Tremor patches in Cascadia revealed by seismic array analysis

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[1] Episodic tremor and slip (ETS) events in Cascadia have recently been observed, illuminating the general area that radiates seismic energy in the form of non-volcanic tremor (NVT). However, the picture of the ETS zone remains fuzzy because of difficulties in tremor detection and location. To observe the intimate details of tremor, we deployed a dense 84-element small-aperture seismic array on the Olympic Peninsula, Washington, above the tremor migration path. It recorded the main ETS event in May 2008, as well as a weaker tremor episode two months earlier. Using a beamforming technique, we are able to capture and track tremor activity with an unprecedented resolution from southern Puget Sound to the Strait of Juan de Fuca. The array technique reveals up to four times more duration of tremor compared to the conventional envelope cross-correlation method. Our findings suggest that NVT is not uniformly distributed on the subduction interface, and unveils several distinct patches that release much of the tremor moment. The patches appear to be devoid of ordinary earthquakes, and may indicate the heterogeneity in fault strength that affects the modes of stress release within the ETS zone. **Citation:** Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, and A. G. Wech (2009), Tremor patches in Cascadia revealed by seismic array analysis, *Geophys. Res. Lett.*, *36*, L17316, doi:10.1029/2009GL039080.

1. Introduction

[2] Discovery of slow slip and non-volcanic tremor (NVT) adds a new dimension to our understanding of plate boundary dynamics. NVT has been found in many subduction zones worldwide including Nankai in southwest Japan [*Obara*, 2002], Cascadia [*Rogers and Dragert*, 2003], Costa Rica [*Schwartz et al.*, 2008], Alaska [*Peterson and Christensen*, 2009], Mexico [*Payero et al.*, 2008], and also in a strike-slip setting under the San Andreas Fault (SAF), California [*Nadeau and Dolenc*, 2005]. In Cascadia, slow slip and associated tremor show strikingly periodic nature, recurring about every 14.5 months [*Rogers and Dragert*, 2003], prompting the name episodic tremor and slip (ETS). Interestingly, NVT is sometimes found to be triggered by dynamic stresses from passing teleseismic waves [e.g., *Ghosh et al.*, 2009; *Gomberg et al.*, 2008; *Rubinstein et al.*, 2007], and also responds to tidal stressing [*Rubinstein et al.*, 2008]. Even tiny stresses from teleseismic *P* waves can excite NVT near SAF [*Ghosh et al.*, 2009], showing its sensitivity to very small stress perturbations.

[3] In the last several years, spatio-temporal distribution of NVT has been mapped using envelope cross-correlation (ECC) methods [e.g., *Obara*, 2002; *Wech and Creager*, 2008] and a source-scanning algorithm [*Kao et al.*, 2006]. However, NVT is difficult to detect and locate due to its noise-like, emergent waveforms. Therefore, the level of tremor detectibility, and the resolution of location methods are not so clear, and still remain areas of active research. While useful for larger-scale tremor detection and location, none of the techniques have sufficiently high resolution to examine the ETS zone in great detail. In addition, these methods ignore the amplitude variations in the population of detected tremors, which is due to the uneven moment released by this seismic phenomenon. The variability of seismic moment released by the NVT activity from different parts of the ETS zone not only provides insight into the tremor mechanism, but also is necessary to understand the evolving state-of-stress in the subduction zone, and how it affects the seismic hazard in the region.

[4] In this paper, we address the aforementioned issues by scrutinizing high-quality seismic data acquired from a dense small-aperture seismic array during the May 2008 Cascadia ETS event, and a preceding tremor episode in March. A beamforming method is applied to track the evolution of NVT in space and time. This method allows us to extract even weak NVT signals that are otherwise buried in the noise, and map parts of the ETS zone in Cascadia with an unprecedented resolution. We locate tremor, assuming it is occurring at the subduction interface, and resolve variability of relative tremor moment release in the ETS zone, exposing some hitherto unseen features in this zone.

