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Source Characterization of Mendocino Offshore Earthquakes for Improvements in Monitoring Active Deformation and Estimates of Earthquake Potential in the Mendocino Triple Junction Region

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Abstract

The Mendocino Triple Junction (MTJ) region is the one of the most seismically active areas of California and has experienced significant subduction quakes such as the 1700 M 9.1 Cascadia Megathrust and the 1992 M 7.1 Cape Mendocino earthquakes. Resent seismic and geodetic monitoring have shown that the occurrences of various modes of fault slip in the MTJ region such as aseismic slip events, tectonic tremors, slow/low-stress-drop earthquakes, deep low-frequency earthquakes, and characteristically repeating earthquakes. However, the locations of those fault slips are not well constrained because of greater distances between the offshore fault slips and the available land stations. Subsequently, the nature of interactions between seismic and aseismic deformation processes remains unclear.

We have performed a master event approach to improve the locations of MTJ offshore earthquakes. In the case of the aftershock activity following the 15 June 2005 Mw 7.2 Gorda Plate earthquake (~170 km far from the closest land station), we find that the majority of relocated aftershocks are more closely located in space with regions of Coulomb stress increase induced by the 2005 Gorda Plate mainshock, compared with the original catalog hypocenters. Additionally, we have been detecting previously uncataloged early aftershocks with a waveform cross-correlation approach, in order to further understand the spatiotemporal changes in stress field induced by the 2005 Gorda Plate mainshock.

To characterize subsurface fault slip in the MTJ region, we have identified the characteristically repeating microearthquakes. Our analysis identifies a number of repeating earthquake sequences (~50 sequences) with magnitudes ranging from 2.5 to 4.0. These sequences appear to be localized along the Mendocino fracture zone that has experienced a number of M > 5 offshore earthquakes. Our result suggests that this fracture zone exhibits some degree of aseismic creep.

Another component of our research project is to explore tectonic tremor activities associated with M > 5 earthquakes around the MTJ region. We find a tectonic tremor activity that might be associated with the 2008 Mw 5.3 normal-faulting earthquake near Weaverville, CA. With the measurement of pP-P and sP-P differential times, the focal depth of the 2008 Mw 5.3 earthquake is determined to be 39.5 km, suggesting that this earthquake occurred within or below the subducting plate. Our analysis shows that toward the end of the tectonic tremor activity in the end of April 2008, the 2008 Mw 5.3 earthquake occurred around the area in which the tectonic tremors were identified. This spatiotemporal correlation may suggest that the occurrence of the 2008 Mw 5.3 earthquake is related to aseismic slip, assuming the detected tremor as a slow slip indicator.

Project Results

Background

The Mendocino Triple Junction (MTJ), a fault-fault-trench junction, is one of the most seismogenic regions of California (Figure 1). In 1700, the Mw 9 Cascadia Megathrust earthquake is believed to rupture the entire length of the subduction zone from northern California to south coastal British Columbia [e.g., Satake et al., 1996]. The 1992 M 7.1 Cape Mendocino earthquake was confined to the extreme southernmost extent of the Cascadia subduction zone [e.g., Oppenheimer et al., 1993b]. The MTJ region has been experienced a number of different fault slips such as aseismic slip events [Szeliga et al., 2004], tectonic tremors [Brudzinski and Allen, 2007; Boyarko and Brudzinski, 2010], slow/low-stress-drop earthquakes [Guilhem et al., 2007], deep low-frequency earthquakes [Boyarko and Brudzinski, 2010], and characteristically repeating microearthquakes [Waldhauser and Schaff, 2008]. Apparently, the small-magnitude ambient seismicity (regular and characteristically repeating microearthquakes) is spatially anticorrelated with the distribution of tectonic tremor sources and low-frequency events [Boyarko and Brudzinski, 2010]. However, the locations of those fault slips are not well constrained because of greater distances between the offshore fault slips and the available land seismic stations. Subsequently, the nature of interactions between seismic and aseismic deformation processes remains unclear.

Relocation of Offshore Earthquakes in the Mendocino Triple Junction Region

We performed a master event approach [e.g., Waldhauser and Richards, 2004] to improve the locations of MTJ offshore earthquake occurring in 1984-current, by using a two-step procedure: 1) identifying depth phases to constrain focal depths, and 2) improving earthquake locations by using the source-specific station terms (SSST) approach [Richards-Dinger and Shearer, 2000; Lin and Shearer, 2006]. Here, we mainly show the result for the relocated aftershocks following the 16 June 2005 Mw 7.2 Gorda Plate earthquake because the high-precision double-difference earthquake catalog developed by Waldhauser and Schaff [2008] dose not include the most of these aftershocks mainly due to less available phase picks in the Northern California Seismic Network (NCSN) catalog.

We first focused on improving the locations of the M > 5 MTJ earthquakes, particularly their focal depths, by making use of the observations of depth phases (pP and sP phases). Using broadband seismic data from Gräfenberg Broadband Array (GRF) in southeast Germany, we identified pP and sP depth phases and measured pP-P and sP-P differential times. Figure 2 shows an example of observed GRF data for the 2008 Mw 5.3 normal-

faulting earthquake. The pP and sP differential times obtained indicate that the focal depth of this event is 39.5 km (Figure 2).

