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Along-strike coupling heterogeneity in Cascadia’s slow-slip zone constrained by GNSS and reduced-order rate-and-state friction modeling

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Key Points:

- Transient SSEs recover $\sim 36\%$, $\sim 18\%$, and $\sim 69\%$ of plate convergence in northern, central, and southern Cascadia.
- Rate-and-state friction simulations show that effective normal stress controls SSE recurrence; inter-SSE coupling controls SSE moment.
- GNSS and rate-and-state Bayesian inversions reveal persistent inter-SSE slip-deficit, largest in central Cascadia.

Abstract

Slow slip events (SSEs) in the Cascadia subduction zone exhibit along-strike segmentation, where the central segment has longer recurrence intervals but smaller moments. We quantify the controls on this variability by combining geodetic inter-SSE coupling inversion with Bayesian inference of a quasi-dynamic rate-and-state friction SSE-cycle model accelerated by reduced-order modeling. Our simulations show that effective normal stress controls the SSE recurrence interval, while subduction coupling controls the SSE moment. Our inversion of inter-SSE GNSS velocities yields comparable inter-SSE coupling along strike ($\sim 60\text{--}70\%$), whereas long-term coupling ranges from near zero in the south to $\sim 42\%$ in central Cascadia. Transient SSEs recover the full slip deficit in the south but leave persistent deficits of $\sim 30\%$ and $\sim 42\%$ of plate convergence in the north and central segments. These results indicate that effective normal stress and inter-SSE coupling provide a unified geodetic and physics-based explanation for Cascadia SSE segmentation.

Plain Language Summary

The Cascadia subduction zone, which stretches from northern California to Vancouver Island, is a major hazard capable of producing damaging earthquakes and tsunamis. In addition to these rare, large events, the megathrust also experiences “slow-slip events” deep underground, repeating every 7 to 21 months. These events release accumulated strain slowly over days or weeks rather than seconds and are not felt by humans, though they are detected by GPS stations on the surface. We combine GPS data with computer simulations and machine learning to understand why these slow-slip events vary in frequency and size along the coast. Between slow-slip events, the two sides of the fault are locked together to a similar degree all along the margin. What differs is how much of that built-up strain the slow-slip events release: in the south they release nearly all of it, but in the central section only part. The unreleased strain, largest in the central section, must be released in the future, whether in slow slip or in a megathrust earthquake. This helps us better understand how strain builds up along the subduction zone, which is critical for assessing earthquake hazard.

1 Introduction

Slow slip events (SSEs) are transient slip events, spanning days to months, that can occur up-dip or down-dip of the seismogenic portion of global megathrusts (Bürgmann, 2018; Dascher-Cousineau & Bürgmann, 2024). Such slow transient slip is often accompanied by a low-amplitude, extended-duration (minutes to days) seismic signal named tectonic (non-volcanic) tremor, and the combined phenomenon is termed Episodic Tremor and Slip (ETS, Rogers & Dragert, 2003; Brown et al., 2009). ETS are part of a broad spectrum of possible mechanisms to relieve stress accumulated on subduction zone interfaces from fast, potentially devastating earthquakes to continuous creep (Ide & Beroza, 2023; Peng & Gomberg, 2010). Over the past 25 years, SSEs have been well-documented phenomena in the Cascadia subduction zone (CSZ) in the Pacific Northwest (Dragert et al., 2001), yet the mechanisms driving their spatio-temporal kinematics are not fully understood (Behr & Bürgmann, 2021; Gomberg et al., 2016). Understanding how much tectonic loading is released during those SSEs and how much is accumulated on the ETS zone is essential for understanding the subduction zone’s long-term stress accumulation and mitigating seismic and tsunami hazards.

The CSZ is formed by the young and hot Juan de Fuca plate to the north and the Gorda microplate to the south, which are subducting in an eastward motion beneath the North American plate at a rate decreasing along strike from ~ 3.7 cm/year in the north to ~ 2.7 cm/year in the south (DeMets et al., 2010, Figure 1a). The margin exhibits along-strike segmentation in past earthquake slip, state of kinematic coupling, and distribu-

tion of ETSs (e.g., Audet & Bürgmann, 2014; Brudzinski & Allen, 2007; Morton et al., 2023; Schmalzle et al., 2014; P.-L. Wang et al., 2013; Watt & Brothers, 2020; Carbotte et al., 2024; Goldfinger et al., 2025). The reasons underlying this segmentation are challenging to constrain, partly due to the rapid decrease in geodetic resolution with distance from the coast (Lindsey et al., 2021). In addition, the interplay of variations in structural and frictional properties, kinematic geodetic coupling and prestress, remain poorly understood (Watt & Brothers, 2020; Walton et al., 2021; Carbotte et al., 2024). The relative abundance of slow slip observations and their spatial location within a relatively short distance from the geodetic network provide an opportunity to understand the sources of the CSZ’s along-strike segmentation and the underlying driving factors.

Numerical simulations leveraging rate-and-state friction laws have reproduced key aspects of Cascadia’s slow slip cycle, including observable recurrence intervals (Liu & Rice, 2009) and along-strike segmentation (Li & Liu, 2017), and have been used to investigate the influence of slab geometry, loading, and fluid interaction, among other factors (Li & Liu, 2016; Segall et al., 2010; Ozawa et al., 2025; Biemiller et al., n.d.; Yun et al., 2026).

ETS observations partition the CSZ into northern, central, and southern segments based on variation in SSE recurrence interval, slip magnitude, and tremor density (Figure 1, Brudzinski & Allen, 2007; Audet & Bürgmann, 2014; Bartlow, 2020; Gualandi, 2025; Zhang & Houston, 2025). Offshore of Vancouver Island and Washington state in northern Cascadia, SSEs are larger ($\sim M_w 6.6$) with a regular recurrence interval of 14 ± 2 months. Central Cascadia, offshore of Oregon state, experiences longer recurrence intervals of 19 ± 4 months and shows smaller magnitudes ($\sim M_w 6.45$) than its northern counterpart, although it is ~ 100 km longer along trench (see, e.g., Figure S10). To the south, where the CSZ approaches the complex Mendocino triple junction with the San Andreas and Mendocino strike-slip faults to the south and west, respectively, ETS activity shows a shorter recurrence interval of 10 ± 2 months (Brudzinski & Allen, 2007) and small magnitude SSEs ($\sim M_w 6.0$, Michel et al., 2019) with complex spatiotemporal distribution (Nuyen & Schmidt, 2024).

Here, we investigate the mechanical properties driving the along-strike segmentation of the CSZ, focusing on the role of megathrust coupling. Geodetically, interseismic kinematic coupling scales the local subduction slip deficit to plate convergence (Savage, 1983). A coupling of 60% means the interface accumulates a slip deficit of 60% of the plate convergence rate while slipping at 40%. This measure is purely kinematic and carries no direct information about frictional strength or stress (K. Wang et al., 2003). Coupling also depends on the observation timescale. For example, since transient SSEs periodically release part of the accumulated slip deficit, the well-studied long-term (Lindsey et al., 2021; Schmalzle et al., 2014; Sherrill et al., 2024; Pollitz, 2025) and short-term coupling will differ where SSEs occur.

We constrain the Cascadia SSE zone coupling through three independent estimates. We derive the inter-SSE Global Navigation Satellite System (GNSS) velocity field following the method of Bartlow (2020) and invert for the subduction coupling within the ETS zone, yielding the inter-SSE coupling c_{is} . We compare those to the long term coupling c_{LT} derived from long term GNSS velocities (Blewitt et al., 2018), their difference $c_{is} - c_{LT}$ is the slip deficit recovered by transient slip. The inversion shows a mean coupling of $\sim 66\%$ in northern CSZ, $\sim 60\%$ in central Cascadia and $\sim 68\%$ in the southern segment. To understand the physical implications of this heterogeneity, we use Bayesian inversion of a 2D rate-and-state friction model (Dieterich, 1979; Ruina, 1983), accelerated by scientific machine-learning reduced-order modeling (Magen, May, & Gabriel, 2026) which yields the mean inter-SSE coupling $\hat{c}$ of each of the CSZ segments. We specifically analyze if variations in megathrust coupling and effective normal stress can explain the diverse SSE moment and recurrence interval observed along strike, testing whether the independent coupling estimates c_{is} and $\hat{c}$ agree and using c_{LT} to quantify the persistent deficit (we provide a summary of key parameters used in Table S1). By integrating geode-

tic coupling inversion and physics-based modeling, we demonstrate that along-strike variation in megathrust locking and elevated pore-fluid pressure are required to explain CSZ ETS segmentation.

2 GNSS Data Processing and Geodetic Coupling Inversion

We derive the inter-SSE velocity field in the Pacific Northwest from the daily time series of 446 GNSS stations processed by the Nevada Geodetic Laboratory (NGL, Blewitt et al., 2018) in a fixed North America reference frame (Text S1). To resolve the distinct components of the ETS cycle, we decompose each station time series into inter-SSE velocities, the assumed steady motion between SSEs, SSE transient offsets, and a seasonal signal, following the methodology of Bartlow (2020). To identify and mask transient SSE deformation, we use periods of high tremor productivity from the CSZ regional catalog (Wech & Creager, 2008; Wech, 2010, 2021). While we remove coseismic offsets, isolating CSZ inter-SSE velocities near the Mendocino Triple Junction remains challenging. GNSS in the region record the superposed deformation of the CSZ, San Andreas, and Mendocino faults, alongside internal deformation in the Gorda plate (Shelly et al., 2024). The time series may also include postseismic signal from multiple $M_w \geq 6.0$ earthquakes, including the 2021 $M_w 6.1$ and $M_w 6.0$ Petrolia, 2022 $M_w 6.4$ Ferndale, and 2024 $M_w 7.0$ Mendocino earthquakes. Together, those process make the triple junction difficult to model. This GNSS processing chain yields a velocity field representing the steady deformation during the periods between SSEs, excluding the transient deformation contribution (Figure 1).

We invert our derived inter-SSE velocity field and long-term velocity field (Median Interannual Difference Adjusted for Skewness (MIDAS), Blewitt et al., 2018) to determine the inter-SSE c_{is} and long-term coupling (c_{LT}) distribution across the megathrust, using Slab2 geometry (Hayes et al., 2018). We determine the spatially variable coupling coefficient ($\mathbf{c} \in \{c_{IS}, c_{LT}\}$) by minimizing the regularized least-squares misfit (see Text S2):

$$\underset{\mathbf{c}, \boldsymbol{\theta}}{\operatorname{argmin}} \left(\|\mathbf{A}\mathbf{m}(\mathbf{c}, \boldsymbol{\theta}) - \mathbf{d}\|_2^2 + \beta \|\mathbf{D}\mathbf{m}(\mathbf{c}, \boldsymbol{\theta})\|_2^2 \right) \quad \text{s.t.} \quad 0 \leq c_i \leq 1, \quad (1)$$

where $\mathbf{A}$ are the homogeneous elastic half space Green’s functions (Okada, 1992; Nikkhoo & Walter, 2015), $\mathbf{d}$ is the observed surface velocity field, and $\mathbf{m}(\mathbf{c}, \boldsymbol{\theta})$ is the megathrust back-slip rate (Savage, 1983), so $\mathbf{A}\mathbf{m}$ is the predicted surface velocity. The back-slip rate is parameterized by the coupling vector $\mathbf{c}$, where c_i denotes the coupling coefficient of the i^{th} megathrust patch, the rake vector $\boldsymbol{\theta}$, and the long-term convergence rate from DeMets et al. (2010), which decreases from ~ 3.7 cm/year in the north to ~ 2.7 cm/year in the south (Figure SS6). The discrete first-order gradient (finite difference) matrix $\mathbf{D}$ is applied to the megathrust back-slip rate, and β is the smoothing coefficient that controls the strength of regularization.

Geodetic resolution decreases rapidly with distance from onshore-only observational network (Lindsey et al., 2021). To mitigate limited offshore resolution, previous studies typically impose additional assumptions on coupling distribution (Schmalzle et al., 2014; Lindsey et al., 2021; Saux et al., 2022). Here, we focus on coupling in the ETS region, which we define as the set of $0.05^\circ \times 0.05^\circ$ grid cells with more than 75 identified tremors (Wech & Creager, 2008; Wech, 2010, 2021). This ETS region lies at 25-50 km depth and ~ 10 km inland. It is a portion of the subduction interface that is relatively close to the geodetic network and therefore better resolved than the shallower portions.

To evaluate the reliability of our inversion within the ETS zone, we analyze the model resolution and model covariance (Figure S5). The resolution matrix identifies which model parameters are uniquely resolved by the data. The model covariance matrix maps the GNSS data uncertainties in the inferred model parameters. Together, this analysis en-

ables us to evaluate whether the onshore geodetic network can robustly resolve coupling variations within the ETS region.