2. Data and Methodology

[5] Aiming to capture an ETS event that was anticipated to occur sometime between March and May 2008 (H. Dragert, personal communication, 2007), we installed a dense 84-element, small-aperture ($\sim$1300 m) seismic array (henceforth Big Skidder array) above the expected tremor migration path across the Olympic Peninsula (Figure 1). The short-period vertical-channel L28 sensors with 4.5 Hz natural frequency were laid out on a relatively flat part of a hill in an approximately 100 by 100 meters grid. The western part of the array was augmented with additional stations reducing the grid size to 50 meters. We recorded 8 days (March 5 to 13, 2008) of seismic data of an inter-ETS event (K. C. Creager et al., Cycles within cycles, manuscript in preparation, 2009), and 16 days during the main ETS event from May 5 to 21, 2008, when strong tremor rumbled near the Big Skidder array. In the following sections, we present results from the both recording periods, focusing on the main ETS event in May.

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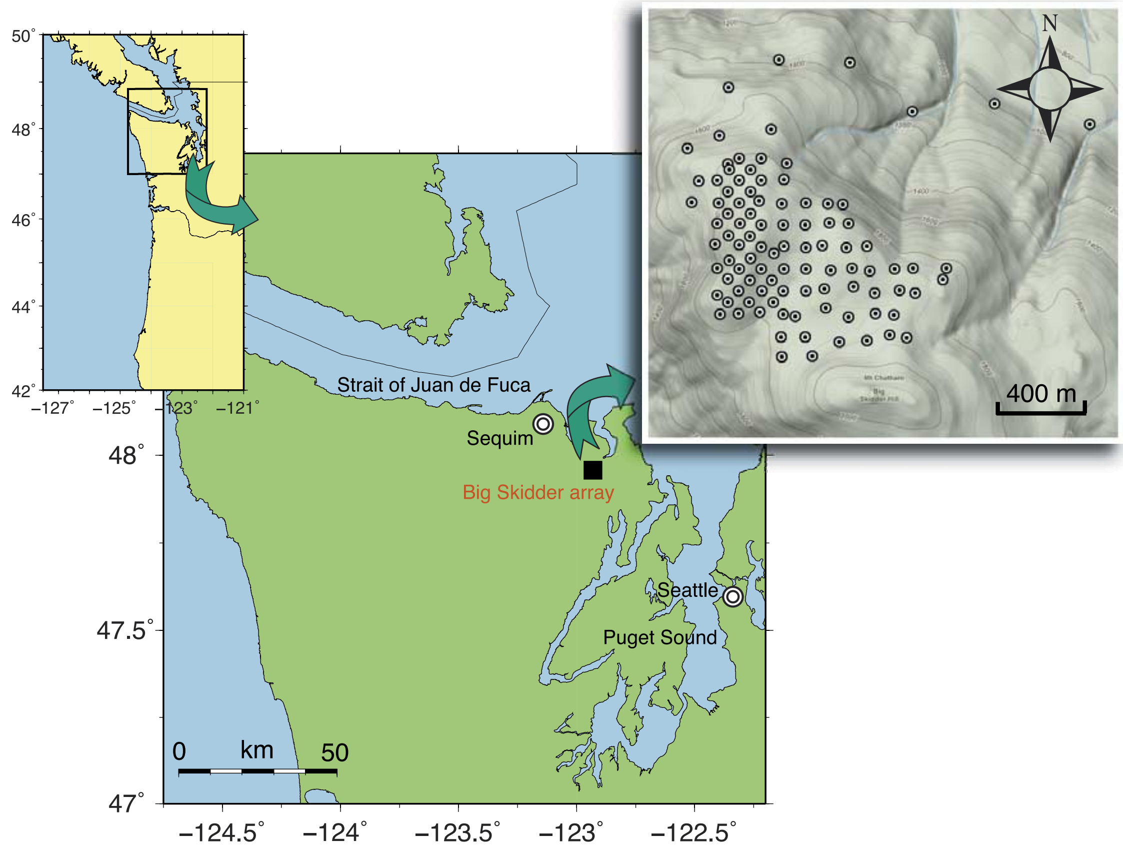

Figure 1. Location and station map of the Big Skidder array.

