Characteristics of secondary slip fronts associated with slow earthquakes in Cascadia

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Abstract

We implement an algorithm to automatically detect migrations of low frequency earthquakes at time scales between 30 min and 32 h during the 2003, 2004 and 2005 slow slip events in Cascadia. We interpret these migrations of seismicity as a passive manifestation of secondary slip fronts (SSFs) that propagate faster than the main front. We identify the dominant features of 383 SSFs, including time, location, duration, area, propagation velocity and estimate: their moment, stress drop, slip, and slip rate. We apply the same algorithm to continuous tremor detection in Cascadia between 2009 and 2015 and characterize 693 SSFs at time scales between 4 h and 32 h. We identify — to our knowledge for the first time — numerous 10-24 h long SSFs that propagate at velocities intermediate between slow slip events and previously reported SSFs. The systematic detection of SSFs fills a gap between seismically and geodetically detectable slow earthquake processes. Analyses of SSF basic features indicates a wide range of stress drops and slip rates (with me-

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dians of 5.8 kPa and 1.1 mm/h) as well as an intriguing relationship between SSF direction and duration that was observed in other contexts and could potentially help discriminate between the different physical models proposed to explain slow slip phenomena.

Keywords: Slow slip, low-frequency earthquakes, nonvolcanic tremor, secondary slip fronts, Cascadia

1. Introduction

Slow slip events (SSEs) in subduction zones propagate along the plate interface at velocities of 5-10 km/day and are largely confined to the region known as the transition zone, located down-dip of the seismogenically locked zone (Dragert et al., 2001; Bartlow et al., 2011). As SSEs propagate, small on-fault asperities capable of generating seismic radiation fail in earthquake-like events known as low-frequency earthquakes (LFEs) and nonvolcanic tremor (Obara, 2002; Kao et al., 2006; Ide, 2010; Ueno et al., 2010; Houston et al., 2011). Multiple lines of evidence indicate that LFEs and tremor — which has been interpreted as a superposition of LFEs (Shelly et al., 2007b) — are a passive manifestation of surrounding aseismic slow slip (Shelly et al., 2007b). The occurrence of LFEs and tremor during SSEs are not random. Instead, spatially and temporally coherent migrations of LFEs and tremor can often be identified within the actively slipping portion of the fault after the main slip front associated with the SSE has passed. These migration patterns are thought to represent secondary slip fronts (SSFs) occurring over several different length and timescales. For example, Houston et al. (2011) and Royer et al. (2015) used tremor and LFEs to image approximately 40 km long slip

fronts — known as rapid tremor reversals (RTRs) — that propagate back in the opposite direction but 10 to 40 times faster than the main slip front. Ghosh et al. (2010) used tremor in Cascadia to image seismic migrations — known as streaks — that propagate back and forth along the main slip front (i.e., perpendicular to its propagation direction) but approximately 100 times faster. Rubin and Armbruster (2013) reported tremor migrations at the kilometer scale that propagate along strike either towards or away from the main front, but approximately ten times faster. Finally, Peng et al. (2015a) and Peng and Rubin (2016) found evidence for complex tremor migration patterns beneath that evolve as the main front propagates. While all of the aforementioned studies were conducted in Cascadia, similar observations have been reported in Japan (Shelly et al., 2007a; Ueno et al., 2010; Obara et al., 2012), Mexico (Radiguet et al., 2012; Frank et al., 2014; Peng and Rubin, 2017) and along the San Andreas fault (Ryberg et al., 2010; Shelly, 2009, 2010; Peng et al., 2015b), suggesting that SSFs may be a ubiquitous feature of slow slip.

