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Tremor bands sweep Cascadia

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[1] During the slow slip events in Cascadia and Japan, a well-documented feature of nonvolcanic tremor (NVT) is its puzzling slow along-strike migration. But the cause, possible implications, and underlying physics of this long-term tremor migration and its relationship with slow slip remain elusive. Here, we use tremor data recorded by a dense seismic array in Cascadia, and apply a beam-backprojection technique to map the spatiotemporal evolution of tremor with high resolution. It reveals that elongated slip-parallel bands of tremor activity illuminate the slipping part of the plate interface over the time-scale of several hours, and sweep Cascadia along-strike from south to north. We propose that small changes in static stress due to slow slip in a section of the fault cause slip and associated NVT activity in the adjacent section, and the resulting progressive along-strike transfer of stress is responsible for the long-term tremor migration during a slow slip event. **Citation:** Ghosh, A., J. E. Vidale, J. R. Sweet, K. C. Creager, A. G. Wech, and H. Houston (2010), Tremor bands sweep Cascadia, *Geophys. Res. Lett.*, *37*, L08301, doi:10.1029/2009GL042301.

1. Introduction

[2] The recent discovery of slow-slip and nonvolcanic tremor (NVT) in several major plate boundary faults challenges our understanding of fault dynamics. NVT is characterized by apparently noise-like, emergent waveforms that are depleted in high-frequency energy compared to ordinary small earthquakes, lasts for a few seconds to days, and has envelopes that are coherent between seismic stations kms apart. It has been documented in subduction zones worldwide including southwest Japan [*Obara*, 2002], Cascadia [*Rogers and Dragert*, 2003], Mexico [*Payero et al.*, 2008], Costa Rica [*Schwartz et al.*, 2008], Alaska [*Peterson and Christensen*, 2009], and the San Andreas Fault SAF [*Nadeau and Dolenc*, 2005] as well, a transform plate boundary. In subduction zones, slow slip and tremor are often coupled in space and time, and occur in the transition zone, between updip locked and downdip freely slipping segments of the fault. Episodic tremor and slip (ETS) [*Rogers and Dragert*, 2003] refers to the remarkably periodic slow-slip events and associated NVT activity in Cascadia that recurs every 14.5 months or so. NVT responds to very small stress changes. It is modulated by tides [*Lambert et al.*, 2009; *Rubinstein et al.*, 2008], and can also be triggered by tiny stressing induced by teleseismic surface [e.g., *Ghosh et al.*, 2009a; *Gomberg et al.*, 2008; *Rubinstein et al.*, 2007], and *P* waves [*Ghosh et al.*, 2009a].

[3] ETS events load the updip locked section of the plate interface, taking it a step closer to the next big megathrust earthquake [*Dragert et al.*, 2004] in the subduction zone. Hence, it is important to comprehend the physical processes controlling this phenomenon, and its impact on the seismic hazard of the region concerned. Also, observing these events will help close the gap between the observed and predicted seismic moment release on the plate boundary, furthering our understanding of how faults work. During an ETS event in the Cascadia Subduction Zone (CSZ), NVT shows interesting migration patterns on different time scales. While tremor activity generally migrates along strike at a long-term velocity of ~10 km/day [e.g., *Ghosh et al.*, 2009b; *Obara*, 2002], it also exhibits continuous slip-parallel migration roughly 2 orders of magnitude faster, but over the time scales of several minutes to an hour [*Shelly et al.*, 2007a] (A. Ghosh et al., Rapid, continuous streaking of tremor in Cascadia: Toward a unified view of tremor distribution in space and time, submitted to *Geophysical Research Letters*, 2010). Fluid flow [e.g., *Obara*, 2002], and shear slip [e.g., *Ghosh et al.*, 2009a; *Ide et al.*, 2007; *Shelly et al.*, 2006] have been invoked to explain the generation of tremor. However, the details of the long-term migration, its cause, possible implications, and its relationship with the slow slip and the evolving stress regime in the ETS zone remain unknown. Here, we show that elongated slip-parallel bands of NVT, swept the CSZ during the May 2008 ETS, and propose a model to explain this phenomenon.