3 Bayesian inference of inter-SSE coupling using reduced-order modeling

We estimate the mean inter-SSE coupling ($\hat{c}$) of the CSZ segments using rate-and-state friction simulations. The forward models are 2D quasi-dynamic SSE cycle simulations in a Cascadia-like subduction zone setting (Figure 3, Magen, May, & Gabriel, 2026). Megathrust friction follows rate-and-state friction, and the state variable evolves according to the ageing law (Dieterich, 1979; Ruina, 1983, see Text S3). We generate a data set of 110 simulations using the open-source software **Tandem** (Uphoff et al., 2022; Gabriel et al., 2026), varying $W \in [62.5, 100]$ km and $\sigma_W \in [1, 10]$ MPa to explore the parameter space controlling Cascadia’s along-strike segmentation. This expands the range of $\sigma_W \in [1, 6]$ MPa with same W range explored in Magen, May, and Gabriel (2026) which focused on northern Cascadia.

We use a Markov Chain Monte Carlo (MCMC, Hastings, 1970) approach to infer the posterior probability distribution of three parameters governing the SSE characteristics: the mean inter-SSE coupling of the ETS zone, $\hat{c} = M_0^{obs}/M_0^{ROM}$, which scale the fully coupled simulated moment to observed moment, the ETS-zone width (W), and the effective normal stress (σ_W). The inversion is constrained by observed SSE recurrence intervals (T_c^{obs}) and moments (M_0^{obs}) from the geodetic inversion of Michel et al. (2019), which are consistent with tremor-based recurrence time estimates (Brudzinski & Allen, 2007, Table S2 and Figure S10).

Evaluating all required forward models within the MCMC inversion is, however, computationally infeasible, because convergence to the posterior distribution typically requires $\mathcal{O}(10^4)$ – $\mathcal{O}(10^5)$ model evaluations (Mosegaard & Tarantola, 1995; Cui et al., 2015). To accelerate the Bayesian inference, we replace the full-order numerical simulations with a reduced-order model (ROM, Sirovich, 1987; Benner et al., 2015; Degen et al., 2023) that serves as a non-intrusive data-driven surrogate. ROM approaches have recently been applied to accelerate similar computational geophysics problems, including slow slip sequences (Kaveh et al., 2024; Magen, May, & Gabriel, 2026).

Our ROM methodology follows (Rekoske et al., 2023, 2025; Hobson & May, 2025; Magen, May, & Gabriel, 2026) and is a two-stage approach that comprises a computationally intensive ROM construction stage performed only once and dominated by the cost of the forward models, and an inference stage in which we evaluate unseen models in a fraction of the computational cost (Text S4). Evaluating $ROM(W^*, \sigma_W^*)$ takes only ~ 30 seconds on a single CPU, corresponding to a speedup of $\mathcal{O}(10^5)$ compared to the typical $\sim 2,000$ CPU hours required to run a single **Tandem** simulation.

In the MCMC, we assume uniform prior distributions for the inter-SSE coupling $\hat{c} \in [0, 1]$ and $\sigma_W \in [1, 10]$ MPa. For W (in km), we assume a normal distribution whose parameters are derived from the local width of the ETS area (Text S6, Figure S13), restricted to the ROM training domain $W \in [62.5, 100]$ km via a logit reparameterization. The posterior distribution is sampled using the Metropolis-Hastings algorithm (Hastings, 1970). For each proposed parameter vector ($W^*, \sigma_W^*, \hat{c}^*$), we evaluate $ROM(W, \sigma_W)$ to obtain the predicted recurrence interval T_c^{ROM} and a characteristic moment M_0^{ROM} (Text S6). This moment is calculated by extruding the 2D model-predicted SSE slip along-strike (Liu & Rice, 2009). The 3D extrapolation is motivated by the high aspect ratio characteristic of large Cascadia SSEs, for which the along-strike slip length (hundreds of kilometers) far exceeds the down-dip width W (~ 60 – 70 km) (Gualandi, 2025). In our simulations, the SSE zone is effectively locked between SSEs (slip rate $\sim 10^{-12}$ m/s), so each simulated event releases the full accumulated slip deficit and M_0^{ROM} is the moment

expected under complete inter-SSE coupling ($\hat{c} = 1$). We model the observed moment as $M_0^{obs} = \hat{c} M_0^{ROM}$, interpreting $\hat{c}$ as the mean inter-SSE coupling of the ETS zone, and infer it jointly with the effective normal stress and the width of the SSE zone.

The likelihood function $\mathcal{L}((T_c^{obs}, M_0^{obs})|(W^*, \sigma_W^*, \hat{c}^*))$ is given by:

$$\mathcal{L}((T_c^{obs}, M_0^{obs})|(W^*, \sigma_W^*, \hat{c}^*)) \propto \exp \left[-\frac{1}{2} \left(\frac{(T_c^{obs} - T_c^{ROM})^2}{\sigma_{T_c}^2} + \frac{(M_0^{obs} - \hat{c} M_0^{ROM})^2}{\sigma_{M_0}^2} \right) \right] \quad (2)$$

4 Results

4.1 Along-strike segmentation of ETS-zone coupling from GNSS

Our inversion of the inter-SSE and long-term GNSS velocity fields reveals along-strike segmentation in the locking state of the Cascadia ETS zone. The derived inter-SSE velocity field shows velocity magnitudes that are on average $\sim 10\%$ higher than the long-term GNSS velocities (Blewitt et al., 2018) over the 446 GNSS stations used in this study (Figure 2). The northern Cascadia SSE region has a mean coupling of $\sim 66\%$ during the inter-SSE period, with a maximum coupling of 81% and a long-term coupling of $\sim 30\%$ (Figure 2, S7, S8). The border between northern and central Cascadia is strongly coupled in the inter-SSE period, with the peak coupling values of the northern segment occurring at the segment border. South of this strongly coupled boundary, the central segment shows mean values over the entire segment of $\sim 60\%$ and $\sim 42\%$ for the inter-SSE and long-term periods, respectively. The boundary between the central and southern segments is completely decoupled at both inter-SSE and long-term timescales, suggesting constant creep at the SSE depth. The southern segment shows inter-SSE coupling of $\sim 69\%$ and is almost completely decoupled in the long term.

The difference between the inter-SSE and long-term coupling quantifies the fraction of megathrust slip deficit recovered by transient slow slip (Michel et al., 2025).

We emphasize that such geodetically inferred kinematic coupling is an effective, spatially smoothed estimate (e.g., GNSS resolution, assumed geometry, and spatial regularization) and is therefore only approximately comparable to the segment-averaged coupling parameter $\hat{c}$ introduced in our 2-D ROM-MCMC framework (Sec. 3). By taking the difference between the mean inter-SSE and long-term coupling ($c_{is} - c_{LT}$), we can quantify the fraction of slip deficit recovered by transient motion. Although inter-SSE coupling is changing by only 10% across segments, the long-term coupling differs by 43% . In the south, the inter-SSE coupling ($c_{is} \sim 69\%$) is almost entirely recovered by transient SSEs. In the north they recover $\sim 36\%$ and in the central segment transient SSEs recover only $\sim 18\%$ of the plate convergence rate, leaving $\sim 42\%$ to accumulate as a persistent slip deficit at SSE depths.

4.2 ROM exploration of physics-based SSE-cycle models

We use our ROM-accelerated SSE-cycle modeling framework (Sec. 3) to connect the geodetically inferred along-strike segmentation of ETS coupling with constraints on frictional model parameters, the segments mean inter-SSE coupling ($\hat{c}$), and SSE source properties. Our ROM approach enables a comprehensive exploration of the modeled SSE recurrence intervals and moments over the (W, σ_W) parametric plane for which we use 15,000 ROM evaluations complementing the 110 forward simulations (Figure 3c,d).

Consistent with previous Cascadia findings (Liu & Rice, 2007; Li & Liu, 2016; Magen, May, & Gabriel, 2026), the magnitude of the effective normal stress acts as the primary control of the SSE recurrence interval across the entire margin (Figure 3a). Varying σ_W from 1 to 10 MPa reproduces the full range of recurrence intervals observed across all three Cascadia segments. In contrast, the simulated moments systematically over-

estimate the observed values. Because the SSE zone is effectively locked during inter-SSE period, each simulation predicts the moment expected if the margin were fully locked between SSEs, over-predicting the geodetically derived values. The magnitude of this overshoot determines the inter-SSE coupling ($\hat{c}$) which we derive via the Bayesian inversion.

4.3 ROM-accelerated Bayesian inversion and posterior constraints

We perform a ROM-accelerated physics-based MCMC inversion to identify the inter-SSE coupling ($\hat{c}$) alongside the ETS-zone width and, effective normal stress required to reproduce the diverse SSE characteristics observed along the Cascadia margin. To evaluate the information gained from the inversion, we apply the two-sample Kolmogorov-Smirnov test (Massey, 1951). The test confirms that posterior distributions of the ETS-zone width are statistically different from the tremor-based prior distribution we derived from the spatial distribution of tectonic tremors in all three segments (Text S6). However, the posterior means and uncertainties remain close to the assumed priors, with inferred widths of 69.4 ± 3.3 km, 64.0 ± 1.0 km, and 67.6 ± 3.5 km for the northern, central, and southern segments, respectively (Figure S15b).

For the inter-SSE coupling and effective normal stress amplitude, the posterior distributions are clearly different from the uniform priors. Effective normal stress is primarily constrained by the observed recurrence intervals, where values of 4.0 ± 1.1 MPa, 6.1 ± 2.2 MPa, and 2.7 ± 1.0 MPa (Figure S15a) correspond to recurrence intervals of 13.5 ± 1.4 months, 20.5 ± 3.7 months, and 7.0 ± 4.0 months on the northern, central, and southern segments, respectively. To reconcile the seismic moments, the inversion requires mean inter-SSE coupling coefficients of 0.64 ± 0.24 in the north, 0.45 ± 0.25 in the central segment, and 0.38 ± 0.24 in the south (Figure S15c). In the north, this physics-based coupling agrees with the independently derived geodetic inter-SSE coupling ($\hat{c} \approx 0.64$, $c_{is} \approx 0.66$). In the central segment the geodetic estimate exceeds the ROM derived estimate within the confidence interval ($c_{is} \approx 0.60$, $\hat{c} \approx 0.45$). In the south, the rate-and-state friction Bayesian inversion underestimates the geodetic inter-SSE coupling ($c_{is} \approx 0.69$, $\hat{c} \approx 0.38$). The agreement in the northern and central segments supports spatial variations in inter-SSE coupling as an important control on along-strike segmentation of Cascadia’s slow slip events. We discuss the origin of the simulation discrepancies with coupling values in the south in Section 5.

5 Discussion

Our results demonstrate that spatially distinct regimes of inter-SSE megathrust coupling and effective normal stress primarily control the along-strike segmentation of seismic moment and recurrence intervals of Cascadia’s SSEs. We suggest that the different recurrence intervals observed in the three Cascadia segments are due to variations in effective normal stress, ranging from 2.7 to 6.1 MPa. This low effective normal stress is consistent with V_p/V_s velocity measurements (Audet & Bürgmann, 2014). Previous numerical results for the Cascadia and other subduction zones also suggest that deep SSEs occur under near-lithostatic pore fluid pressure conditions (Liu & Rice, 2009; Perez-Silva et al., 2023; Rubin, 2008; Ozawa et al., 2025). In Cascadia, our results imply pore-fluid pressures of $\sim 99.3\%$ to 99.7% of lithostatic stress, with the pore-fluid pressure ratio defined as $\lambda = 1 - \sigma_W/(\rho g z)$, assuming a uniform crustal density of $\rho = 2670$ kg/m³ and $z = 37$ km, the mid-depth of the ETS zone. Variations in σ_W between 2.7 and 6.1 MPa account for most of the observed variation in recurrence intervals.

In contrast to SSE recurrence intervals, our numerical models indicate that SSE moment is controlled primarily by inter-SSE coupling and cannot be explained by variation in the effective normal stress or the SSE zone width. The inferred variations in ETS-zone width are too small to explain the observed differences in the characteristic moments.

For example, the northern Cascadia ETS zone is only $\sim 10\%$ wider than in central Cascadia, based on numerical simulations and observed tectonic tremor productivity, which cannot explain the 60% difference in SSE moments.

If the ETS zone were fully coupled ($c = 1$) during the inter-SSE period, the accumulated moment deficit would far exceed the moment release observed in periodic SSEs (Michel et al., 2019). On the other hand, the inter-SSE coupling value must be larger than 0 to produce SSEs. This suggests the ETS zone is partially locked, as we here infer geodetically. Our 2D rate-and-state friction simulations have an effectively locked SSE zone during the inter-SSE period. We infer the inter-SSE coupling $\hat{c} = M_0^{obs}/M_0^{ROM}$ to quantify the degree to which the real margin differs from the simplified model. We hypothesize that $\hat{c}$ can represent 3D heterogeneity (Carbotte et al., 2024; Luo & Liu, 2021), along-strike variations in frictional properties (Brudzinski & Allen, 2007; Luo & Ampuero, 2018), fluid-related processes (Segall et al., 2010; Perez-Silva et al., 2023; Ozawa et al., 2025), or thermal processes (Behr & Bürgmann, 2021; Bürgmann, 2018) not captured in our 2D SSE-cycle model. These process could reduce the inferred coupling parameter. While $\hat{c}$ is an empirical parameter derived via Bayesian inversion and not the numerical simulations, it serves as a first-order approximation of the coupling control on SSE moment.