Slow-slip phenomena require the fault slip rate to increase to observed speeds, typically 10 to 100 times the plate rate, but abstain from accelerating to typical earthquake slip rates. The specific physical mechanisms responsible for imposing this speed limit are still debated. SSFs generally propagate at least an order of magnitude faster than the main front associated with the SSE, and estimates of the ratio of the SSF stress drop to that of the main front range between one tenth and one (Rubin and Armbruster, 2013; Royer et al., 2015; Hawthorne et al., 2016). These stress drop estimates combined with the propagation speeds mentioned above imply that SSFs must be slipping either

44 as fast as or faster than the main front. Hence, reproducing stress drops, slip
 45 and propagation speeds of both the main and secondary fronts requires a
 46 rheology that limits the speed of the main front while allowing the SSFs to slip
 47 one to two orders of magnitude faster. Such behavior is difficult to reproduce
 48 with a single state variable friction law (Rubin, 2011). Additionally, SSFs
 49 appear to be sensitive to very small (≈ 1 kPa) tidal stress perturbations
 50 (Thomas et al., 2013; Royer et al., 2015; Houston, 2015) allowing them to
 51 be used to probe in situ conditions in deep faults. Observations of SSFs, in
 52 addition to SSEs, may provide useful constraints on physical models of slow
 53 slip processes (Rubin, 2011; Hawthorne and Rubin, 2013).

54 To date, most studies that have documented SSFs have relied on subjective
 55 identification methods such as visual identification, often using only one
 56 dimension of space and time (Shelly et al., 2007a; Ueno et al., 2010; Ghosh
 57 et al., 2010; Houston et al., 2011; Rubin and Armbruster, 2013; Royer et al.,
 58 2015; Peng et al., 2015a; Savard and Bostock, 2015). While these approaches
 59 successfully find some SSFs, such subjective identification makes it possible
 60 and even likely that many SSFs go undetected. Here we develop an algorithm
 61 that systematically identifies SSFs based on spatial and temporal migration
 62 of tremor/LFEs and discuss its advantages compared to the similar method
 63 developed by Obara et al. (2012). We apply our algorithm to both tremor
 64 and LFE datasets resulting from SSEs that occurred between 2003 and 2015
 65 in Cascadia. We detect over 1000 SSFs, determine their locations, duration,
 66 directions, and estimate some of their physical properties, such as moment,
 67 average slip, stress drop and slip rate.

68 2. Data and algorithm

69 We use two types of data: a catalog of LFEs located near Vancouver Is-
70 land during the 2003, 2004 and 2005 SSEs (Savard and Bostock, 2015) and a
71 catalog of continuous tremor detections from August 2009 to December 2015
72 that occur throughout the Cascadia subduction zone (Wech and Creager,
73 2008; Wech, 2010). The LFE catalog was obtained using cross-station wave-
74 form correlation; thanks to a dense campaign seismic network, it has very
75 good spatial (location errors of < 1 km) and temporal resolution (Savard
76 and Bostock, 2015). The tremor catalog contains locations and detection
77 times of tremor events determined using waveform envelope correlation and
78 clustering (Wech and Creager, 2008; Wech, 2010). Detections correspond to
79 5-minute seismogram windows that likely represent a superposition of LFEs
80 (Shelly et al., 2007b). Therefore, resolution of both time (each detection
81 is separated by at least 2.5 min) and location (5-10 km) is worse than for
82 the LFE catalog. Because the tremor detection algorithm is independently
83 implemented on several adjacent seismic networks, some tremor detections
84 appear twice in the final catalog (Wech, 2010). To eliminate duplicate de-
85 tections, when two tremors are detected at the same time within 25 km, we
86 exclude one (Wech, 2010).

87 These two catalogs provide a large number of identified LFE and tremor
88 events. To identify possible SSFs, we analyze LFE and tremor migration pat-
89 terns in 3 dimensions: distance along strike, distance along dip, and time.
90 The algorithm is illustrated in Figure 1. As in the approach of Obara et al.
91 (2012), we look for SSFs in time windows of various durations. The different
92 time windows considered in our analysis are 30 min, 1 h, 2 h, 4 h, 8 h, 16 h,

93 32 h for the LFE catalog and 4 h, 8 h, 16 h, 32 h for the tremor catalog. As
 94 individual detections are all separated by at least 2.5 min (Wech and Crea-
 95 ger, 2008), the number of potential detections in a ≤ 2 h time window too
 96 small to analyze their potential migration. The analysis is performed inde-
 97 pendently on the different time windows. Therefore, tremor/LFE detections
 98 may theoretically be part of more than one SSF in different time windows;
 99 thus a short duration SSF may be a part of a longer duration SSF.

