

1 Earthquake cycle modeling of the Cascadia subduction 2 zone

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5 Key Points:

- 6 • Ten thousand years of geometrically accurate Cascadia earthquake cycle simula-
7 tions.
- 8 • Ephemeral rupture barriers due to the stress history from prior earthquakes.
- 9 • Novel model observations of “fast” slow slip events with slip rates over 1 $\mu\text{m/s}$.

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Abstract

The Cascadia subduction zone hosts great $M_W > 8.5$ earthquakes, but studying these events is hindered by our short observational record. Earthquake cycle simulation provides an alternative window into the behavior of the subduction zone. Here, we present simulations over 3,800 years, 14 ruptures and hundreds of slow slip events on a high-fidelity geometric representation of the Cascadia subduction zone beneath surface topography. The boundaries of these ruptures are defined by ephemeral stress barriers that last for several cycles but are eliminated by a barrier-crossing rupture. Thus, it is possible that many real world rupture barriers are due to remnant stress shadows from previous slip events and may not persist over several earthquake cycles. In addition, we see “fast” slow slip events with $M_W \approx 8$. These events may occur in nature and reduce the seismically available moment or they may be a spurious feature of an unrealistic friction law.

1 Plain Language Summary

The Cascadia subduction zone underneath Washington and Oregon has magnitude 8.5 - 9 earthquakes every 250 to 500 years. Because we only have 100 years of data, it’s difficult to study the physics and statistics of this fault system. Computational earthquake cycle simulation offers a potential alternative window into the behavior of the Cascadia subduction zone. However, previous simulations have neglected the complex geometry of the fault. Here, we present ten thousand years of simulated fault behavior in the first geometrically accurate simulations of the Cascadia subduction zone. We see a wide range of fault slip behaviors, including full fault ruptures, smaller earthquake ruptures, and slow slip events. In particular, we explore the ephemeral barriers that stop earthquakes and previously undiscussed “fast” slow slip events that might reduce the earthquake potential of the fault. These Cascadia earthquake cycle simulations show the promise of a new generation of geometrically and physically realistic fault modeling in understanding and quantifying fault and earthquake behavior.

2 Introduction

Subduction plate boundaries host great $M_W > 8.5$ earthquakes (Lay et al., 2005; Vigny et al., 2011; Simons et al., 2011). But, they also exhibit a wide range of other earthquake cycle behaviors, including smaller partial ruptures (Anderson et al., 1986; Giovanni

40 et al., 2002; Yamanaka & Kikuchi, 2003), creep (Wang et al., 2003; Schmalzle et al., 2014;
41 Loveless & Meade, 2016), and slow slip events (Dragert et al., 2001; Schwartz & Rokosky,
42 2007). Studying the physics and statistics of these faults is very difficult because only
43 100 years of the earthquake cycle is captured in the modern observational record. Nu-
44 merical modeling offers a potential alternative window into the earthquake cycle.

45 Elastic rate-and-state friction models of the earthquake cycle exhibit many of the
46 space-time behaviors observed in subduction zones around the world. However, studies
47 of these systems commonly assume planar geometries for the fault and Earth's surface
48 (Liu & Rice, 2005; Lapusta & Liu, 2009; Segall & Bradley, 2012; Noda & Lapusta, 2013;
49 Erickson & Dunham, 2014). Fault geometry has been explored in some studies of dy-
50 namic earthquake rupture (Dunham et al., 2011; Shi & Day, 2013), but that work has
51 not yet been extended to models that study multiple earthquake cycles. Here, we incor-
52 porate this fundamental geometric nonlinearity into quasi-dynamic earthquake cycle mod-
53 els of the Cascadia subduction zone.

54 Seismic, geodetic and paleoseismic observations have revealed a wide range of slip
55 behaviors on the Cascadia subduction zone. Despite the lack of major earthquakes on
56 the plate boundary since 1700, there is significant geological (coastal subsidence, sed-
57 imentary deposits) and historical (orphan tsunami records in Japan) evidence for great
58 earthquakes and tsunamis every 250-500 years (Satake et al., 1996; Clague, 1997; Goldfin-
59 ger et al., 2012). At shorter time intervals the subduction zone exhibits intermittent lo-
60 calized slow slip events (Dragert et al., 2001; Miller et al., 2002) while other sections of
61 the fault release strain continuously through creep (Wang et al., 2003; Schmalzle et al.,
62 2014). Previous Cascadia focused quasi-dynamic earthquake cycle modeling work has
63 demonstrated that slow slip events (SSEs) may occur spontaneously in rate and state
64 earthquake cycle simulations on three-dimensional planar faults (Liu & Rice, 2005). Sim-
65 ilarly, recent short-duration (< 100 year) simulations have demonstrated that geode-
66 tically observed slow slip events can evolve on non-planar models of the Cascadia sub-
67 duction zone (Li & Liu, 2016).

