Final Report

SCEC Project #12007: Investigating tectonic tremor beneath the San Andreas Fault near Parkfield with the PASO array

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Summary

Tectonic or non-volcanic tremor (NVT) is arguably one of the most exciting and enigmatic seismological discoveries of the last decade. Initially, observations of NVT were restricted to subduction zone settings, often in association with slow slip events and/or low-frequency earthquakes (LFE's) (Obara, 2002; Rogers and Dragert, 2003; Shelly et al., 2007). Subsequently, its occurrence as both "ambient" and triggered NVT was recognized in other settings, including ambient NVT beneath the San Andreas Fault (SAF) (Nadeau and Dolenc, 2005) and triggered NVT beneath the SAF and in other regions in California (Gomberg et al., 2008) and elsewhere. One overarching question is, what is the spatial relationship among earthquake rupture zones, slow slip events, and NVT? Another is, what if any role do fluids play in the occurrence of NVT? We are using a previously untapped source of data, the PASO array (Thurber et al., 2003, 2004; Zhang et al., 2009), and other available data, to investigate NVT in the Parkfield region. This work is being done in close collaboration with David Shelly (USGS), and with assistance from Justin Brown (Caltech/USGS Pasadena) and Danielle Sumy (USGS Pasadena).

We extended the successful stacking approach developed with 2011 SCEC support to process and pick P and S arrivals recorded by the 59-station PASO array for dozens of LFE families identified and located by Shelly and Hardebeck (2010). We then used a combination of P and S arrival times and corresponding differential times from 14 LFE families directly beneath the PASO array, along with absolute and differential times from shallower microearthquakes, to provide higher-precision locations of the LFE's and to image the three-dimensional (3-D) P- and S-wave velocity structure to ~20 km depth. Our initial focus was on the crustal volume directly below the PASO array, near SAFOD. Our results indicate that the LFE's align close to the vertically-downward extension of the SAF, but they show some variability along strike, suggesting a somewhat complex structure for the SAF at lower crustal depths. Furthermore, the LFE's near SAFOD lie within or adjacent to zones with slightly reduced P-wave velocity and more sharply reduced S-wave velocity. The estimated Vp/Vs values are approximately 1.9 in these zones. The elevated Vp/Vs values are interpreted to reflect high pore fluid pressure and low effective stress (Shelly et al., 2007). This is consistent with results from previous findings in subduction zones and with observations of triggering and tidal modulation of LFE’s and tremor on this deep extension of the SAF.

Technical Report

Methods

UW undergraduate student Dana Peterson has been working with the PI, collaborators David Shelly (USGS) and Justin Brown (Caltech/USGS, and a former UW undergrad), and UW postdocs Ninfa Bennington and Emily Montgomery-Brown, analyzing NVT data from the PASO array and combining the results with other sources of data. Initially, Shelly provided us with the individual window start times for all the events in his stack for one LFE family (37102) near SAFOD (Shelly and Hardebeck, 2010). These window start times are, within measurement accuracy, at a constant time offset from the P and S arrival times for all recurrences of the tremor family at any station. Thus we were able to window all PASO data in the same way, using Shelly's window start times (precise to 0.05 s), and stack the waveforms to produce "tremorgrams." This successful approach was then applied to PASO data for all LFE's in Shelly's catalog that lie below the PASO array, and the stacks with sufficient signal-to-noise ratio were picked manually. We also assisted Danielle Sumy in the application of this approach to data from the PERMIT array in the Cholame area. Our next step was to integrate the PASO LFE picks into an existing dataset for the SAFOD area (Zhang et al., 2009) for double-difference tomography.

Results

Our stacking technique yielded a total of 3,775 stacks of LFE waveforms across three station components, from which we were able to pick 1,375 P- and S-wave arrivals. These picks, along with Shelly's LFE picks, were integrated into a large existing tomography dataset for the SAFOD region (Zhang et al., 2009), but with an expanded station distribution (Figure 1).

We adopted a modified version of the Zhang et al. (2009) velocity model for this area as our starting model, with a coordinate system centered on the SAFOD drill site (35.97420383° N, 120.5521413° W). We expanded the model to cover a region 60 km northeast-southwest by 60 km northwest-southeast. In the X direction, nodes are positioned at -30, -20, -10, -7, -4, -2, 0, 2, 4, 7, 10, 20, and 30 km and in the Y direction at -30, -20, -12, -8, -4, 0, 4, 8, 12, 20, and 30 km. In the Z direction nodes are positioned at -1, 1, 4, 7, 10, 13, 16, 20, 24, and 28 km relative to sea level. A trade-off analysis indicated an optimal smoothing value of 3 (Figure 2). Inversions were carried out using both absolute and differential time data using the tomoDD algorithm (Zhang and Thurber, 2003), which jointly solves for 3-D velocity structure and event locations, with a progressive weighting strategy (Waldhauser and Ellsworth, 2000).