100 We first identify clusters of LFE and tremor detections in the individ-
 101 ual catalogs. We use the subclust matlab routine to identify LFE/tremor
 102 clusters of different duration. The subclust routine estimates the centers
 103 of subclusters of a given duration in a data set using subtractive clustering
 104 (Chiu, 1994; Yager and Filev, 1994). We set the duration of the subclusters
 105 to correspond to the different time windows. The subclust routine then re-
 106 turns the tremor/LFE clusters of 30 min to 32 h duration with the highest
 107 concentration of events. For each identified cluster, we then calculate the lin-
 108 ear regression of the distance along strike as a function of time and exclude
 109 points farther than two standard deviations (2σ) from the regression line.
 110 After removing those points, we do the same linear regression but for the
 111 distance along dip as a function of time and remove events farther than 2σ
 112 from the linear regression. Finally, we project the remaining points along the
 113 best-fitting migration axis and remove again events that lie outside 2σ from
 114 the linear regression of the distance along the migration axis as a function
 115 of time. The remaining points are then tested: if the cluster still contains
 116 more than 20 LFE or tremor detections and if the root mean square (RMS)
 117 of their distance to the last regression is smaller than 15% of the migration

length, then the cluster is identified as an SSF. For a given time window, if the SSF length is small, then the front is not moving quickly (the signal is low). Thus we require the deviation from the propagation axis (the noise) to be very low (to ensure a decent signal to noise ratio). If the SSF length is larger, then the front is clearly moving (the signal is larger) and we can be more tolerant with the deviation from the propagation axis (as we have a clear signal). We repeat the process for all the clusters. We then remove the LFE or tremor detections identified as part of an SSF from the catalog and rerun the clustering routine on the new catalog with identified SSFs removed. We iterate until the catalog no longer contains any LFE or tremor. If no SSF is identified on one iteration, we remove all the tested clusters from the catalog and iterate once more in the truncated catalog. All the detected SSFs are then tested to ensure the continuity of the migration. We subdivide the successfully identified SSFs into 4 equal portions along their best-fitting migration axis and 3 equal periods and if one of the parts or periods contains less than 1/20th of the number of LFE/tremor detections that compose the SSF, the SSF is rejected in order to ensure that each SSF is continuous rather than composed of two distinct SSFs.

Our approach is inspired by Obara et al. (2012) (who implemented an automatic SSF detection based on principal component analysis of tremor in Japan), but has some significant differences. Obara et al. (2012) identified SSFs using moving time windows shifted by discrete increments. As it is unlikely that SSFs all start and end at the specific times of arbitrary time windows, this may result in detecting SSFs that either are just a part of a larger undetected SSFs or include LFE/tremor that should not be associated

143 with the SSF, potentially affecting the apparent migration velocities. The
 144 use of a clustering subroutine allows for flexibility in the start and end time
 145 of the explored SSFs — as tested time windows are not shifted by discrete
 146 increments but determined in respect of high concentrations of tremor/LFEs
 147 — substantially increasing the number of SSF detections. Another significant
 148 difference is the detection thresholds. In the work of Obara et al. (2012),
 149 SSF acceptance is based on linearity, angular difference and in the number
 150 of tremor detections, all of which vary with the given time window. We
 151 apply only two thresholds, which are the same for all time windows: the
 152 number of LFE/tremor detections (20 for all time windows) and a deviation
 153 criteria based on the ratio of the misfit to the SSF length (required to be
 154 $\leq 15\%$), which can be interpreted as a signal to noise ratio. Our choices of
 155 20 LFE/tremor detections and 15% are arbitrary — as are the thresholds
 156 used by Obara et al. (2012) — but these values do provide visually coherent
 157 patterns in all the detected SSFs (Figures 2, 3).

158 To ensure that our algorithm does not interpret noise as SSF, we test
 159 it on synthetic catalogs. To produce the synthetic catalogs, we use the ac-
 160 tual catalog locations and randomize the time of occurrence. We run the
 161 algorithm for all the time windows of our analysis and detect no SSF in the
 162 synthetic catalogs.

