nature geoscience

LETTERS

PUBLISHED ONLINE: 7 AUGUST 2011 | DOI: 10.1038/NGEO1215

A continuum of stress, strength and slip in the Cascadia subduction zone

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As oceanic lithosphere subducts beneath continental lithosphere it experiences variable degrees of interaction with the overriding plate and movement is accommodated by a continuum of slip modes[1]. At shallow depths, the plates are locked and movement occurs intermittently as earthquakes. By contrast, at large depths the down-going plate slips into the mantle continually. In the transition zone between locked and stable slip, plate movement is accommodated by slow slip[2], which generates tectonic tremor[3]. Here we use tectonic tremor to infer the location and duration of slow slip in the Cascadia subduction zone from 2006 to 2011. We find that individual slow-slip events are initiated deep on the plate interface and migrate upwards. With decreasing depth, we observe a gradation from small, frequent slip, to large, infrequent slip. These observations fill in the transition zone with a continuum of slip size and periodicity, and indicate that the fault weakens with depth, which we attribute to lower friction. We suggest that stable sliding loads the fault at depth and transfers stress to the base of the transition zone, causing the initiation of slow slip. In a self-similar process, slow slip migrates upwards and ratchets stress up the fault, towards the shallower seismogenic zone. Our conceptual model provides an intuitive understanding of subduction zone dynamics.

In Cascadia, where the oceanic Juan de Fuca plate is subducting beneath North America from northern California to mid-Vancouver Island at a rate of 4 cm yr^{-1}, the transition zone hosts the repeated spatio-temporal coincidence[4,5] of seismically observed tectonic tremor[3] and 2–3 cm of geodetically observed slow slip[2] for ∼3 weeks every 15 ± 2 months[4,6]. From a hazards perspective, previous studies have inferred episodic tremor and slip (ETS) to transfer stress to the updip seismogenic zone with the potential as triggering a megathrust earthquake[7,8] such that, with each discrete ETS-induced stress drop, the seismogenic zone experiences a discrete increase in stress. We present 5.5 years of northern Cascadia tremor data to support a model that expands this stress transfer concept to the entire transition zone.

We employ tremor as a tool for inferring slow slip on the plate interface. A growing body of evidence supports the interpretation that tremor is the result of slow slip[9–11] at the plate boundary[9,12,13], and that the geodetically determined seismic moment (fault area × displacement) scales with the total duration of tremor[14,15]. Detailed spatial comparisons of tremor duration and slip[5] naturally allow tremor duration to be used as a slip indicator. Therefore, just as the long tremor durations of ETS are accompanied by geodetically observed slip, we interpret minor tremor to represent slip below geodetic resolution, with their durations synonymous with slip totals. This interpretation leverages the moment-duration scaling more than the nature of tremor. So, despite ongoing research of depth and mechanism, we only require that tremor serves as a proxy for slip. That