2. Data and Methods

[4] Aiming to record fine details of an ETS event, we installed a temporary 84-element, short-period, vertical-channel, small-aperture seismic array (henceforth the Big Skidder array) on the Olympic Peninsula, Washington, USA, above the migration path of NVT activity during previous ETS events in Cascadia (Figure 1). We were able to capture almost the entire ETS event in May 2008, when strong NVT activity rumbled through the region. In this paper, we concentrate on two days, May 6 and 7, 2008, when tremor reached its peak activity in the vicinity of our dense array. During these days, tremor was strong and virtually continuous under the array [*Ghosh et al.*, 2009b], which provided exceptionally high signal-to-noise ratio (SNR) and well-resolved observations of NVT. Other days are excluded from the present analysis to remove any possible artifacts due to incomplete imaging of tremor activity in space and time.

[5] We develop and use a beam-backprojection (BBP) method to detect and locate tremor [*Ghosh et al.*, 2009b].

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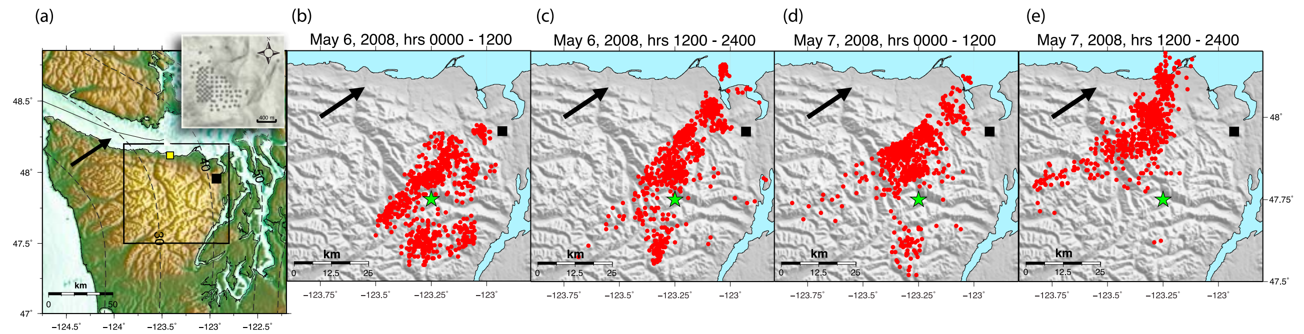

Figure 1. (a) The location map of the study area. The solid black and yellow squares mark the location of the Big Skidder array and Port Angeles tide station, respectively. The arrow indicates direction of slip along the subduction fault. Dashed contour lines represent depth (in km) of the subduction interface [*McCrory et al.*, 2006]. Black box defines the area of the subsequent maps. Inset figure shows station distribution of the Big Skidder array. (b–e) A half-day of tremor locations (red solid circles) using our beam-backprojection method. The solid black square marks the location of the Big Skidder array. Arrows indicate overall slip direction of CSZ. Note band-like distribution of tremor aligned parallel to the overall slip direction. The green star is for reference to help show northward migration of slip-parallel tremor band.

The data are analyzed in the time domain using 2-minute sliding time-windows with 50% overlap. We apply a delay-and-sum approach to stack the data for a range of slownesses in the tremor frequency band (3–8 Hz). Resulting beams are used to detect and locate tremor assuming that NVT is occurring at the plate interface. Despite a lack of unanimity in the seismological community [*Kao et al.*, 2005], there is mounting evidence that the majority of NVT is located near the interface, and is a result of shear failure [e.g., *Ghosh et al.*, 2009a; *Ide et al.*, 2007; *Ito et al.*, 2007; *La Rocca et al.*, 2009; *Rubinstein et al.*, 2007; *Shelly et al.*, 2006; *Shelly et al.*, 2007b; *Shelly et al.*, 2009]. The validity of the assumption, the station distribution of the Big Skidder array, and the BBP technique are discussed in detail by *Ghosh et al.* [2009b].