The separation of those two parameters ($\hat{c}$, σ_W) arises from the Bayesian inversion rather than from the physical model. In rate-and-state friction SSE models both the recurrence interval and event cumulative slip scale with W/h^* where $h^* \propto 1/\sigma_W$ is the characteristic nucleation size (Liu & Rice, 2009; Rubin, 2008; Li & Liu, 2017); in our simulations all other frictional parameters are held constant. Barbot (2019) further shows that the SSE recurrence interval depends on σ_W at first order through W/h^* . In our inversion, however, W is constrained independently by the observed ETS-zone tremor distribution and varies by only $\sim 10\%$ along strike, so it cannot account for the along-strike variation in SSE moments. With W fixed, σ_W is set by the recurrence interval which in turn fixes the modeled moment M_0^{ROM} , then the residual moment misfit defines the inter-SSE coupling $\hat{c} = M_0^{obs}/M_0^{ROM}$.

Our inferred inter-SSE coupling, which we derive from numerical and geodetic modeling, suggests that SSEs relieve the entire of the slip deficit accumulated in the southern Cascadia segment. In northern and central Cascadia, $\sim 30\%$ and $\sim 42\%$ of the plate convergence rate is accumulated as a slip deficit in the ETS zone, respectively. This may suggest two possible scenarios: the slip deficit may be accommodated during a future Cascadia megathrust earthquake, or it may be relieved by long-term variation in SSE recurrence intervals (Luo & Liu, 2019). Our finding of long-term slip deficit in central Cascadia is consistent with the trends identified by previous margin-wide models (e.g., Lindsey et al., 2021, Figure S9).

Our results are consistent with the spatially resolved ETS slip-rate estimates of Bartlow (2020). Our long-term coupling reproduces their segmentation of near-zero long-term coupling in the south and low long-term coupling in the north, implying that transient slip and inter-SSE creep together accommodate most of the plate convergence in both segments. The central Cascadia segment retains a persistent long-term deficit. The difference between the geodetic inter-SSE coupling (c_{is}) and the physics-based estimate ($\hat{c}$) increases from north to south (from ~ 0.02 to ~ 0.31). One candidate explanation is the assumed constant loading rate. The simulations underlying the Bayesian inversion are loaded at 3.7 cm/yr, whereas the convergence rate decreases to 2.7 cm/yr in the south (DeMets et al., 2010). We perform a loading-rate sensitivity test to rule this out for the coupling. The characteristic SSE moment, and hence $\hat{c}$, is insensitive to the loading rate ($M_0 \propto V_p^{-0.33 \pm 0.06}$, Text S5). The increasing gap may instead reflect a growing fraction of slip deficit released by frequent, small transient events toward the Mendocino Triple Junction that our characteristic-event framework does not capture (Bartlow, 2020), or

a contribution from internal Gorda plate deformation to the geodetic estimate (Shelly et al., 2024).

The recurrence interval, in contrast, scales with the loading rate ($T_c \propto V_p^{-1.57 \pm 0.18}$, Text S5); matching the observed southern recurrence at the lower local convergence rate would require a lower σ_W , so the southern σ_W is an upper bound and the implied pore-fluid pressure a lower bound.

We caution that the onshore-only geodetic network and the spatial regularization in our kinematic inversion necessarily smooths potential coupling heterogeneity along the ETS zone (Figure S5). Moreover, our 2D quasi-dynamic SSE cycle simulations, and consequently the ROM surrogate, rely on prescribed geometry and frictional constitutive law choices which may neglect unresolved 3D heterogeneity or coupled hydrologic/rheologic processes. Thus, we interpret the inferred coupling and effective normal stress parameters as segment-scale, effective values.

Finally, inter-SSE coupling might also control the along-strike propagation of SSEs between segments. Gualandi (2025) shows that SSEs can sometimes slip across the northern and central segments during a single SSE, whereas no SSEs rupture across the central-southern segment boundary. Consistent with this asymmetry, our geodetic coupling inversion finds a highly coupled boundary between the northern and central Cascadia segment. In contrast, the boundary between the central and southern segments is constantly creeping (Figure 2c). Previous studies have proposed that major transverse strike-slip faults segment the subducting Gorda-Juan de Fuca plates and influence margin segmentation (McCaffrey & Goldfinger, 1995; Goldfinger et al., 1997). In addition recently, Carbotte et al. (2024) identified major strike-slip faults in the subducting Gorda-Juan de Fuca plates, using detailed seismic imaging, which bound crustal blocks. These lower plate faults spatially coincide with the segmentation boundaries identified in our coupling models. We hypothesize that these structural boundaries act as SSE barriers. Under this hypothesis, strong coupling at the north-central boundary allows large SSEs to rupture across segments, while the creeping, decoupled nature of the central-southern boundary arrests SSE propagation, confining southern SSEs to remain smaller.

6 Summary

This study integrates GNSS-derived inter-slow-slip-event (SSE) velocities and reduced-order-modeling (ROM)-accelerated rate-and-state friction SSE-cycle models to investigate the mechanisms controlling along-strike SSE segmentation in the Cascadia subduction zone. The scientific machine learning ROMs enable Markov Chain Monte Carlo (MCMC) inversion by reducing the cost of a single model evaluation to ~ 30 s on one CPU ($\mathcal{O}(10^5)$ speedup). Our cycle models indicate that SSE recurrence interval is primarily controlled by low effective normal stress, whereas SSE moment is governed by along-strike variations in the inter-SSE coupling ($\hat{c}$) within the ETS zone. Mechanically, the inferred effective normal stresses may imply near lithostatic pore fluid pressures governing the Cascadia ETS zone ($\sim 99.3\%$ - 99.7%). ROM-MCMC yields mean inter-SSE coupling of $\hat{c} \approx 0.64$ in the north, $\hat{c} \approx 0.45$ in central Cascadia, and $\hat{c} \approx 0.38$ in the south. These physics-based estimates agree with the independently inferred geodetic inter-SSE coupling in the north, broadly in the center and differ in the southern segment. Comparing inter-SSE and long-term coupling indicates that transient SSEs recover the entire slip deficit in the south, while persistent deficits of $\sim 30\%$ and $\sim 42\%$ of plate convergence accumulate in northern and central Cascadia, with important implications for seismic and tsunami hazard.

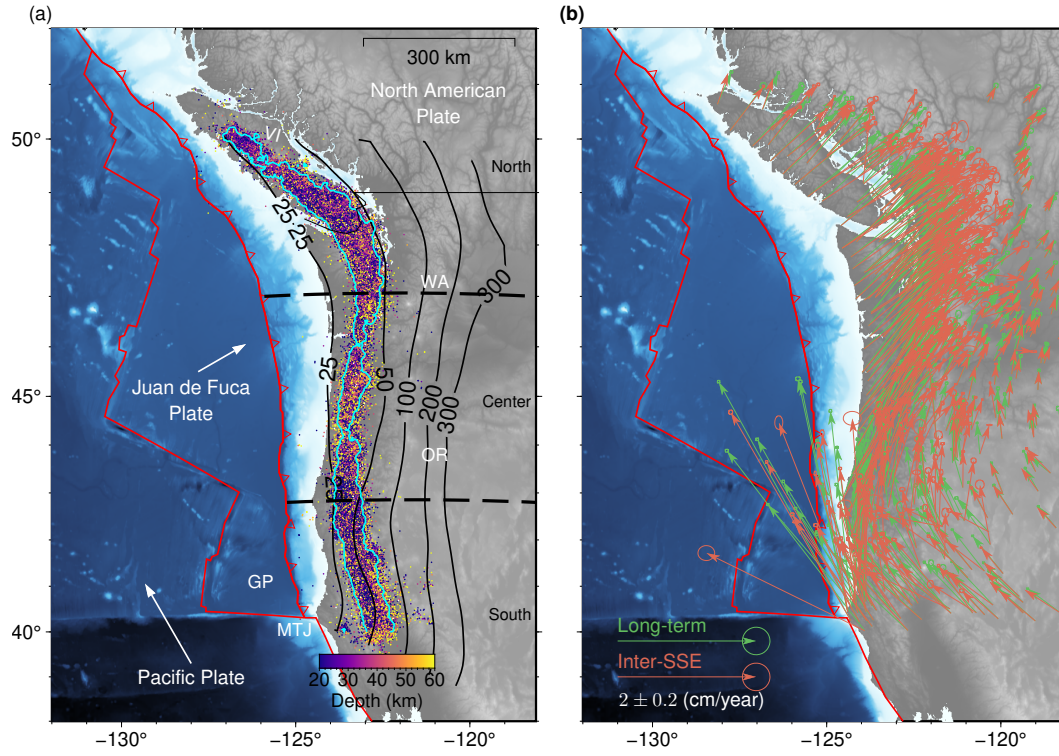


Figure 1. Tectonic setting and Cascadia geodetic GNSS network velocity fields. (a) Tectonic setting of the Cascadia subduction zone: white text and arrows show plate names and motion relative to a fixed North American plate. Red lines mark plate borders. Black contours depict the Cascadia subduction zone interface depth (Hayes et al., 2018). Colored circles show the Cascadia tremor catalog (Wech & Creager, 2008; Wech, 2010). A cyan contour marks the region with over 75 identified tremors in a $0.05^\circ \times 0.05^\circ$ grid, defining the ETS region in this study. Dashed black lines separate northern, central, and southern Cascadia segments. Geographic abbreviations: VI, Vancouver Island; WA, Washington; OR, Oregon; MTJ, Mendocino Triple Junction; GP, Gorda plate. (b) GNSS network velocities: green arrows show MIDAS long-term secular velocity (Blewitt et al., 2018) and light red arrows show the here derived inter-SSE velocities.

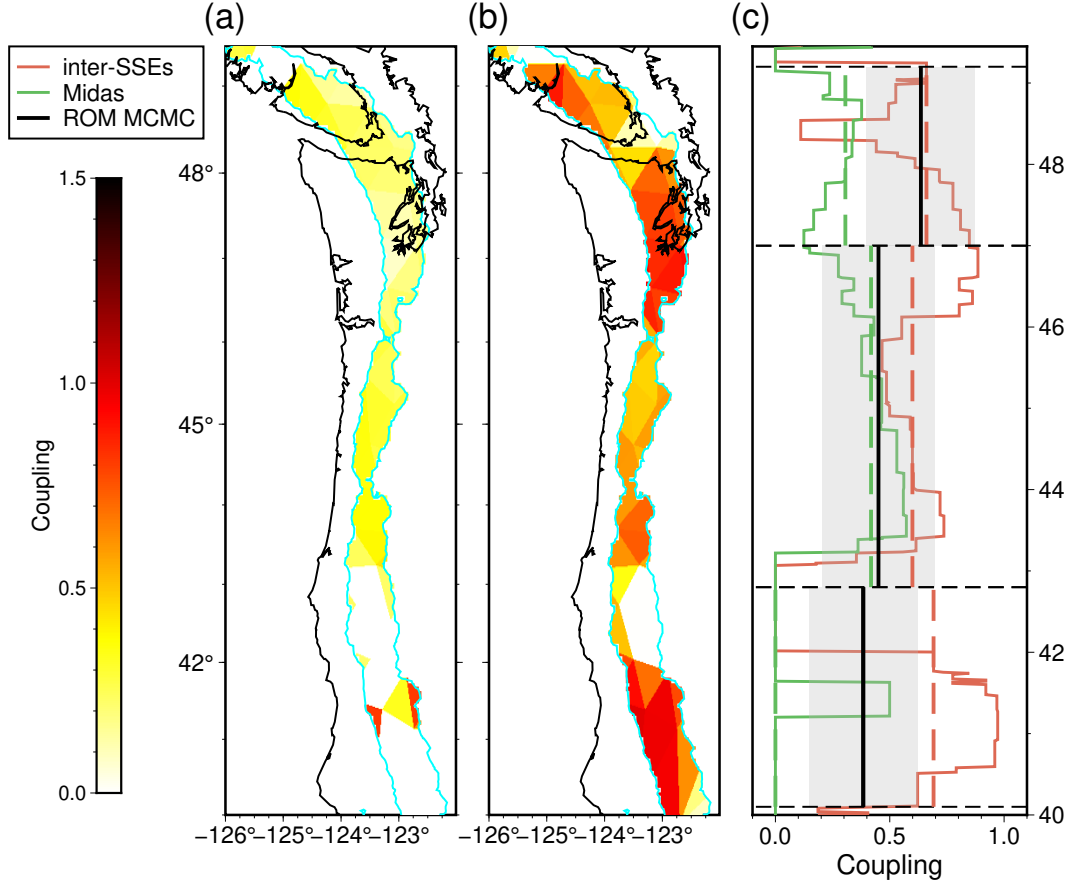


Figure 2. Cascadia ETS zone coupling. (a) Coupling distribution from long-term GNSS station velocities (MIDAS, Blewitt et al., 2018) inverted onto a discretized megathrust mesh. (b) Same as (a), but inverted from our derived inter-SSE GNSS velocities. (c) Along-strike profiles compare geodetic and numerical results. Solid green and red lines show geodetic coupling ($\hat{c}$), averaged along-dip, for the long-term and inter-SSE fields. Dashed lines show the mean coupling for each segment. The solid black line shows the mean coupling in the ETS zone ($\hat{c}$) inferred by the ROM-MCMC rate-and-state friction inversion. Gray-shaded regions indicate the standard deviation of $\hat{c}$ per segment.