For the aftershock sequences following the 2005 Mw 7.2 Gorda Plate earthquake, we used the USGS National Earthquake Information Center (NEIC) event locations as initial locations and improved the focal depths with constraints from the measurement of the pP-P and sP-P differential times. We also conducted the moment tensor analysis [Dreger and Romanowicz, 1994] for the earthquakes ($3 < M < 4$) to refine focal depths by using the velocity model that is calibrated for the MTJ offshore earthquakes [Tajima et al., 2000].

Secondary, we estimated a minimum one-dimensional (1-D) velocity model that leads to a minimum average of root mean square of travel-time residual through VELEST, the 1-D velocity inversion program [Kissling et al., 1994]. To improve the locations of the aftershocks following the 2005 Gorda Plate earthquake, we made use of well-located 17 earthquakes (hereafter referred to as the master events) occurring within a 100-km radius of the 2005 Gorda Plate epicenter (hereafter referred to as the 2005 Gorda Plate earthquake region). The focal depths of these earthquakes were improved by either the depth phase measurement or the moment tensor analysis mentioned above.

We increased the number of P and S phase arrivals to improve the accuracy of the minimum 1-D velocity model (and the locations of the earthquake with the SSST approach below), with an automatic phase arrival detection and picking algorithm based on the Akaike information criteria (AIC) [Zhang et al., 2003]. For example, we find that there is no phase pick information from broadband data recorded at station BK.JCC for the 2005 Gorda Plate mainshock and the subsequent aftershock sequence in the NSCN catalog. Station BK.JCC is the closest land station for the MTJ offshore earthquakes. It appears that the data from BK.JCC have the highest signal-to-noise ratio for the MTJ offshore earthquakes among the land stations installed near the MTJ region. We were able to identify P and S phase arrivals with the AIC-based phase picking algorithm (Figure 3).

As the initial 1-D velocity model, we used the USGS velocity model [Oppenheimer et al., 1993a] that has been used to locate the MTJ earthquakes with the HYPOINVERSE location program [Klein, 1989]. We fixed the event locations and their origin time to obtain the minimum 1-D velocity model (Figure 4) and the station correction terms by minimizing the residual between the predicated and observed travel times.

Finally, we systematically relocated the earthquakes (162 events) that occurred at the 2005 Gorda Plate earthquake region in June-July 2005 by software COMPLOC [Lin and Shearer, 2006]. We used the minimum 1-D velocity model and the station correction terms derived from VELEST mentioned above for the SSST relocation process with

COMPLOC. We modified COMPLOC to fix the locations of the master events throughout relocation process while the relative locations of other events are refined through the SSST approach.

Following Rollins and Stein [2010], we explored the spatial correlation between the coseismic stress change induced by the 2005 Mw 7.2 Gorda Plate earthquake and the relocated aftershocks that we obtained. We used the G. Shao and C. Ji source model (http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/2005/06/smooth/northernca.html) to compute the Coulomb stress changes with Coulomb 3.2 software [Toda and Stein, 2002]. We find that the majority of relocated aftershocks are more closely located in space with regions of Coulomb stress increase induced by the 2005 Mw 7.2 Gorda Plate earthquake, compared with the original catalog hypocenters (Figure 5).

Identifying Undetected Early Aftershocks Following the 2005 Gorda Plate Earthquake

Aftershocks are triggered by abrupt changes of stress induced by a larger earthquake. Detailed images of spatiotemporal changes in aftershock activity help delineate the mainshock rupture area [e.g., Ziv, 2012]. Additionally, high-resolution aftershock observations will provide insight into the stress transfer from the mainshock rupture [Toda et al., 2012]. However, large numbers of early aftershocks are not detected because they are masked by large-amplitudes and long-duration of seismic coda waves from the mainshock and other aftershocks.

We examined the early aftershock activity following the 2005 Mw 7.2 Gorda Plate earthquake. Following Peng and Zhao [2009], we use waveforms from 162 MTJ earthquakes detected by the NCSN during a 2-month period spanning the 2005 Mw 7.2 Gorda Plate mainshock (1 June through 31 July, 2005) as templates to identify additional, previously undetected earthquakes. Using continuous broadband seismic data, our analysis has detected ~100 individual earthquakes, with the averaged cross-correlation threshold of 0.75 (Figure 6). Our ongoing effort is to determine the locations of the identified early aftershocks.

Characteristically Repeating Earthquakes

Characteristically repeating earthquakes (CREs) are thought to be a result of repeated ruptures of the same fault asperity. This asperity is believed to be loaded to failure by aseismic slip on the surrounding fault surface [Nadeau and Johnson, 1998; Schaff et al., 1998]. The distribution of CRE patches associated with the weak slipping zones in turn tend to outline or delineate regions of large locked fault at depth that could be responsible for future significant earthquakes. Additionally, repeating earthquake systematics (frequency and magnitude) can be used to fault creep rates on faults at depth.

