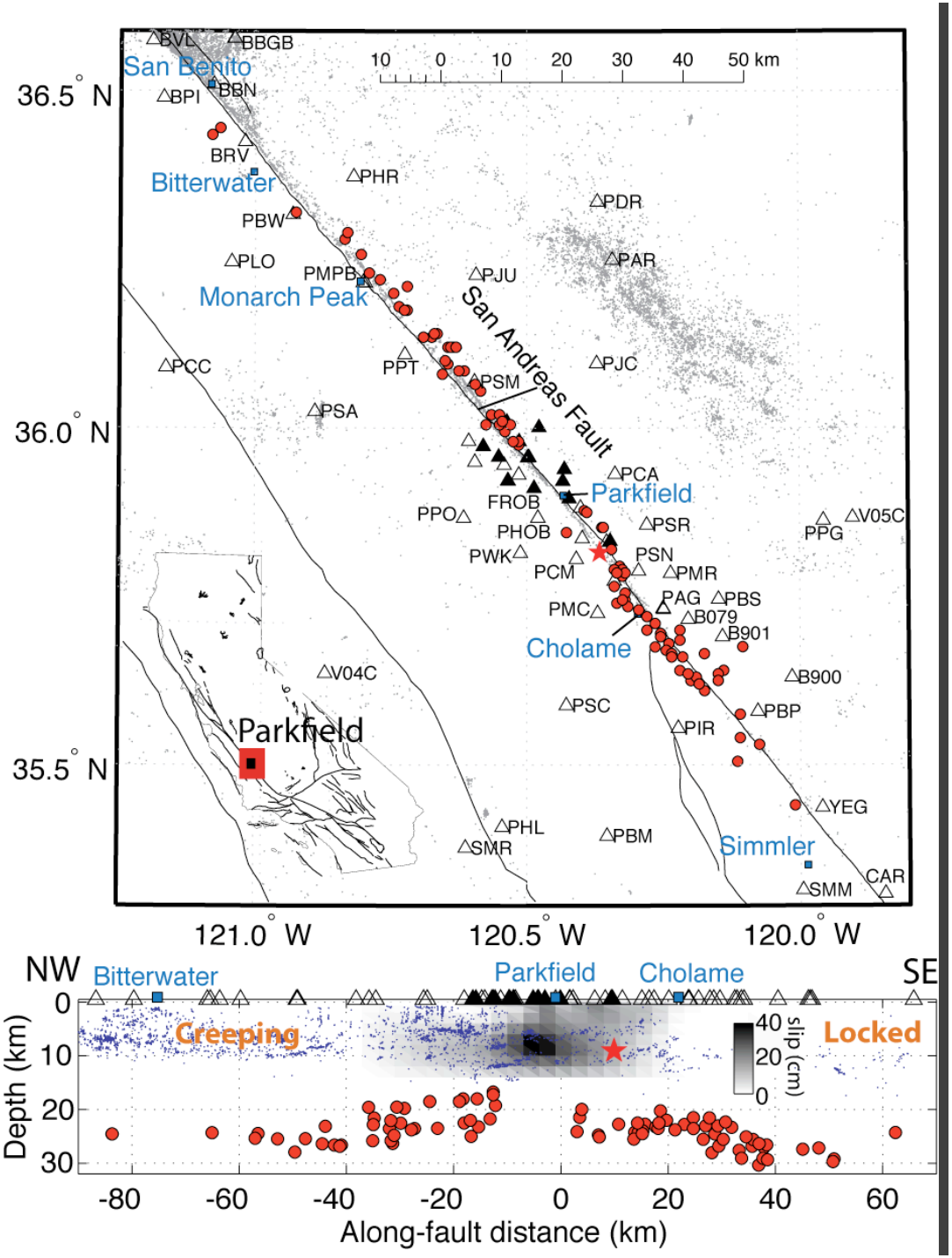


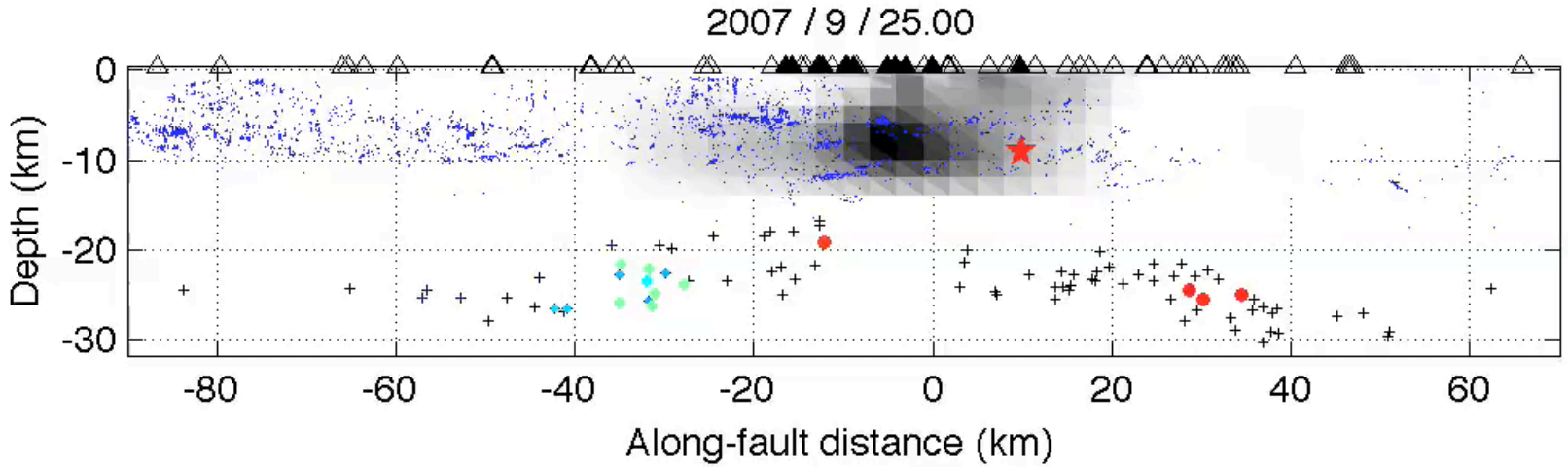
Shelly and Hardebeck, GRL, 2010

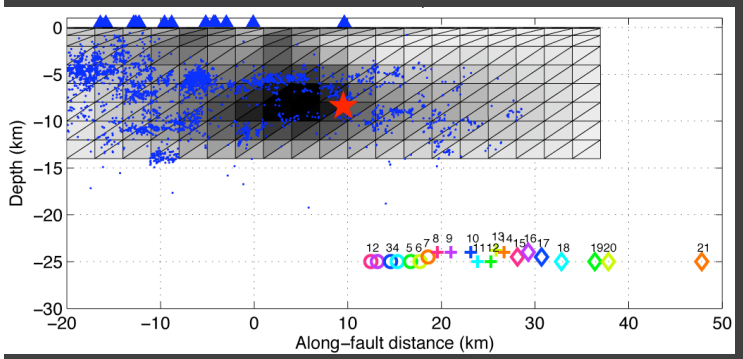
Parkfield Tremor Locations

- 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

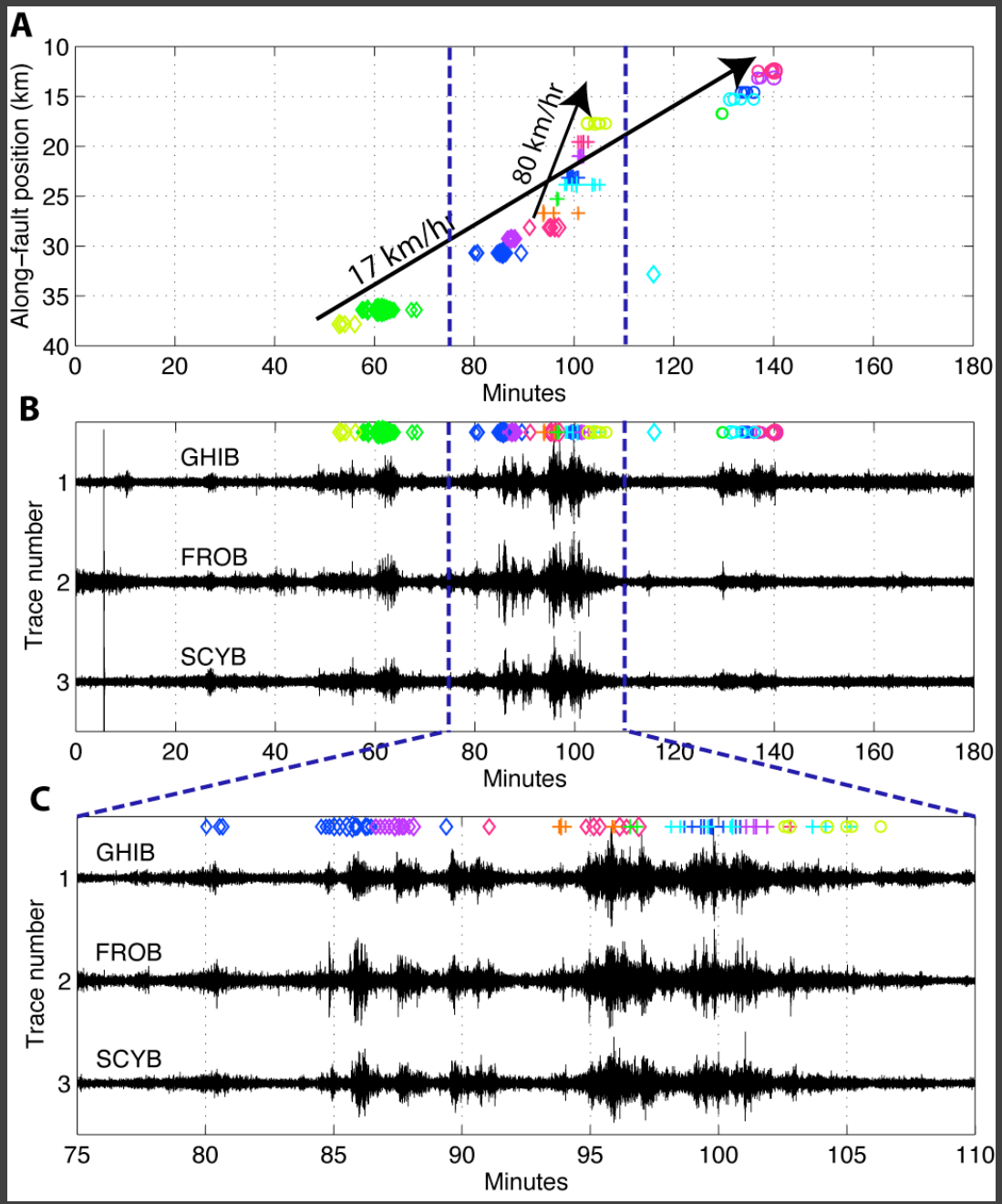
Shelly and Hardebeck, GRL, 2010




2007 / 9 / 25.00
0
-10
-20
-30
Depth (km)
-80
-60
-40
-20
0
20
40
60
