FINAL TECHNICAL REPORT: Award Number G14AP00038 The Mechanics of Episodic Tremor and Slip with Implications for Seismic Hazards in Cascadia

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Abstract

We continue developing physics-based models that explain the occurrence and characteristics of slow slip events (SSE) and are consistent with geodetic and seismic observations of Episodic Tremor and Slip (ETS) in the Pacific Northwest. In previous reports we described physics based models of SSE based on rate-state friction and dilatancy strengthening, found depth distributions of mechanical properties and pore-pressure that are consistent with the magnitude and depth extent of SSE, and developed efficient algorithms for 2D and 3D quasi-dynamic boundary element modeling.

In northern Cascadia, kinematic inversions of GPS and tide-gauge/leveling data display an unresolved "gap" between the down-dip limit of the locked megathrust and the top of the ETS zone. During this reporting period, we combined physics-based models of slow slip events with both mean ETS displacements and decadal-averaged deformation rates to explain the gap and determine how interseismic stress accumulates on the megathrust.

We first apply the physics-based models of *Segall and Bradley* (2012a) to the Cascadia subduction zone, with the intention of fitting both the average ETS displacements and the decadal-averaged geodetic velocities. Although model predictions can match the ETS displacements, they fail to fit observed decadal-scale velocities, in particular the uplift rates from a combination of leveling and tide-gauge data, when the fault is locked to the top of the ETS zone (Fig. 1). We investigated the potential bias caused by the use of homogeneous Green's functions to relate the slip on the megathrust to the surface displacements, compared to more realistic Green's functions that account for a stiff oceanic slab. We also test a common suggestion that the gap is creeping steadily due to velocity strengthening friction in that region.

We find that the misfit between observations and predictions from physics-based simulations with creep in the gap persists, leading us to develop a new approach to assess the mechanical behavior of the ETS region and to construct more accurate physics-based models. Specifically,

we invert for shear stress rates on the megathrust that best fit the data. Using this approach we show that the deformation data can be explained by negative shear stress rates, up to 2.5 kPa/yr, at the top of the ETS region. This small change in shear stress on the megathrust is sufficient to produce steeper slip-rate gradients at the up dip limit of the ETS region required to fit the long-term geodetic data. We also show that among the models that fit the entire data set, only those with locking depths to $\sim$ 21 km are able to fit to the observed uplift rates. A paper describing this work is now in revision at JGR–Solid Earth.

1 Report

Numerical simulations of slow slip and dynamic rupture applied to Cascadia

Observations of deformation rates in the Olympic Peninsula - southern Vancouver Island region include (1) displacements and velocities obtained from GPS measurements; and (2) uplift rates, determined from tide-gauges and leveling measurements. We use daily GPS positions at 51 stations from 2000 to mid 2015, from which we compute horizontal velocities averaged over numerous past SSEs as well as average displacements during ETS events. We also employ decadal-averaged uplift rates from tide gauges and leveling surveys in the northern Washington area from *Krogstad et al.* (2016), which we correct for postglacial rebound.

We use FDRA (Fault Dynamics Radiation-damping Approximation) (*Segall and Bradley*, 2010, 2012a,b) to predict ETS slip and long-term slip displayed in Figure 1a and 1b. This model, which assumes a locked plate boundary between 0 and 30 km, an ETS region between 30 and 42 km and an imposed down-dip velocity below 42 km, fit the average ETS displacements reasonably well, especially the horizontal component (Figure 1b). However, it over-predicts the horizontal long-term velocity in the western part of the network (Figure 1d). The misfit indicates too much locking between 15 and 30 km, in other words, in the “gap” defined previously. Significantly, the forward model completely fails at fitting the long-term uplift rates.

Explaining long-term rates with physics-based models

Potential inaccurate Green's functions. The discrepancy between the long-term observations, especially the vertical rates, and the predicted rates from physics-based models could potentially be caused by inaccurate Green's functions. To address this issue, we compute Green's functions for a more realistic earth model using the finite-element code PyLith (*Aagaard et al.*, 2013). We then test the effect of the heterogeneous Green's functions by assuming a slip-rate distribution where the megathrust is locked above 25 km, from which we compute synthetic horizontal and vertical displacements, using the heterogeneous Green's functions. The synthetic data are then inverted with both homogeneous and heterogeneous Green's functions. Using heterogeneous Green's functions results in slightly less slip above 25 km, but the difference is small and insufficient to account for the gap between the bottom of the locked zone and the top ETS region.