The previously identified seismic velocity contrast across the San Andreas fault in the upper crust (Michelini and McEvilly, 1991, Eberhart-Phillips, 1993, Thurber et al., 2003, 2004, 2006; Zhang et al., 2009) is apparent in the Vp model (Figure 3a). A low velocity anomaly at approximately 15 km depth beneath the fault trace is present in both the P- and S-wave velocity models (Figures 3a and b). The LFE's (events deeper than 15 km) are in or adjacent to zones of relatively low Vs. An estimate of the Vp/Vs ratio in the tremor source regions yields values of approximately 1.9.

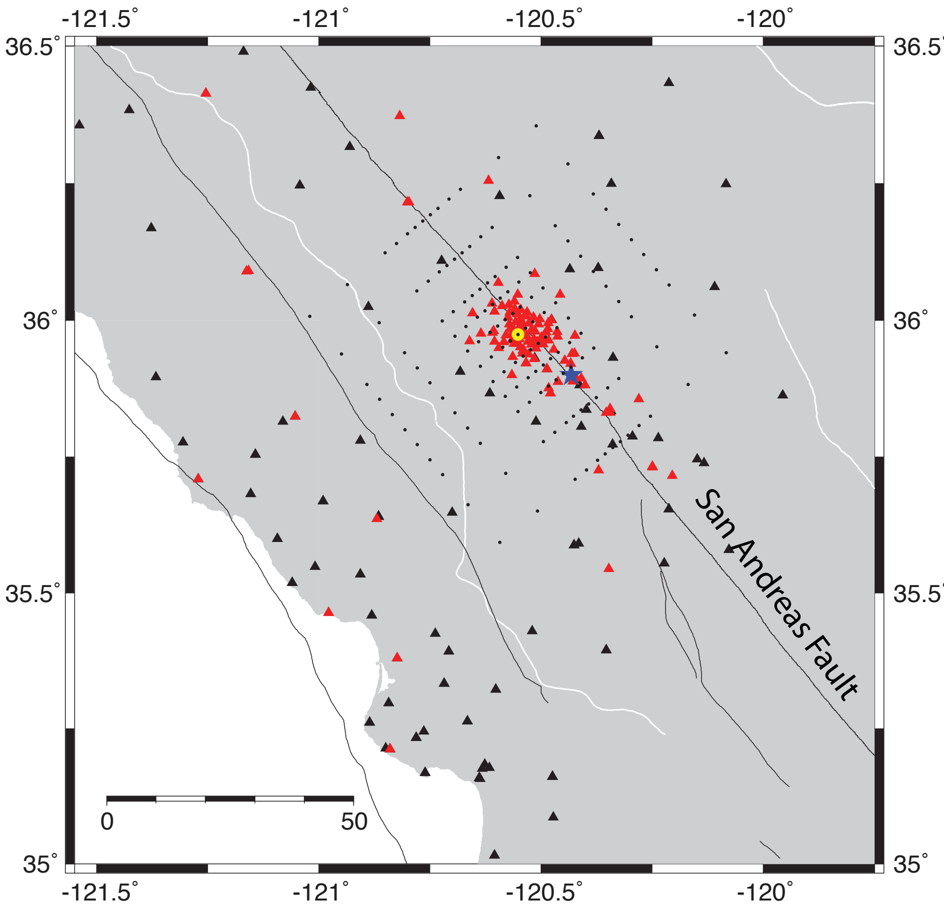


Figure 1. Stations used for the updated tomographic inversion including the LFE picks. Three-component stations are shown as red triangles, others are vertical-only.