163 **3. Spatial distribution of secondary slip fronts**

164 We identified 383 SSFs in the LFE catalog of the 2003, 2004, and 2005
 165 SSEs beneath Vancouver Island and 693 SSFs in the tremor catalog between
 166 August 2009 and December 2015 in Cascadia. While SSFs lasting from 10

167 min to 11 h have been documented in multiple subduction zones (Ghosh
 168 et al., 2010; Houston et al., 2011; Obara et al., 2012; Rubin and Armbruster,
 169 2013; Royer et al., 2015; Peng et al., 2015a; Savard and Bostock, 2015), we
 170 identified — to our knowledge for the first time — numerous SSFs lasting
 171 between 11 and 22.5 h in both catalogs (243 in the tremor catalog, 57 in
 172 LFEs catalog). They propagate at intermediate speeds (≈ 3 km/h) between
 173 those of the main front (≈ 0.2 – 0.5 km/h) and previously documented SSFs
 174 (≈ 40 km/h) (Ghosh et al., 2010; Houston et al., 2011; Obara et al., 2012;
 175 Rubin and Armbruster, 2013; Royer et al., 2015; Peng et al., 2015a; Savard
 176 and Bostock, 2015).

177 The spatial distribution of SSFs is of particular interest because it can
 178 reveal atypical behaviors of some fault areas and may highlight spatial vari-
 179 ations of fault properties. Figure 4 shows the distribution of tremor derived
 180 SSFs during the 2009-2015 period along the Cascadia megathrust by time
 181 window. Note that some long duration tremor derived SSFs may correspond
 182 to the main front of short duration SSEs. In the inset diagrams we plot
 183 the number of SSFs as a function of their propagation directions. Some ar-
 184 eas show a clear tendency to host numerous SSFs (for instance at latitude
 185 40°N – 41.5°N , 42°N – 42.5°N , or 44.5°N – 45.5°N) whereas other regions had no
 186 detectable SSFs. Additionally, there is a clear preference for along-strike
 187 propagation for the majority of the tremor derived SSFs. Both the spatial
 188 distribution and propagation directions are consistent from SSE to SSE, sug-
 189 gesting that the physical mechanism responsible for generating SSFs does
 190 not change over a timescale of several years.

191 Because both the temporal and spatial resolution are much better in the

192 LFE catalog, we are able to detect short timescale SSFs beneath Vancouver
 193 island (Figure 5). Since the 3 SSEs that drove LFEs in this area all roughly
 194 propagated in the same direction (blue arrow in Figure 5), this catalog is also
 195 more convenient to analyze the direction of SSFs with respect to the direction
 196 of SSEs. SSFs propagate in all directions and encompass phenomena pre-
 197 viously described as RTRs or streaks. They also encompass slip fronts that
 198 propagate in the direction of the SSE (Figure 5). Such forward-propagating
 199 SSFs are hard to distinguish by eye from LFE or tremor migration associated
 200 with the main front. They typically initiate after the main front has passed
 201 and migrate towards the tip of the main front. Interestingly, we observe a
 202 clear relationship between the direction and the duration of SSFs. The vast
 203 majority of short duration (i.e. 30 min and 1 h) SSFs propagate along dip.
 204 As the SSF duration increases, the proportion of SSFs propagating along
 205 strike gradually increases (see Rose diagrams in Figure 5) resulting in the
 206 longest duration LFE derived SSFs propagating almost solely along strike.
 207 Similar relationships were observed by Ghosh et al. (2010) and Houston et al.
 208 (2011) in Cascadia and by Obara et al. (2012) beneath the Kii peninsula in
 209 the Nankai subduction zone. Potential physical mechanisms responsible for
 210 SSFs will have to explain this enigmatic dependence between duration and
 211 direction (Rubin, 2011). The ratio of along-strike SSFs propagating in the
 212 SSE direction to along-strike SSFs propagating in the opposite direction also
 213 seems to depend on the duration. While reversal SSFs are predominant in
 214 the 8 h time window, almost all SSFs propagate forward in the 32 h time
 215 window.

