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Constraints on accumulated strain near the ETS zone along Cascadia

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ABSTRACT

Current national seismic hazard models for Cascadia use the zone of episodic tremor and slip (ETS) to denote the lower boundary of the seismogenic zone. Recent numerical models have suggested that an appreciable amount of long-term strain may accumulate at the depth of ETS and questions this assumption. We use uplift rates from leveling campaigns spanning approximately 50–70 yrs in Washington and Oregon to investigate the amount of potential long-term locking near the ETS zone. We evaluate the potential for deeper locking in Cascadia by exploring a range of locking parameters along the subduction zone, including the ETS zone. Of the four east–west leveling profiles studied, three show a reduction in the misfit when secondary locking near the ETS zone is included; however the reduction in misfit values is only statistically significant for one profile. This would suggest that models including a small amount of secondary locking are broadly indistinguishable from models without any secondary locking. If secondary locking is considered, the leveling data allow for locking up to ∼20% of the plate rate near the updip edge of the ETS zone. These results are consistent with, but less resolved, by GPS observations.

1. Introduction

The Cascadia subduction zone poses a significant seismic hazard to the Pacific Northwest due to the potential of a megathrust earthquake (Atwater, 1987; Goldfinger et al., 2003). Geodetic and thermal data suggest that strain is actively accumulating along the plate boundary (Hyndman and Wang, 1995). Seismic hazard maps that quantify the expected strong motion from a megathrust event are constructed from a logic tree of rupture scenarios. One branch of these rupture scenarios implicitly assumes that seismic rupture will not extend into the zone of episodic tremor and slip (ETS) (Peterson et al., 2014). Considering the importance that this assumption has on the seismic hazard, we explore the potential for long-term strain accumulation near the ETS zone.

In Cascadia, ETS events represent the transient release of accumulated strain along the plate interface downdip from the seismogenically locked zone at 25–45 km depth. These ∼M_w 6 ETS events last approximately 10–20 days and have recurrence intervals of 11–22 months (Dragert et al., 2001; Rogers and Dragert, 2003; Brudzinski and Allen, 2007; Schmidt and Gao, 2010). The existence of ETS demonstrates that the subducting and overriding plates are capable of storing strain at this depth for months to years, and perhaps longer. The limited resolution of slip on the deep part of the plate interface leaves considerable uncertainty as to whether any strain might accumulate over multiple ETS cycles near the ETS zone, thereby potentially elevating the seismic hazard by increasing the down-dip limit of the seismogenic locked zone and extending the rupture zone inland toward large population centers.

Geodetic inversions of major slow slip events (SSEs) in northwest Washington from 1997–2008 reveal that only 50–60% of the long-term strain accumulation is released at 25–45 km depth (Chapman and Melbourne, 2009; Schmidt and Gao, 2010). Smaller SSEs, which are difficult to resolve geodetically, may account for the remaining slip deficit within the ETS zone. Based on tremor that accompanies slow slip, Wech et al. (2009) inferred that up to 45% of the strain budget might be attributed to background activity in the inter-ETS interval. This would suggest that nearly the entire strain budget that is accumulated around the plate boundary within the depth interval of ∼25–45 km is released in ETS activity. In contrast, rate-and-state numerical models of SSEs have predicted that a sizable portion (∼30–50%) of the slip deficit remains after multiple events (Segall et al., 2010; Colella et al., 2013).

In this work, we investigate the presence of elastic strain that is accumulated within the depth range of 25–45 km on the plate

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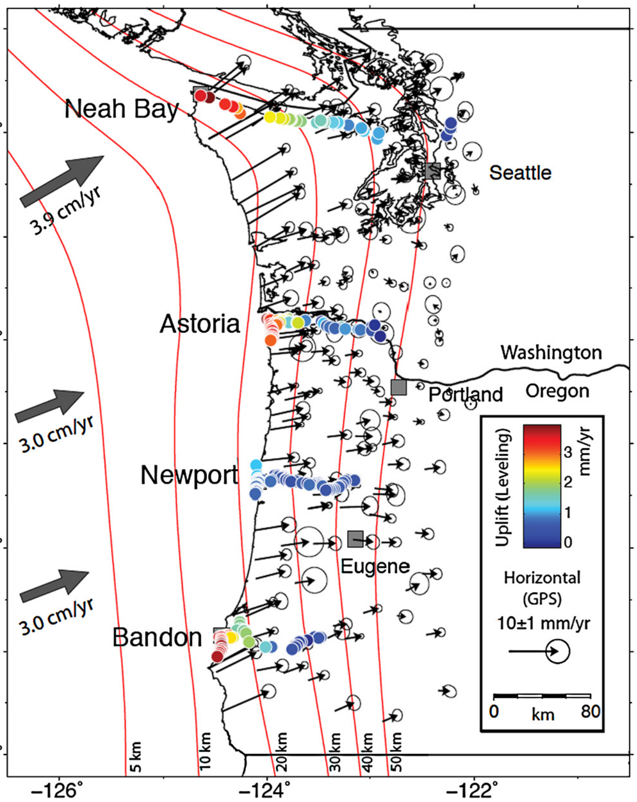