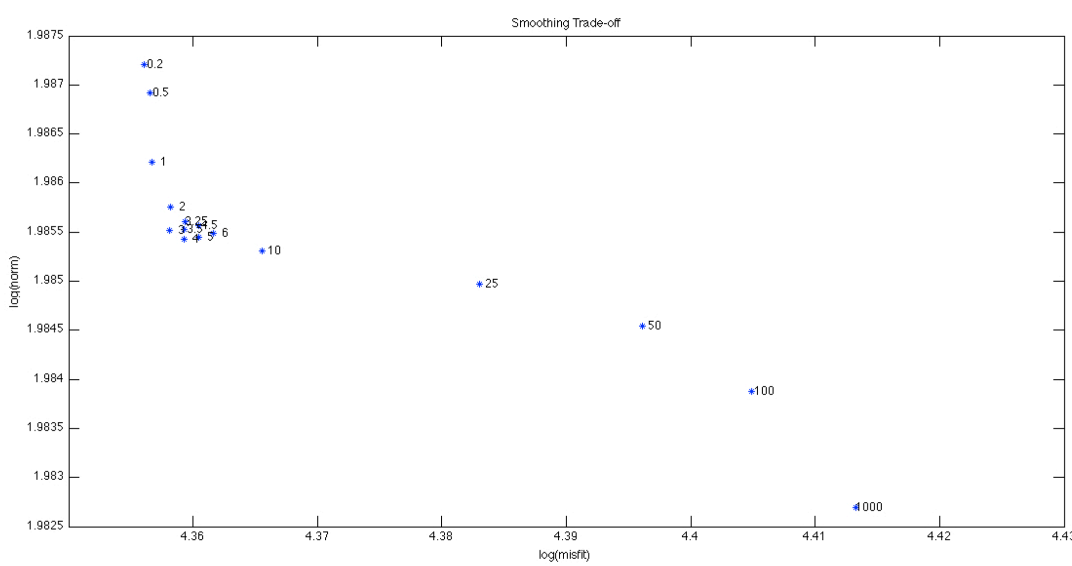
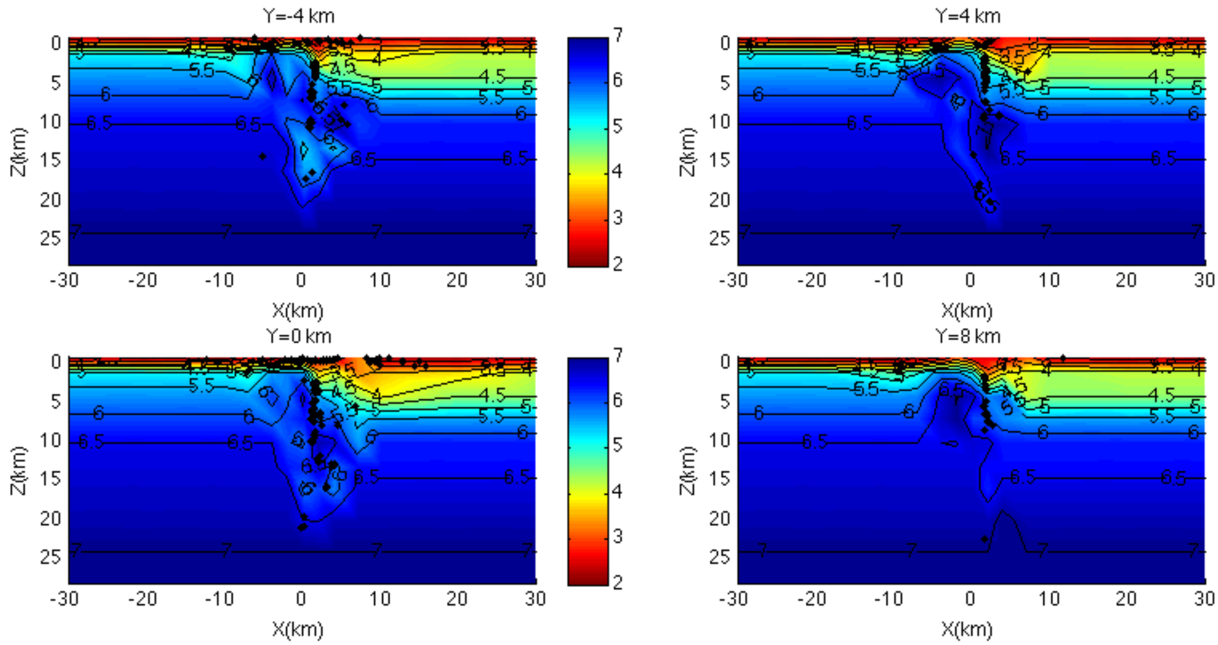
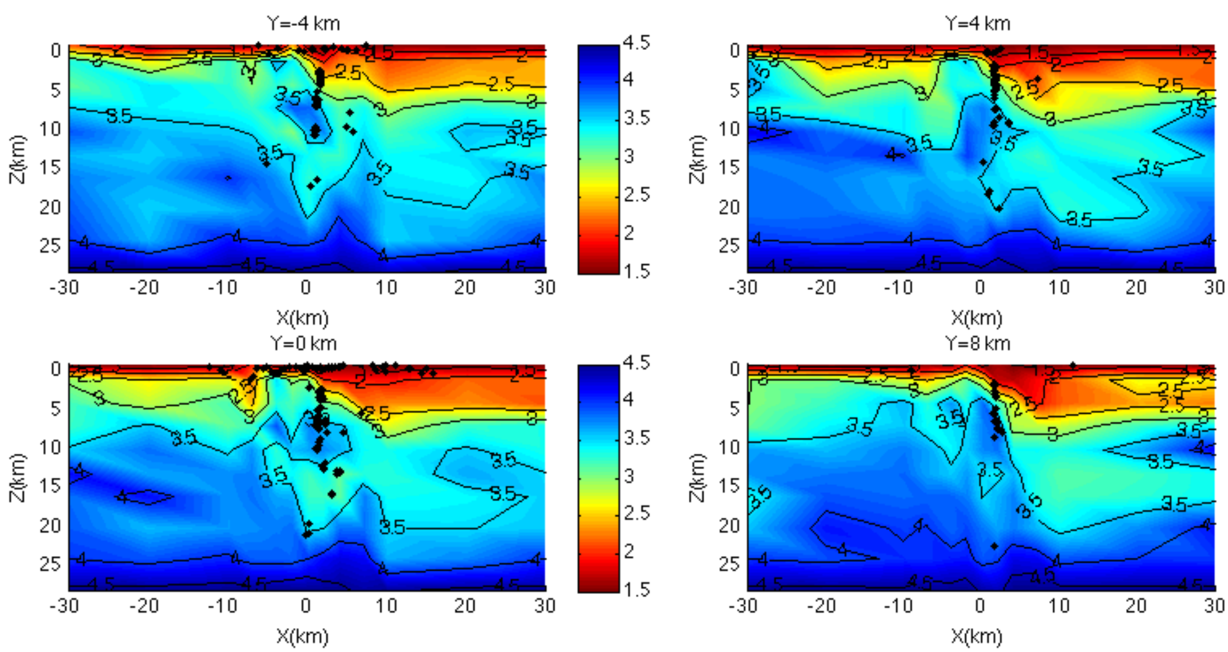