216 The distribution of propagation velocity V_{prop} is shown at the bottom of

each subfigure in Figures 4 and 5. In individual time windows, along-dip SSFs do not appear faster than along-strike SSFs. However, as the length L of SSFs is limited by the extent of the fault, the average propagation velocity decreases with the duration T (because $V_{prop} = L/T$). Accordingly, the limited number of distinct time windows in the analysis of the tremor catalog results in little difference in the propagation velocity (Figure S1.f).

4. Physical characteristics of secondary slip fronts

Our detection algorithm provides a number of direct observations characterizing each SSF including start time, location, direction (Figures 4, 5), duration T , length L , width W , pulse (i.e. actively slipping) length l (Figure 6), propagation velocity V_{prop} (defined as L/T), and number of LFE or tremor detections n_e . The distributions of these SSF properties are shown in Figure S1 (catalogs are available in the supplementary materials). Assessing other physical characteristics of SSFs, such as moment or stress drop, is challenging because these quantities require an estimate of the total slip associated with each SSF.

Individual SSFs are too small to generate a surface deformation signal detectable with GPS and hence most studies that have estimated slip for individual SSFs have relied on the total SSE moment and the fraction of LFE detections or bursts that occurred as part of the SSF (Rubin and Armbruster, 2013; Royer et al., 2015). Here, we adopt a similar approach and assume that the total moment M_e associated with each LFE or tremor detection is the same (although different for LFEs and tremor). This assumption is demonstrably false for individual LFE repeats, which have been shown to

241 have very different moments (Bostock et al., 2015), and for individual tremor
 242 events, as their definition (i.e. the 2.5 minute timescale used to separate
 243 individual events) is arbitrary and includes no contribution from waveform
 244 amplitudes (Wech and Creager, 2008). However, since moment estimates
 245 for each SSF include a minimum of 20 LFEs or tremors, it is likely that
 246 the average moment will be a more accurate measure of total SSF moment.
 247 Nevertheless, our estimates of the physical characteristic of SSFs (such as
 248 moment, slip, stress drop, slip rate) are tentative and caution should be
 249 exercised when interpreting them.

250 We obtain M_e , the average moment associated with each LFE or tremor,
 251 by dividing the moment M_0 (assessed by geodetic studies (Schmidt and Gao,
 252 2010; Krogstad and Schmidt, 2015)) associated with an SSE by the number
 253 of events N_e detected during the event:

$$M_e = \frac{M_0}{N_e}. \quad (1)$$

254 An implicit assumption behind equation (1) is that moment associated with
 255 aseismic slip that does not generate LFE or tremor detections is negligible.
 256 The moment, M_{SSF} , associated with one SSF, is defined as the sum of the
 257 moment associated with all the LFE or tremor detections that are part of
 258 that SSF,

$$M_{SSF} = \sum_{i=1}^{n_e} M_e(i), \quad (2)$$

259 where n_e is the number of LFE/tremor detections part of the given SSF. As
 260 we assumed that for all i , $M_e(i) = \frac{M_0}{N_e}$,

$$M_{SSF} = \frac{n_e}{N_e} M_0. \quad (3)$$

261 Note that possible deviations from constant $M_e(i)$ would tend to be averaged
 262 out over the number of events in equation (3) because $M_e(i)$ is sometimes
 263 larger and sometimes smaller than the assumed average $M_e = \frac{M_0}{N_e}$. We further
 264 estimate an average slip d for each SSF,

$$d = \frac{M_{SSF}}{\mu A}, \quad (4)$$

265 where μ is the shear modulus and $A = WL$ is the SSF slip area, with the SSF
 266 width W and length L both estimated from our analysis (Figure 6). To be
 267 consistent with geodetic inversions, we use $\mu = 40$ GPa (Schmidt and Gao,
 268 2010; Krogstad and Schmidt, 2015). The stress drop $\Delta\sigma$ is then given by

$$\Delta\sigma = \frac{4(\lambda + \mu)}{\pi(\lambda + 2\mu)} \mu \frac{d}{W}, \quad (5)$$

