Segmentation in episodic tremor and slip all along Cascadia

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ABSTRACT

The recent discovery of episodic tremor and slip (ETS) in subduction zones is based on slow slip episodes visible in global positioning system observations correlated with nonvolcanic tremor signals on seismometers. ETS occurs just inboard from a region capable of great megathrust earthquakes; however, whether there is any communication between these two processes remains unknown. In this study we use new single-station methods to compile an ETS catalog for the entire Cascadia subduction zone, offshore western North America, and compare the patterns with a variety of along-strike trends for the subducting and overriding plates. Correlated ground vibrations and strain observations are found all along the subduction zone, demonstrating that ETS is an inherent part of the subduction process. There are three broad (300–500 km), coherent zones with different recurrence intervals (14 ± 2, 19 ± 4, 10 ± 2 months), where the interval duration is inversely proportional to upper plate topography and the spatial extent correlates with geologic terranes. These zones are further divided into segments of ETS that occur at times typically offset from each other. The seven largest (100–200 km) segments appear to be located immediately landward from forearc basins interpreted as manifestations of megathrust asperities, implying that there is a spatial link between ETS and earthquake behavior. It is not yet clear if any temporal link exists, but the regional time between ETS episodes could be controlled by strength variations due to composition of geologic terranes.

Keywords: episodic tremor and slip, nonvolcanic tremor, slow slip, segmentation, subduction zone, Cascadia, subduction thrust earthquakes.

INTRODUCTION

As oceanic plates subduct down into the mantle, friction on the interface with the overriding plate causes stick-slip behavior in the megathrust zone, pulling the upper plate down until it pops back up during a potentially devastating earthquake (Ruff and Kanamori, 1983). Recent observations have also revealed slow slip episodes that occur regularly on parts of the deeper plate interface, with motion indicating release of accumulated strain (Dragert et al., 2001; Lowry et al., 2001; Ozawa et al., 2002). Their frequency and amount of slip (Mw ~6.5–7.5) (Kostoglodov et al., 2003; Melbourne et al., 2005) imply they are a substantial portion of the interplate deformation budget. The duration of these episodes is much greater than earthquakes, yet they are accompanied by weeks of nonvolcanic tremor (Obara, 2002; Rogers and Dragert, 2003; Szeliga et al., 2004). As such, they represent another section of the strain rate continuum between earthquake and geologic time scales. Processes that govern episodic tremor and slip (ETS) or potential relationships to major earthquakes and local geology remain unknown, although ETS has been proposed to affect the likelihood of megathrust earthquakes (Mazzotti and Adams, 2004).

Previous observations of ETS in Cascadia have focused on southern Vancouver Island, northern Washington, and northern California because of the density of geophysical observatories (Fig. 1). When observed, slow slip episodes representing weeks of transient displacements are visible in data obtained from global positioning system (GPS) stations within a few hundred kilometers of the trench and show westward motions back toward the trench (Dragert et al., 2001; Melbourne et al., 2005). Corresponding nonvolcanic tremor composed of relatively small, non-earthquake signals are most prominent in the 1–10 Hz frequency band and appear to occur in a region from the plate interface into the upper plate (Kao et al., 2005; McCausland et al., 2005; Obara, 2002). ETS was first established on southern Vancouver Island with regular recurrence at ~14 months (Fig. 2) (Rogers and Dragert, 2003). Prevalent instrumentation in northern California has detected similar ETS signals at the other end of the subduction zone, but revealed a shorter recurrence interval of ~11 months (Fig. 2) (Szeliga et al., 2004). Previous observations from Oregon are sparse; a few seismic stations in southern Oregon showed a period of nonvolcanic tremor