Figure 2. Plot of trade-off between data misfit versus model perturbation size as a function of the smoothing parameter. A smoothing value of 3 was chosen based on this trade-off curve.



(a)



(b)

Figure 3. Cross-sections through the (a) P-wave and (b) S-wave velocity models obtained with tomoDD using the merged dataset. Note the zone of slightly reduced Vp and sharply reduced Vs centered around 15 km depth in the Y = -4 and 0 km panels, where the LFE's are concentrated.

Conclusions

We have capitalized on the power of a dense array to analyze waveforms of SAFOD-area LFE families recorded by the PASO array and utilize LFE picks for seismic tomography of the tremor zone. The well-defined seismogenic fault plane (extending to 13+ km depth) combined with the relatively shallow LFE depths (many less than 20 km) provides the opportunity to define the geometry of the extension of the SAF deeper into the crust. We also obtain the first detailed tomographic images of the tremor zone in this region. Our results provide evidence for the presence of fluid in the tremor-generating zone. The elevated Vp/Vs values are interpreted to reflect high pore fluid pressure and low effective stress (Shelly et al., 2007). This is consistent with results from previous findings in subduction zones and with observations of triggering and tidal modulation of LFE's and tremor on this deep extension of the SAF. A manuscript on the results of this work is in preparation.

Project Publications

Peterson, D. E., C. H. Thurber, D. R. Shelly, N. L. Bennington, H. Zhang, and J. R. Brown, Tomographic imaging of the tectonic tremor zone beneath the San Andreas fault in the Parkfield region, SCEC Annual Meeting, 2012.

Peterson, D. E., C. H. Thurber, D. R. Shelly, N. L. Bennington, H. Zhang, and J. R. Brown, Tomographic imaging of the tectonic tremor zone beneath the San Andreas fault in the Parkfield region, Fall AGU Meeting, abstract S41A-2420, 2012.

Intellectual Merit

We have produced the first detailed image of the three-dimensional seismic velocity structure in the tectonic tremor zone beneath the San Andreas fault. We find slightly reduced P-wave velocity and more sharply reduced S-wave velocity, and hence a high Vp/Vs ratio. This is consistent with the presence of fluids in the tremor-generating zone.

Broader Impact

This project has supported the research experience of a female UW-Madison undergraduate student, Dana Peterson, as well as providing partial support for an early-career female post-doc, Ninfa Bennington. Peterson has learned a range of seismological analysis techniques and has gained substantial experience in computational methods and computer programming, particularly MATLAB. Peterson will be continuing her career in geophysics, initially with a research position at the Earth Observatory of Singapore.

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