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Future Cascadia megathrust rupture delineated by episodic tremor and slip

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[1] A suite of 15 episodic tremor and slip events imaged between 1997 and 2008 along the northern Cascadia subduction zone suggests future coseismic rupture will extend to 25 km depth, or $\sim$60 km inland of the Pacific coast, rather than stopping offshore at 15 km depth. An ETS-derived coupling profile accurately predicts GPS-measured interseismic deformation of the overlying North American plate, as measured by $\sim$50 continuous GPS stations across western Washington State. When extrapolated over the 550-year average recurrence interval of Cascadia megathrust events, the coupling model also replicates the pattern and amplitude of coseismic coastal subsidence inferred from previous megathrust earthquakes here. For only the Washington State segment of the Cascadia margin, this translates into an $M_w = 8.9$ earthquake, with significant moment release close to its metropolitan centers.

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1. Introduction

[2] The Cascadia subduction zone stretches 1100 km from Northern California to central British Columbia, Canada and accommodates 3–4 cm/year of convergence between the Juan de Fuca and North American tectonic plates (Figure 1) [*Miller et al.*, 2001; *Wang et al.*, 2003]. It is known to produce magnitude-9 earthquakes roughly every 550 years [*Atwater*, 1987; *Atwater and Hemphill-Haley*, 1997; *Satake et al.*, 1996; *Savage et al.*, 1981]. Unlike many known faults, for which background seismicity is used to estimate the depth of seismogenic coupling, the Cascadia plate interface has had few smaller earthquakes over the last century. Instead, estimates of future Cascadia rupture have been derived from geodetic data and from thermal modelling of the 350°C isotherm, the temperature thought to mark the onset of frictional transition from stick slip to stable sliding [*Hyndman and Wang*, 1995; *Hyndman and Wang*, 1993]. These models suggest slip should concentrate primarily offshore, at depths less than 15 km, distant from large metropolitan regions. Moreover, these models also provide a source constraint used in urban peak ground velocity simulations [*Gregor et al.*, 2002; *Olsen et al.*, 2008]. However, more recent thermal modelling incorporating heat advection from hydrothermal circulation within basaltic ocean crust suggests the 350°C isotherm may lie significantly deeper along the subduction plate interface, which directly impacts the source assumptions used to constrain current seismic hazards estimates [*Kummer and Spinelli*, 2009].

[3] The discovery of transient slow slip [*Dragert et al.*, 2001; *Hirose et al.*, 1999; *Kawasaki et al.*, 1995; *Miller et al.*, 2002] and its accompanying seismic tremor [*Obara*, 2002], collectively known as episodic tremor and slip (ETS) [*Rogers and Dragert*, 2003], marked the beginning of routine instrumental measurement of moment release from the Cascadia megathrust fault. Because ETS and its attendant moment release are thought to occur along the transition between stick-slip and stable-sliding frictional regimes [*Liu and Rice*, 2007], it potentially constrains the down-dip limit of current stress accumulation and future megathrust rupture.

[4] In this paper, we show that for the densely-instrumented Washington State region of Cascadia, the ensemble of ETS-related moment release, when summed over the last 11 years, suggests the down-dip limit of current seismogenic stress accumulation reaches well-inland, to 25 km depth, rather than stopping offshore at 15 km. An interplate coupling profile based on these observations accurately predicts the observed long-term interseismic velocity field throughout the WA forearc. Moreover, when 'run in reverse' to simulate future coseismic deformation, the coupling profile also replicates the spatial pattern and amplitude of paleoseismic subsidence observed from the AD 1700 event. These observations argue for a reappraisal of Cascadia megathrust seismic hazards.