Velocity-strengthening friction within the gap. We investigate physical mechanisms that could explain why the long-term deformation rates seem to require less locking up-dip of the SSE region. One possibility is that creep updip of the ETS zone results from velocity-strengthening rheology, which allows the “gap” to creep at constant stress. We return to the numerical simulations and expand the size of the fault up-dip, accounting for velocity-strengthening regions of different length at the top of the ETS zone, that is above 30 km. The ETS region is still defined between 30 and 40 km. We test four lengths of the velocity-strengthening region, with up-dip extent from 26 km

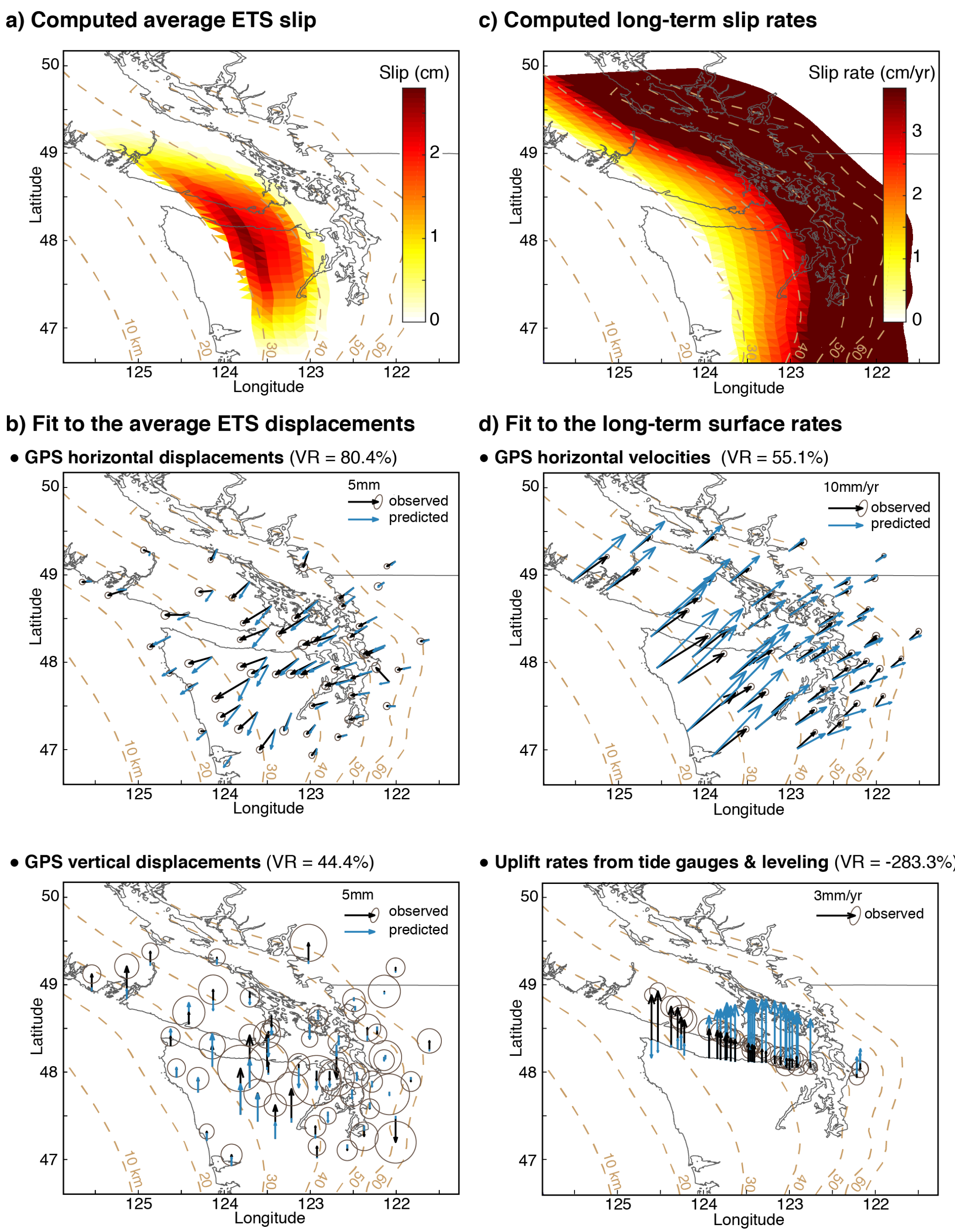

Figure 1: Computed average ETS displacement (a) long-term slip rates (c), and their corresponding fit to the surface data (b and d). VR stands for Variance Reduction. Numerical simulations consider a fully locked region between 0 and 30 km and an ETS zone spanning 30-42 km depth. Our physics-based predictions fit the average ETS event within the uncertainties, but fail at matching the long-term rates, particularly the uplift rates.

to 14 km depth. Predicted surface deformation rates from those models improve the fit to the horizontal displacements; however, they still severely misfit the vertical rates.

To understand what the data require, we invert the residuals from the five starting physics-based models, attempting to find the *smallest possible deviations* from the physics-based models that prove plausible fits to both the vertical and horizontal data. The adjusted slip-rate distributions are displayed in Figure 2a. These models all exhibit shallow creep (∼10 to 15 mm/yr), in a region between 15 and 25 km and slip rates in excess of those predicted by constant stress models below 25 km. The transition near 25 km is characterized by a steep increase in slip rates, from nearly 10–15 mm/yr to ∼ 30 mm/yr. This sharp rise in slip rates at is necessary to fit the high uplift rates along the Juan de Fuca Strait. So, although a velocity-strengthening region above the ETS zone allows creep in the gap, creep at constant stress predicts neither the sharp gradient in slip-rate nor the high slip rates between 25 and 40 km depth required to fit the uplift data.