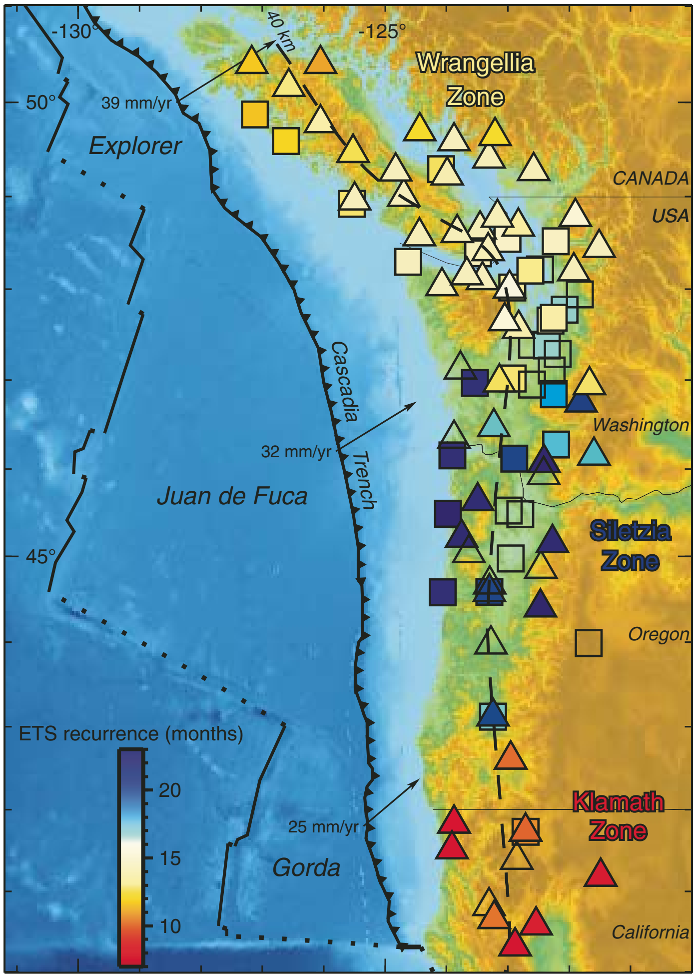

Figure 1. Map illustrating patterns in episodic tremor and slip (ETS) along the entire Cascadia subduction zone. Colored base map shows topography and bathymetry. Dashed line onshore marks 40 km depth contour of the subduction interface. Arrows and associated annotations show directions and speeds of subduction relative to North America. Locations of continuous global positioning system stations (squares) and broadband seismometers (triangles) that exhibit ETS are shown, with colors indicating the recurrence interval when multiple ETS events were observed. Recurrence intervals establish three zones that are labeled based on the continental terrane block with which they are associated.

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in 2005 (McCausland et al., 2005), and data obtained using one GPS station in central Oregon showed slow slip episodes with a longer recurrence interval (Szeliga et al., 2004). This initial set of observations raises some important questions. (1) Is ETS a phenomenon present throughout the subduction zone and thus an inherent part of the subduction process? (2) What generates the spatial variability in recurrence rates of ETS despite their temporal regularity in a given region? (3) Is ETS linked in any way to properties of the megathrust seismogenic zone? Each of these questions requires a broad set of observations in space and time.

ETS OBSERVATIONS

We utilize a new set of ETS information generated by automated identification of nonvolcanic tremor and slow slip episodes at individual GPS and seismic stations that circumvents the need for dense networks. These methods are not replacements for network solutions, but are simply used as surrogates to perform a uniform investigation of ETS over the entire subduction zone while network density is still heterogeneous. For GPS data, we identify slow slip episodes by applying a hyperbolic tangent fit (Larson et al., 2004; Lowry et al., 2001) over a scrolling window of the publicly available Pacific Northwest Geodetic Array (PANGA) time series. An f-test confirms when the fit is better than a linear fit at 99% confidence, and a threshold value for the transient displacement marks events that are larger than background noise. For seismic data, we calculate a time series from the mean amplitude of filtered envelope seismograms for each nighttime hour recorded at individual stations, instead of using a station network to judge hours when nonvolcanic tremor is present (Obara, 2002; Rogers and Dragert, 2003). After a moving average and normalization, large peaks rising above background noise at 99% confidence are identified as periods during which nonvolcanic tremor dominates. (See the GSA Data Repository[1] for details on automated data processing.)

Figure 2 summarizes results from seven different segments throughout Cascadia. A typical seismic trace indicating the times of nonvolcanic tremor and a GPS time series showing the times of slow slip episodes are plotted for each region. In regions with previous ETS estimates (McCausland et al., 2005; Rogers and Dragert, 2003; Szeliga et al., 2004), our results are in good agreement with timing of ETS (e.g., Fig. 2C, Fig. DR2). More important, nonvolcanic tremors that correlate with slow slip episodes are apparent in several new locations along the subduction zone, particularly along central Cascadia, despite more limited observatories (Figs. 2D–2F). Corresponding seismic and GPS data availability ranges from 1 to 8 yr, with 30 stations reporting slow slip episodes and 55 stations reporting nonvolcanic tremor (Fig. 1), of the >300 stations that have been investigated with our automated techniques (Brudzinski and Allen, 2006; Holtkamp et al., 2006). It is clear that ETS occurs along the entire subduction zone, meaning that localized geological conditions special to a particular site are not controlling factors that prohibit ETS. This finding is supported by a growing number of observations in other subduction zones showing nonvolcanic tremor source locations and displacements from slow slip episodes over broad regions (e.g., Hirose and Obara, 2006), ruling out hypotheses that require particular along-strike variations to produce ETS (Mitsui and Hirahara, 2006).