2. GPS Constraints on Transient Slip

[5] Raw GPS phase observables from the combined networks of the Pacific Northwest Geodetic Array, the Plate Boundary Observatory, and the Western Canada Deformation Array were processed with the GIPSY software package [*Zumberge et al.*, 1997]. The resultant position time series relative to cratonic North America were then factored into linear tectonic convergence (the rate between ETS events), annual and semiannual seasonal artifacts modelled as sinusoids, and step functions of known earthquakes, GPS instrumentation upgrades, and the transient deformation that accompanies ETS. To invert for slip the plate boundary surface [*Fluck et al.*, 1997] was divided into variable sized subfaults whose typical dimensions are approximately 25×15 km. The model space thus consists of the amplitude and rake of slip along each subfault. We enforce positivity (thrust-only slip) in the inversion by employing a smoothed, non-negative least-squares algorithm; although smoothing trades off with maximum slip, the resultant moment inverted from the transient data is largely invariant with respect to smoothing, and changes the estimated moment by less than 15 percent over four orders of magnitude change

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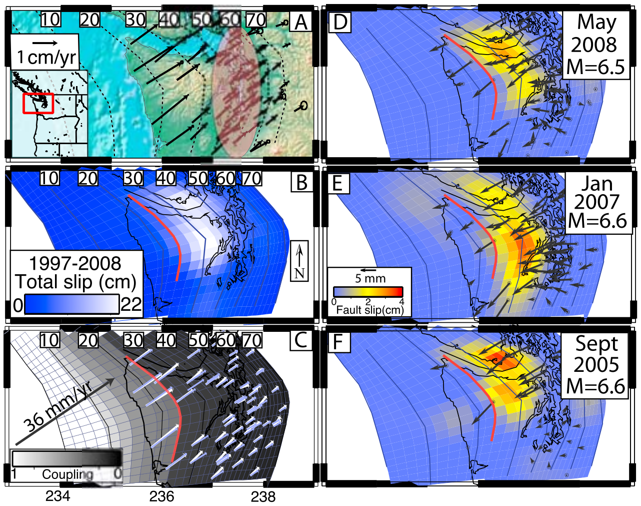

Figure 1. (a) Northern Cascadia long-term interseismic velocity vectors with respect to stable North America. Dashed lines indicate isodepth contours of the Juan de Fuca - North American plate interface fault, labeled in km. Red ellipse denotes greater Puget Sound metropolitan region (Seattle, Tacoma, Olympia). (b) Cumulative thrust fault slip recorded during 15 distinct episodic creep events (M_w = 6.3–6.7) along the deeper Cascadia plate interface over the 11-year period between April 1997 and June 2008. Slip and tremor dissipate 80–100% of convergence-related stress accumulation down-dip of 25 km, whereas little moment release is found up-dip of 25 km depth, thus interpreted as the lower limit of seismogenic coupling (red line). The southerly and northerly decrease in inferred slip is due to inadequate GPS instrumentation prior to 2005. (c) Plate interface coupling profile derived from the observed 25 km up-dip limit of cumulative episodic slow slip. Full-coupling offshore diminishes gradually eastwards (down dip) over 100 km towards the 25 km depth contour and the onset of episodic creep, where it drops quickly to near zero (red line in Figures 1a and 1b). Interseismic deformation based on this coupling model (blue vectors) cannot replicate continuous GPS measurements (white vectors) without the break in seismogenic coupling near 25 km depth. Assuming a 550-year recurrence interval, nine meters of slip is expected along the 25 km depth profile, and diminishing down-dip towards the east. (d–f) Transient surface deformation vectors and inferred thrust faulting from three recent Cascadia slow slip events, September 2005 – June 2008. Magnitudes average M_w = 6.6, produce ~5 mm of static deformation, and last between 2–4 weeks total duration across the network. For slip distributions of individual events and their aggregate, little slip is imaged up-dip of the 25 km isodepth contour or down-dip of the 40 km contour. Note vector scale differs between Figures 1a and 1c.

in smoothing. Transient deformation and slip for three recent ETS events are shown in Figures 1d–1f; inversions for ten earlier events are given by *Szeliga et al.* [2008].