[6] An array processing technique, called beamforming is employed to stack the data in the tremor frequency band (3–8 Hz). This method assumes plane waves, and applies a delay-and-sum approach to stack for a range of horizontal slownesses [*Johnson and Dudgeon*, 1993]. For automatic data processing, we use 5-minute sliding time windows with a 2.5-minute overlap; bandpass filter each window from 3 to 8 Hz, normalize, and beamform to find the power of the stacked seismograms as a function of slowness. We compared the beam results with the local earthquakes recorded by the Pacific Northwest Seismic Network, and found a satisfactory match. Also, tremor beams and ECC locations agree reasonably well when both the methods pick up same tremor event (Figure 2a).

[7] For tremor detection, time windows having a focused beam with good signal-to-noise ratio are selected. To further refine the NVT detection, we choose only the time windows with energy coming up at steep angles, as shallow angle energy is often in reality cultural noise. This methodology results in conservative tremor detection, but we are fairly confident that the time windows with positive detection do represent NVT activity (Figure 2).

[8] We use the beamforming result in each time window to get the best slowness of the tremor energy, and project it to the subduction interface to determine the NVT source location. For this, we assume a plate interface model derived from local seismicity and active-source seismic experiments [*McCrory et al.*, 2006], and a layered 1-dimensional *P* wave velocity model of this area [*Crosson*, 1976].

[9] This procedure assumes that tremor is occurring on the plate interface. Despite a lack of unanimity in the seismological community [*Kao et al.*, 2005], there is growing evidence that the majority of NVT is located at the fault plane, and a result of shear failure. *Shelly et al.* [2006] examined NVT in southwest Japan subduction zone, and based on the LFE locations, demonstrated that tremor is occurring at the plate interface. Application of a similar technique to the transform fault system in California shows that tremor originates at the deep extension of SAF [*Shelly et al.*, 2009]. Also, focal mechanisms of LFEs, and very low-frequency earthquakes in southwest Japan are consistent with the model of slip on the plate interface [*Ide et al.*, 2007; *Ito et al.*, 2007]. Moreover, use of *S* minus *P* waves time on NVT in Cascadia collapsed tremor locations near the plate interface [*La Rocca et al.*, 2009]. In addition to this direct evidence, bursts of NVT triggered by the surface waves of teleseismic earthquakes at both Cascadia [*Rubinstein et al.*, 2007], and SAF [*Ghosh et al.*, 2009; *Peng et al.*, 2008] correlate strongly with long-period Love waves, and the phasing suggests that tremor originates due to the shear slip on the main fault plane. Hence, tremor taking place at the subduction interface is a reasonable assumption.

[10] To evaluate the relative distribution of moment released by NVT activity from different parts of the megathrust, we estimate the relative band-limited moment released by the detected tremor. For this, we took each tremor time window, stacked all the available velocity seismograms (bandpassed filtered from 3 to 8 Hz) using the best slowness for that particular window. We divide this trace by the