[6] We use a subduction interface model by *McCrory et al.* [2006] to locate tremor, although debate on the depth of the interface in the ETS zone is ongoing. This study, however, does not heavily depend on a specific interface model because our results are based on the pattern in relative tremor locations. A subduction interface shifted in depth only results in small horizontal shifting of the whole set of tremor location without changing the overall pattern.

3. Results

[7] BBP method results in a tremor catalog with almost continuous NVT detections during the two days considered here. Tremor locations span ~50 km north-south, and lie between the interface depth contours of 30 and 40 km. The NVT generally migrates northwards over time, except a small patch in the south that remains stationary, isolated from the rest of the activity (Figures 1, 2a, and 3). Because we are interested in tremor migration in this study, we do not focus on the immobile southern source here. Figure 1 displays tremor locations divided into arbitrarily chosen half-a-day time periods. Aside from the static southern source, NVT activity fills band-like tremor-zones aligned parallel to the overall slip direction of the CSZ. These slip-parallel bands contrast with much more scattered tremor locations derived using an envelope cross-correlation (ECC) method [*Wech and Creager*, 2008], which shows no such

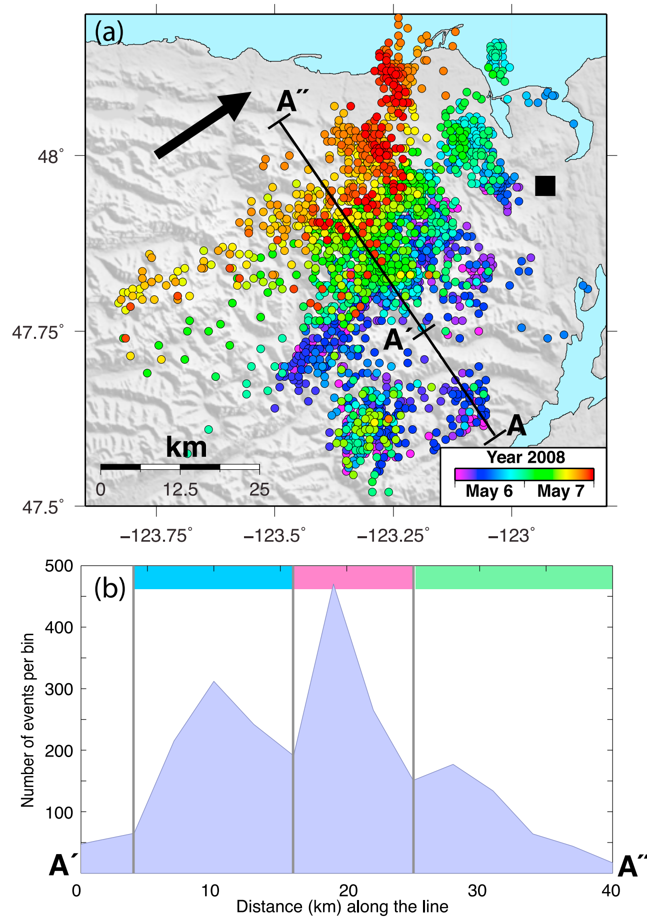

Figure 2. (a) Tremor locations (solid circles) during May 6, and 7, 2008, using the beam-backprojection technique. Time is color-coded. The solid black square marks the location of the Big Skidder array. Arrow indicates overall slip direction of CSZ. Line A-A′-A″ is perpendicular to the slip direction. (b) Tremor locations are projected on the line A-A′-A″. Only A′-A″ part is shown. Note three peaks of tremor activity, and the segmented distribution of tremor locations. Gray vertical lines define three segments, which are assigned different colors to be used in Figure 4. Three km bin length is used.