269 where λ is Lamé’s parameter (Lay and Wallace, 1995), which we set to $\lambda = 40$
 270 GPa. The total slip d accumulates in the time the front propagates the
 271 distance l . Thus, we can deduce the slip rate V_{slip} from the propagation
 272 velocity V_{prop} as

$$V_{slip} = \frac{d}{l} V_{prop}. \quad (6)$$

273 The distributions of assessed physical characteristics (moment, slip, stress
 274 drop and slip rate) are shown in Figures S2 and S3 (catalogs in the supple-
 275 mentary materials). Because we did not estimate these parameters indepen-
 276 dently, their distributions are correlated with each other (Figure S4). How-
 277 ever, most of the correlation coefficients between the different parameters are
 278 relatively weak (i.e. below 0.6 in magnitude, see Figure S4). As expected,
 279 high correlation coefficients are found for slip and stress drop, since the stress
 280 drop is estimated from slip (eq. 5), and between the different spatial dimen-
 281 sions (L , W and l), implying that the aspect ratios of SSFs do not vary

282 appreciably. Significant anticorrelations are observed between propagation
 283 rate V_{prop} and duration T , as well as between the spatial dimensions and both
 284 slip d and slip rate V_{slip} . It is also noteworthy that stress drop $\Delta\sigma$ appears
 285 to be independent of moment M in both catalogs (Figure S4).

286 The median stress drop among all SSFs is 5.8 kPa, which is very con-
 287 sistent with stress drop estimates obtained for RTRs using strainmeters (8
 288 kPa) (Hawthorne et al., 2016). These values of stress drop are several times
 289 smaller than typical stress drops in SSEs (10 - 100 kPa), and over 2 or-
 290 ders of magnitude smaller than regular earthquakes (Gao et al., 2012). The
 291 estimated stress drops are also all consistently smaller than effective nor-
 292 mal stress (0.2-3 MPa) inferred in LFE source regions (Liu and Rice, 2007;
 293 Hawthorne and Rubin, 2013; Royer et al., 2015). The median slip is 3 mm
 294 and the median slip rate is 1.1 mm/h, which is much faster than slip rates in-
 295 ferred for SSEs (on the order of 1-2 mm/day (Wech and Bartlow, 2014)). The
 296 observation that SSF slip rates are significantly faster than SSE slip rates is
 297 consistent with previous studies (Rubin and Armbruster, 2013; Royer et al.,
 298 2015; Hawthorne et al., 2016) and implies that the fault rheology limits the
 299 main front speed and then allows secondary fronts to slip faster. As ac-
 300 knowledged in the introduction, such a time dependent behavior is not easy
 301 to reproduce with a single state variable friction law (Rubin, 2011). SSF slip
 302 rates may then be used to constrain physical models of slow slip phenomena.

303 Though variations in the moments and slip distributions of SSFs range
 304 within a single order of magnitude (4.10^{16} to 4.10^{17} N.m and 0.1 to 40 mm)
 305 for all SSFs, stress drop varies by over 3 orders of magnitude (from 0.1 to
 306 300 kPa), as does slip rate (between 0.02 and 30 mm/h) (Figures S2 and

307 S3). We recall here that our estimates of stress drop are based on the orig-
 308 inal assumption that SSF moment scales with the number of LFE/tremor
 309 detections, which could be inaccurate for some SSFs. Large scatter in slip,
 310 stress drop and slip rate is also expected from equations (4), (5) and (6)
 311 as a result of multiplying quantities (M_{SSF} , L , W , l and V_{prop}) that have
 312 large variability. Therefore a large part of the scatter in slip rate and stress
 313 drop might be attributed to assumption inaccuracy and propagation of un-
 314 certainties, but some of this scatter could also be sourced to changes in fault
 315 properties. As SSF areas widely overlap — this is particularly clear in the
 316 LFE catalog (Figure 5) — the varying SSF properties might suggest that, in
 317 addition to being able to slip at different rates, the same fault area is also
 318 able to release very different amounts of stress.