Fig. 1. Vertical and horizontal velocities in Cascadia used in this study. Colored dots represent absolute uplift rates from the four east–west trending leveling profiles. Black arrows represent horizontal velocities from permanent and campaign GPS measurements. GPS velocities are relative to North America and have been corrected for the Oregon block rotation. Error ellipses are 95% confidence. Red contour lines are depths of the subducting Juan de Fuca plate beneath North America from McCrory et al. (2004). Grey arrows indicate the Juan de Fuca to fore-arc convergence rates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

boundary and released during a typical megathrust cycle through the optimization of locking parameters. Although the kinematic behavior of ETS has predominately been characterized using geodetic (i.e. GPS and strain gauges) and seismic measurements (i.e. tremor) from the last 1–2 decades, historical leveling and tide gauge data, which extend back nearly 8 decades, provide a means to supplement and extend these recent observations to gain a better understanding of long-term deformation in the ETS zone. When tied to an absolute reference frame with tide gauge data, leveling data provide precise uplift measurements with uncertainties significantly lower than current vertical GPS measurements. Our findings suggest that the long term accumulated strain is less than predicted by some numerical models, but the data do allow for a small portion of the slip budget to be stored over multiple ETS cycles.

2. Data and methodology

For this study, the vertical displacements of four east–west leveling profiles along Cascadia are analyzed: three in Oregon (Burgette et al., 2009), and one in northern Washington reprocessed with a similar methodology (Fig. 1; Supplementary Text S1). Relative uplift rates are derived from National Geodetic Survey (NGS) first- and second-order leveling surveys along highways in western Oregon and Washington, spanning a time-scale from the early 1930s to the late 1980s. Burgette et al. (2009) estimated up to 80 years worth of uplift rates along the surveys in Cascadia by making secondary ties to benchmarks, correcting for sea level rise rates, and improving the data processing.

Each leveling profile is tied to benchmarks at tide gauge stations. After accounting for regional sea level rise, the tide gauge uplift rates are used to provide an absolute reference frame to the relative uplift rates from the leveling profiles. This, along with additional processing methods, helps to significantly reduce the standard error of benchmark uplift rates to $\sim$0.3 mm a^{-1} along the coast, with the error increasing to the east away from the tide gauge benchmarks to $\sim$1 mm a^{-1}. Refer to Burgette et al. (2009) and the supplement for the complete details of the processing procedure. We have greater trust in data points with higher uplift rates, since individual benchmarks tend to subside over time and can be biased downward. However, all reported data are used in our analysis.

To complement the leveling results we also include an analysis of GPS displacements near the leveling profiles. Due to higher uncertainties and scatter in the vertical component of GPS compared to our leveling data set, we choose to only use the horizontal GPS components. We use network site velocities in Cascadia from continuous and campaign GPS observations compiled, analyzed, and made available by McCaffrey et al. (2013), which includes data from the Plate Boundary Observatory, Pacific Northwest Geodetic Array, Western Canada Deformation Array, National Geodetic Survey Continuously Operating Reference Sites, and several others. The velocities are restricted to sites with at least five years of data, and are spatially binned to coincide with the leveling profiles. Sites near major volcanic centers are removed. The rotation of Oregon and southern Washington is removed using the pole and rate of rotation derived by McCaffrey et al. (2013). The north and east oriented velocity vectors are rotated into convergence normal and convergence parallel components. This allows us to focus on the convergence parallel component, where the maximum deformation signal is observed.

Time-dependent deformation along the fault since the last major rupture (i.e. viscous relaxation of the lower crust or upper mantle) could affect the GPS and leveling data differently. Considering our model assumes an isotropic elastic medium, we do not explore how the deformation might evolve with time. Due to the difference in averaging intervals and the relative difficulty of resolving the expected signal due to secondary locking in horizontal displacements (Fig. 2) the leveling and GPS datasets are analyzed individually.

To model the subduction zone, a backslip method is used to estimate the slip deficit on the subduction interface (Savage et al., 2000). The convergence rate is calculated using the Juan de Fuca–Oregon forearc Euler pole of Wells and Simpson (2001) for the Oregon profiles and the Juan de Fuca–North America pole of Mazzotti et al. (2007) for the Washington profile. The Juan de Fuca slab interface is modeled by discretizing the depth contours of McCrory et al. (2004) into triangular subfault patches. Surface deformation is estimated using an isotropic elastic half space with a Poisson's ratio of 0.25 and a shear modulus of 40 GPa. Green's functions are calculated using the boundary element program Poly3D (Thomas, 1993). Slip is ascribed using a combination of dip-slip and strike-slip motion to account for oblique convergence of the Juan de Fuca plate with North America. The slip deficit along the plate interface is prescribed by four free parameters: the down-dip extent of the primary seismogenic zone (locked zone), the down-dip extent of the transition zone, and a zone of partial locking near the ETS zone (also referred to as the zone of secondary locking) where the location and magnitude of the locking are allowed to vary separately.

The slip deficit rate in the seismogenically locked zone is assumed to be the full convergence rate and fully locked to the trench. Although this assumption may not hold true, our model re-