We have been identifying CREs in the MTJ zone by utilizing waveforms from ~5,500 MTJ local earthquakes (M > 2.5 in 1992-current). A 1-8 Hz bandpass filter and a 40.96-s time window from the direct P-wave were used to indentify CREs. This time window typically includes the direct S-wave arrivals. We used 0.95 for the waveform cross-correlation threshold for identifying CREs (Figure 7). Our cross-correlation analysis identifies around 50 CRE sequences with magnitudes ranging from 2.5 to 4.0. The majority of the CRE sequences appear to be localized along the Mendocino fracture zone that has experienced a number of M > 5 offshore earthquakes (Figure 1). Our result suggests that this fracture zone exhibits some degree of aseismic creep.

Tectonic Tremor Activity Associated with the 2008 Normal-Faulting Earthquake

Geodetic measurements of the MTJ zone with GPS arrays observed an aseismic slip episode with the west component of displacement up to 8 mm (Figure 8). GPS time series have suggested that this aseismic slip episode may have nucleated near Weaverville, CA in March 2008 and propagated to the northwest over a 2-month period. At the same time, broadband seismic records have revealed that an area of northernmost California (e.g., Yreka) experienced an episode of tectonic tremors. Tectonic tremor observed consists of intermittent weak seismic signals at relatively low frequency (1-5 Hz) (Figure 9). An array of broadband stations (~30 stations) was temporally deployed at the Cape Mendocino area in 2007-2009 through the Flexible Array Mendocino Experiment [e.g., Porritt et al., 2011]. These Mendocino broadband data significantly improve detectability of tectonic tremor signals and enhance the spatial resolution in the locations of tectonic tremors. We systematically analyzed high-quality broadband data to identify and locate tectonic tremors.

Following Ide (2012), we use a waveform-envelope correlation method to detect tectonic tremors. Our analysis finds around 500 tectonic tremors that occurred in 2008, showing that a slow migration occurs parallel to the strike of the subducting slab at an average velocity of about 3-4 km/day (Figure 10) during March through April, 2008. The observed temporal correlation between the aseismic slip transient and the tectonic tremor activity may suggest that a single mechanism is mainly responsible to nucleate these transient deformations. We also note that toward the end of the transient deformations (e.g., aseismic slip and tremor) in the end of April 2008, a normal-faulting event with Mw=5.3 occurred around the aseismic deformation area. Although we do not yet estimate the spatial extent of the aseismic slip transient and its temporal behavior, the stressing from the aseismic slip transient may have triggered this extensional earthquake.

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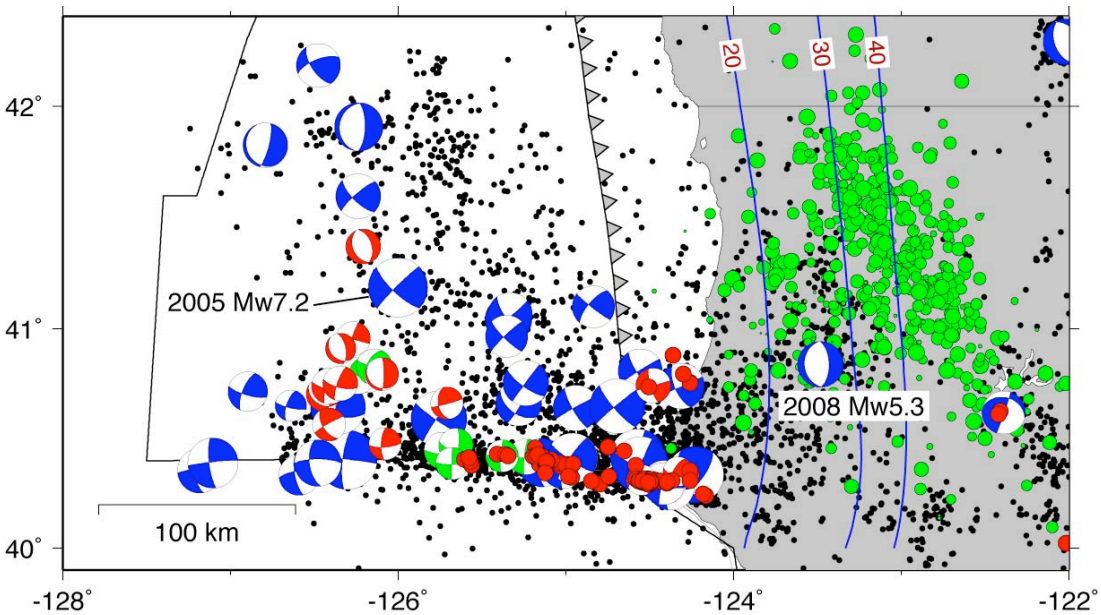

Figure 1. Map view of the seismicity in the Mendocino Triple Junction region. Black circles are the MTJ earthquakes (M > 2.5) relocated by Waldhauser and Schaff [2008] that were used to identify the characteristically repeating earthquakes. Red and green circles are the identified repeating earthquakes (1992-curent) and the tectonic tremors that occurred in 2008, respectively. Also shown are focal mechanisms for M > 4 events determined from the NCSN moment tensor analysis. The focal mechanisms shown in red and green are newly determined and reviewed moment tensor solutions in our study, respectively. Blue lines are the plate interface from McCrory et al. [2004].