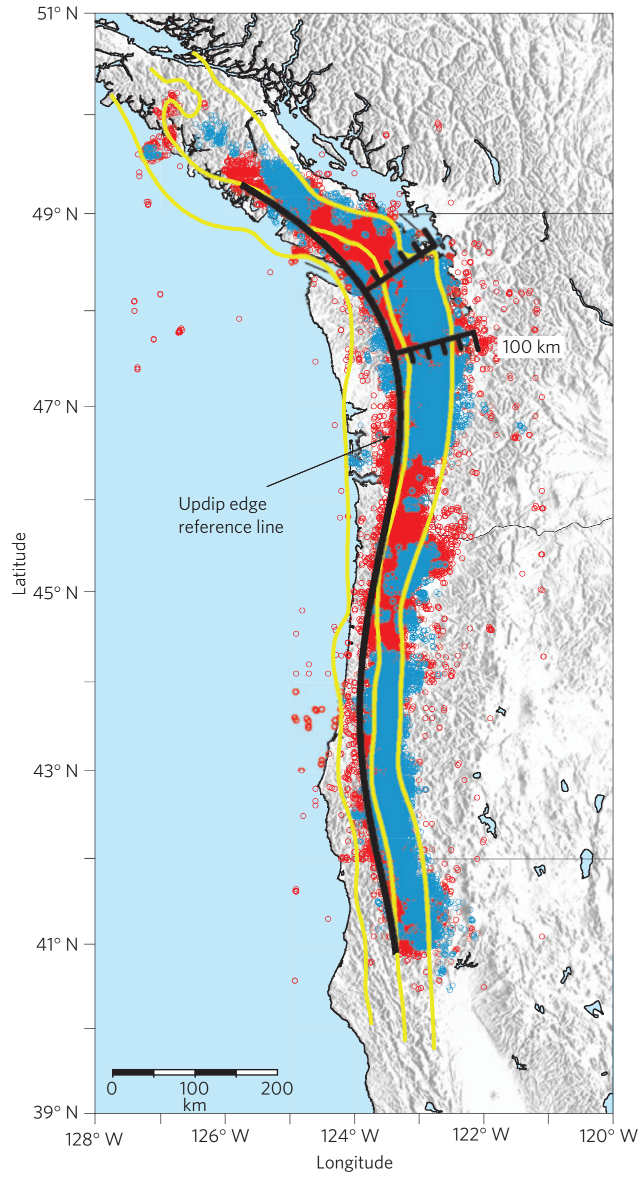

Figure 1 | Tremor reference line and swarm size distribution. Margin-wide epicentres (red circles) used to define the updip edge (black line) of the tremor region. Epicentres from minor tremor swarms <20 h concentrate on the downdip side (dark circles). We limit our analysis to a wedge in northern Washington where our catalogue is the most uniform and the plate dips the most shallowly as seen by 20, 30 and 40 km slab isodepths[18] (yellow lines).

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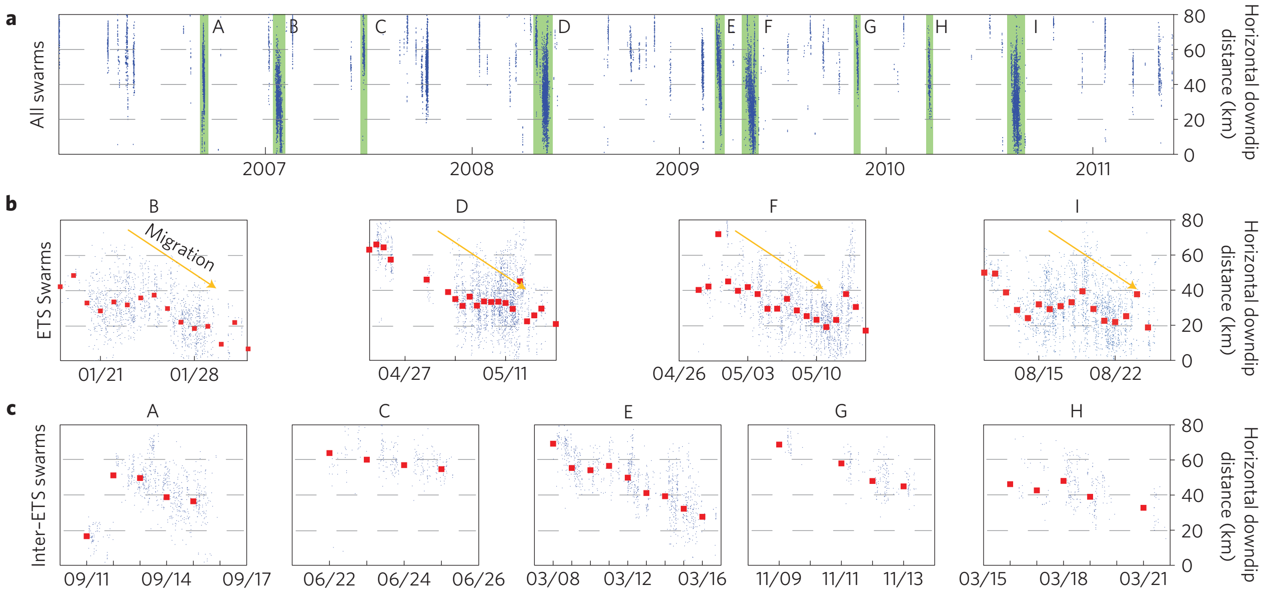

Figure 2 | Updip tremor migration. a, Downdip tremor distance versus time for the northern Washington catalogue, showing many small swarms downdip and larger swarms initiating deep and migrating updip. **b**, Detailed migration of the four ETS episodes showing tremor epicentres (blue dots) and median daily downdip distance (red squares). **c**, Example migration of five small and large inter-ETS slip events.

is, if tremor is happening—through whatever process—slip is occurring.