319 **5. Moment – duration scaling**

320 Ide et al. (2007) suggested that slow slip phenomena — including LFEs,
 321 very low frequency earthquakes (VLFs) and SSEs — follow a moment –
 322 duration scaling law distinct from regular earthquakes. While regular (fast)
 323 earthquakes have moment proportional to the cube of their duration, slow slip
 324 phenomena would have moment proportional to duration (with $M/T = 10^{12}$ –
 325 10^{13} N.m/s) (Figure 7). In this representation, important gaps separate the
 326 various slow slip phenomena (Ide et al., 2007). The question of whether these
 327 gaps result from detection limitations or from the inherent behavior of fault
 328 slip is of importance because it could provide us with physical constraints on
 329 earthquake processes (Ide et al., 2007; Ide, 2008; Ide et al., 2008; Peng and
 330 Gomberg, 2010; Gao et al., 2012; Ide and Yabe, 2014; Liu, 2014; Gomberg

331 et al., 2016).

332 In the far field, seismic amplitudes scale with moment rate (Aki and
333 Richards, 2002). Thus, the threshold for seismically detectable signals follows
334 the noise level in the different frequency bands. We use the USGS low noise
335 model (Peterson et al., 1993; Ide, 2014) and empirically calibrate it on the
336 smallest moment rate events that have been seismically detected (VLFs
337 from Ide and Yabe (2014)) to determine a threshold for seismically detectable
338 events (red dashed line in Figure 7). Existing geodetic instrumentation has
339 proven capable of detecting magnitude 5.7–6.0 events and above regardless of
340 their duration (Peng and Gomberg, 2010) (blue dashed line in Figure 7). The
341 gap between LFEs and VLFs (Figure 7) may be attributed to particularly
342 large noise in the frequency band corresponding to the gap (Ide et al., 2008)
343 while the gap between the VLFs and SSEs corresponds to moments too
344 low to be detected by geodesy (Peng and Gomberg, 2010) and characteristic
345 periods too long to be detected in seismograms (Ide et al., 2008).

346 The large range of duration and moment among the SSFs we detected
347 follows the slow slip scaling law and fills the gap between VLFs and SSEs,
348 where signal is not directly detectable either from seismic or geodetic records
349 (Figure 7). The vertical (moment) threshold in SSFs corresponds to the
350 minimum number of LFE/tremor detections (20) in one SSF times M_e and
351 the distinct horizontal lines in SSF duration correspond to our different time
352 windows. These two noncontinuous characteristics are consequences of our
353 approach. Interestingly, SSFs appear to follow the same threshold of con-
354 stant moment rate — on the order of 10^{13} N.m/s — as the other slow slip
355 phenomena (Figure 7). The fact that SSFs follow the slow slip phenomena

356 scaling law may be a consequence of estimating SSF moment from moment
357 of SSEs (eq. 3), as SSEs follow this law. Nevertheless, it is worth noting that
358 our moment estimates are in agreement with SSF moments estimated from
359 strain meters (Hawthorne et al., 2016) (green square in Figure 7).

360 While individual slow slip phenomena do not appear to have moment pro-
361 portional to duration (e.g. Ide et al. (2008); Bostock et al. (2015); Gombert
362 et al. (2016)), they all fit a constant moment rate scaling law (within less than
363 2 orders of magnitude variation) when considered together on a 10 orders of
364 magnitude scale (Figure 7). More generally, fast and slow slip phenomena
365 appear to be well distinguished in Figure 7. Fault slip processes that would
366 range between the two scaling laws are, in theory, detectable — and should
367 therefore have been detected — by seismology, geodesy or both (Figure 7).
368 The large gap in detection of fault slip processes between the two scaling laws
369 suggests that earthquakes and slow slip phenomena are two very distinct fault
370 slip processes.

371 6. Conclusion

372 We identified a total of 1076 SSFs in Cascadia at timescales between 30
373 min and 32 h. We cataloged their duration, width, length, pulse length and
374 time of occurrence and provided estimates for some of their physical prop-
375 erties such as moment, slip, slip rate, and stress drop. The median moment
376 is 5.3×10^{16} N.m (corresponding to a moment magnitude of 5.1), the me-
377 dian slip is 3 mm, the median slip rate is 1.1 mm/h and the median stress
378 drop is 5.8 kPa. Moment estimates suggest that SSFs bridge a major gap
379 between seismically and geodetically detectable events in the slow slip phe-

380 nomena scaling law (Ide et al., 2007). As previously observed with different
 381 approaches (Ghosh et al., 2010; Houston et al., 2011; Obara et al., 2012),
 382 we found that short duration SSFs dominantly propagate along dip while
 383 long duration SSFs dominantly propagate along strike. We also found that
 384 inferred SSF stresses drops and slip rates range over 3 orders of magnitude,
 385 suggesting that the same fault region could be able to slip at very different
 386 rates and to release very different stresses. These findings may be used to
 387 constrain models of slow earthquake processes.