Along-fault distance (km)



Tremor Migration



Shelly, Nature, 2010

What does it mean? (1)

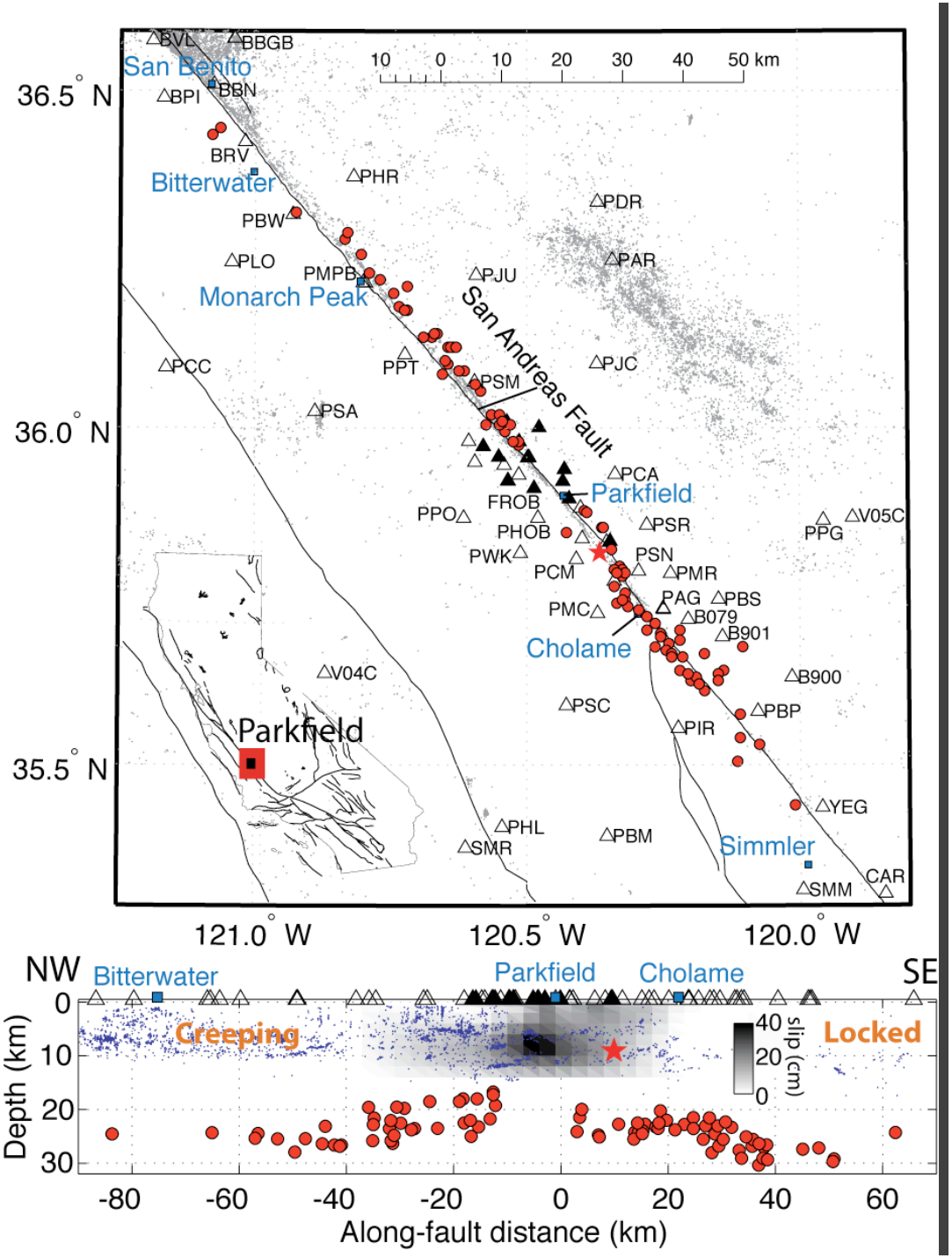
Conclusion 1.1: The San Andreas fault does not end at the base of the "seismogenic zone." Tremor sources are located on the deep extension of the fault, in the lower crust. Migration suggests the fault exists as a through-going structure at this depth.