ETS RECURRENCE INTERVALS

While ETS is observed throughout the Cascadian subduction zone, the characteristics vary coherently along strike, revealing clear segmentation in the recurrence interval and relative timing of ETS events. There are three broad geographic zones with different recurrence intervals of ETS

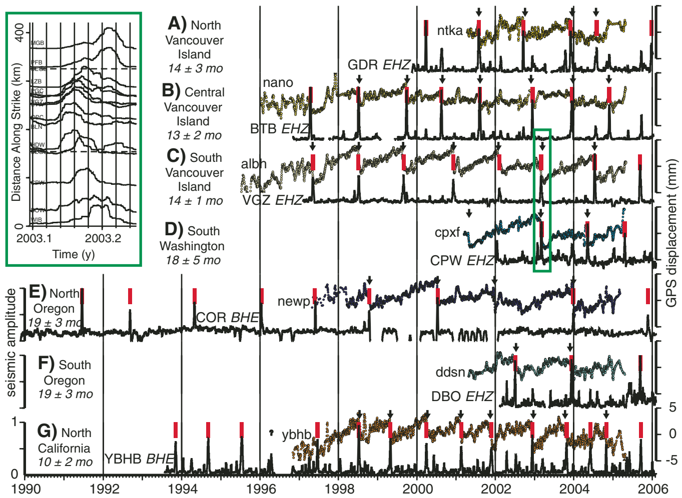

Figure 2. Summary of slow slip episodes and nonvolcanic tremor measurements that characterize seven segments along Cascadia. Colored circles show processed east displacement of global positioning system (GPS) station and black curves are normalized, mean seismic amplitudes, where high spikes are bursts of nonvolcanic tremor activity. Red rectangles and black arrows mark the peak of nonvolcanic tremor and center of slow slip episodes, respectively, with clear temporal correlation in any given segment. GPS data are colored by recurrence interval of slow slip episodes, as in Figure 1. Inset shows time offsets in nonvolcanic tremor activity for the 2003 episodic tremor and slip event (green box) from C and D, plotting stations according to distance from the Oregon-Washington border (see the GSA Data Repository, section A3, for details [see footnote 1]). Mo—months. Uppercase labels are seismic station names with component type in italics, lowercase are GPS station names (see Fig. DR4 for map).

(Fig. 1). For example, in the Siletzia zone in the central part of Cascadia, data from station COR in Corvallis, Oregon, extend the history of nonvolcanic tremor back by a factor of two to 1989 (Fig. 2E), giving a robust estimate of 19 ± 3 months for the recurrence interval at this station. The average interval across the Siletzia zone (19 ± 4 months) is longer than those observed on Vancouver Island to the north (14 ± 2 months), and is nearly twice as long as that from California to the south (10 ± 2 months). The broader geographic extent of our ETS measurements relative to previous studies allows us to identify that a coherent Wrangellia zone extends from northern Vancouver Island to ~47.5°N, and that a Klamath zone extends from the southern end of the subduction zone to ~42.8°N (Fig. 1).

This pattern of recurrence intervals is not tied to the overall rate of subduction, which drives the earthquake cycle as a whole. Overall convergence velocities decrease slowly from the north to the south (Fig. 1) (DeMets et al., 1990), while the longest recurrence interval occurs in the middle of the subduction zone. Even if one considers the Oregon forearc as a separate rotating microplate (e.g., Wells et al., 1998), the impact on convergence rates would be gradual and would not aid in matching the coherent patterns in recurrence intervals.