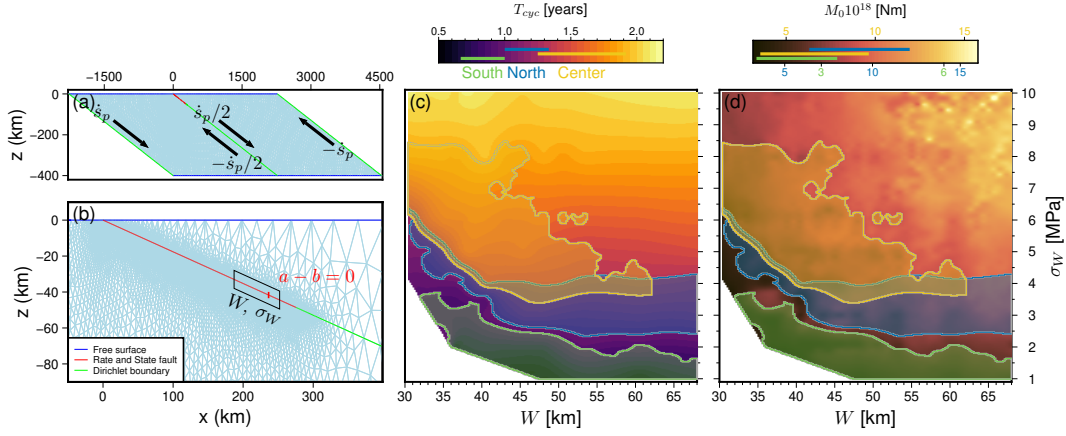


Figure 3. Rate-and-state friction physics-based model settings and ROM parametric exploration. (a) View of the physics-based model computational domain, boundary conditions, and applied loading, where $\dot{s}_P$ is the applied loading rate. Not to scale; note the $4.5\times$ vertical exaggeration of the y -axis. (b) Zoomed view of the rate-and-state friction portion of the megathrust, showing the adaptively refined mesh. Here, W denotes the width of a low effective normal stress zone on the fault, σ_W is the magnitude of the low effective normal stress, and a and b are the constitutive rate-and-state friction parameters controlling the frictional response to sliding velocity and state evolution, respectively. As in (a), note the $2.5\times$ vertical exaggeration of the y -axis. (c) ROM parametric exploration of the physics-based model using 15,000 $ROM(W^*, \sigma_W^*)$ evaluations. Colors show the SSE recurrence interval of simulations. In the panel colorbar, the values of observed recurrence interval (Brudzinski & Allen, 2007; Michel et al., 2019) are indicated as blue, yellow, and green lines for north, center, and south Cascadia, respectively. (d) ROM-based parametric exploration of possible SSE moments. Colors indicating the characteristic SSE moments predicted by the simulations, scaled by the inferred inter-SSE coupling (cM_0^{ROM}). Because the three Cascadia segments differ in along-strike lengths, the same simulated slip yields different SSE moment for each segment. Therefore, the colorbar includes segment-specific colored ticks (blue for northern, yellow for central, and green for southern Cascadia) that map the ROM results to the corresponding segment. Observational moment ranges from Michel et al. (2019) are shown as horizontal bars in the same colors.

Author contributions:

Conceptualization: YM, AAG, DAM. Methodology: YM, DAM. Software: YM, DAM. Data curation: YM. Formal analysis: YM. Investigation: YM. Resources: AAG. Visualization: YM. Validation: AAG, DAM. Supervision: AAG, DAM. Writing—original draft: YM. Writing—review & editing: AAG, DAM. Funding acquisition: YM, AAG.

Open Research Section

All codes and data products supporting this study are openly available. A Python script to process the NGL GNSS daily data, the input files required to reproduce the **Tandem** simulations, a static version of the **Tandem** code, and the ROM analysis code are publicly hosted on Zenodo (Magen, Gabriel, & May, 2026). The complete raw outputs from all simulations are archived on the National Data Platform S3 bucket. The Zenodo repository provides the direct link and instructions for accessing these raw data. Daily GNSS solutions are available from the Nevada Geodetic Laboratory (Blewitt et al., 2018). The tectonic tremor catalog (Wech & Creager, 2008; Wech, 2010, 2021) can be downloaded from the Pacific Northwest Seismic Network website.

Conflict of Interest declaration

The authors declare no conflicts of interest.

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Supporting Information for “Along-strike coupling heterogeneity in Cascadia’s slow-slip zone constrained by GNSS and reduced-order rate-and-state friction modeling”

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S1 GNSS Data and Processing

To calculate the inter-SSE velocity field in Cascadia, we collected daily time series from 820 GNSS station processed by the Nevada Geodetic Laboratory (Blewitt et al., 2018). We generally followed the processing chain of Bartlow (2020) to separate the SSE contribution from other contributions to the GNSS daily displacement time series. We extended the processing up to August 1st 2025 and used it to invert the inter-SSE coupling within the ETS zone.

We downloaded data from all available stations whose locations fell within the longitude range of -127° to -118° and the latitude range of 40° to 55° . All station positions are referenced to the global IGS20 with a fixed North American reference frame. We then preprocess the raw daily GNSS position time series to mitigate noise and correct for non-tectonic signals. The process begins by filtering out stations with fewer than 100 days of data. For the remaining stations, we first identify and remove outliers using a 20-day moving-median window filter. Following outlier removal, we correct for step-discontinuities from two primary sources. We address non-tectonic offsets, such as those from equipment changes documented by the Nevada Geodetic Laboratory, and then correct for coseismic offsets from a regional earthquake for all earthquakes with $M_w \geq 5.5$ in the US Geological Survey earthquake catalog in the region. For each earthquake, stations are considered for correction if they fall within a magnitude-dependent empirical radius of influence, calculated as $10^{M_w} 1.5 \cdot 10^4$ m, where M_w is the earthquake moment magnitude. In all cases, the offset is quantified as the difference between the median positions of the data windows immediately preceding and following the event. This value is subtracted from the subsequent time series to ensure continuity. We continued to remove sites near Mount St. Helens, which exhibit non-negligible volcanic deformation (see Table S2). We then considered only stations with at least 4 years of data, excluding time periods with data gaps exceeding 6 months. If a station contained a single large gap, we retained the longest continuous segment for analysis, provided it still met the minimum duration requirement of four years. Following this initial preprocessing stage, we have 458 GNSS stations with time series cleaned of outliers, non-tectonic and regional earthquake offsets, and at least 4 years of data.

To isolate signals related to the inter-SSE secular velocity, we modeled each GNSS time series separately using linear least-squares inversion to separate the long-term secular velocity from transient SSE motion and seasonal contributions. To achieve this, we added a Heaviside step function to the least square fit whenever the number of tectonic tremors out of the Pacific Northwest Seismic Network tectonic tremor catalog (Wech, 2021; Wech & Creager, 2008; Wech, 2010) in the empirical proximity to the station exceeded a certain threshold, where the tremors serve as a proxy for possible slow slip. For each station, we considered all tremors within a 250 km radius and flagged any day with 50 or more tremor detections. For all continuous flagged dates of 6 or more days (Figure S1), we masked those dates from the position time series and added the Heaviside function at the midpoint of the continuous ETS time interval (Figure S2). We model each component (East, North, Up) of the station position time series $d(t)$ (in cm, with time t in years) as:

$$d(t) = d_0 + vt + s_1 \sin(2\pi t) + s_2 \cos(2\pi t) + s_3 \sin(4\pi t) + s_4 \cos(4\pi t) + \sum_{m=1}^n \Delta d_m H(t - t_m) \quad (\text{S1})$$

Where d_0 is a reference position (cm) v is the station inter-SSE secular velocity (cm/year), s_i , $i \in [1, 2, 3, 4]$ are annual and semi-annual seasonal terms (cm), H is a Heaviside function, and Δd_m (cm) is the size of the step related to the m^{th} identified ETS time period in a specific station.

From the modeled parameters, we calculated the inter-SSE secular velocity field (Figure 1) by directly extracting the linear rate (v) term from the least-squares fit to the time-series data (see Figure S3). To estimate the uncertainties in these velocities, we used bootstrap resampling. For each station, we repeated the entire least-squares inversion process 20 times, using a random 80% subset of the interseismic data each time. The final reported velocities are the mean of these 20 iterations, and the uncertainties are reported as the standard deviation. Following the completion of the analysis of all 458 GNSS stations, we visually inspect the data and screen out an additional 12 stations in which our processing chain yields unrealistic velocities in at least one station component (East-West, North-South, Up-Down).

To ensure the robustness of our derived velocity field, we performed a sensitivity analysis on the ETS detection parameters. We vary the tremor-count threshold (30-80 tremors/day), the search radius around the station (200-300 km), and the minimum number of consecutive days required for an ETS (3-10 days), yielding an ensemble of 530 distinct velocity fields. We quantified the stability of the velocity field by calculating the difference between the 95th and the 5th percentiles for each velocity component at each station (Figure S4). The resulting velocity field is highly stable with respect to the choice of detection parameters, with a mean variability of ~ 0.003 , ~ 0.002 , and ~ 0.006 mm/year for the East-West, North-South, and Up-Down components, respectively. We observed a maximum outlier variability of ~ 0.3 mm/year in the East-West component of station P161. This sensitivity test validates that the derived inter-SSE velocity field is insensitive to the choice of specific ETS detection parameters.

S2 Geodetic Inversion for ETS zone Coupling

We invert the Cascadia geodetic velocity fields to infer the distribution of interseismic coupling along the Cascadia subduction megathrust. To discretize the subduction interface, we use high-resolution 3D point-cloud data from the Slab2.0 (Hayes et al., 2018) model for the Cascadia region. We first downsample the raw data using a spatially weighted resampling algorithm that maintains higher point density in regions where the slab is closer to the onshore GNSS network, ensuring optimal model sensitivity. Using these re-sampled coordinates, we generate a three-dimensional curved mesh through a Delaunay triangulation. To ensure a physically realistic fault surface, we filter the resulting mesh by removing triangles with edge lengths exceeding 2.5° , thereby eliminating artifacts at the grid boundaries. This process yields a final fault mesh comprising 232 triangular elements that accurately capture the non-planar geometry of the megathrust while remaining computationally efficient for subsequent inversions.

The inversion solves for a spatially variable coupling coefficient, c , and a rake angle, θ , for each triangular patch. We employ a two-step procedure, a preliminary least-squares inversion for backslip components is used to generate a starting model for a subsequent, non-linear inversion for coupling and rake.

In the first step, we solve for the backslip (i.e., slip deficit rate, Savage (1983)) along the Cascadia subduction zone by minimizing the following objective function:

$$\operatorname{argmin}_{\mathbf{m}} \left(\|\mathbf{A}\mathbf{m} - \mathbf{d}\|_2^2 + \beta^2 \|\mathbf{D}\mathbf{m}\|_2^2 \right) \quad (\text{S2})$$

where $\mathbf{A}$ are the elastic Green’s function matrix derived from Okada (1992) solutions for triangular dislocations (Nikkhoo & Walter, 2015), $\mathbf{m} = (\mathbf{m}_{ss}, \mathbf{m}_{ds})$ denotes the strike-slip and dip-slip backslip components on the fault patches, $\mathbf{d}$ are the observed GNSS velocities, $\mathbf{D}$ is the discrete first finite difference derivative matrix, which penalizes roughness in the slip distribution, and β is a parameter controlling the slip smoothing. The optimal value for β is selected by analyzing the trade-off curve between model misfit and solution roughness (L-curve).

The second inversion step is implemented as a constrained optimization problem. The results of the first inversion step are used to derive an initial guess for the coupling and rake of each patch:

$$\theta_i = \operatorname{atan2}(\mathbf{m}_{ds}, \mathbf{m}_{ss}) \quad (\text{S3})$$

and

$$c = \min \left(1, \frac{\sqrt{\mathbf{m}_{ds}^2 + \mathbf{m}_{ss}^2}}{|V_{pl}|} \right) \quad (\text{S4})$$

where $|V_{pl}|$ is the magnitude of the plate convergence rate at the center of each sub-fault element (DeMets et al., 2010, , Figure S6). We then solve the same minimization problem (Eq. S2) using the L-BFGS-B algorithm (Zhu et al., 1997) to find the optimal coupling ($0 \leq c \leq 1$) and rake (θ) for each patch. The backslip vector $\mathbf{m}$ is now parameterized as:

$$\mathbf{m}_{ss} = c \cdot |V_{pl}| \cdot \cos(\theta) \quad (\text{S5})$$

and

$$\mathbf{m}_{ds} = c \cdot |V_{pl}| \cdot \sin(\theta) \quad (\text{S6})$$

Here, the rake angle θ is defined counter-clockwise from the strike direction, such that $\theta = 90^\circ$ corresponds to pure thrust motion.

We apply this inversion procedure independently to two different velocity fields. The first inversion uses the inter-SSE velocity field derived in Text S1. The second inversion uses the MIDAS GNSS velocity solution (Blewitt et al., 2018).