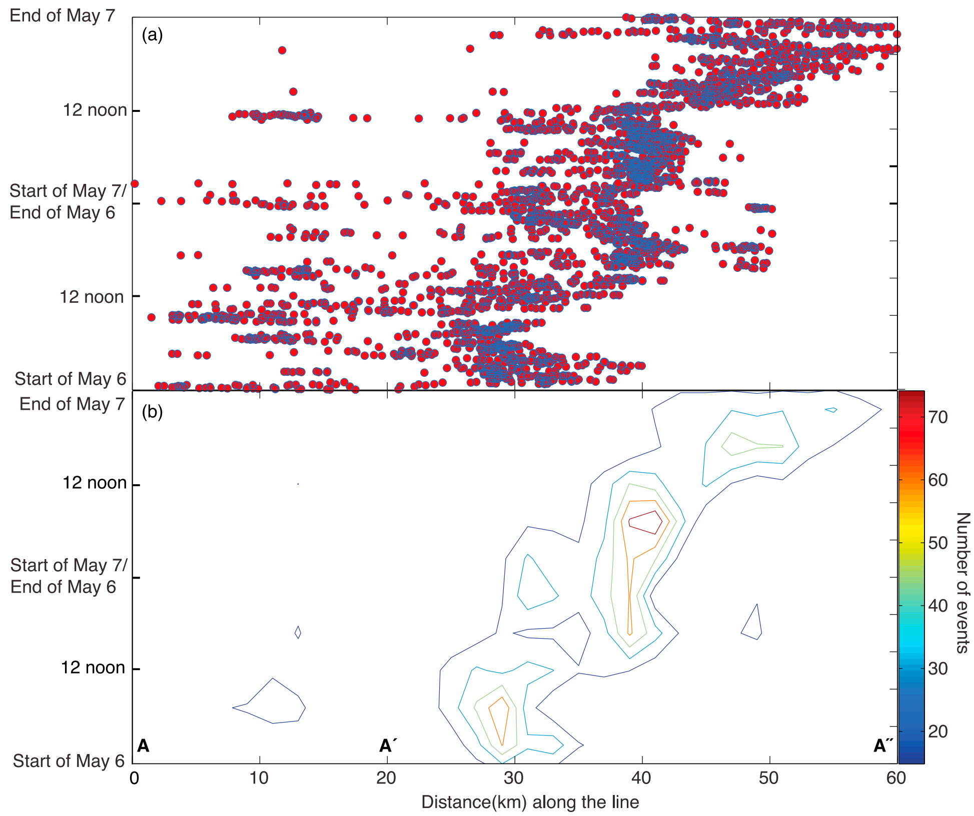

Figure 3. Spatiotemporal distribution of tremor. (a) Red solid circles show tremor locations in space-time domain. Space represents distance along the line A-A′-A″ in Figure 2a. Tremor migrates NW at a velocity of ~10 km/day. (b) Contour plot of tremor distribution in space-time domain. Note that tremor activity is separated in space, but overlaps in time. 2 km by 0.2 day bin is used for contouring.

clearly resolvable pattern over the same time scale, demonstrating the greater resolution of relative tremor location using BBP method. Uncertainties in the tremor locations using BBP method increase as a function of the distance between tremor source and the seismic array. Particularly, locations southwest to the array beyond (west of) longitude −123.5 have larger errors. As the number of locations with larger uncertainties is relatively small, and band-like pattern still exists even without these locations, we do not eliminate them from this study.

[8] In order to define and examine the bands in detail, we projected the tremor locations along a line (Figure 2a) perpendicular to the slip direction. Activity along the line reveals a segmented pattern in space, with two pronounced peaks, and another weak one in the north (Figure 2b). They are separated by ~10 km along the line. Weakness of the northernmost peak is partially caused by the slight change of strike of the northern band relative to the projection direction. This change coincides with the distinct bending of the subduction interface in this locale, and possibly is an effect of complicated plate geometry. Tremor activity shows a similar pattern in the space-time plot (Figures 3a and 3b), with zones of activity fairly well separated in space. Additionally, it illustrates that the tremor-active zones are not completely distinct in time, but overlap to some extent. Based on this observation, we define three tremor-active zones in space (Figure 2b). In map view, the selected regions form elongated bands of tremor with their long axes aligned parallel to the overall slip direction (Figure 4b) of CSZ. The bands are ~40 km long in the slip-direction but only ~10 km in width. It is important to note that the slip-and-dip-direction of the subduction fault significantly differ for most of the study area.