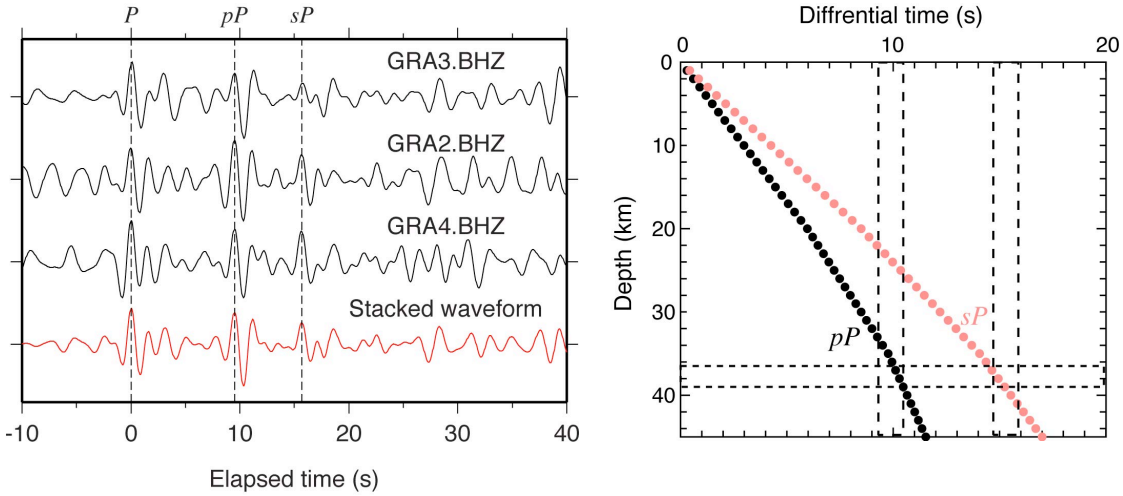

Figure 2. Left panel shows waveforms for the 2008 Mw 5.3 normal-faulting event recorded at the GRF array. The pP and sP phases are seen at ~10 s and ~15 s after the direct P wave arrival, respectively. Right panel shows predicted time difference between P and depth phases as a function of source depth using the ak135 velocity model [Kennett et al., 1995]. Both pP-P and sP-P time differentials of 10 s and 15 s observed correspond to a depth of 39.5 km.

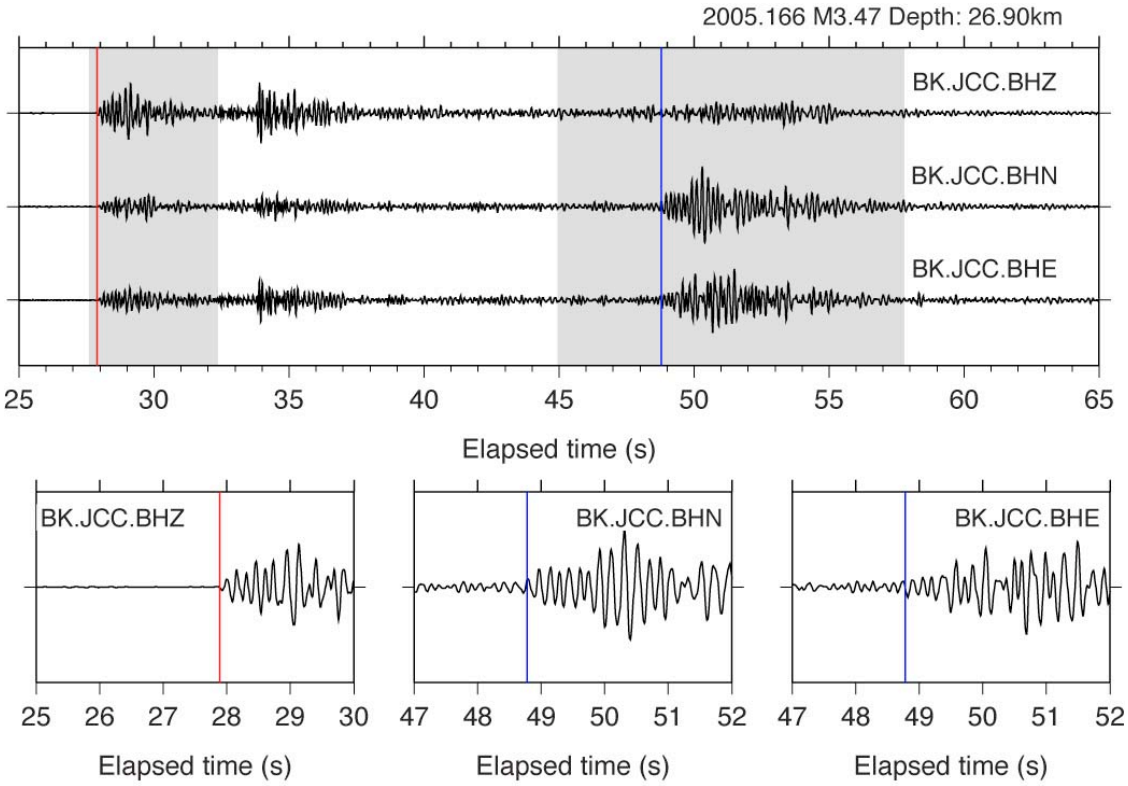

Figure 3. Example of the automatic phase arrival detection. Top panel shows three component waveforms recorded at station BK.JCC for one of aftershocks following the 2005 Mw 7.2 Gorda earthquake. Red and blue lines are the P and S phase arrivals obtained, respectively. A 4-16 Hz bandpass filter was applied. Gray areas indicate the time windows in which we search for the phase arrivals. Bottom three panels show enlarged views of P (BHZ channel) and S phase (BHN and BHE channels) arrivals. Note that phase information from station BK.JCC for this M 3.5 earthquake is not listed in the NCSN catalog.