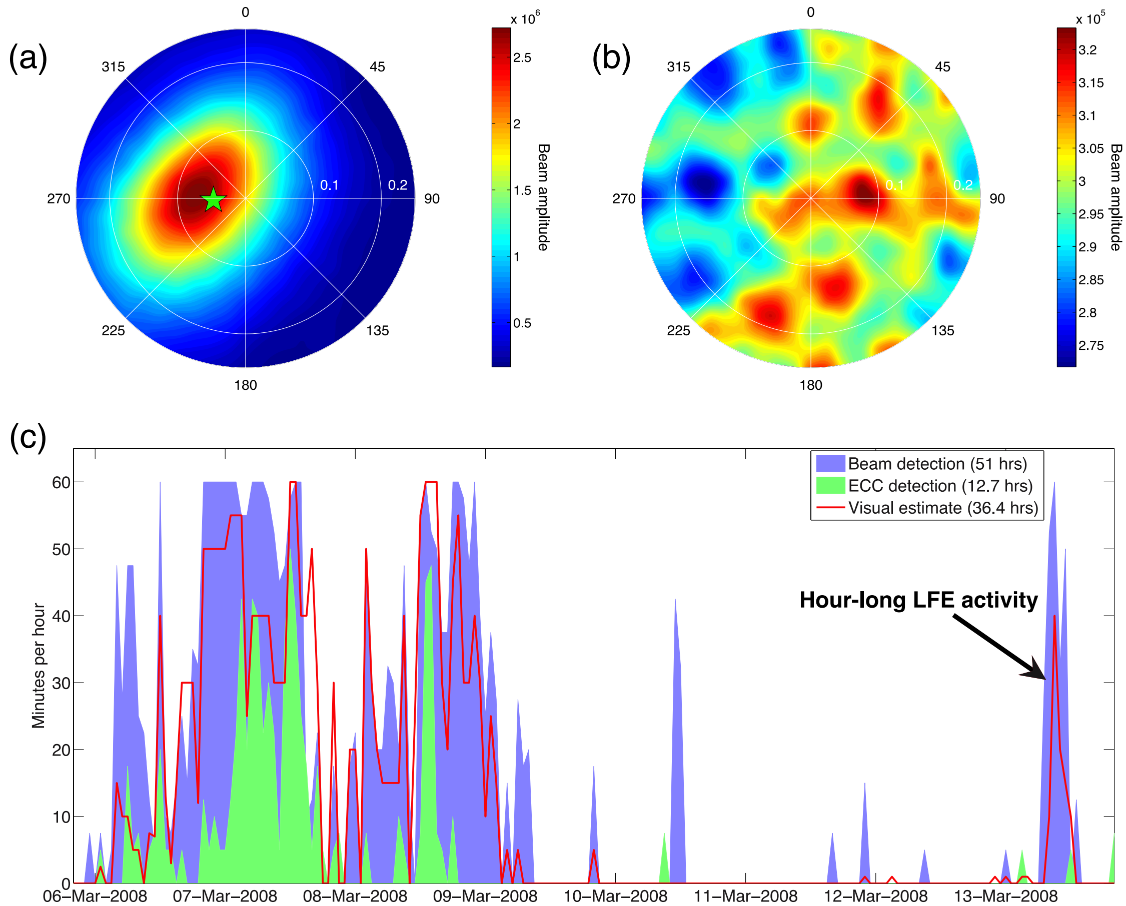

Figure 2. Example beams of time windows with (a) positive and (b) negative tremor detection. Beams are shown in polar plot, where the peripheral numbers indicate azimuth (in degrees clockwise from north), and the radial distance represents slowness in s/km. Please note the difference in the amplitude scale. The green star in Figure 2a shows the tremor location by ECC method for the same time window. (c) Comparison of tremor duration detected from beamforming method with ECC detection, and visual estimate during March 2008 episode.

number of seismograms stacked, convert it to displacement, and calculate the area under the curve defined by the absolute values of the displacement trace [*Houston*, 2007]. The displacement trace is proportional to the moment rate assuming that the signal consists mainly of far-field direct body waves. This measure gives a relative estimate of the band-limited moment in each 5-minute tremor window.

3. Results

[11] Our beamforming method detects significantly larger duration of tremor than the ECC method, and considerably lowers the threshold of tremor detection. During the feeble March 2008 tremor episode, beamforming detects four times more tremor (Figure 2), in terms of its duration, than detection using the conventional ECC method. The majority of the tremor activity (hypocentral locations) during the May 2008 ETS episode is concentrated between 30 and 40 km depth contours of the plate interface (Figure 3), while the weaker March 2008 episode mainly remains between the 35 to 45 km contour levels (Figure S1 of the auxiliary material).[1]

[12] The array recording started when tremor was ~50 km to the SSW. NVT activity slowly migrated NNW to cross the Strait of Juan de Fuca with an average long-term migration velocity of ~10 km/day only to jump back to the southern Puget Sound toward the end of the ETS event. The high spatial resolution of this array technique also enables us to record streaks of tremor with steady and rapid migration in minutes to hour-long time scale (A. Ghosh et al., Steady, rapid migration of tremor activity within an episodic tremor and slip episode, manuscript in preparation, 2009). In the late phase of the ETS, NVT was also occurring to the north of the array beneath southern Vancouver Island, Canada, but we do not include these locations in our tremor catalog because the incidence angle of the energy is too shallow to be confidently distinguished from the cultural noise.