[9] The most intense activity in the bands coincides with the tremor patches that released much of the tremor moment during the May 2008 ETS event [*Ghosh et al.*, 2009b]. These patches on the fault also witnessed the highest geodetic slip during this ETS event (K. Wang, personal communication, 2009). The time evolution of tremor bands also unveils some interesting features (Figure 4a). Each tremor band remains active for a good part of a day. It slowly rises for several hours to reach its peak activity, and subsequently fades away in a similar way. The tremor bands show significant overlap in time. While a band is still going strong, the next adjacent one in the north slowly starts growing active. Interestingly, it appears that tremor activity starts to shift to the adjacent band around the time of high tides (Figures 4a and S1).[1] Overall, the tremor bands sweep Cascadia from south to north at a velocity of ~10km/day, producing the long-term tremor migration.

4. Discussions and Conclusions

[10] Tremor distribution using ECC and source-scanning algorithm shows long-term tremor migration along the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL042301.

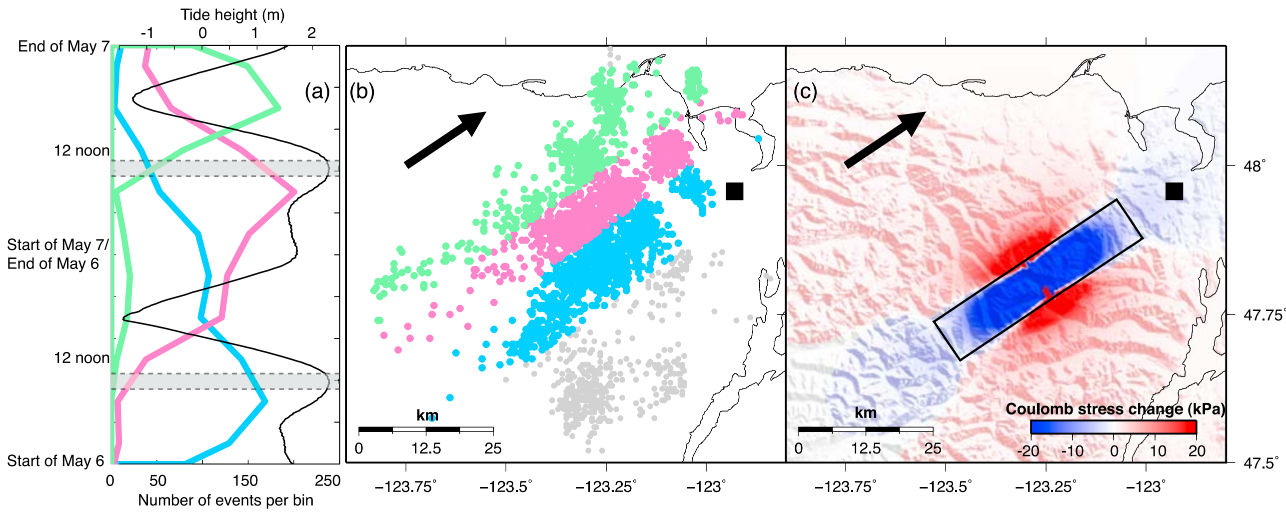

Figure 4. Color-coded time history, spatial distribution of tremor bands, and stress change due to slip in a band. (a) Tremor activity in each band over time. Note that peak activity of each tremor band is clearly separated in time. 0.2 day bin with 2-point smoothing is used. Black line represents water level height over time at Port Angeles station. Gray boxes highlight the correspondence between high tides and the initiations of the tremor bands. (b) Tremor bands in map view. Colored solid circles represent tremor locations. Gray solid circles shows tremor locations outside three segments defined in Figure 2b. Colors associated with tremor bands in Figures 4a and 4b correspond to the colors assigned to the segments in Figure 2b. (c) Coulomb stress change due to slip in a representative tremor band (black rectangle) with approximately 10 km by 40 km dimension, and 15° dip. Positive stress change encourages slip. A frictional coefficient of 0.4 is used to compute stress change at 36.5 km depth. Note significant stress change on both sides of the band. In Figures 4b and 4c, the solid black square marks the location of the Big Skidder array, and the arrow indicates overall slip direction of CSZ.