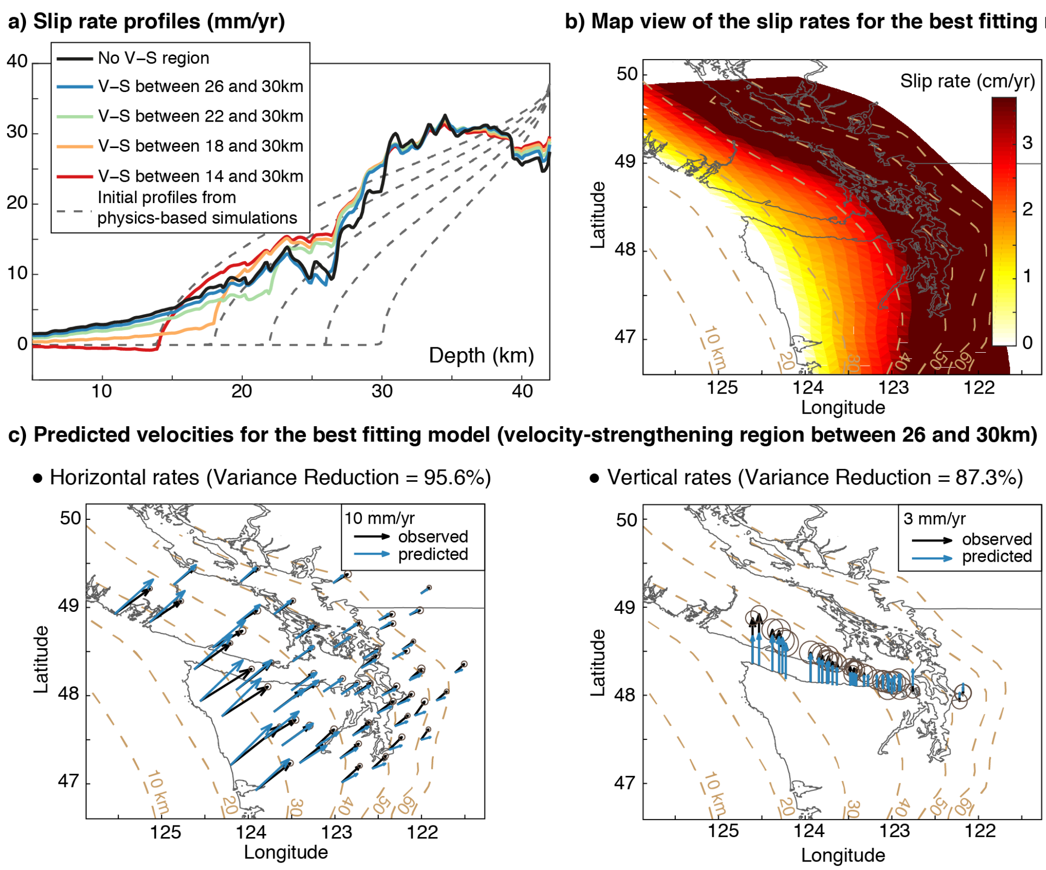

Figure 2: Inverted slip distributions, which fit both the horizontal and vertical rates. a) Grey dashed curves show forward slip-rate predictions with various sized velocity-strengthening zones up dip of the ETS zone. Colored curves show slip-rates adjusted to fit GPS and uplift data. b) Map view of the slip rate distribution for the best fitting model, with a velocity-strengthening region between 26 and 30 km. c) Predicted and observed vertical and horizontal rates for the best fitting model.

Inversion for shear stress rates

For the fault to slip faster between 25 and 45 km, the shear stress must decrease with time in this region. As an intermediate step between kinematic inversions and fully physics-based predictions we invert the long-term data for shear stress rates on the megathrust. We seeks solutions that fit the data with the smallest stressing rates within the slipping region, considering locking depths ranging from 0 km (no imposed locking) to 25 km (5 km above the ETS region). Mathematically, the optimization problem is

$$\min_{\dot{\tau}} ||\mathbf{\Sigma}^{-1/2}(\mathbf{G}\mathbf{A}^{-1}\dot{\tau} - \mathbf{d})||_2^2 + \alpha^2 ||\dot{\tau}_{\mathbf{z}>\mathbf{z_{max}}}||_2^2 \quad \text{s.t.} \quad \dot{\mathbf{s}}_{\mathbf{z}<\mathbf{z_{max}}} = \mathbf{0} \tag{1}$$

where $\mathbf{G}$ and $\mathbf{A}$ are matrices relating slip-rate to data and stress-rate on the fault, Σ is the data covariance matrix, and z_{max} is the fault locking depth. Note that the minimum shear-stress rate regularization applies only to the creeping fault below the locked zone. For a given locking depth z_{max}, and range of regularization parameters α^2 the optimization problem is solved using the MATLAB-built least-squares solver `lsqlin`.