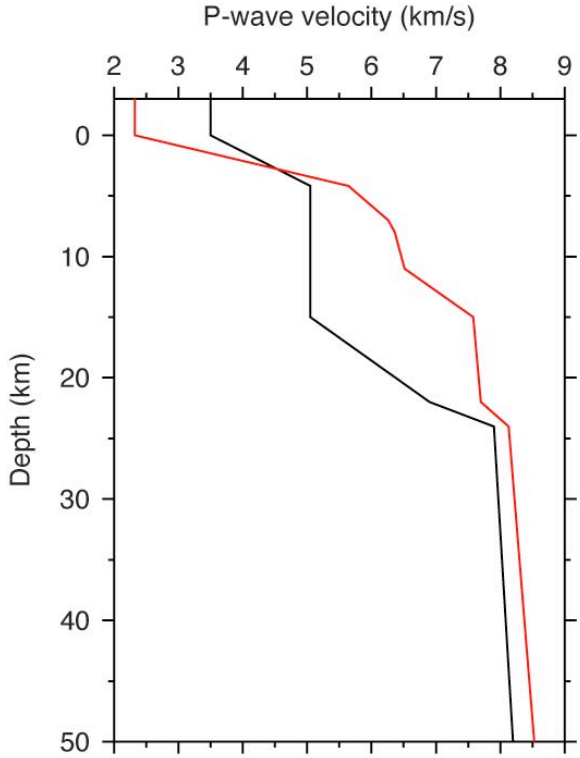

Figure 4. P-wave velocity model. Black line is the 1-D P-wave velocity model that has been used to locate the Mendocino earthquakes while red line is the minimum 1-D model obtained in our study.