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

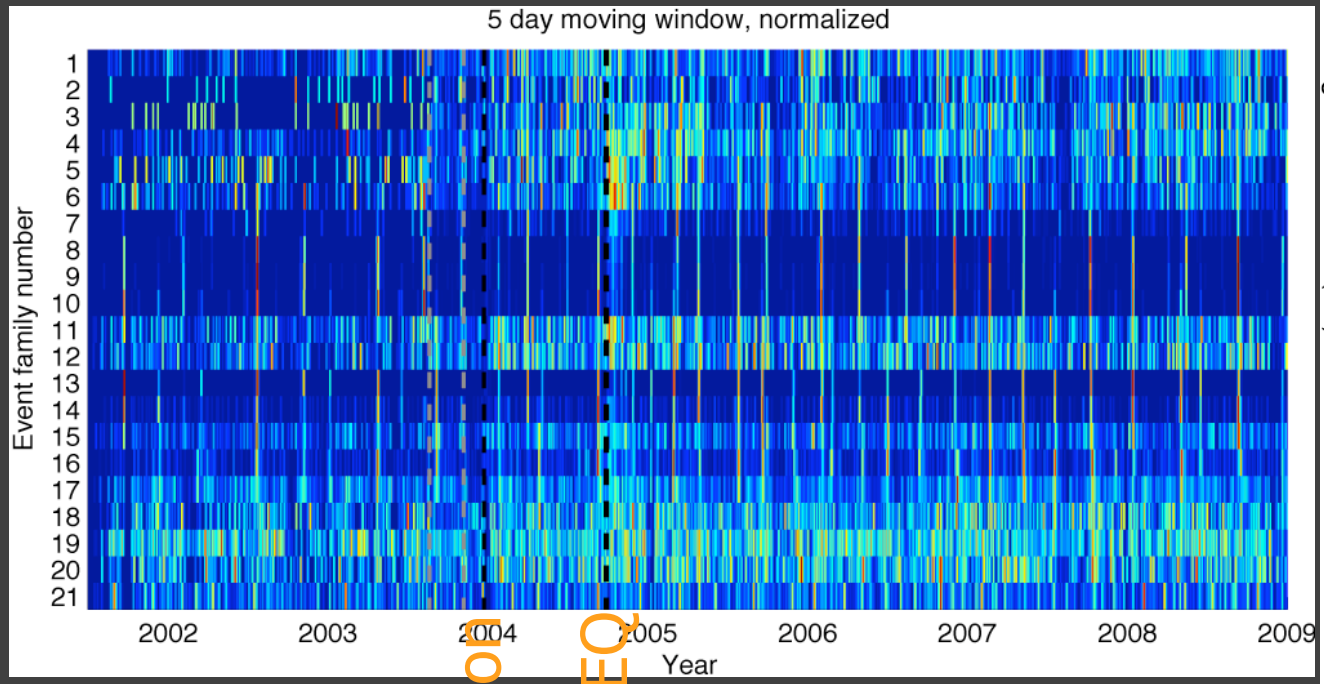
- 9 years of data
- ~36 trillion cross-correlation measurements
- ~600,000 events detected since mid-2001 (3000-20,000 per family)
- Detectible tremor activity in some area every day

Shelly and Hardebeck, GRL, 2010



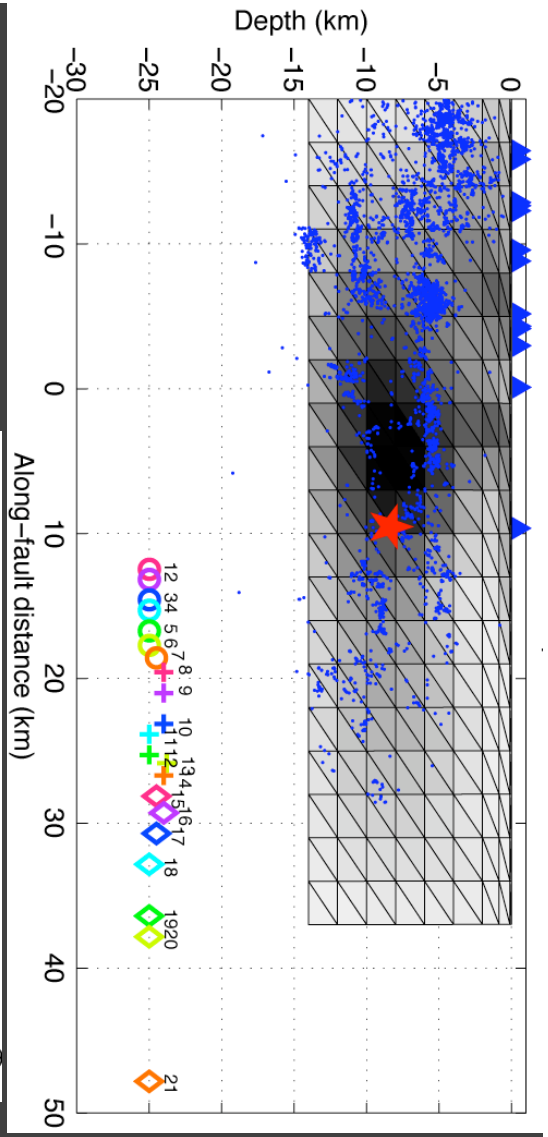
2. Variations in recurrence patterns and amplitudes among tremor families