We used waveform envelope correlation and clustering (WECC; ref. 16) to automatically find ~95,000 tremor epicentres from 2006 to mid-2011. Assuming that each epicentre represents 5 min of tremor, WECC identifies ETS and inter-ETS tremor swarms across the margin with durations from one to hundreds of hours.

We separate these tremor swarms by duration and find a spatial segregation of sizes of tremor activity. Minor swarms shorter than 20 h concentrate on the downdip side of the tremor region in comparison with the larger swarms (Fig. 1). This margin-wide observation, which suggests that downdip slip episodes are smaller than updip episodes, is consistent with previous observations from northern Cascadia[5] and Japan[17].

Next, we investigate the depth dependence of tremor activity using a reference line at the updip edge of 95% of all swarms (Fig. 1). By analysing tremor epicentres in terms of their horizontal, downdip distance from this line, we avoid WECC's large depth uncertainties[16] and discrepancies between different depth models of the subducting plate[18,19].

Studying the transition of slip behaviour in the tremor region necessitates both a uniform catalogue and the ability to resolve strike-perpendicular differences in tremor activity. We therefore limit our analysis to northern Washington (Fig. 1), where we have the longest, most homogenous data set of tremor occurring above where the plate is dipping the shallowest. This approach restricts us to a consistent catalogue where the tremor zone is widest, maximizing our chances of resolving any depth dependence.

Smaller tremor swarms occur downdip of larger swarms, but we find that this downdip edge is the initiation point of almost all tremor swarms. Temporal observations of downdip distance show tremor initiating downdip and subsequently propagating updip (Fig. 2). This pattern holds for the past four ETS swarms as well as for all but one of the intermediate to larger inter-ETS swarms in our catalogue. Both ETS and inter-ETS tremor swarms initiate about 80 km away from the updip reference line and slowly migrate updip, but ETS swarms propagate further, reaching shallower depths.

We also investigate depth dependence by separating the tremor region into four 20-km-wide strike-perpendicular bins. We create a profile of cumulative tremor timelines in each bin and find a striking pattern with decreasing depth. Moving from downdip to updip reveals a transition from small, frequent tremor activity to larger, less frequent tremor activity (Fig. 3).

If we recall that each epicentre represents 5 min of tremor and that tremor duration is a proxy for slip, we can interpret each tremor profile as a profile of the displacement history across that portion of the fault. We propose a model in which the size and periodicity of slip in each region reflects the local fault strength, or relative stress threshold of the fault for failure, which decreases with plate depth (Fig. 3). Downdip of the tremor region, the plates are stably sliding past one another and constantly loading the lower edge of the tremor zone. But, as evidenced by the small and frequent slip on this downdip side, this region cannot build up much stress before relieving it through small slow slip and short-duration tremor. This small slip event, however, also statically transfers stress updip to a slightly stronger portion of the fault, which has a higher stress threshold. After a few downdip slip episodes have transferred enough stress to this updip portion, it will slowly slip and transfer stress even further updip to an even stronger portion of the fault. This is supported by our observed gradation of tremor duration and periodicity. It also explains why tremor initiates deep and propagates updip and is consistent with the thought that deep slip may lead to dynamic rupture on the seismogenic portion of the fault[7,8,20,21].

Consequently, each downdip inter-ETS episode can be thought of as a failed ETS event. ETS will only occur when those updip-most portions of the tremor region have experienced enough stress transfers from below to reach its stress threshold for local failure. These ETS swarms migrate all the way to the updip limit and then migrate along strike[5].