[13] The location density map gives some insight into the spatial distribution of NVT (Figures 3 and S1). The most important one is that tremor is not uniformly distributed in the ETS zone; instead it appears in distinct patches. This is particularly clear in the main ETS event, where 4–5 rather discrete patches host the majority of the tremor locations (Figure 3). The highest location-density patch, which marks the area of the late-ETS activity, is located to the south of the array. There are also several patches WSW, and one to the NW of the array.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL039080.

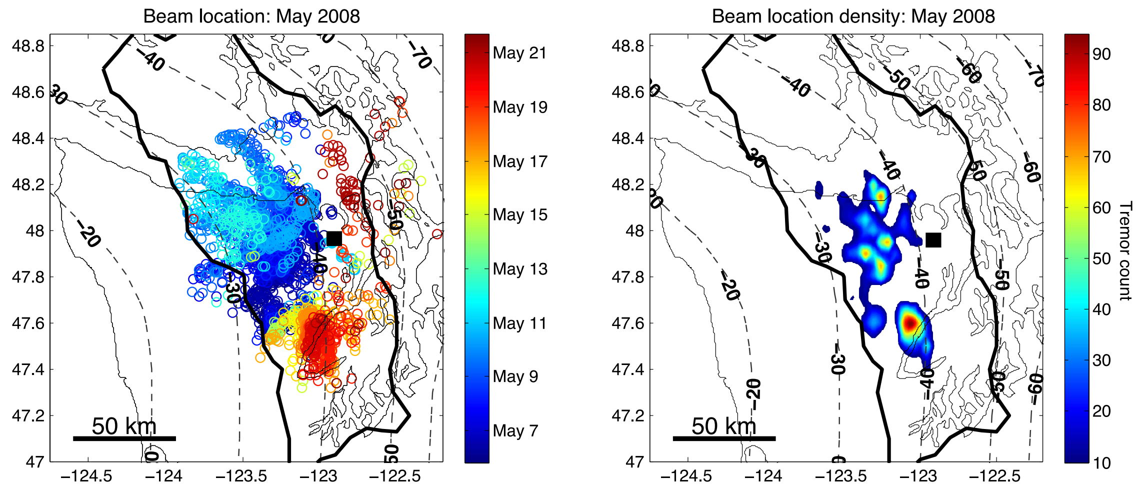

Figure 3. (left) Tremor location (colored open circles) using beamforming method during the main ETS event (May 2008). Time is color-coded to illustrate temporal evolution. Bold black line demarcates the boundary of ETS zone based on the ECC tremor location of 4 ETS events (2004–2008). Dashed contour lines define the plate interface [*McCrory et al.*, 2006]. Black box marks the location of the Big Skidder array. (right) Tremor location density during the same time period.

[14] Tremor density, however, does not give the full picture, as it does not contain tremor amplitude information. A more appropriate measure of NVT activity, which incorporates the tremor amplitude data, is the moment released by the tremor from the different parts of the subduction interface that are active during a tremor episode. Figure 4 maps the relative band-limited tremor moment released from the plate interface during May 2008 ETS event. The relative moment release map readily shows patchy nature on the interface, similar to that observed in the location density map, indicating that it is a robust observation. What is striking though is that the moment release map markedly changes the brightness of the patches that are illuminated by the location density maps. Three patches just WSW of the array become brighter while the southern patch, which is the brightest one in the location density map, gets dimmer. In fact, the strongest tremor patch releases ~5 times the moment of the surrounding areas. Therefore, relative band-limited tremor moment map reveals that subduction interface in Cascadia is distinctly patchy in terms of the NVT activity, and there are just a few distinct patches that release much of the tremor moment during May 2008 ETS event.

[15] An intriguing suggestion is that earthquakes may avoid the strongest tremor patches found in this study. The events close to the interface in the last ~50 years seem to lie near the edge of the patches, but do not breach them (Figure 4). However, due to paucity of earthquakes in this region, it is not clear whether tremor and ordinary earthquakes occur in complementary patches.