strike of the subduction zone in Cascadia and Japan. What is not known, however, are the details of this migration pattern, its relationship with slow slip, and the underlying physics controlling the migration. This study reveals that slip-parallel bands of tremor, with their peak activity clearly separated in space and time, sweep CSZ from south to north. The enhanced tremor detectibility [*Ghosh et al.*, 2009b], and high resolution of the BBP method allow us to extract the details of migration from seemingly erratic clusters of tremor locations. Seismic tremor and slow slip in Cascadia, and southwestern Japan subduction zones correlate well in space and time [*Maeda and Obara*, 2009; *Rogers and Dragert*, 2003; *Wech et al.*, 2009]. Based on this observation, we interpret that each band is the result of slow slip in the direction of convergence on a part of the plate interface that is roughly defined by the tremor bands. The slip-parallel alignment of the tremor bands are possibly guided by overall slip direction of CSZ, and the weak linear slip-parallel features on the fault plane [*Power and Tullis*, 1992; *Resor and Meer*, 2009; *Rubin et al.*, 1999]. Hence, tremor locations derived by the BBP technique may illuminate the slipping section of the fault over the time scale of several hours. We propose that as one part of the fault slips, it transfers stress along-strike to the adjacent section to the north activating the next band. Therefore, sweeping tremor bands represent progressive slip in the direction of subduction, and resulting stress transfer along the strike of the megathrust.

[11] We estimate the magnitude of transferred stress with a model of reverse slip on a 15° northeasterly-dipping fault that represents a part of the Cascadia megathrust in the ETS zone (Figure 4c). Fault dimensions are set to approximate the geometry of the tremor bands, while slip distribution (Figure S2) is consistent with the result of geodetic model constrained by GPS motions (K. Wang, personal communication, 2009). We find that 3-cm of slip in the middle of the fault throws 10–20 kPa Coulomb stress [*Toda et al.*, 2005] to the center of the adjacent band along the strike. It has been shown that 6–14 kPa increments of Coulomb and shear stress from nearby large earthquakes results in elevated NVT activity near SAF [*Nadeau and Guilhem*, 2009]. Even tinier dynamic stresses from teleseismic body- and surface-waves also excite tremor beneath SAF [*Ghosh et al.*, 2009a]. In Cascadia, tidal stresses in the order of 5–15 kPa modulate tremor amplitude [*Rubinstein et al.*, 2008] as well. Hence, each tremor band loads the adjacent band to the north with sufficient stress (10–20 kPa) to produce NVT and associated slip. Our results imply that the small static stress change by slow slip associated with NVT can stimulate tremor nearby if the fault is close to failure, and the conditions conducive for tremor-generation exist. However, the discrepancy between the velocity at which Coulomb stress transfer occurs (seismic wave velocity) and the slow along-strike advance of tremor bands (~10 km/day) is noteworthy. Previous study shows that high tremor activity correlates with high tide in this region [*Rubinstein et al.*, 2008]. Hence, it is plausible that high tides provide the additional stress that may help tremor bands shift a few kms along-strike initiating slow slip and associated tremor activity in a new fault segment (Figures 4a and S1). While speculative, this scenario offers a mechanism that may explain the slow advance of tremor bands along-strike of the subduction zone. Sweeping tremor bands support the notion that the whole ETS zone does not slip concurrently during an ETS event; instead slow slip migrates along-strike with tremor activity, somewhat analogous to the rupture propagation during an ordinary fast

earthquake. While geodetic methods can resolve slow slip that occurred over several days, our BBP technique is able to delineate slipping part of the fault over the time scale of several hours. Our findings suggest that a small change in static stress due to slow slip in a section of the fault causes slip and associated tremor in the adjacent section, and resulting progressive along-strike transfer of stress is responsible for the long-term migration of tremor during an ETS event.

[12] **Acknowledgments.** We thank Steve Malone, and many volunteers who helped in the fieldwork. Maps are created using Generic Mapping Tools [*Wessel and Smith*, 1998]. We thank the Editor Ruth Harris, and two anonymous reviewers for their thoughtful and constructive comments.

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