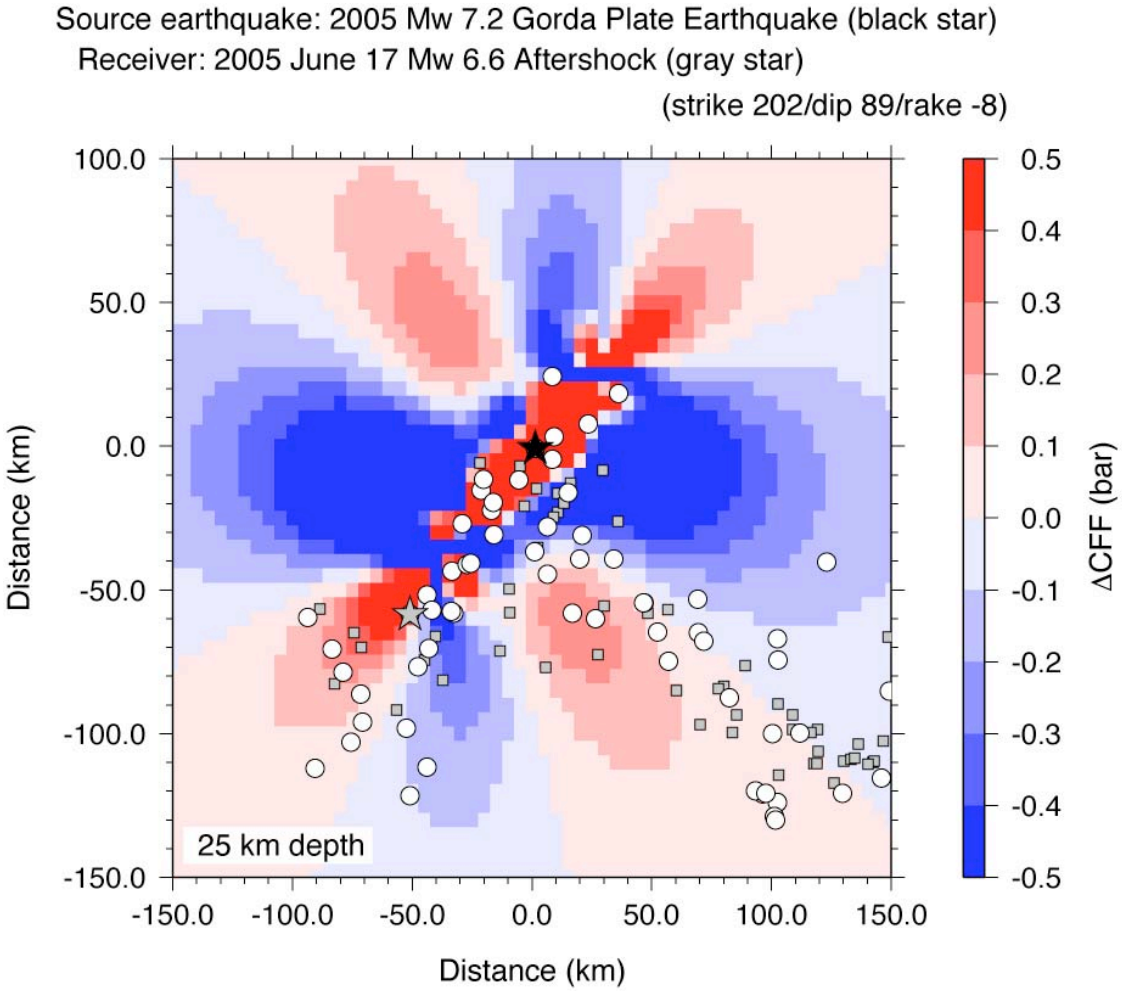

Figure 5. Coulomb stress changed induced by the Shao and Ji rupture model for the 2005 Mw 7.2 Gorda Plate earthquake. Calculation depth is 25 km in which the majority of aftershocks occured. Solid circles and gray squares are the locations of the aftershocks that occurred during 15 June through 31 July, 2005, determined by our relocation procedure and the NCSN standard approach (i.e., the original catalog hypocenter), respectively.

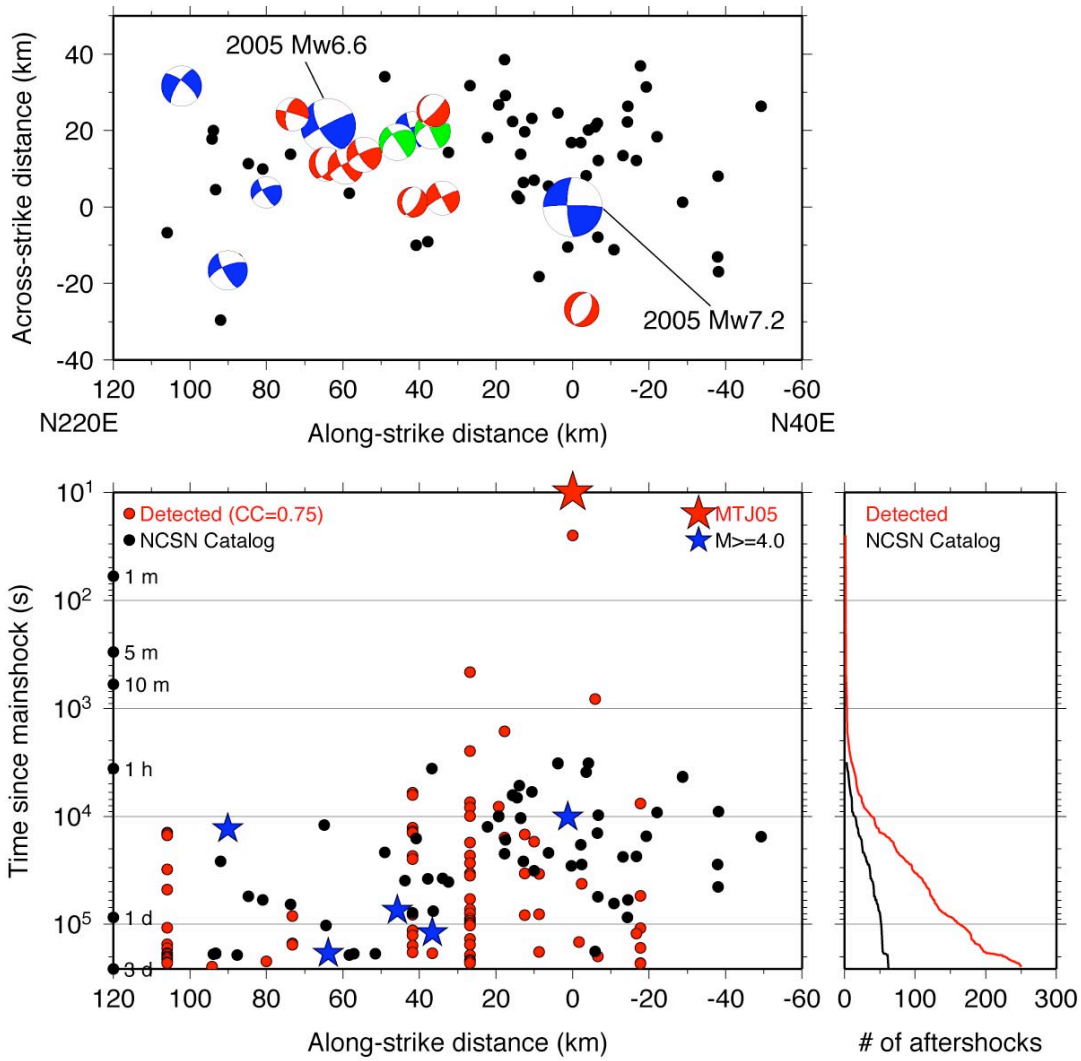

Figure 6. Aftershock activity following the 2005 Mw 7.2 Gorda Plate earthquake. Top panel shows the map view of aftershocks occurred in the first 3-day postseismic period. Also shown are focal mechanisms for M > 4 events determined from the NCSN moment tensor analysis. The focal mechanisms shown in red and green are newly determined and reviewed moment tensor solutions in our study, respectively. Bottom left panel shows the occurrence times of aftershocks since the 2005 Gorda Plate mainshock as a function of the along-strike distances (N200E). The black circles are the events listed in the NCSN catalog and the red circles are newly detected events by the cross-correlation analysis in this study. Bottom right panel shows the cumulative numbers of aftershocks by the NCSN catalog (black) and this study (red).