3. Cumulative Moment Release by ETS

[6] Of three-dozen Cascadia-wide ETS episodes resolved with GPS since 1991, 15 events between 1997 and 2008, all located beneath northwestern Washington State, are discussed here. Magnitudes range from M_w = 6.3 to 6.7, with faulting for all events largely confined to depths between 25 and 40 km (Figures 1d–1f). The aggregate slip from these events, which reaches a maximum of 22 cm at 30 km depth over the 12-year period, shows a well-resolved, sharp up-dip limit near 25 km depth (Figure 1b). Down-dip to the east, the average total GPS-inferred slip along the interface during the 11-year period equals just over half of the total Juan de Fuca-North American convergence (assuming a rate of 36 mm/yr) during the same time period, suggesting, in turn, that just over half of the stress accumulation accrued over the time period is relaxed during GPS-detectable ETS events.

[7] In addition to periodic 14-month ETS events beneath NW WA [*Miller et al.*, 2002], which typically show 150–300 hours of quasi-continuous tremor [*Aguiar et al.*, 2009; *McCausland et al.*, 2005], there are frequent short-lived tremor bursts that produce no GPS-resolvable deformation, but which consistently locate to the same or directly adjacent fault regions as the major tremor episodes [*Wech et al.*, 2009]. Because the moment release attendant with tremor scales linearly with its temporal duration [*Aguiar et al.*, 2009; *Ide et al.*, 2007], it is possible to estimate the total moment release of both major and minor ETS by summing the total quantity of tremor recorded over a given period. However, currently available estimates of the total contribution of short-duration bursts, as measured in hours of observed duration, are variable.

[8] The most comprehensive analysis, from Vancouver Island between 1997–2007, showed that on average a third of total tremor occurs as minor bursts [*Kao et al.*, 2008]. In northwestern WA from 2005–2007 [*Aguiar et al.*, 2009] found that an additional 25% of tremor occurs between major ETS events, while for the 2007–2008 time frame in NW WA closer to half of all tremor occurs outside the major ETS events [*Aguiar et al.*, 2009; *Szeliga et al.*, 2008; *Wech and Creager*, 2008; *Wech et al.*, 2009]. Using the low and high values of these estimates, the combination of small and major tremor events dissipate somewhere between 75% (low-end estimate) to 100% (high-end estimate) of moment accumulation along the plate interface between 25–40 km depth. These estimates imply that between 25% and 0% of moment accrual during the 1997–2009 time frame remains, after accounting for dissipation by ETS, to drive future coseismic rupture in the 25–40 km depth region. By contrast, almost no moment release, either as GPS-imaged slip or tremor, is observed up-dip of 25 km (Figures 1d–1f) [*Szeliga et al.*, 2008; *Wech and Creager*, 2008; *Wech et al.*, 2009].

4. ETS-Delineated Interplate Coupling

[9] To test the idea of total or near-total dissipation of moment below 25 km depth, we use the steady state surface velocity field of the overriding North American plate. In western Washington State ~50 GPS receivers operating in the region show a pronounced drop in the rate of northeasterly contraction directly above the ETS zone, qualitatively suggestive of a lack of moment accumulation along the megathrust fault underlying this region (Figure 1c). West of the surface projection of the 25 km fault depth contour, GPS-measured interseismic contractional deformation

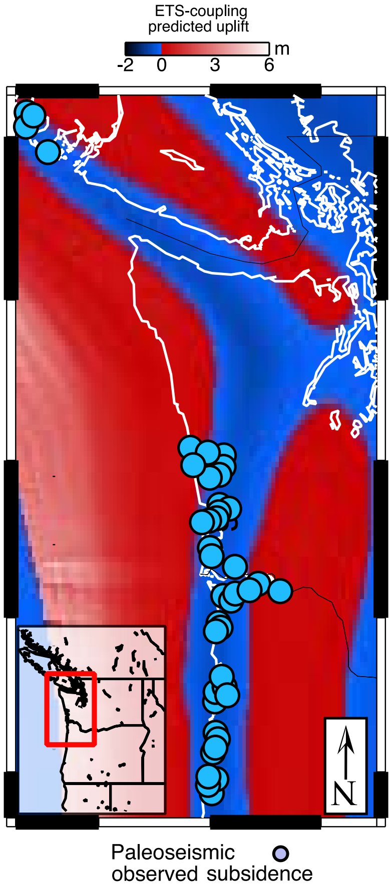

Figure 2. The predicted pattern of coseismic subsidence caused by a megathrust rupture following the creep-delineated coupling in Figure 1c replicates both the spatial distribution and amplitude of paleoseismic subsidence inferred for previous megathrust ruptures. Paleoseismic subsidence compilation drawn from *Leonard et al.* [2004].

approaches 2 cm/yr, as expected for a shallow, strongly coupled underlying megathrust fault. East of the 25 km contour, the measured northeasterly compression drops quickly towards zero, more consistent with a creeping underlying fault.