Event Recurrence Patterns



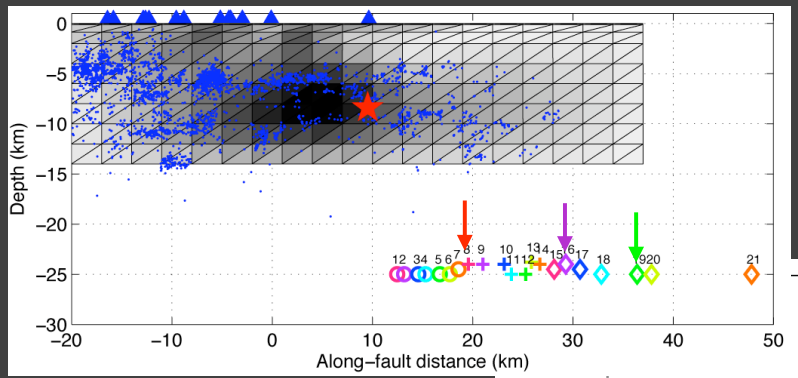
San Simeon

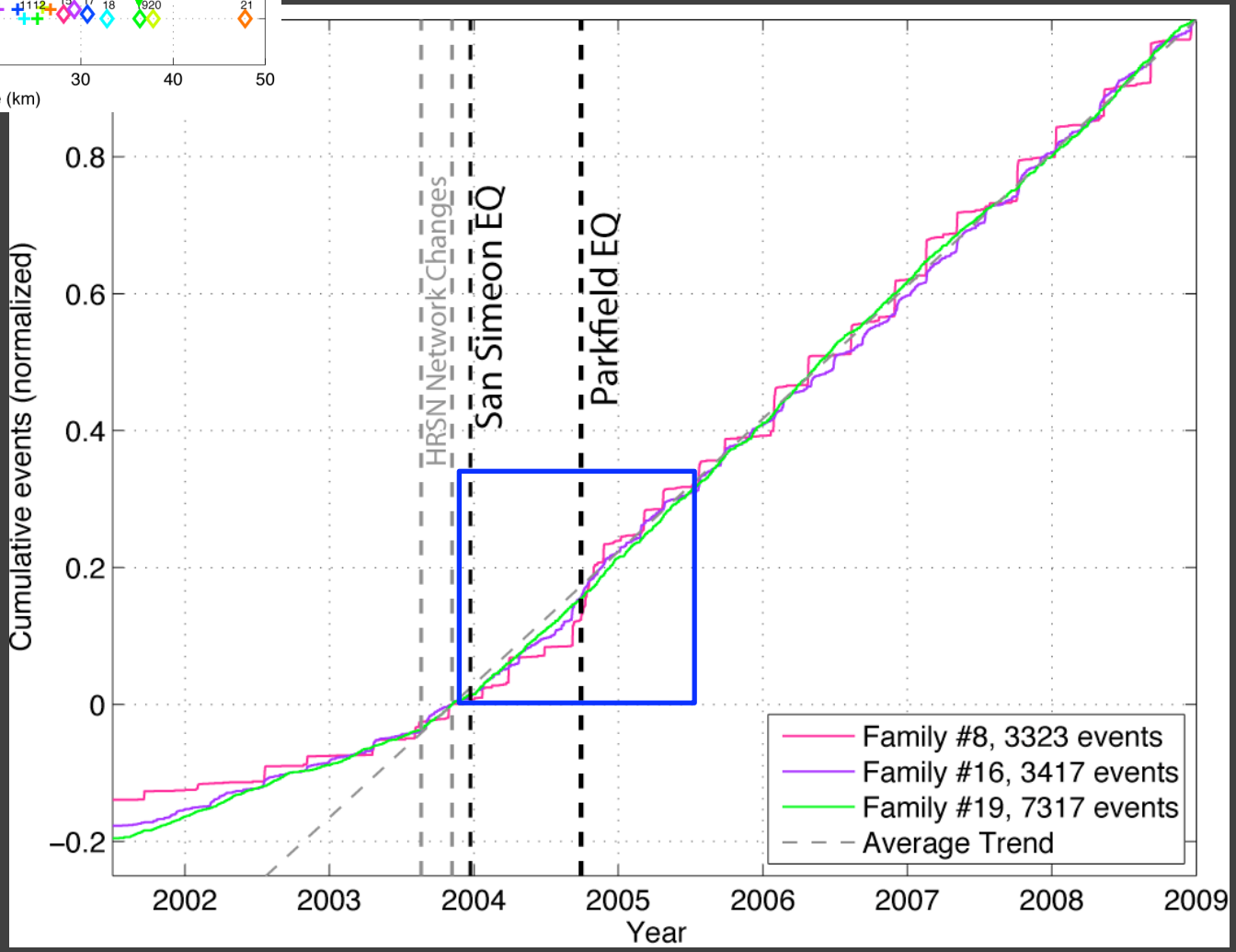
Parkfield EQ



Shelly, Nature, 2010

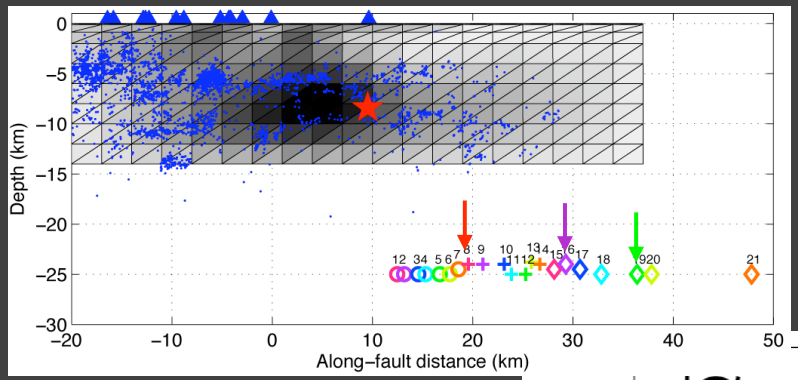
Cumulative Events

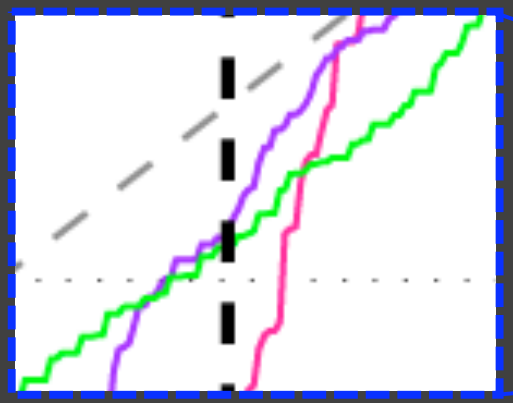


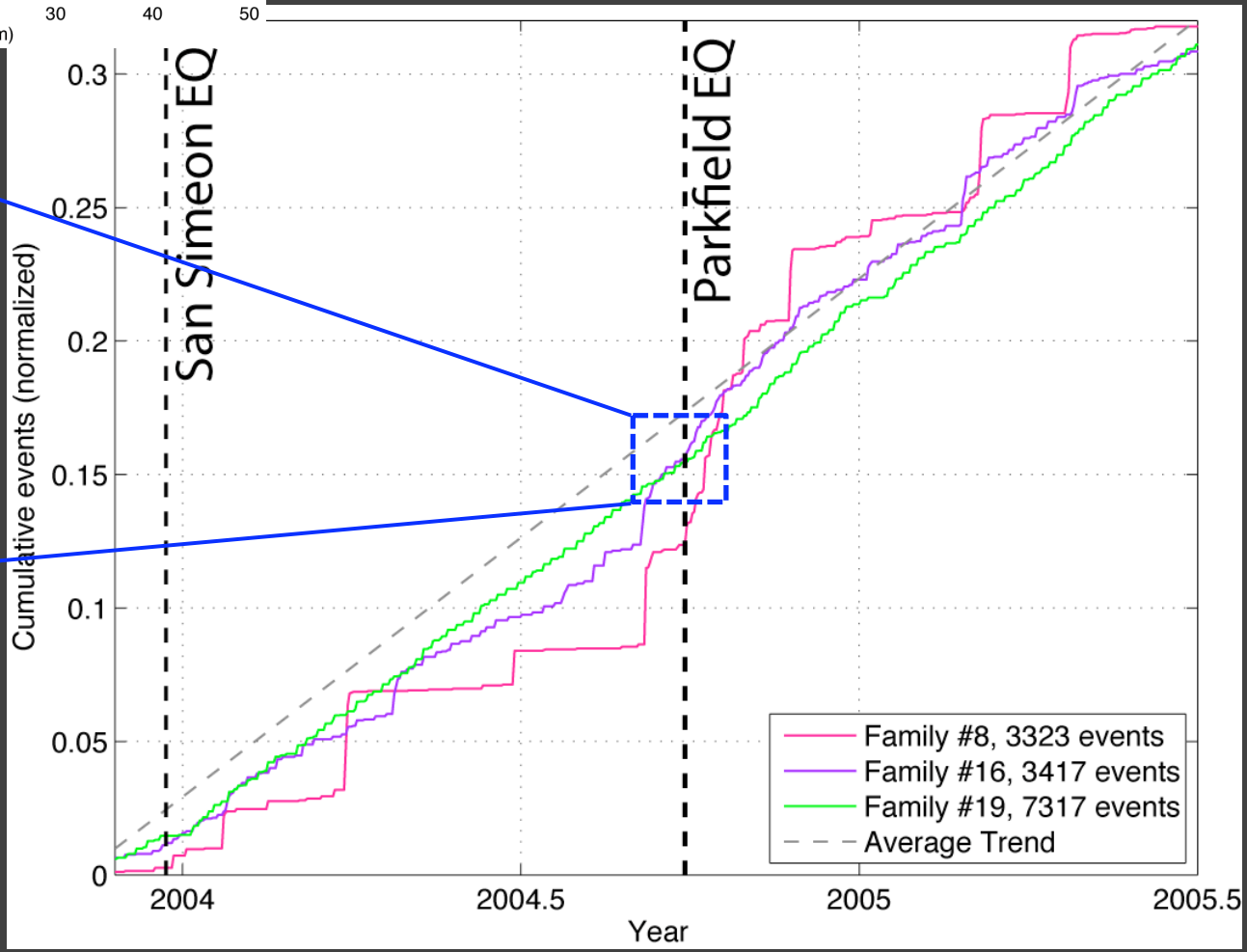