Our preferred model, which adequately fits both horizontal and uplift rates, is the one with a 21 km locking depth. Figure 3 displays the inferred distributions of stress rate and slip rate, and the corresponding fits to the data. The shear stress rate is negative immediately below the locking depth, reaching a minimum around -2.5 kPa/yr between 25 and 30 km. The associated slip rate profile (Figure 3b) is locked between the trench and 21 km (as constrained), followed by a steep increase at 21 km.

Long-term deformation rates can be best explained by a megathrust locked to around 20 km, with a region of decreasing shear stress between ~ 20 km and ~ 40 km (Figure 3). Although this particular solution is not unique it appears to embody characteristics of all models that reasonably well fit the data, including the uplift rates. The ETS zone lies within the region of negative shear stress rates, between ~ 30 km and ~ 45 km. As the data favors deeper locking depths, the gap is constrained to the region of high long-term slip rates up dip of the ETS region, $\sim 20 - 30$ km depth. The inversions do not constrain the mechanical behavior of this region, but confirm that it is creeping, while, ETS events are located on a deeper part of the fault.

Our data driven results contrast with simple physics-based models that predict roughly constant shear stress within the SSE zone when averaged over many SSE cycles (*Segall and Bradley*, 2012a). Specifically, the long-term velocities, particularly the vertical, require a shear stress decrease within the gap and the up-dip part of the ETS zone. Future work should provide an explanation for this discrepancy by finding physics-based mechanisms that reconcile the inversion predictions with the numerical modeling.