Like the model of ETS loading the seismogenic zone[7,8,21], each segment loads the fault zone above it and the local stress is the integrated effect of downdip slip. In this sense, it can be thought of as a fractal-like stress transfer process, where the stress dynamics of each region appear the same regardless of position: each region receives a discrete increase in static stress transferred from a weaker portion below and discretely increases the stress on the stronger region above whenever it exceeds its stress threshold and slowly slips.

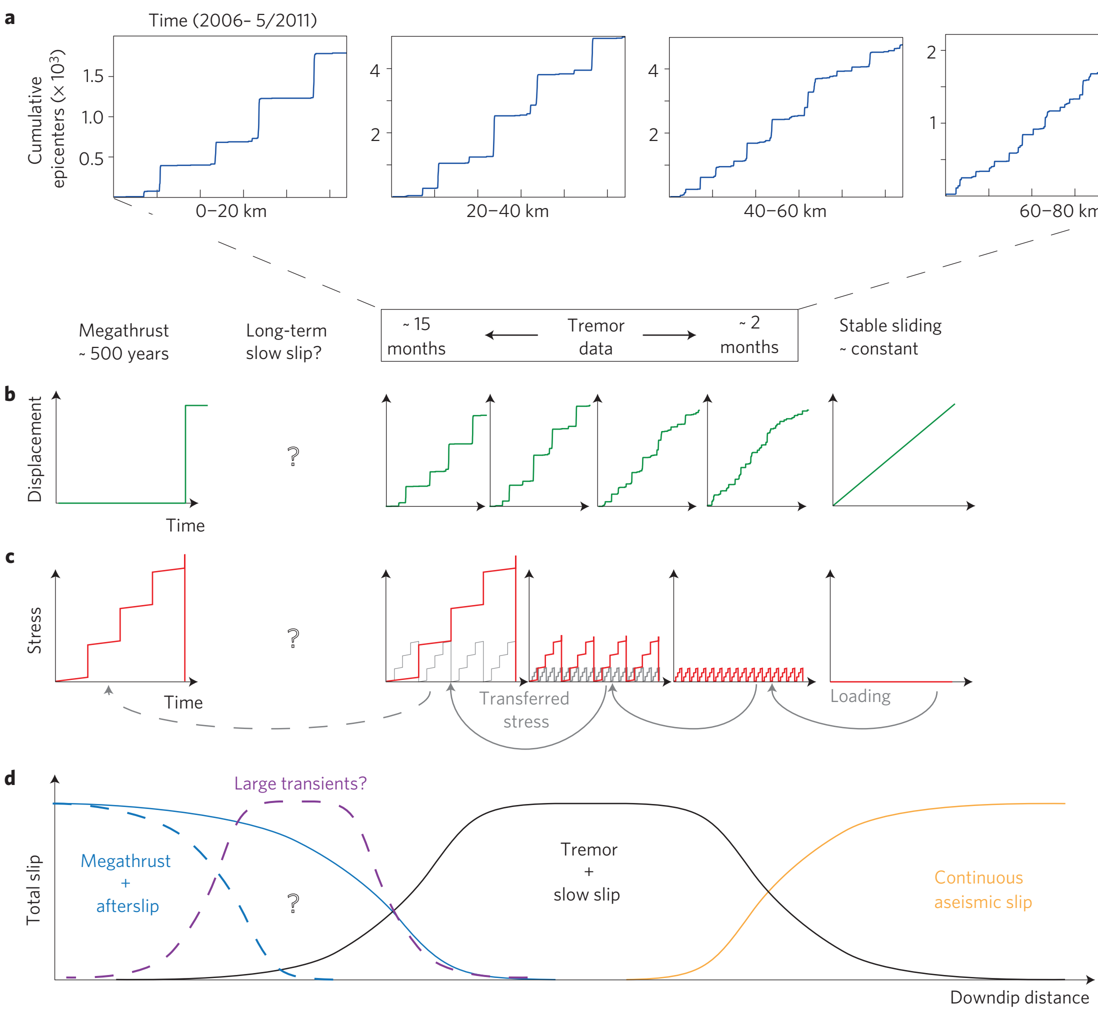

Figure 3 | Displacement history profiles and transition zone model. a, Cumulative tremor profile from January 2006 to May 2011 in each strike-perpendicular bin, showing a transition from small, frequent slip downdip to larger, less frequent slip updip. **b**, Profile of displacement timelines from the locked zone to stable sliding, with results from **a** inserted in the transition zone. **c**, A schematic profile of stress timelines illustrating our stress transfer model. Stable sliding loads the downdip tremor region, which is weakly coupled and slips easily. Each slip relieves stress locally and transfers stress updip to a stronger portion of the fault with a higher stress threshold. This is a fractal-like process, where the local stress is the integrated effect of downdip slip. **d**, A profile schematic showing how the different regions accommodate plate convergence. Extrapolating results from Fig. 4 predicts long-term slow slip updip (purple dashed line), which would shift the downdip limit of the megathrust (blue dashed line) updip.

In this model, relative shear strength decreases with depth, but the underlying physics of this system remain elusive. One clue may lie in the depth dependence of slip periodicity. In each depth bin, we calculate an average recurrence interval. This ranges from the 15-month ETS periodicity on the updip side to ~2 months on the downdip side, producing a trend with periodicity decreasing exponentially with depth (Fig. 4). This observation provides a framework for investigating what controls the stress threshold. Considering a Coulomb model for frictional strength, failure will occur when the shear stress exceeds the local shear strength