Shelly, Nature, 2010

Cumulative Events

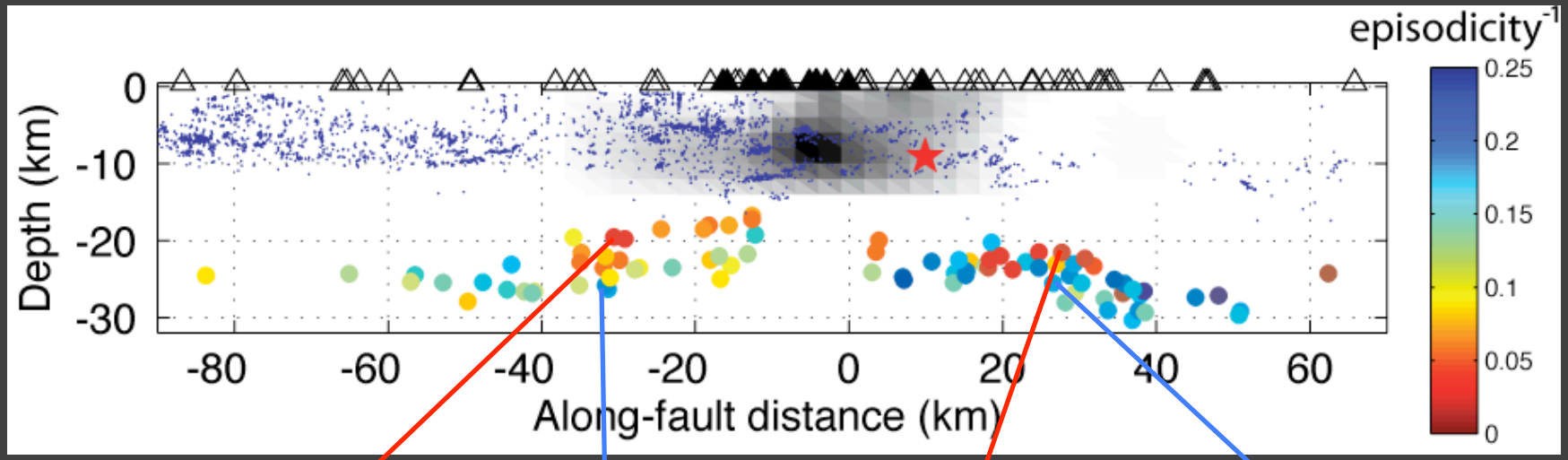


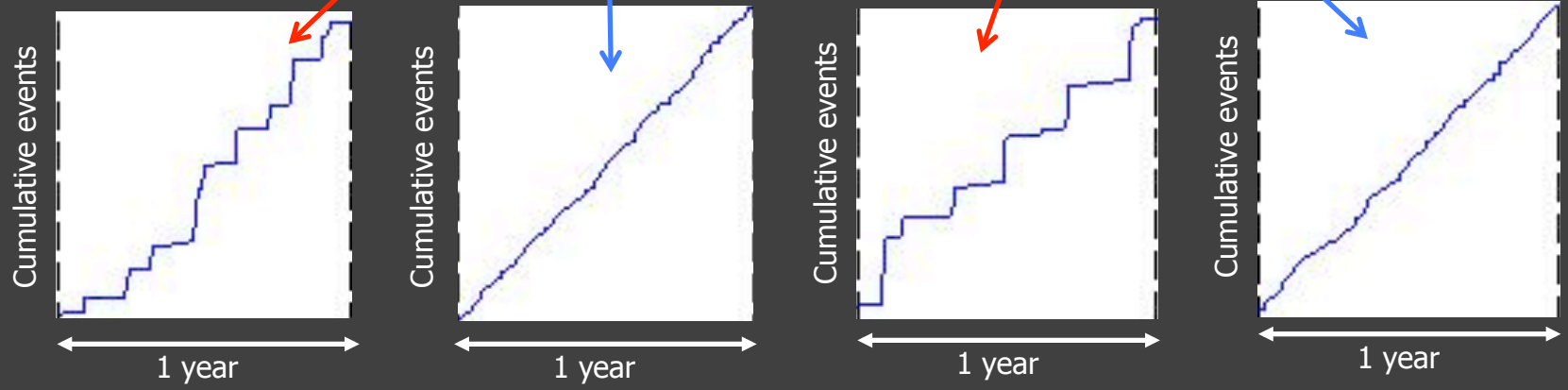




Shelly, Nature, 2010

Shallower sources have larger, less frequent bursts



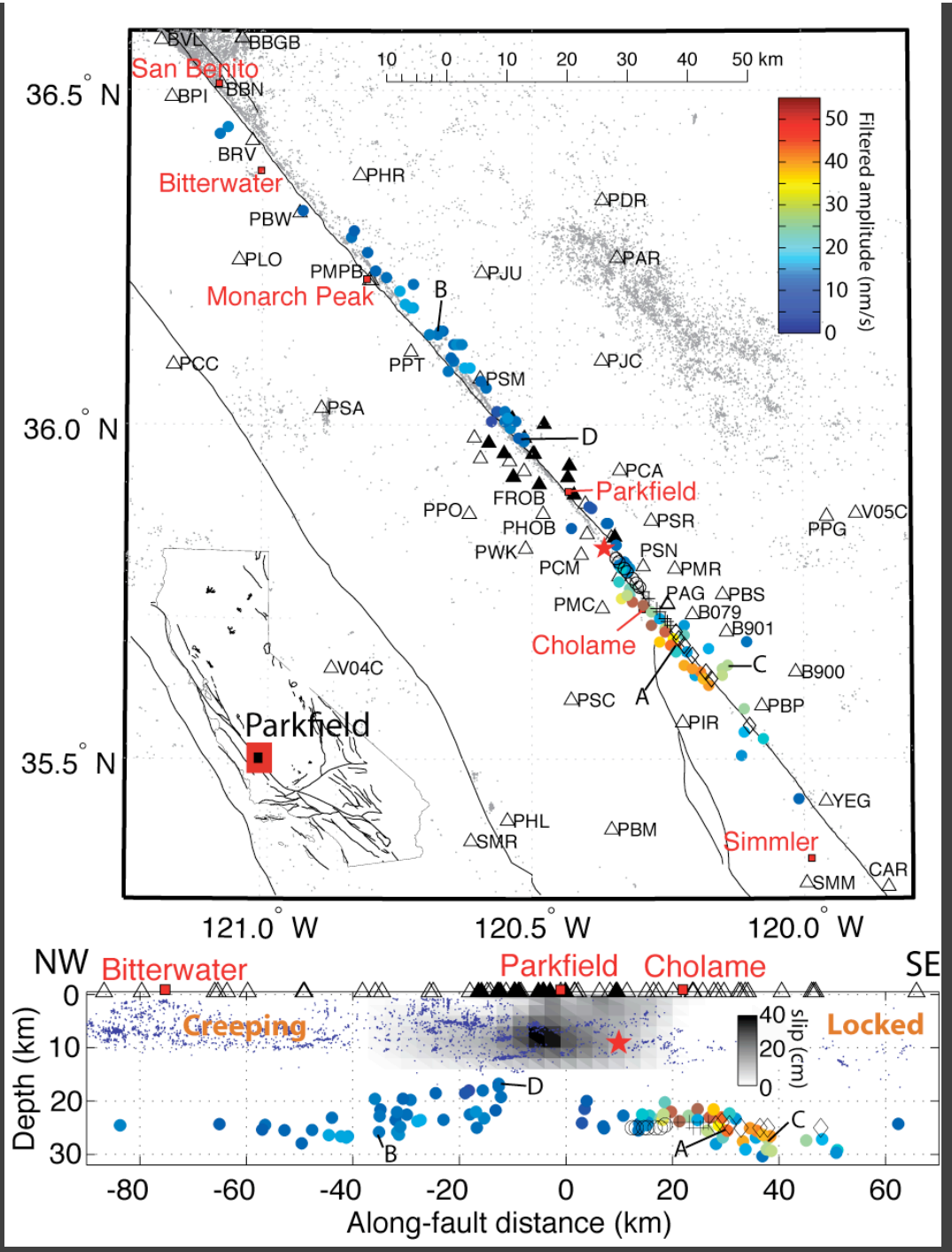


Shelly, in prep.

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, 2010