To quantify our model uncertainties, we assume that the model and GNSS uncertainties are uncorrelated and follow a Gaussian distribution. The data covariance matrix can be written as a diagonal matrix $\mathbf{C}_d$ where $\text{diag}(\mathbf{C}_d)$ are the GNSS uncertainties. The model uncertainties can then be calculated by (Tarantola, 2005):

$$\mathbf{C}_m = \left(\mathbf{A}^T \mathbf{C}_d^{-1} \mathbf{A} \right)^{-1} \quad (\text{S7})$$

The model uncertainties estimation is shown in Figure S5.

S3 Cascadia SSE cycle simulations

We perform a two-dimensional quasi-dynamic simulation of SSE cycles in CSZ-like settings. The fault stress evolution in this model follows the regularized form of the rate-and-state friction law (Dieterich, 1979; Ruina, 1983; Lapusta et al., 2000; Rice & Ben-Zion, 1996), given by

$$\tau(\dot{s}, \psi) = a \operatorname{arcsinh} \left(\frac{\dot{s}}{2\dot{s}_0} \exp \left(\frac{\psi}{a} \right) \right) \quad (\text{S8})$$

where the fault shear stress τ is a function of the slip-rate $\dot{s}$ and a state variable ψ , with a representing an empirical friction parameter to describe the “direct effect” and $\dot{s}_0$ a reference slip-rate. The state variable evolves temporally according to the Dieterich-Ruina aging law

$$\frac{d\psi}{dt}(\dot{s}, \psi) = \frac{b\dot{s}_0}{L} \left(\exp \left(\frac{f_0 - \psi}{b} \right) - \frac{\dot{s}}{\dot{s}_0} \right) \quad (\text{S9})$$

where b is an empirical frictional parameter describing the time-dependent “evolution” effect, L denotes the characteristic slip distance, and f_0 is a reference friction coefficient.

All full order physics based simulations in this study consist of two-dimensional parallelogram-shaped domains measuring 4500 km in length and 400 km in width, containing a single planar fault that bisects the domain into two geometrically identical regions (Figure 1). To approximate the CSZ, both the fault and lateral domain boundaries are inclined at a shallow dip angle of 10° relative to the upper and lower domain free surface boundaries. We prescribe loading as steady tectonic convergence (Figure 1), imposed via Dirichlet boundary conditions, with velocities of $V_p = 3.7$ cm/year to the fault at depths exceeding 280 km along-dip and $\pm V_p/2$ at the domain right and left boundaries.

SSEs arise spontaneously in rate-and-state friction models from specific combinations of frictional stability regimes along the fault, particularly including a conditionally stable region near the transition between fully locked and continuously creeping sections. These models incorporate a fault portion with reduced effective normal stress (e.g., Liu & Rice, 2009; Li & Liu, 2016; Rubin, 2008; Luo & Ampuero, 2018). We follow a similar setup to Liu and Rice (2009), applying transitional frictional stability near the down-dip limit of the seismogenic zone with a reduced effective normal stress of σ_W over a region of W km width (Figure S14).

We employ the open-source Sequences of earthquakes and aseismic Slip (Erickson et al., 2020) simulation software **Tandem** (Uphoff et al., 2022; Gabriel et al., 2026) to conduct quasi-dynamic simulations of SSEs in this two-dimensional Cascadia-like setting (Liu & Rice, 2009). Each simulation constitutes a full-order model (FOM), in which the simulation is run for at least 30 SSE cycles (in the order of ~ 10 months per cycle) following a spin-up phase of 110 years. We conducted 110 distinct simulations across a parametric space with W ranging from 62.5 to 100 km and σ_W from 1 to 10 MPa. This included an additional 34 simulations beyond those presented in Magen, May, and Gabriel (2026), which were necessary to resolve longer recurrence intervals, as observed in central Cascadia.

S4 Reduced-Order Modeling and MCMC Inversion Details

To construct the reduced-order model (ROM), we initially sample the W and σ_W parametric space uniformly, and then refine the sampling in regions of low reconstruction fidelity during the construction process. For each forward simulation, we compress the temporal evolution of slip, slip rate, and state variables at 280 observation points along the megathrust into a compact fixed-length vector. By stacking the 110 fixed-length vectors, we create a single data matrix. To efficiently interpolate between the matrix rows (the simulation’s vector representation), we perform a Proper Orthogonal Decomposition (POD, Bui-Thanh et al., 2003) that decomposes the data matrix into basis vectors

and coefficients. Thus, POD represents this matrix in a reduced basis and allows us to obtain the corresponding modal coefficients. Finally, we interpolate the coefficients using radial basis functions (Audouze et al., 2009) to predict the coefficients of any (W^*, σ_W^*) pair that falls within the training W and σ_W intervals but was not simulated.

During the Markov Chain Monte Carlo (MCMC) inference stage, we perform independent inversions for each Cascadia segment (north, central, south). We run 10 parallel chains of 4000 iterations using an adaptive Gaussian proposal distribution tuned during a 10% burn-in period (Andrieu & Thoms, 2008). Convergence is assessed using the Gelman-Rubin potential scale reduction factor, which compares variance across the 10 chains to that in a single chain (Gelman & Rubin, 1992). Convergence is achieved for all parameters (Gelman-Rubin factor ≤ 1.02), with an effective sample size exceeding 400, supporting robust sampling of the posterior distribution.

To keep all proposals within the ROM training domain without discarding samples, we sample each bounded parameter in a logit-transformed unconstrained space. A physical value $x \in [a, b]$ is mapped to $y = \text{logit}((x - a)/(b - a))$, and the random walk is performed in y ; the inverse logistic map returns $x \in (a, b)$ for every proposal. The prior is evaluated in physical space with the corresponding change-of-variables Jacobian, $\ln |dx/dy| = \ln(b - a) + \ln p + \ln(1 - p)$ with $p = (x - a)/(b - a)$.

S5 Loading-rate sensitivity of SSE moment and recurrence

Our full-order simulations are loaded at a fixed reference convergence rate ($V_p = 3.7$ cm/yr), whereas the along-strike convergence in Cascadia varies from ~ 27 mm/yr near the Mendocino Triple Junction to ~ 37 mm/yr near Vancouver Island (DeMets et al., 2010). To assess whether this affects the inferred inter-SSE coupling $\hat{c} = M_0^{obs}/M_0^{ROM}$, we performed a loading-rate sweep at the southern posterior operating point ($W = 67.6$ km, $\sigma_W = 2.7$ MPa), varying V_p from 2.4 to 4.1 cm/yr while holding all frictional parameters, geometry, and mesh fixed. For each simulation we extracted the characteristic recurrence interval T_c and the 2D characteristic potency $P_0 = \int s d\xi$ where s is the slip during a single SSE and ξ is down-dip coordinate along the fault (Figure S16). The recurrence interval scales strongly with loading rate ($T_c \propto V_p^q$, $q = -1.57 \pm 0.18$), whereas the characteristic potency is nearly loading-rate independent ($P_0 \propto V_p^p$, $p = -0.33 \pm 0.06$). The weak moment dependence arises because the mean slip per event decreases slightly with loading rate while the mean rupture width increases, largely offsetting one another.

S6 Extraction of SSE Characteristics and Tremor Zone Width for MCMC Inversion

To constrain the posterior probability distributions in our MCMC inversion (Section 3), we extract observational priors and likelihood parameters for SSE characteristics and ETS-zone widths across the Cascadia margin. The margin is partitioned into three segments based on latitude: southern ($40.1^\circ \leq \text{latitude} < 44.0^\circ$), central ($44.0^\circ \leq \text{latitude} < 47.0^\circ$), and northern ($47.0^\circ \leq \text{latitude} < 49.2^\circ$).

We derive the observed SSE recurrence intervals (T_c^{obs}) and characteristic moments (M_0^{obs}) using the SSE catalog and the spatiotemporal moment rate data from Michel et al. (2019, see Figure S10). To avoid over-counting segmented or overlapping signals, events occurring within one month of each other within the same region are merged. The moment rate is integrated over time and space using the trapezoidal rule to calculate total moment release. The regional recurrence intervals are calculated as the mean temporal difference between consecutive events and compared to values derived from tectonic tremors observations (Brudzinski & Allen, 2007, see Table S2), while the characteristic moments are derived from the mean and standard deviation of the regional M_0 distributions.

To define the prior distributions for the ETS-zone width (W), we analyze the spatial density of the regional tectonic tremor catalog (Wech & Creager, 2008; Wech, 2010, 2021). We calculate a map view tremor density grid with a 0.05° spatial resolution (Figure S11). Margin-perpendicular density profiles are then extracted along constant latitudes. For each extracted profile, we fit a second-order polynomial to the tremor density distribution (Figure S12). The local width of the tremor band is defined as the geodesic distance (in km) between the symmetric points of the parabola, which is equal to 75 tremors, and is then projected onto the slab interface. Then we calculate the mean and standard deviation of the widths for each segment (Figure S13) which are used as prior $W \sim \mathcal{N}(\mu, \sigma)$.

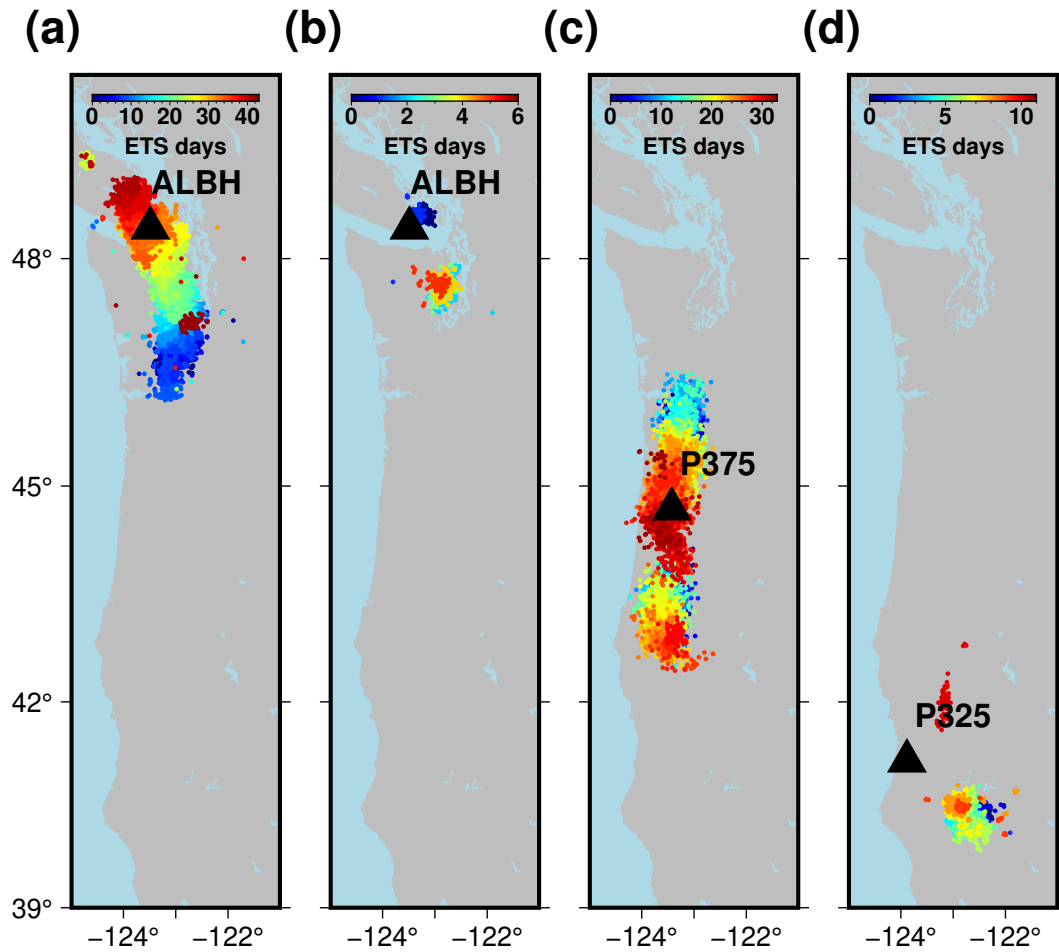


Figure S1. Map view of four example ETS sequences used to define ETS offsets in the respective station time series. Black triangles and text show station locations and a four-character identification codes. Tremors are plotted as circles colored by time since the start of the ETS. (a) Longest ETS identified for station ALBH. (b) Shortest ETS for station ALBH. (c) Longest ETS for station P375. (d) Median-length ETS for station P325