$$\sigma_s > \mu(\sigma_n - p)$$

where σ_s is the accumulated stress transferred from below, μ is the coefficient of friction, σ_n is the normal stress, and p is the pore pressure. Slip can initiate because σ_s has increased, μ has decreased, perhaps because it depends on slip rate, or p has increased over time.

σ_n increases by about 50% with plate depth from 30 to 45 km. However, the effective stress $(\sigma_n - p)$ in the ETS zone is thought to be about 1 MPa (ref. 22), which is three orders of magnitude smaller than σ_n. Highly anomalous Poisson's ratios in northern Cascadia suggest the presence of high pore pressure throughout the thickness of the subducting crust[23].

Our observations suggest a similar slip process occurs from the ETS zone to the downdip tremoring zone characterized by smaller events, with a fine balance between p and σ_n, such that p closely tracks σ_n with depth. Although fluids probably play a crucial role in the slow slip process, it is not so clear what controls the observed exponential dependence of periodicity on downdip distance. One possibility is that time variations in p are the controlling factor: either through variations in the recharge rate or recharge amount with depth. However, our preferred interpretation is that the friction, μ, is the primary controlling factor. At high fluid pressure, friction decreases with increasing temperature[24], which in turn increases with depth, potentially producing a weaker fault at depth that fails more often with smaller events characterized by smaller slip per event. This one simple concept could explain all our observations and is consistent with our stress transfer model for slip initiation. This model also agrees with the observation that short-duration tremor is more sensitive to tidal triggering[25]. In this model, friction determines strength, updip stress transfer initiates

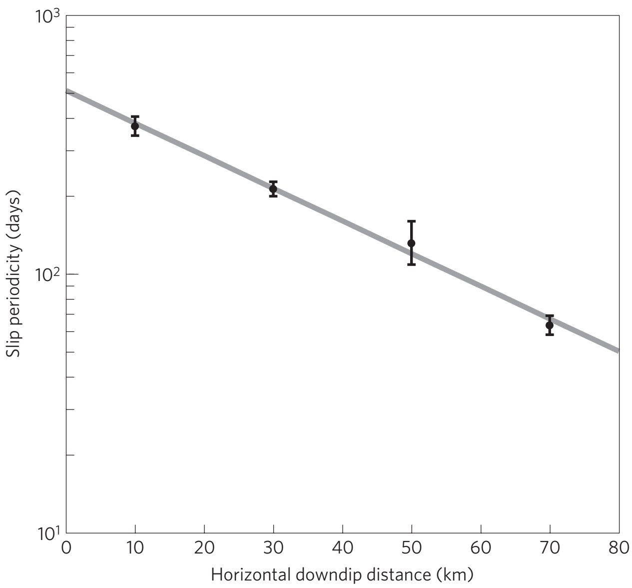

Figure 4 | Slip periodicity trend. The average time in days between slip in each strike-perpendicular bin follows an exponential trend with downdip distance, $\Delta T_{slip} = k \cdot 10^{-(x/x_o)}$, where $k = 512 \pm 59$ days and $x_o = 79 \pm 7$ km.

slip, and dilatancy keeps slip stable[26]. That is, to first order, fluids do not initiate slow slip; they enable slip to be slow.