What does it mean? (2)

Conclusion 2.1: The strength of the lower crust may 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.

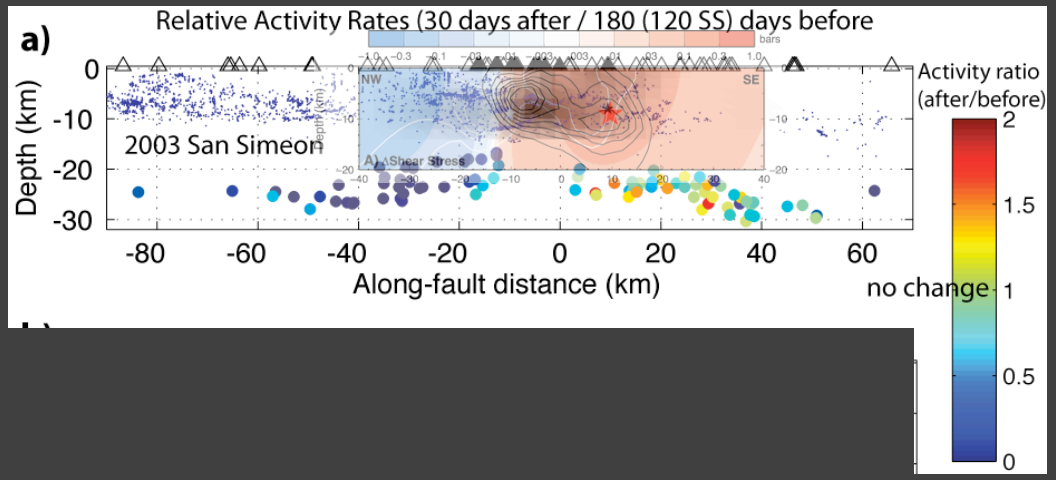
3. Tremor response to nearby earthquakes

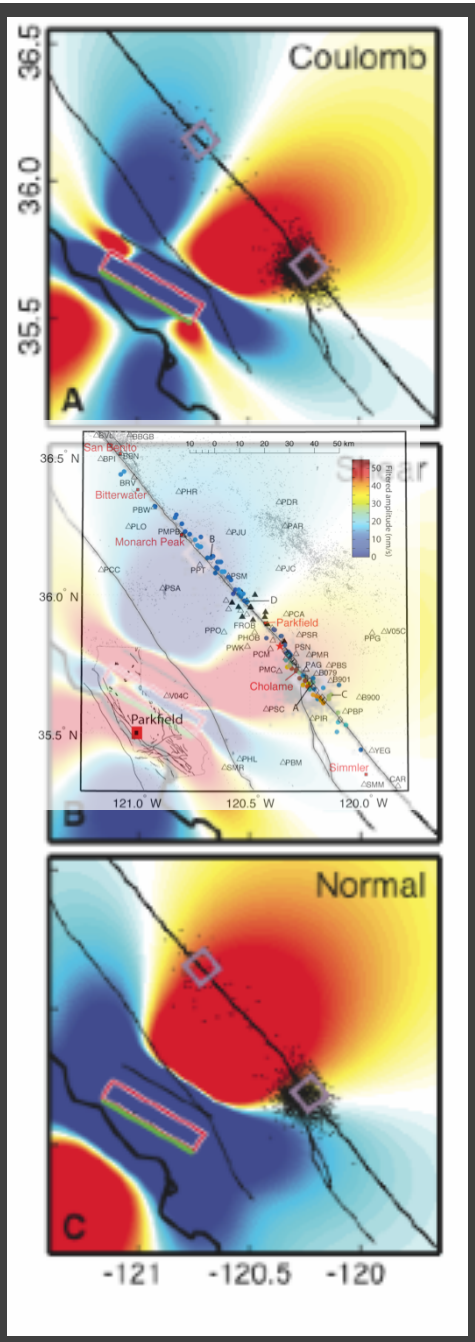
1) 2003 San Simeon (M 6.5)

2) 2004 Parkfield (M 6.0)