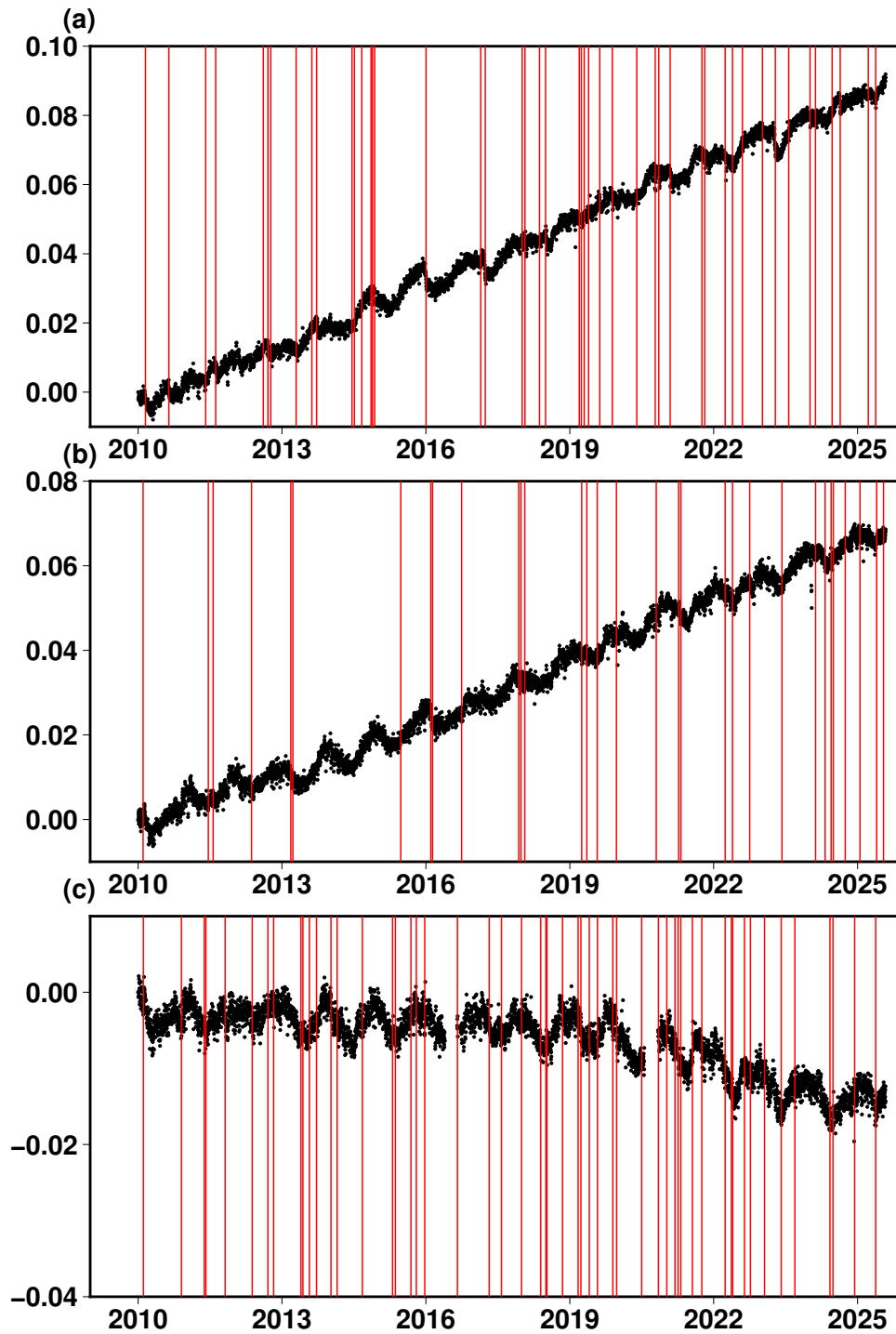


Figure S2. Identified ETSs in three E-W time series. Red vertical lines mark the mid-date of each identified ETS. (a) E-W displacement of station ALBH. (b) E-W displacement of station P375. (c) E-W displacement of station P325.

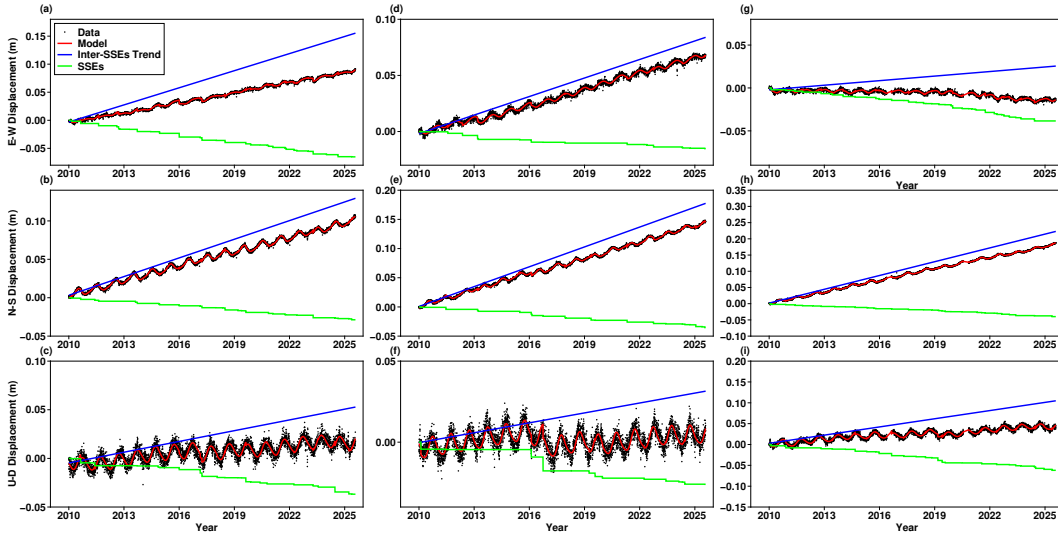


Figure S3. Example of the least-squares fit (Eq. S1) to the E-W, N-S, and U-D components of the stations ALBH, P375, and P325. Black dots show the displacement data, whereas the red line shows the best-fit model, including the inter-SSE secular velocity, SSE steps, and seasonal contribution. The blue line shows the inter-SSE secular motion contribution, and the green line shows the SSE contribution to the time series. (a-c) are the E-W, N-S, and U-D components of station ALBH. (d-f) are the displacement time series of station P375. (g-i) are the displacement time series of station P325.

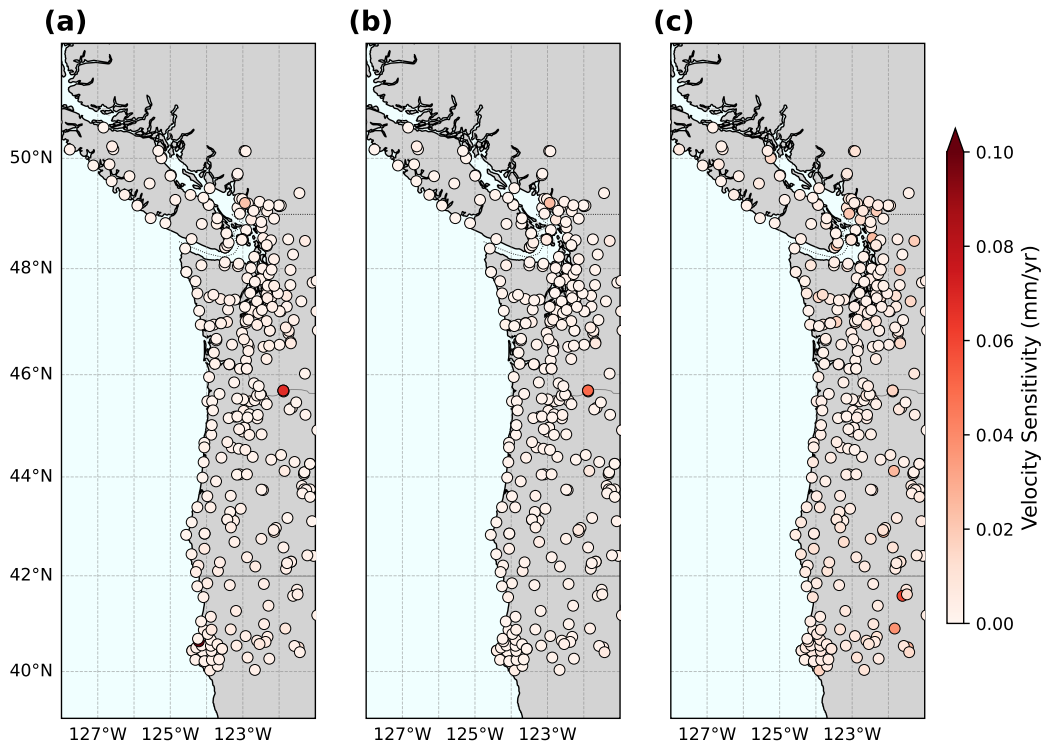


Figure S4. Sensitivity of Cascadia inter-SSE velocity field to ETS detection parameters. The maps show the variability of the derived secular velocity at each GNSS station, calculated as the range between the 95th and 5th percentiles across an ensemble of 530 parameter combinations (varying tremor radius, count threshold, and minimum duration). Panels (a), (b), and (c) correspond to the East-West, North-South, and Up-Down velocity components, respectively.

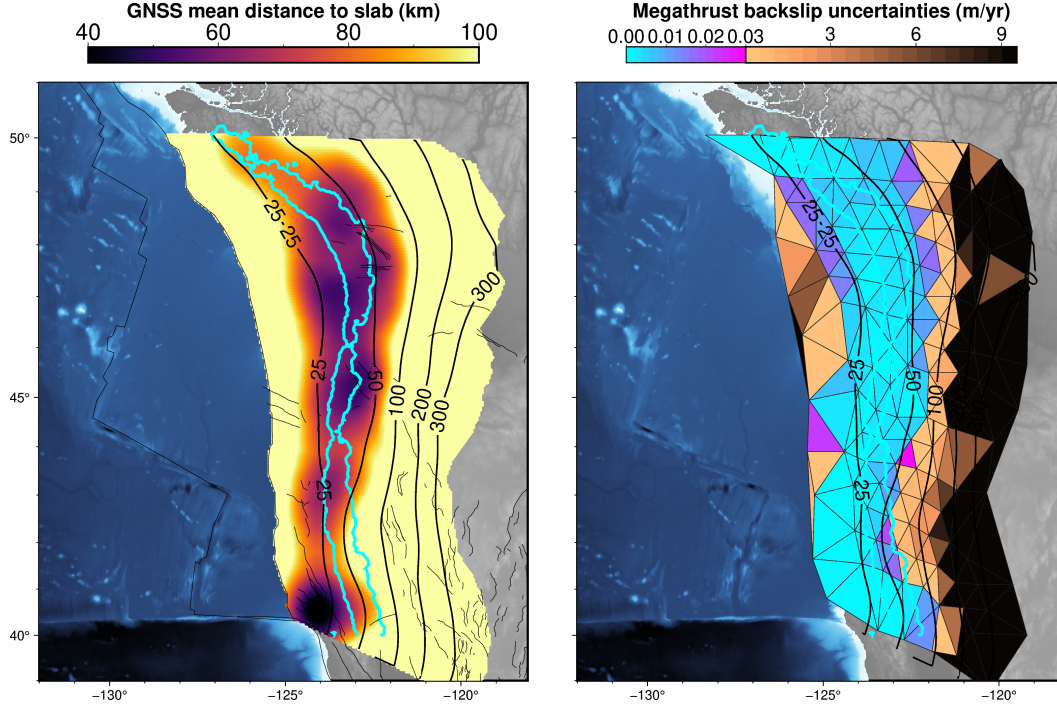


Figure S5. Coupling model resolution and uncertainties. (a) Mean distance of the Cascadia subduction slab from the onshore geodetic network. We define the mean distance as the average distance to the 20 closest GNSS stations for each point on the subduction interface. The resolution of the geodetic inversion diminishes rapidly with distance r from the geodetic network as $\sim 1/r^2$. The ETS region of interest (cyan polygon) is the closest to the geodetic network along the subducting interface. (b) uncertainties of the coupling inverse model calculated as the diagonal of the model covariance matrix $\text{diag}(\mathbf{C}_m)$ for $\mathbf{C}_m = (\mathbf{A}^T \mathbf{C}_d^{-1} \mathbf{A})^{-1}$ where $\mathbf{C}_d$ is the diagonal matrix with the GNSS data uncertainties on its diagonal