We also find that the three zones of relatively uniform recurrence intervals cannot be explained by age of the subducting plate, implying that along-strike variations in ETS are not due to temperature changes. Because the age of oceanic lithosphere is proportional to the distance from the mid-ocean ridge and the thermal state of oceanic plate is proportional to the square root of its age (Parsons and Sclater, 1977), one would look for ETS recurrence to be related to distance from the ridge. However, observations along Vancouver Island and northernmost Washington are nearly perpendicular to the Explorer ridge, with station to ridge distances varying from 300 to 700 km (cf. ~500 km in central Oregon). This means that the age of the oceanic plate beneath the Wrangellia

[1]GSA Data Repository item 2007224, details on analysis, Figures DR1–DR5 (processed time series and station map), and Figure DR6 (animated map of episodic tremor and slip occurrence), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

zone should vary rapidly, causing both warmer and colder plate than that below central Cascadia, where the longest recurrence dominates. Boundaries between the three main ETS zones are ~100 km north of expected age and temperature boundaries in the subducting plate if the existing fracture zones are extended beneath the continent.

We suggest that the recurrence interval of ETS is related to properties of the overriding continental plate instead of the subducting oceanic plate. The age and temperature of the subducting plate likely have some impact on generating ETS, because initial work has shown that slow slip episodes and/or nonvolcanic tremor are prominent in other young, warm subduction zones such as southwest Japan and Mexico (Hirose and Obara, 2006; Larson et al., 2004; Lowry et al., 2001; Obara, 2002). However, the oceanic plates subducting beneath Cascadia are relatively uniform compared to the heterogeneity of the continental plate they dive beneath. The central Siletzia zone, with an ~18 month recurrence interval, corresponds to the relatively low-lying and young Coastal Range block of central and northern Oregon and southern Washington (mostly thick Siletzia terrane) (Trehu et al., 1994). The shorter-recurrence-interval zones to the north (Wrangellia) and south (Klamath) correspond to older pre-Tertiary blocks with higher topography consisting of a mélange of old oceanic material with later silicic intrusion in a continental environment (Harden, 1998; Jones et al., 1977). Figure 3A shows how ETS recurrence intervals are inversely proportional to onshore forearc topography. Correlation of these continental blocks with along-strike patterns of ETS is also consistent with the observation that nonvolcanic tremor appears to occur throughout the continental crust at depths above the interface with the subducting oceanic crust (Kao et al., 2005).

ETS SEGMENTS

The zones of spatially coherent recurrence intervals (Fig. 1) are further divided into segments where individual events recur over roughly the same location. While the average recurrence intervals of ETS are similar within a given zone, the relative timing between ETS events shows variation with location (Fig. 2), a phenomenon that is particularly clear when comparing northern and southern Vancouver Island (Figs. 2A, 2C) (Dragert et al., 2004). The extent of these segments is now emerging from the increased number of ETS observations. Figure 3B illustrates the phase shift in time between different segments by displaying the timing of ETS observations all along Cascadia, with horizontal lines estimating the along-strike extent of a given episode. Because these are station locations instead of source locations, we would expect the gray lines to extend ~50 km beyond the actual source locations. Dashed vertical lines are approximate boundaries defined by events on either side that are separated in time by more than a month for more than 50% of the episodes. We find seven large segments with along-strike widths of 100–200 km (Fig. 3B). The long-term timing of events for each segment is also illustrated by representative GPS and seismic data pairs (Fig. 2; Fig. DR5). Close inspection of nonvolcanic tremor time series for the 2003 ETS event that appears to cross segment boundaries reveals distinct offsets in time of 1–2 weeks precisely at the proposed boundaries (Fig. 2, inset; Fig. DR3).

The largest segments of ETS occur immediately landward from the proposed locations of asperities on the Cascadia megathrust (Wells et al., 2003). The asperity locations are based on large, low gravity, sedimentary basins in the forearc that have been interpreted to indicate potential seismogenic segmentation at depth. This inference is from global surveys that find that most of a megathrust earthquake's seismic moment and area of high coseismic slip (asperities) occur beneath the deep-sea forearc basin features (from gravity, bathymetry, and seismic profiling; Song and Simons, 2003; Wells et al., 2003). Figure 3B shows the along-strike pattern of prominent forearc basins for comparison with the spatial extent of ETS segments (We find a stronger correlation using locations of forearc basins based on bathymetry.) The apparent correlation between segmentation of the seismogenic zone and segmentation of the ETS zone suggests