[10] To model these measurements we use the backslip method [*Savage*, 1983] and the same discretization of the Juan de Fuca-North American plate interface used in inversion for slip and an assumed convergence rate of 36 mm/year at N48E [*Miller et al.*, 2001; *Wang et al.*, 2003]. As with previous models of geodetic data, an effective transition region of partial coupling, which here implies time-averaged creep at a rate less than the Juan de Fuca-North American plate convergence rate, is required to match coastal vectors [*Hyndman and Wang*, 1995; *McCaffrey et al.*, 2007; *Wang et al.*, 2003]. This transition starts offshore near 10 km depth, with coupling dropping smoothly to 50% by 25 km depth. However, unlike previous models, the lower limit of the effective transition zone here is constrained by repeated ETS events to like near 25 km depth. To fit the interseismic GPS data while matching the above estimate of moment release by ETS, plate coupling must drop abruptly from 50% up-dip of 25 km to less than 15% within the ETS zone, before trending smoothly to 0 by 70 km depth. The new constraint provided by ETS thus requires a faster rate of moment accumulation updip of 25 km than that inferred in previous models. Modelled deformation cannot fit the ∼2 dozen easterly interseismic deformation vectors throughout Puget Sound without this rapid drop in seismogenic coupling at 25 km (Figure 1c). Displacing it updip to 22 or down-dip to 28 km depth, results in under- or overshooting, respectively, ∼2 dozen GPS measurements throughout Puget Sound. Dropping coupling to 0 (equivalent to stable sliding, or dissipation by ETS of all fault stress accumulation) undershoots observed inland vectors.

[11] The residual 15% coupling below 25 km may indicate that either ETS does not dissipate quite all moment as fast as it accrues (ETS moment tallys suggest 0–25% remains), or that unmodeled forearc heterogeneity is aliased as residual coupling. This uncertainty does not significantly change the fundamental conclusion that, over the 11-year period of observation, only a small fraction of convergence-related stress accumulation, estimated at 15%, remains below 25 km depth to drive future coseismic rupture. Up-dip of 25 km, by contrast, future coseismic slip accumulates at a rate of approximately 1.8 cm/year (50% of Juan de Fuca-North American convergence rate).

[12] One complication is whether the past dozen years of ETS and deformation are sufficiently representative of the average interseismic period between megathrust events. In particular, whether long-term transients, ∼decades to centuries in length such as postseismic viscoelastic relaxation of the mantle wedge [*Barrientos et al.*, 1992; *Meade and Loveless*, 2009; *Wang et al.*, 2003], may be aliased into partial coupling and thus bias these estimates. To address this, the rupture and attendant ground deformation for the ETS-delineated interplate coupling derived above can be compared to paleoseismic constraints on coseismic deformation from previous great Cascadia megathrust earthquakes [*Atwater*, 1987; *Atwater and Hemphill-Haley*, 1997; *Leonard et al.*, 2004]. When extended over the 550-yr recurrence interval for great events here, this coupling profile predicts both widespread elastic subsidence and uplift along the coast. The predicted pattern tracks both the amplitudes and spatial distribution of available paleoseismic inferences of vertical ground motion along the Cascadia coast during previous events (Figure 2). The Washington coastal regions south of 47°, and all of coastal Oregon and British Columbia are predicted by this coupling model to subside on the order 0.5–1 meter, in coarse agreement with the ∼1 m of subsidence recovered from drowned forests, buried peat layers and tsunami sand horizons from the 1700 AD and previous events. Coseismic uplift, by contrast, is predicted along the northwestern coast of Washington State, a region in which no paleoseismic subsidence has been identified. This would suggest the coupling model derived from recent GPS measurements discussed here is reasonably representative of the long-term average characteristics of strain accumulation over the complete interseismic period.