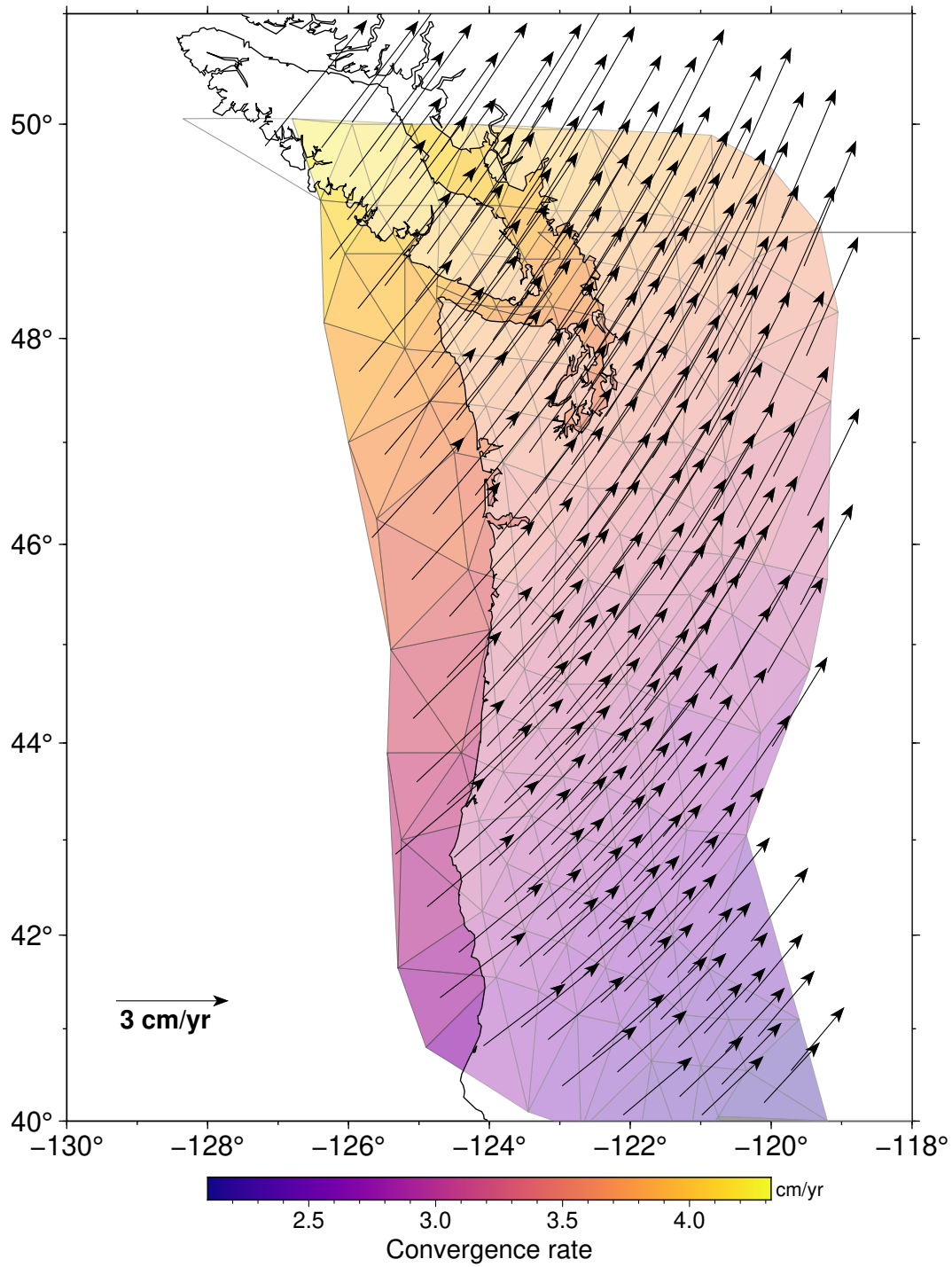


Figure S6. Cascadia subduction interface mesh colored by plate convergence rate (cm/year, DeMets et al., 2010). Black arrows show the local convergence direction and magnitude at the mesh triangle centroids.

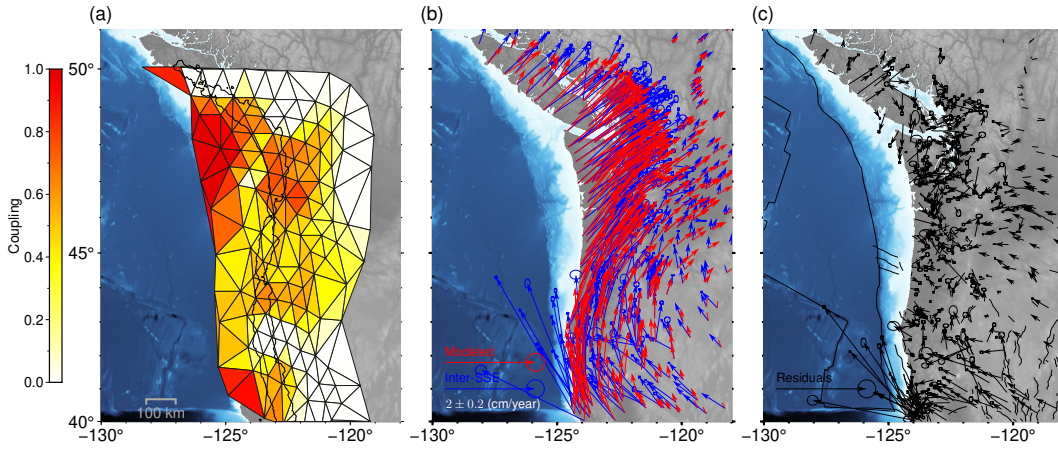


Figure S7. Inter-SSE coupling model, and data fit. (a) Inter-SSE coupling model, the black polygon shows the ETS region of interest. (b) GNSS network data and model displacements. (c) GNSS residuals.

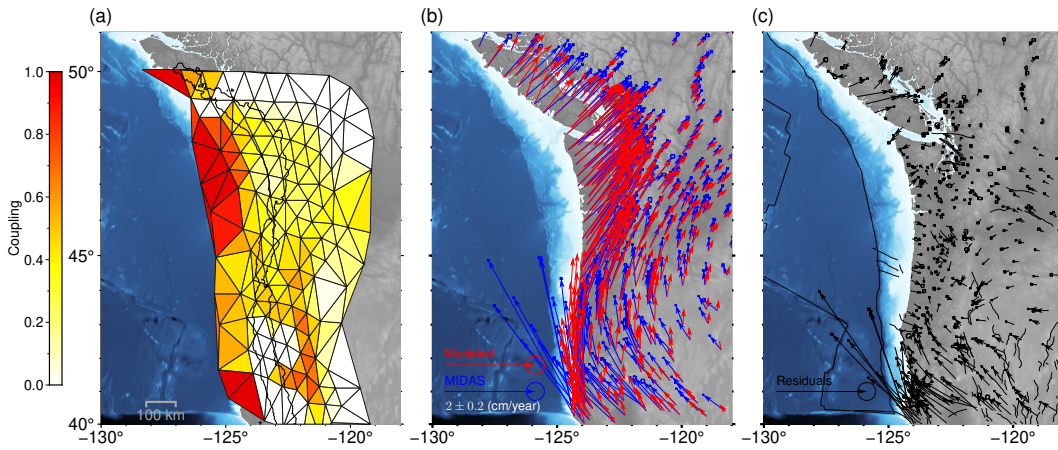


Figure S8. Long-term coupling model, and data fit. (a) Coupling model inverted from MIDAS long-term secular velocities (MIDAS Blewitt et al., 2018), the black polygon shows the ETS region of interest. (b) GNSS network data and model displacements. (c) GNSS residuals.

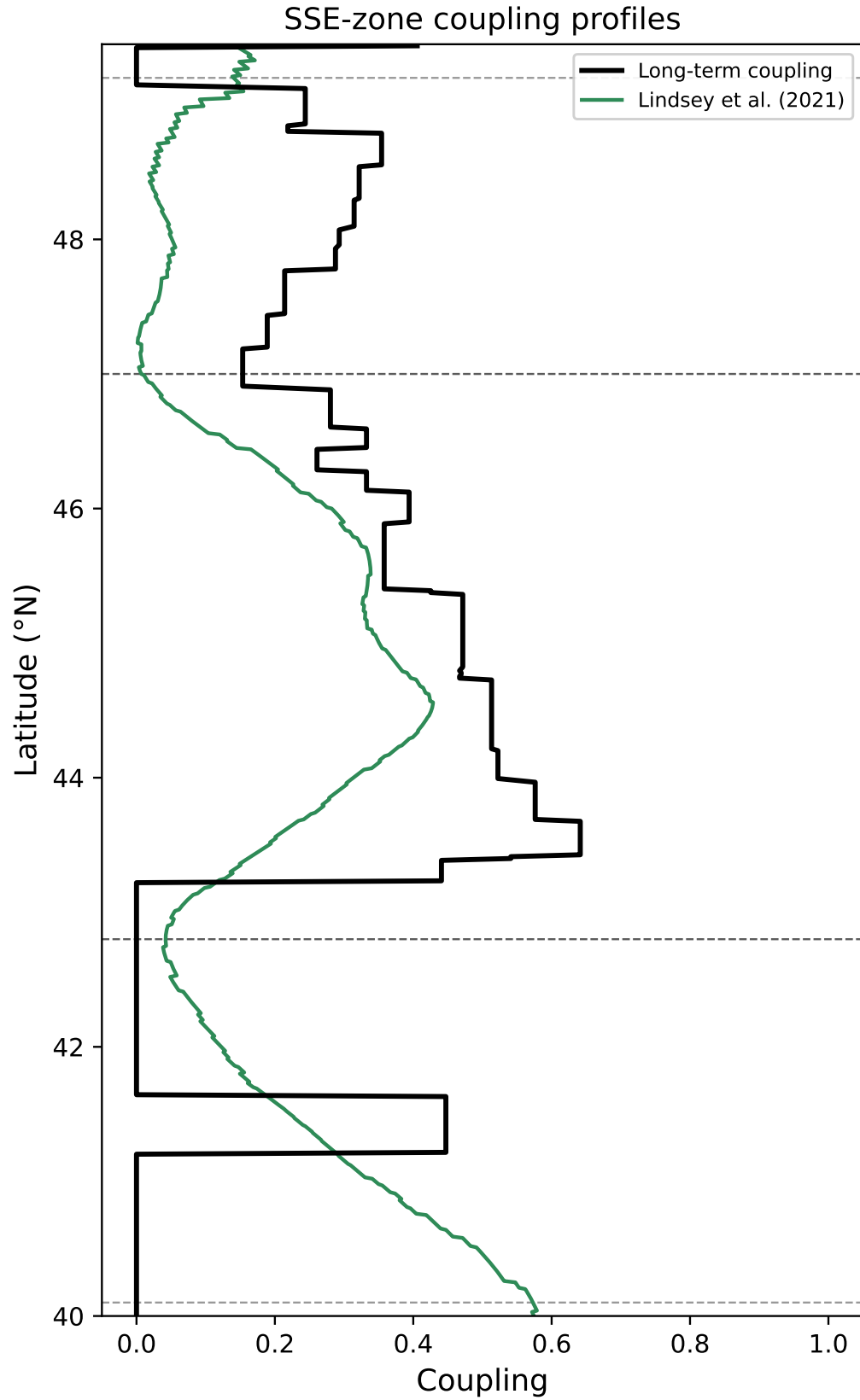


Figure S9. Comparison of along-strike long-term coupling within the Cascadia ETS zone. The solid black line shows the along-dip averaged long-term coupling derived from our inversion of MIDAS GNSS velocities (Blewitt et al., 2018) within the ETS region. The green line shows the corresponding coupling profile extracted from the margin-wide model of Lindsey et al. (2021) at the same ETS depths.

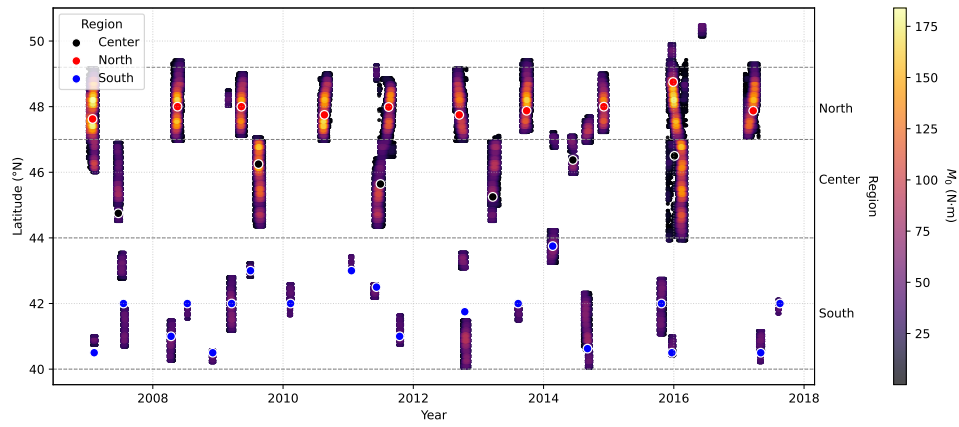


Figure S10. Extraction of SSE segments characteristics from the moment rate inversion of Michel et al. (2019). Background color shows the SSE moment rate. Events within the same segment that separated by less than 2 months are treated as one event.