4. Discussions and Conclusions

[16] Beamforming technique reveals as much as four times longer duration of tremor than a conventional ECC method during the period of weak tremor suggesting that existing methods are missing much of the time that tremor is occurring. Array analysis is able to significantly increase the level of tremor detection allowing us to better estimate the stress released by the NVT activity in a plate boundary setting, which may have significant implications from the seismic hazard perspective.

[17] The dominance of NVT moment release in several distinct patches during the 2008 ETS event in Cascadia shows that the ETS zone is not uniformly tremor-active during this slow slip event. The area with higher tremor moment release also coincides with the zone of the highest

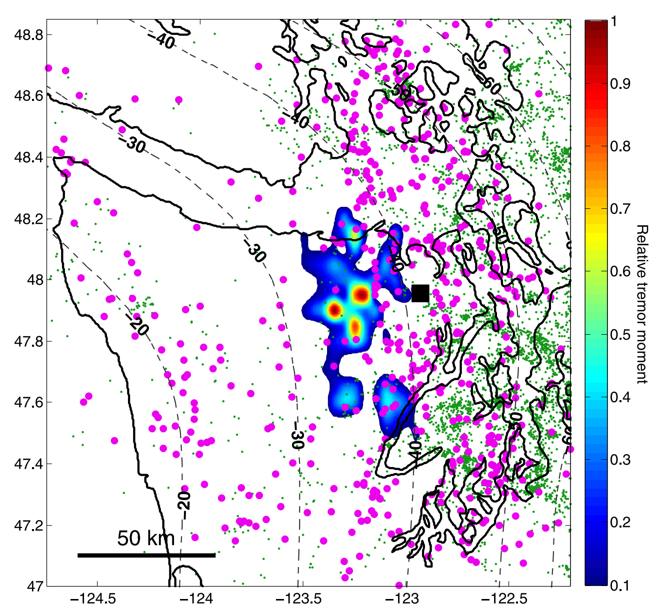

Figure 4. Relative band-limited tremor moment release during the main ETS event (May 2008), and earthquakes locations during 1960–2008 (pink solid circles, and green dots). Moment is normalized by its maximum value. Pink circles represent earthquakes located within 8 km of the subduction interface, while smaller green dots mark locations of off-interface events. Dashed contour lines define the plate interface [*McCrory et al.*, 2006]. Black box shows the location of the Big Skidder array.

slip derived from modeling constrained by GPS motions (K. Wang, personal communication, 2009) indicating that NVT likely represents slip at the plate interface. The condition suitable for tremor may exist in the entire broad ETS zone, but the degree of activity varies remarkably, resulting in greatly heterogeneous moment release.

[18] Tremor patches, together with the absence of earthquakes in the area of high moment release may hint that the subduction interface in this region consists of spots having frictional properties and/or fluid content that are particularly favorable for tremor generation (Figure 4), and different from the rest of the ETS zone. High tremor activity may signify smoother section(s) of the fault, perhaps characterized by lower shear strength. It is consistent with the idea that tremor is a superposition of tiny earthquakes (LFEs) as described by *Shelly et al.* [2007], and a result of shear slip on a fault plane [e.g., *Ghosh et al.*, 2009; *Peng et al.*, 2008; *Rubinstein et al.*, 2007]. The simplest way to reduce the shear strength of a section of the fault is to either decrease the frictional coefficient or increase the fluid pressure. While physical heterogeneity may cause spatially variable frictional behavior, wet spots in the fault may be responsible for higher fluid pressure, thereby reducing the effective normal stress, and creating localized weakness in the plate interface. High v_p/v_s ratio in the vicinity of the LFEs in southwest Japan [*Shelly et al.*, 2006] supports the latter interpretation.

[19] In conclusion, the array technique is able to detect much longer tremor duration than an ECC method, and unveils several tremor patches on the subduction interface that release much of the tremor moment during the May 2008 ETS event in Cascadia. Our beamforming method provides greater resolution than that of conventional approaches of tracking tremor activity. Concentrated tremor moment release from discrete spots suggest that the mode of accommodation of stress on the subduction interface may be governed by the spatially variable frictional property, and/or wet spots on the fault.

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