5. Discussion

[13] The Juan de Fuca-North American plate coupling model discussed here is broadly consistent with previous models based on nearly a century of levelling and trilatera-

tion measurements. The primary refinement is that the enigmatic ∼70 km-wide gap between the down-dip limit of the seismogenic zone, as inferred in earlier coupling models, and ETS, disappears. In this ETS-constrained model, the fault region accumulating stress, and therefore likely to have significant future coseismic rupture, extends to the edge of the ETS zone. The refinement arises because the near-total dissipation of moment below 25 km requires, in order to fit the interseismic regional velocity field, that a significantly greater moment accrual rate predominate up-dip of 25 km depth. It should be noted, however, that the break at 25 km depth inferred here lies within the transitional region previously interpreted to be of rapidly decreasing coupling.

[14] The 25 km lower limit to future megathrust rupture is not atypical of subduction zones, which commonly show coseismic rupture to near, or exceeding, this depth [*Hyndman et al.*, 1997]. Within the Nankai trough of Japan, where more of the seismic cycle has been instrumentally observed over the last century, a similar correspondence between inferred megathrust rupture depth and transient creep may already be apparent. Two damaging, magnitude-8 earthquakes in 1944 and 1946 ruptured to 30–35 km [*Sagiya and Thatcher*, 1999], the depth subsequently identified over the last decade to be the upper limit of episodic creep and non-volcanic tremor here [*Ide et al.*, 2007; *Obara*, 2002]. The 25–30 km depth range also overlies the onset at depth of weak, serpentinized mantle that may enable episodic creep and control down-dip megathrust rupture in this region [*Bostock et al.*, 2002; *Brocher et al.*, 2003].

[15] The most important aspect for northern Cascadia is that stronger coupling between 15 and 25 km implies greater coseismic slip near major population centers, and provides an estimate of future coseismic slip along this region. Assuming a 550-year Cascadia megathrust earthquake recurrence interval [*Atwater and Hemphill-Haley*, 1997] and 36 mm/yr of convergence along northwestern Washington State [*Miller et al.*, 2001; *Wang et al.*, 2003], the 50% coupling suggests 9 meters of slip should be expected directly up-dip of 25 km. This lies well inland of the coast, directly west of the greater Seattle-Tacoma metropolitan basin. Up-dip along the shallower, fully-coupled offshore region of the plate interface, nearly 20 meters of slip is expected. Down-dip of 25 km, by constrast, insignificant slip is expected. For the 300 km-long Washington State segment of Cascadia constrained by this study, this constitutes an $M_w = 8.9$ earthquake.

[16] Along-strike towards the north and south of the northern Washington State region, instrumentation density prior to 2005 precludes inverting for multiple ETS over and an analysis of this nature is premature at this time. Since 2005, however, slip events have been found both to the north and south of the Washington State region, within the same 25–40 km depth range [*Brudzinski and Allen*, 2007; *Szeliga et al.*, 2004, 2008]. If the break in coupling near 25 km depth were to be established along the remainder arc, a rupture of the entire margin would amount to an $M_w = 9.2$ event, in agreement with tsunami modelling of the previous AD 1700 event [*Satake et al.*, 1996].

[17] More generally, episodic creep and non-volcanic tremor are increasingly observed in many subduction [*Schwartz and Rokosky*, 2007] and transform settings [*Gomberg et al.*, 2008; *Nadeau and Guilhem*, 2009; *Nadeau and Dolenc*, 2005] world-wide, and together comprise a common mechanism by which faults accommodate adjacent locked and freely-slipping regions. As hypocentral locations improve, along with estimates of the moment release rate of seismic tremor ETS constitutes a potentially valuable new tool for mapping the future rupture depth, resultant magnitudes, and attendant seismic hazards of future earthquakes on many known faults.

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