2 Supported bibliography

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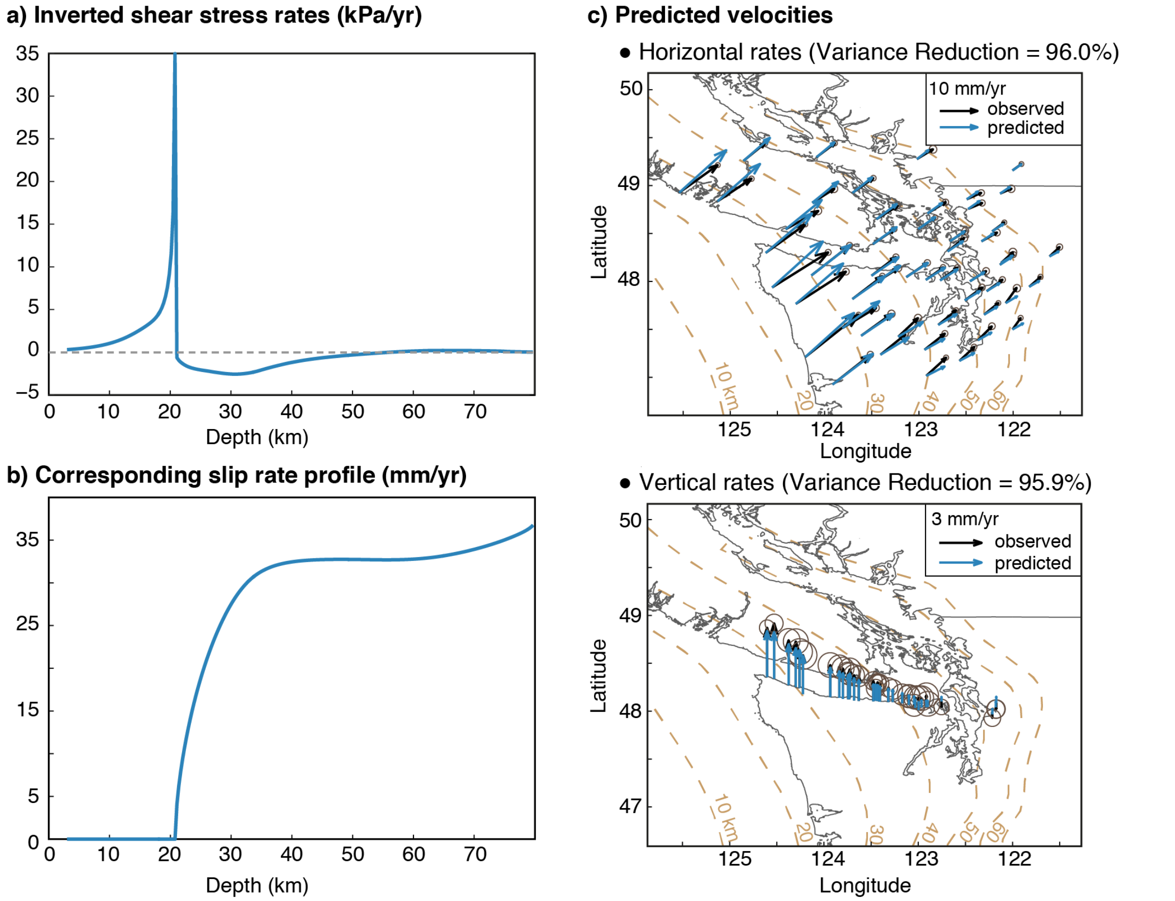

Figure 3: Preferred model from the inversion for shear stress rates with a locking depth of 21 km. a) Inverted shear stress rate profile. The shear stress decreases with time between 21 km and 50 km, i.e., within the gap and ETS region, reaching -2.5 kPa/yr between 25 and 30 km. b) Corresponding slip-rate profile. c) Observed and predicted rates.

3. Bruhat, L. & P. Segall (2016), Coupling on the northern Cascadia subduction zone from geodetic measurements and physics-based models, in review following minor revisions, *JGR–Solid Earth*.

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