This model is based on an apparent decrease in stress drop (slip/swarm length) with depth. We do see a decrease in slip size with depth, but, lacking constraints on swarm length, the observations do not necessitate this interpretation. Alternatively, smaller events could reflect smaller areas slipping, conceding possible uniform stress drops and constant fault strength with depth. Stress concentrates downdip because of asymmetric loading from below, and in this case, inter-ETS slip is limited downdip because the area with high stress is small. However, assuming a constant stress rate, our trend in time between events would be consistent with an equivalent stress drop trend. Neither model rules out fluid flow as an initiator before updip migration, especially given the ability of tiny tidal stresses to initiate tremor[27], but we suggest that loading from the stable sliding region is the primary initiator.

We have presented a model for subduction zone dynamics that can be tested globally, and we have provided additional constraints through our tremor periodicities to be considered for frictional modelling of subduction zone slip. Whatever the set of paramaters, they need to be able to explain the continuum of slip size and periodicity, and remain consistent with the varying slip types from dynamic rupture to stable sliding. Our model of friction-controlled stress transfer explains all of our tremor observations and provides a simple explanation of how the transition from locked to stable sliding might occur. It suggests that ETS is the geodetically observed part of a continuum of repeating slow events. As a consequence, it also predicts so-far unobserved long-term slow slip updip and frequent, small slip possibly with weak tremor downdip of the current tremor region. If we extrapolate our periodicity trend (Fig. 4) and observed stair-step displacement profiles (Fig. 3), we should expect larger, less frequent, slow slip events updip of the currently observed tremor zone (Fig. 3). Of course, this exponential dependence is only observed where we see tremor and may not be applicable in a region that accommodates plate motion through different physical processes. Their absence in Cascadia could be the result of different physics, periodicities greater than the continuous GPS record length, or small slip velocities. Recent scaling arguments suggest that the slip velocity of large slow events may be near the plate convergence rate, making them indistinguishable from apparent partial coupling[28]. Nevertheless, large and infrequent stable moment release would be consistent with the local frequency-magnitude distribution of slow slip[29], and such long-term slow slip events have been aseismically observed updip of tremor in other subduction zones[30,31]. This updip slip could help mediate plate convergence and either lower the slip deficit available for coseismic slip or shift the downward extent of the megathrust rupture away from urban centres.

Methods

WECC (ref. 16) attempts to locate tremor in every 50%-overlapping 5-min time window. Vertical-component seismograms are bandpass filtered at 1.5–5 Hz, rectified by calculating envelope functions, then low-pass filtered at 0.1 Hz. We determine the source location that maximizes a weighted sum of cross-correlations over all station pairs evaluated at the lag times of predicted differential S-wave travel times. Resulting epicentres are kept if bootstrap error estimates are less than 5 km and there is another epicentre with 0.1° during that day. The remaining epicentres naturally cluster into tremor swarms that are spatio-temporally separated by gaps exceeding 30 km or 1.5 days respectively.

For each tremor swarm we count the number of epicentres within a given 20×20 km bin (see Supplementary Figs S1 and S2). Each swarm exceeding 10% of the swarm with the maximum number of epicentres is considered to have slipped in that bin. For each bin we calculate the mean of $\log_{10}$ of the resulting recurrence intervals. Resulting values are averaged along strike to determine a mean and standard error in the mean for each of four downdip zones (Fig. 4).

Received 18 March 2011; accepted 24 June 2011; published online 7 August 2011

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Acknowledgements

This work was funded by grants from the USGS G09AP00024, G10AP00033 and the National Science Foundation EAR-0545441.

Author contributions

A.G.W. performed tremor detection and depth analysis. K.C.C. developed methods for cataloguing tremor into swarms. A.G.W. and K.C.C. collaboratively provided interpretation.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.G.W.