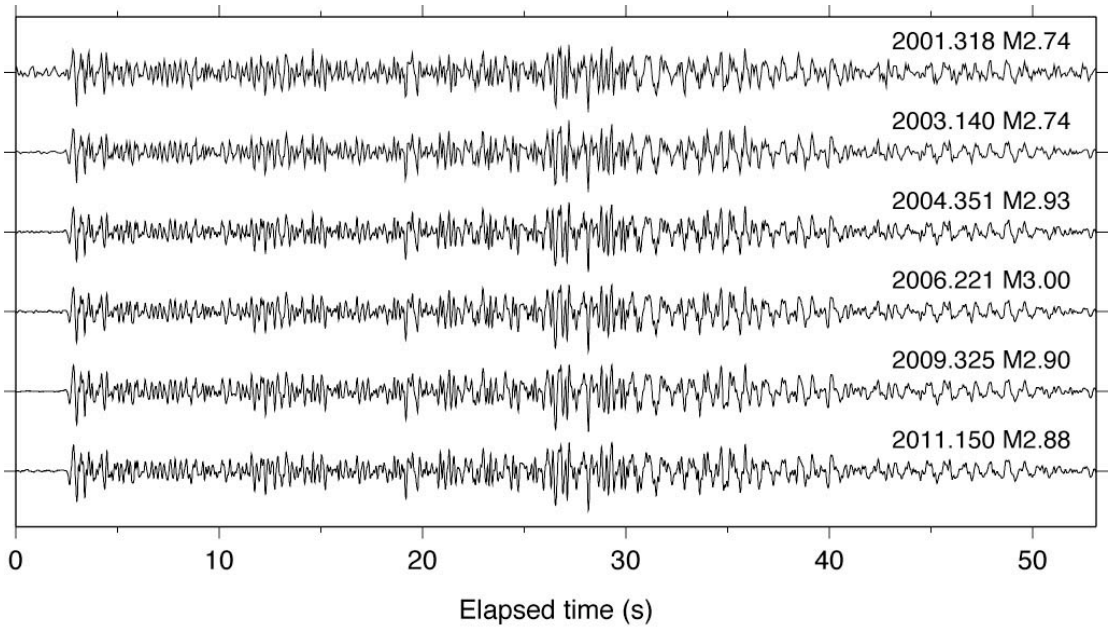

Figure 7. An example of the characteristically repeating earthquakes identified. These earthquakes occurred nears the Mendocino fracture zone. The waveforms shown are recorded at station BK.WDC (vertical component). A 1-8 Hz bandpass filter was applied. Waveforms were normalized by their maximum amplitudes.

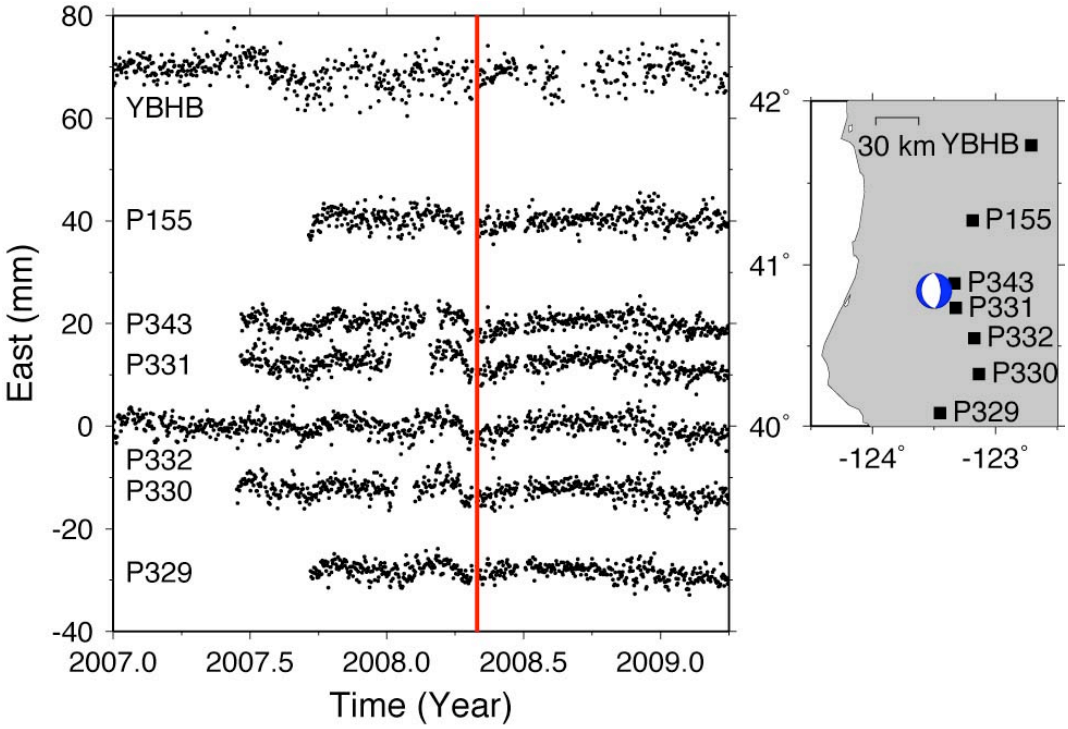

Figure 8. Left panel shows GPS easting obtained from seven sites shown in the right panel, estimated by the Pacific Northwest Geodetic Array (http://www.geodesy.cwu.edu). Red line is the occurrence time of the 2008 Mw 5.3 normal-faulting earthquake (the focal mechanism shown in the right panel).

