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

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Shelly and Hardebeck, GRL, 2010
1. Tremor Locations and Migration

2 simple techniques:

1) Cross-correlation (multiplication)

2) Stacking (addition)
Template Waveforms

10 minutes

25 seconds
Scan template through continuous data, sum correlations

Stacked LFE Templates

Single LFE template

100 LFE stack template

stacking
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*
Tremor Migration

Shelly, Nature, 2010
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)
- Detectable 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

5 day moving window, normalized

Shelly, Nature, 2010
Cumulative Events

Shelly, Nature, 2010
Shallower sources have larger, less frequent bursts.
Amplitude potential

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

Relative Activity Rates (30 days after / 180 (120 SS) days before)

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

Shelly, in prep.
Comparison of Tremor and EQ response

Shelly, in prep.
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...