Coseismic Stresses

2003 M 6.5 San Simeon
(after/before activity rates)



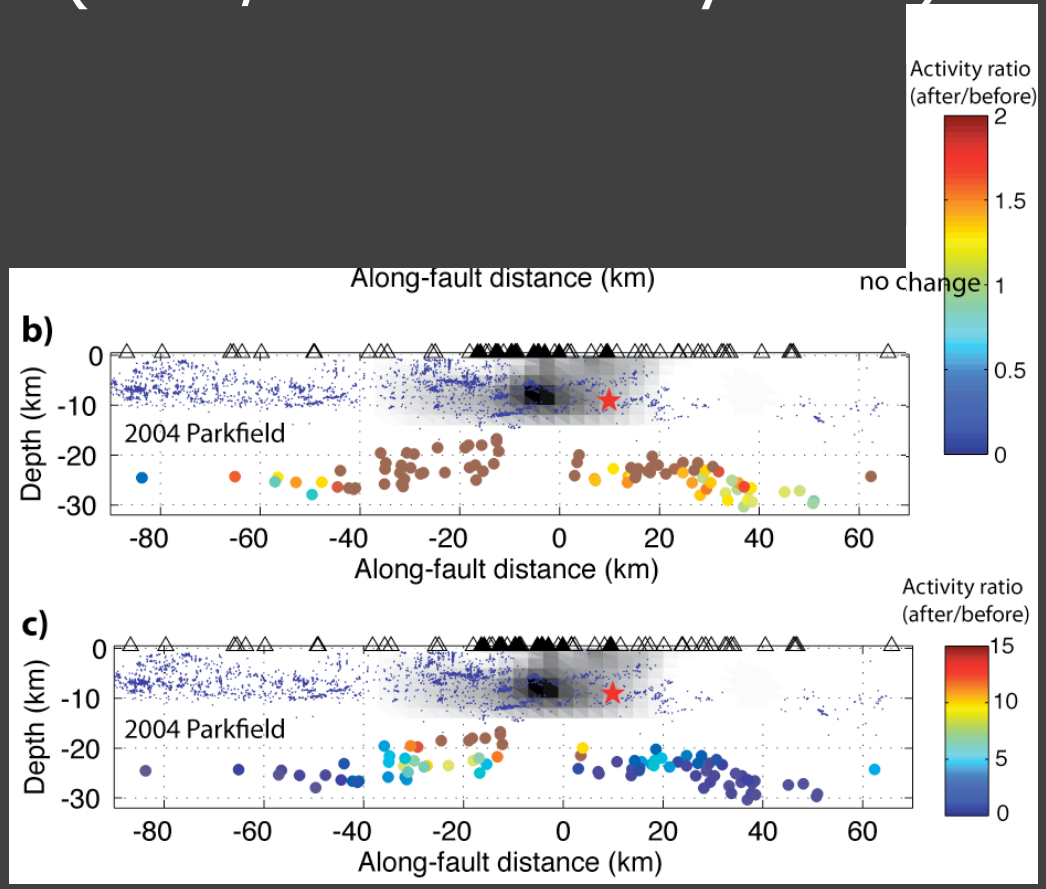


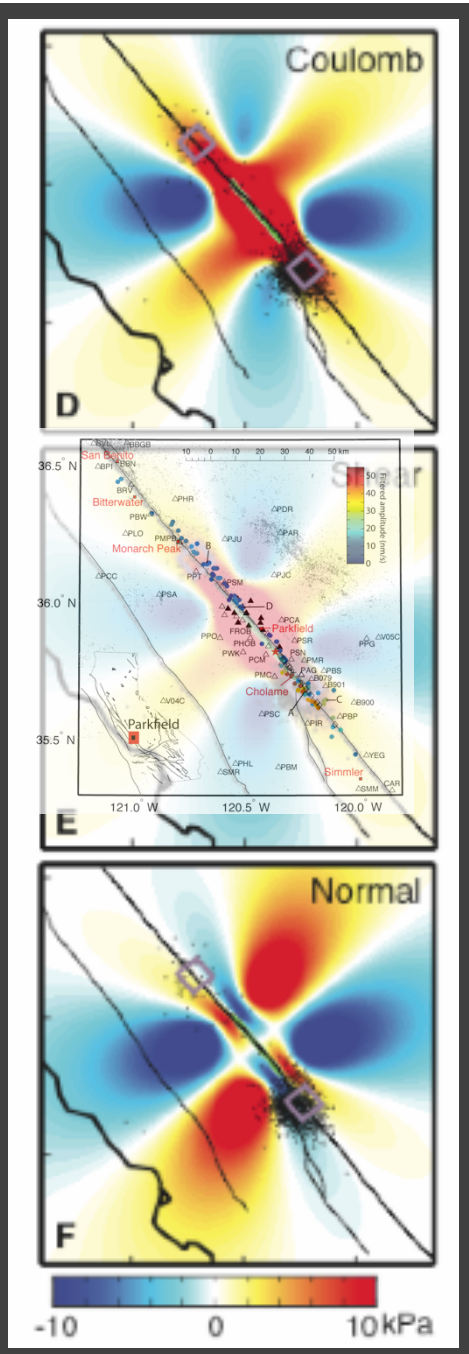
Stress model from Johanson and Bürgmann, 2010