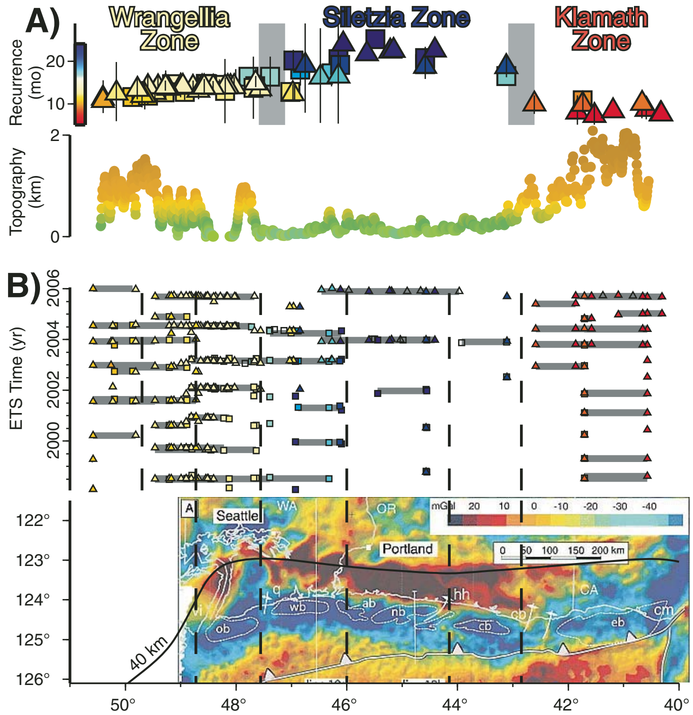

Figure 3. Plot of along-strike patterns of episodic tremor and slip (ETS) and upper plate features. A: Top panel shows distinct variations in ETS recurrence (symbols as in Fig. 1); vertical bars show 1σ of observed intervals. Bottom panel shows topography above the 40 km depth contour of subduction interface, in middle of ETS observations. Topography is inversely correlated with ETS recurrence, roughly matching the primary continental terranes of different age and composition (Wrangellia, Siletzia, Klamath). B: Top panel shows phase of ETS for seven different segments along the subduction zone from ETS timing at individual stations. Horizontal gray lines connect stations that record episodic tremor and slip within a month (mo) of one another. Bottom panel shows color-shaded gravity anomalies and locations of offshore forearc sedimentary basins (white lines), features that have been correlated with megathrust asperities on the subduction interface in recent global studies (Wells et al., 2003). Vertical dashed lines show apparent edges of ETS segmentation from currently available data that seem to correlate with megathrust segmentation from the five largest sedimentary basins. To deal with trench curvature, station latitudes are projected onto 40 km contour (black curve).

that effects of locking (or lack thereof) on the megathrust are transmitted to greater depths where slow slip is believed to occur (Dragert et al., 2001). This spatially links megathrust structure and anticipated seismogenic behavior with ETS characteristics.

DISCUSSION

A remaining question is whether upper plate structure controls plate interface behavior or vice versa. Both models have been proposed for forearc basins, with either basins developing in response to locking on the subduction interface (Song and Simons, 2003; Wells et al., 2003), or thickness of the upper plate critical wedge controlling the frictional behavior on the plate interface (Fuller et al., 2006). For ETS recurrence, the accreted terranes composing the upper plate above ETS generate inherently sizable along-strike variations in structure, composition, and age that are presumably more significant than long-term effects of ETS on upper plate structure. This supports an interpretation where variations in the Wrangellia, Siletzia, and Klamath blocks control behavior of the ETS source zone. A clue to how continental blocks could be responsible for differences in ETS recurrence is geochemical evidence that the different terranes have different fluid content (Schmidt and Grunder, 2006), which could trigger ETS via high pore fluid pressures (Kodaira et al., 2004; Obara, 2002). An intriguing hypothesis is that different terrane composition affects the rheology of the upper plate and hence the plate interface (Kohlstedt et al., 1995). For example, the Siletzia terrane represents denser, stronger, more oceanic crust, while the Klamath terrane represents lighter, weaker, more continental crust. Such a scenario would suggest that the low-lying Siletzia region has a longer recurrence interval because the upper plate has the strength to accumulate strain for longer periods between slow slip episodes. Although it is not yet clear whether rate- and state-dependent friction processes are the best way to explain ETS (Chen and Brudzinski, 2007), initial laboratory fault-sliding experiments suggest that variable fluid pressure and rock composition would both be expected to generate coherent variations in recurrence intervals of transient slip (Liu and Rice, 2005, 2006).

While it is well established that properties of the subducting plate play key roles in determining plate interface behavior, our result adds to growing evidence that the overriding plate is equally important in megathrust and ETS characteristics. More characterization of the upper plate geologic framework will be essential to assess the nature of deformation at convergent margins.

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