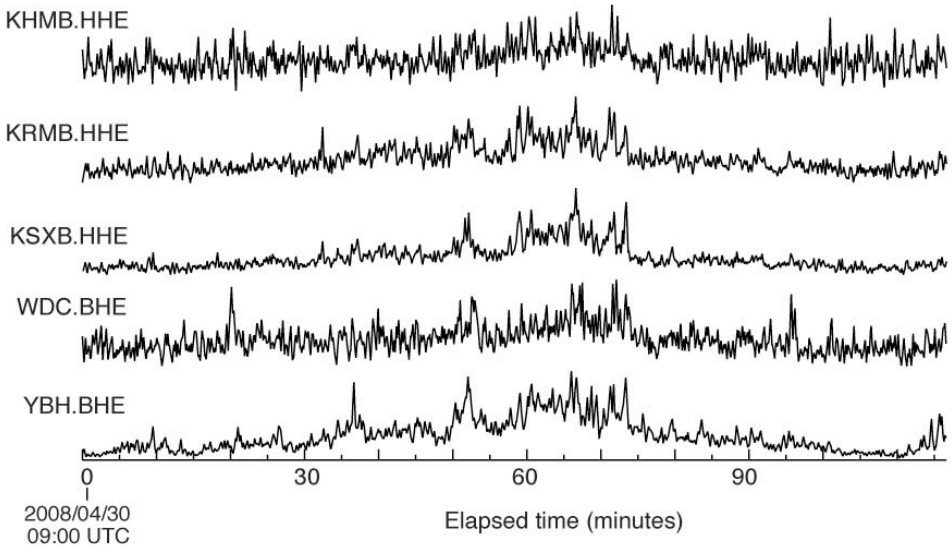

Figure 9. Example of observed tectonic tremor. Traces show 2-hour envelope seismograms including a tectonic tremor activity occurring ~6 hours after the 2008 Mw 5.3 normal-faulting earthquake (the location is shown in Figure 1). A 1-5 Hz bandpass filter was applied.

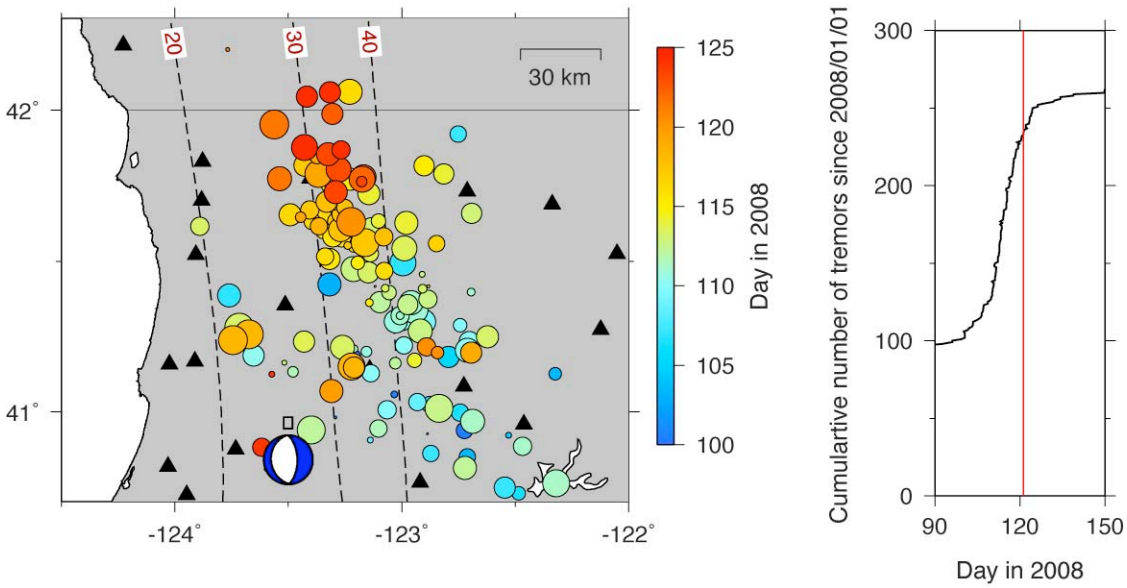

Figure 10. Left panel shows tremor epicenters (circles color coded by time) during the transient deformation in 2008. About 150 tectonic tremors are identified during March through May, 2008. The circle sizes are inversely proportional to the uncertainty in the tremor locations. The focal mechanism shown in purple is the 2008 Mw 5.3 normal-faulting earthquake. Dashed lines are plate interface geometry (contoured at 10-km intervals) from McCrory et al. [2004]. Right panel shows the cumulative number of the tectonic tremors identified in our study. Red line is the occurrence time of the 2008 Mw 5.3 earthquake.

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