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Figure 1: Algorithm scheme. See main text for description.

Figure 2: Examples of SSFs detected in the LFE catalog for the different time windows of our analysis. Grey arrows show SSF direction determined by the algorithm.

Figure 3: Examples of SSFs detected in the tremor catalog for the different time windows of our analysis. Grey arrows show SSF direction determined by the algorithm.

Figure 4: Detected secondary slip fronts in Cascadia from August 2009 to December 2015 for time windows of 4 h, 8 h, 16 h and 32 h (tremor catalog). White to gray color scale indicates the density of tremor detections. Arrows show lengths and directions of the SSFs propagating along strike (red) and along dip (black). Rose diagrams show the number of SSFs in the different directions. Histograms show velocity distributions for SSFs propagating along strike (red) and along dip (black). Red and black vertical lines superimposed on histograms show average velocity for SSFs propagating along strike and along dip, respectively.

Figure 5: Detected secondary slip fronts during the 2003, 2004 and 2005 SSEs for time windows of 30 min, 1 h, 2 h, 4 h, 8 h, 16 h and 32 h (LFE catalog). White to gray color scale indicates the relative density of LFEs. Blue thick arrow show the approximate direction of the three SSEs (45° west from north). Red arrows show lengths and directions of SSFs propagating in the direction of SSE propagation $\pm 45^\circ$ (along strike). Black arrows show lengths and directions of SSFs propagating perpendicular to the direction of SSE propagation $\pm 45^\circ$ (along dip). Rose diagrams show the number of SSFs in the different directions. Histograms show velocity distributions for SSFs propagating along strike (red) and along dip (black). Red and black vertical lines superimposed on histograms show average velocity for SSFs propagating along strike and along dip, respectively.

Figure 6: Scheme illustrating how SSF length (L), width (W), and pulse length (l) are deduced from the analysis. L is defined as the length of the best projection axis (parallel to the propagation direction) (a and b). l is defined as the 2σ dispersion from the linear regression of the distance along the best projection axis as a function of time (a). W is defined as the 2σ spatial dispersion (perpendicular to the propagation direction) from the best projection axis (b).

Moment - Duration scaling laws for regular earthquakes and slow slip phenomena

Figure 7: Moment – duration scaling law for regular earthquakes and slow slip phenomena (gray shaded areas). Colored solid lines are isolines of equal moment rate. Black stars indicate regular earthquakes over a large range of magnitude (compilation of Peng and Gomberg (2010) augmented with M4.8-5.8 events from the GCMT catalog and recent mega-earthquakes (Delouis et al., 2010; Bletery et al., 2014, 2016)). Gray stars indicate tsunami earthquakes (compilation from Peng and Gomberg (2010)). Blue dots are SSEs (compilation of Peng and Gomberg (2010) augmented with events from Gao et al. (2012) and Liu (2014)). Orange dots are VLFES (Ito and Obara, 2006; Matsuzawa et al., 2009; Ide and Yabe, 2014). Orange circles are unnamed 20-200 s long duration earthquakes assimilated to VLFES (Ide et al., 2008). Red circles are LFE moment and duration averaged over 100 (Thomas et al., 2016) and >100,000 events (Bostock et al., 2015). Cyan dashed line shows an approximate moment threshold ($M_w \approx 5.7 - 6.0$) for geodetically detectable events. Red dashed line shows the limit of seismically detectable events (see text). In agreement with moment of large SSFs determined from strain meters (green square) (Hawthorne et al., 2016), SSFs detected in this study (green dots) span a moment – duration region that cannot be directly recorded either by common seismic or geodetic instrumentation.