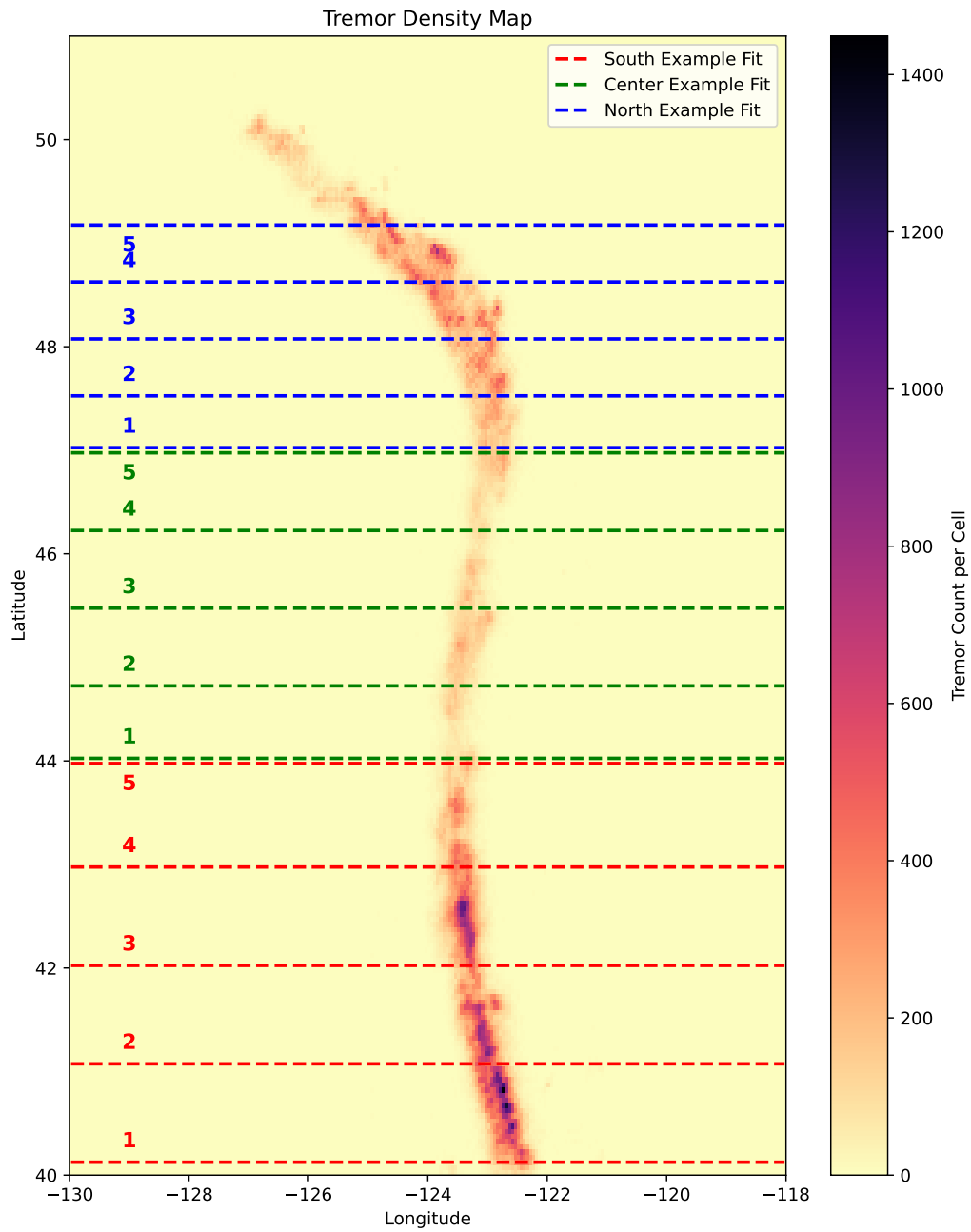


Figure S11. Cascadia tremor density map. Number of tremors (Wech & Creager, 2008; Wech, 2010, 2021) in a $0.05^\circ \times 0.05^\circ$ grid along the Cascadia margin. Red, green, and blue lines show the location of five example profiles for each of the southern, central, and northern Cascadia segments presented in Figure S12.

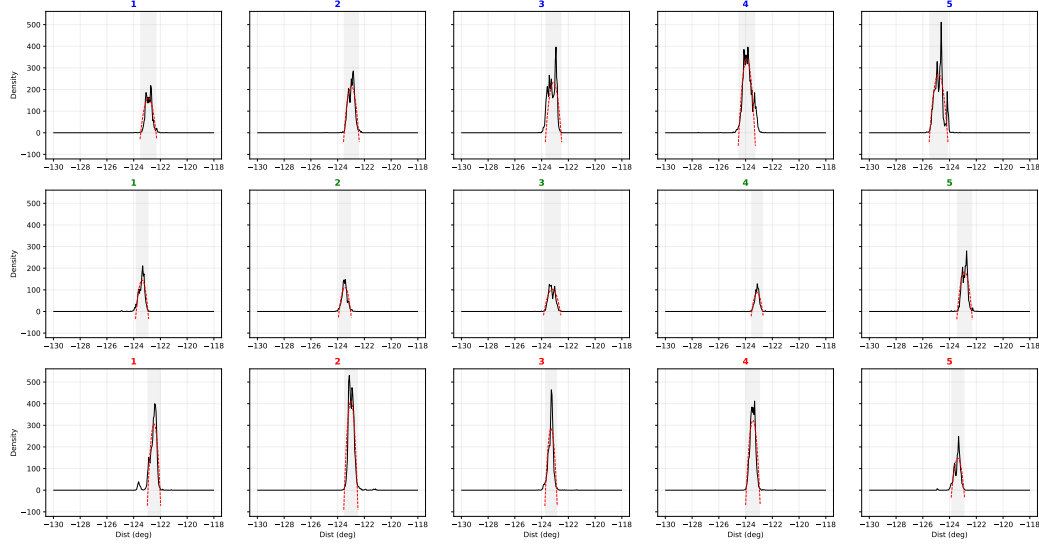


Figure S12. Tremor density profiles. Longitudinal tremor density profile across the Cascadia margin. Each of the 15 panels shows an east–west tremor density profile. The black line shows the tremor density, while the red dashed line represents a second-order polynomial fit. The gray background indicates the width of the ETS region. The profile numbers and colors correspond to those in Figure S11.

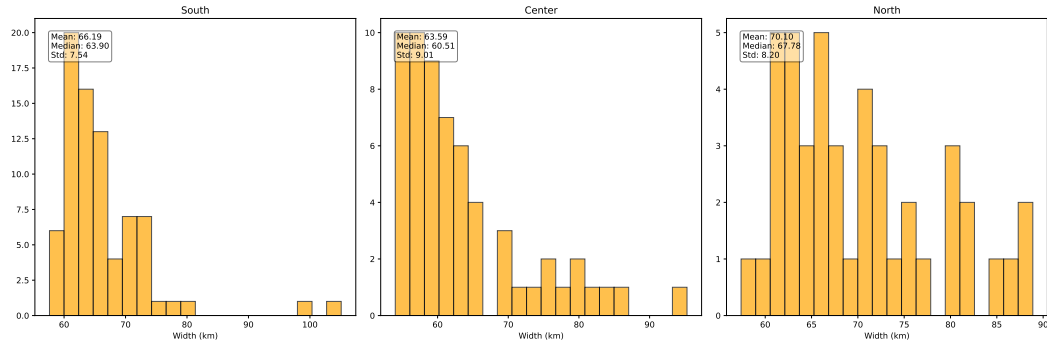


Figure S13. ETS zone width statistics. Histogram of the ETS width derived from the east–west profiles (Figure S12), with widths projected onto the subduction interface. The analysis includes 78 profile widths for the South, 60 for the Center, and 44 for the North segments.

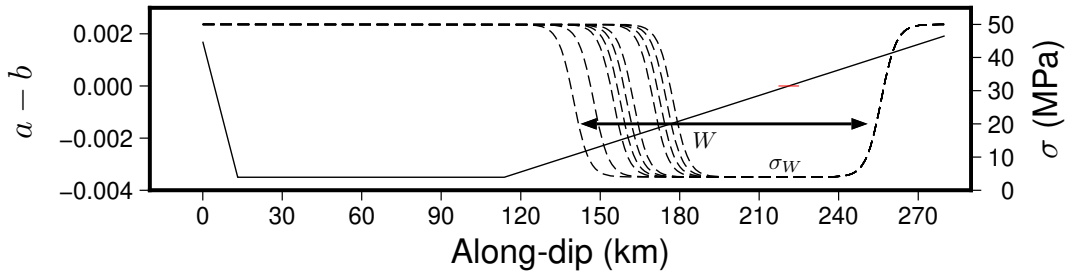


Figure S14. Along-fault profiles of $a - b$ derived from gabbro friction experiments (He et al., 2006) and the initial effective normal stress distribution along the fault where W is the SSE zone width with initial low effective normal stress zone σ_W , red horizontal bar mark the VW-VS transition point. Profiles of normal stress are shown for $\sigma_W = 4$ MPa

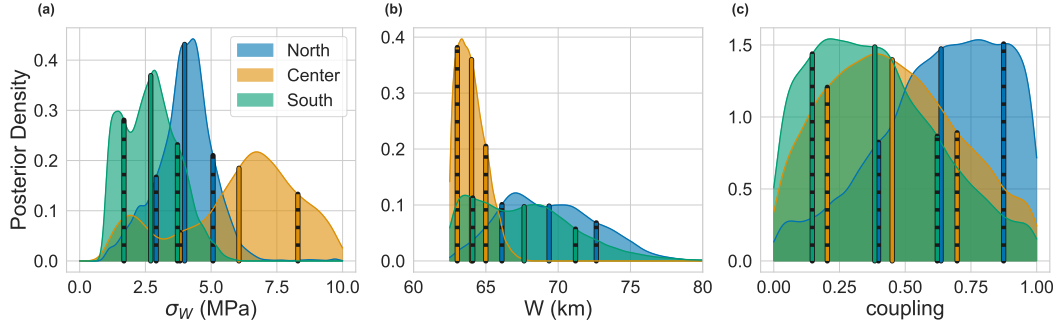


Figure S15. MCMC posterior distribution. We show the results of the MCMC inversion for the posterior distributions of (a) ETS zone width (W), (b) effective normal stress (σ_W), and (c) mean inter-SSE coupling in the ETS zone ($\hat{c}$). The solid and dashed vertical lines indicate, respectively, the expected parameter values and the standard deviations for each region.

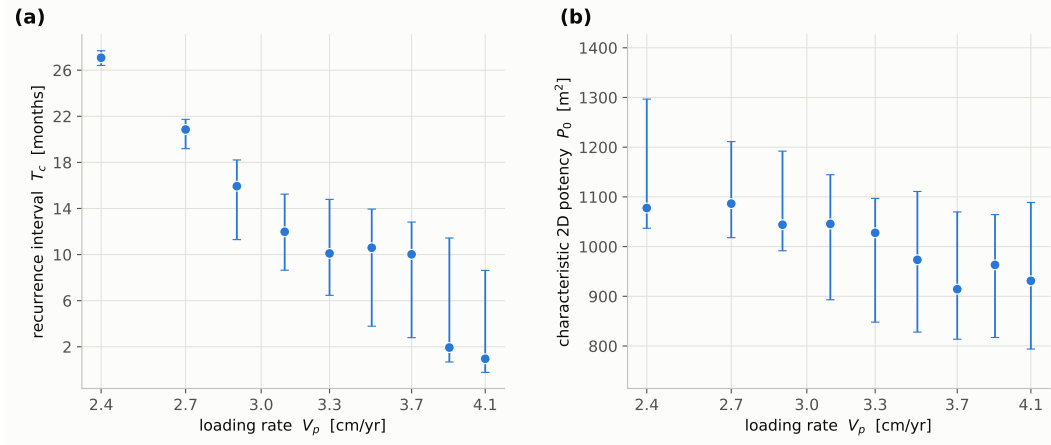


Figure S16. Loading-rate sensitivity of SSE recurrence and moment for Cascadia's southern segment ($W = 67.6$ km, $\sigma_W = 2.7$ MPa). (a) Characteristic recurrence interval T_c versus loading rate V_p . (b) Characteristic 2D moment M_0 versus V_p .

Table S1. Key kinematic and physical parameters constraining megathrust coupling and SSE properties.

Parameter	Description	Derivation / Source	Physical Meaning & Role in Study
c_{is}	Inter-SSE coupling	GNSS velocity inversion	Kinematic megathrust locking during the period between slow slip events.
c_{LT}	Long-term coupling	GNSS velocity inversion	kinematic long-term megathrust locking averaging over multiple SSE cycles (derived from MIDAS).
$c_{is} - c_{LT}$	Fraction of plate convergence recovered by transient slow slip	Calculated difference	Quantifies the fraction of accumulated slip deficit recovered by transient slow slip.
$\hat{c}$	Mean inter-SSE coupling	ROM MCMC Inversion	Segment-averaged inter-SSE coupling derived from rate-and-state friction Bayesian inversion ($\hat{c} = M_0^{obs}/M_0^{ROM}$).
σ_W	Effective normal stress	ROM MCMC Inversion	Frictional parameter controlling the SSE recurrence interval in the quasi-dynamic simulations.
W	ETS zone width	Tremor catalog / MCMC	The down-dip width of the low effective normal stress zone hosting slow slip.
M_0^{obs}, T_c^{obs}	Observed SSE characteristics	Geodetic / Tremor catalogs	The target seismic moment and recurrence intervals used to constrain the Bayesian inversion.

Table S2. Cascadia SSE segments characteristics.

Region	Recurrence (months) ^a	Recurrence (months) ^b	Moment ($\times 10^{18}$ Nm) ^b	M_w
North	14 ± 2	13.52 ± 1.4	8.25 ± 3.29	6.58
Center	19 ± 4	20.5 ± 3.7	5.22 ± 3.5	6.45
South	10 ± 2	7.0 ± 4.0	1.33 ± 1.23	6.05

^aBrudzinski and Allen (2007), ^bMichel et al. (2019)