Nadeau and Guilhem, Science, 2009

Coseismic Stresses

2004 M 6.0 Parkfield
(after/before activity rates)





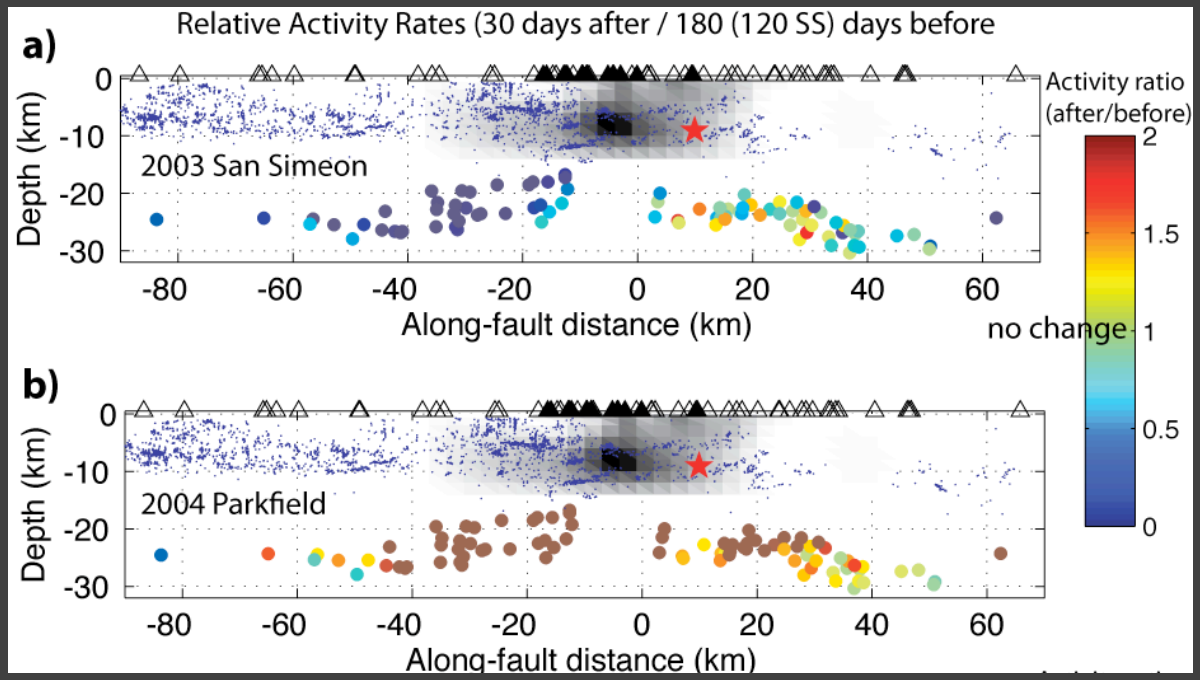
Nadeau and Guilhem, Science, 2009

Response to 2003 San Simeon and 2004 Parkfield Earthquakes

2003 San Simeon

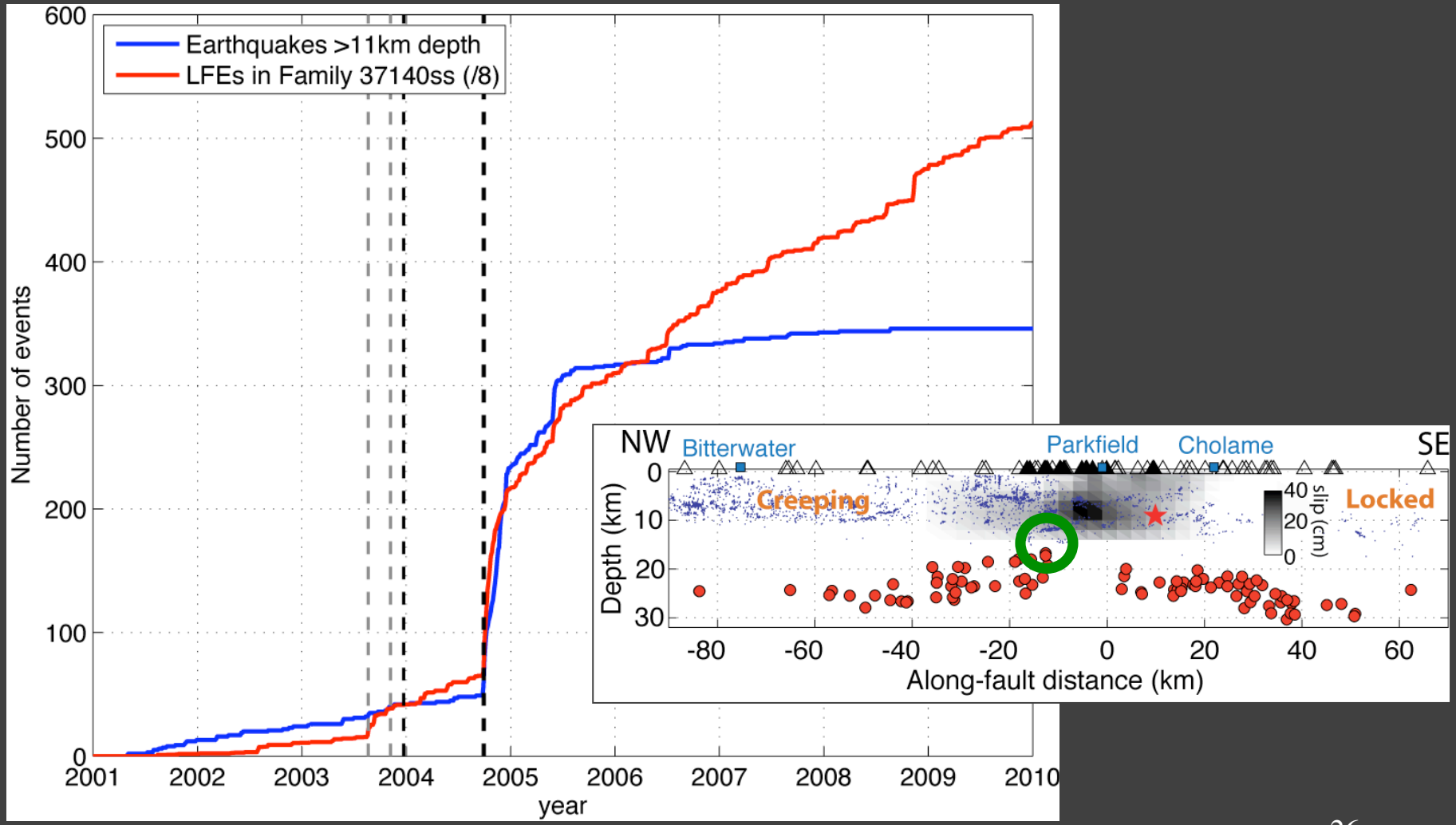
2004 Parkfield

2004 Parkfield (rescaled)



Shelly, in prep.

Comparison of Tremor and EQ response



Shelly, in prep.

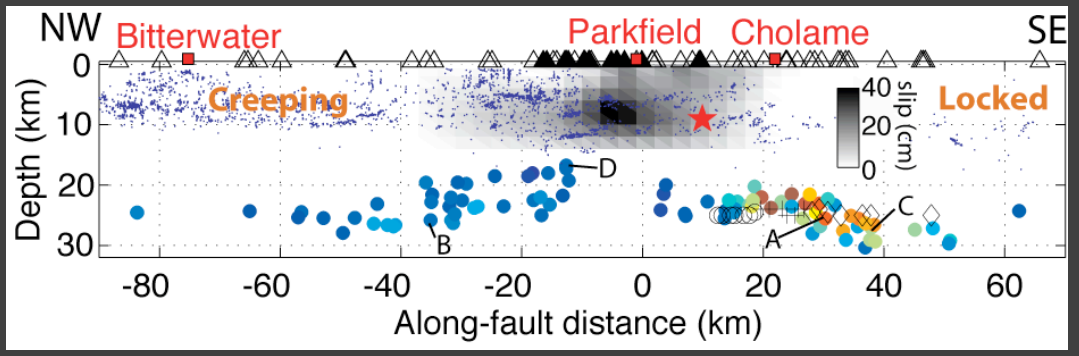
What does it mean? (3)

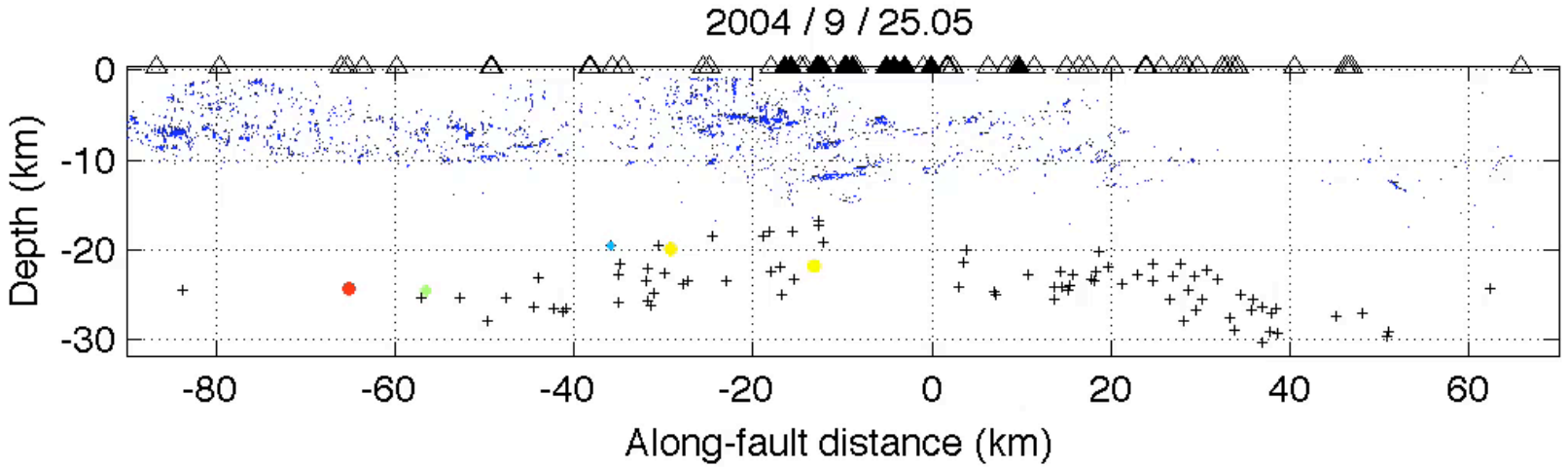
Conclusion 3.1: The 2003 San Simeon earthquake produces a strong "stress shadow" effect for the northern tremor sources.

Conclusion 3.2: Postseismic deformation following the 2004 Parkfield earthquake extends into the lower crust, probably as deep afterslip. Response is asymmetric, with a greater effect beneath creeping section NW of Parkfield.

Remaining Questions (Lots!)

1. How do you get brittle (seismic) 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…




2004 / 9 / 25.05
0
-10
-20
-30
Depth (km)
-80
-60
-40
-20
0
20
40
60
Along-fault distance (km)