68 Here, we present 10,000 years of earthquake cycle simulations of the Cascadia sub-
69 duction zone with geophysically constrained fault geometry and a traction-free surface
70 representing observed topography. We use a new continuous-slip GPU-accelerated bound-
71 ary element method. Because the method has no stress singularities, we can accurately

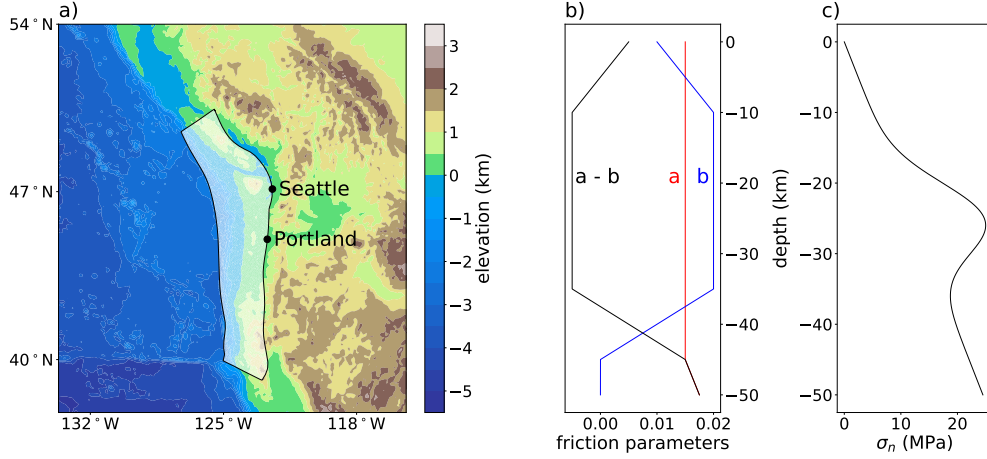
72 models slip and traction on non-planar faults (Thompson & Meade, 2019a). We adopt
 73 realistic vertical profiles of both rate-and-state frictional behavior and the pore pressure
 74 driven variations of effective normal stress (Saffer & Tobin, 2011). These simulations ex-
 75 hibit a diverse range of earthquake cycle behaviors, with periods of coupling, interseis-
 76 mic creep, cyclic SSE behavior, $M_W = 8$ partial plate boundary ruptures, and $M_W =$
 77 9 full plate boundary ruptures. In addition, we explore the occasional “fast” SSEs that
 78 appear in the model.

79 **3 Cascadia subduction zone model**

80 We model slip evolution on a triangulated mesh of the Cascadia subduction zone
 81 derived from Slab 1.0 (Hayes et al., 2012) consisting of 29,860 triangles (Figure 1a). The
 82 fault surface extends from approximately 1200 km from 40° N to 50° N. The topographic
 83 free surface extends 1000 km away from the fault surface. The elevation data is derived
 84 from the Shuttle Radar Topography Mission provided through Tilezen and Amazon Web
 85 Services (Tilezen, 2019) and the surface is triangulated into 14,842 triangles.

86 We adopt the quasidynamic earthquake cycle simulation methodology (Rice, 1993)
 87 combined with rate-state friction and the aging law for state evolution (Dieterich, 1979;
 88 Ruina, 1983). The quasidynamic approximation neglects the full wave-mediated stress
 89 transfer during rupture and instead approximates it with a radiation damping term that
 90 represents the local drop in stress due to slip. The quasidynamic approximation allows
 91 modeling thousands of years of fault evolution efficiently. On the other hand, it produces
 92 some qualitative differences in the shape and slip speed of ruptures (Thomas et al., 2014).
 93 Similar to the model of (Liu & Rice, 2005), the critical a and b parameters vary with depth.
 94 This includes velocity strengthening effects above and below 5 km depth to 35 km depth
 95 while the intermediate depth region is velocity weakening and capable of nucleating rup-
 96 tures (Figure 1b). We use typical values for other material and frictional parameters: $\mu =$
 97 20 GPa, $\nu = 0.25$, $\rho = 2670 \text{ kg/m}^3$, $V_0 = 10^{-6} \text{ m/s}$, $f_0 = 0.6$ and $D_c = 0.075$.

104 The magnitude of relative motion between the Juan de Fuca and North American
 105 plates varies from 29.8 mm/yr at the southern end to 39.7 mm/yr at the northern end
 106 of the fault with a direction $\sim 60^\circ$ east of north (DeMets & Dixon, 1999; Miller et al.,
 107 2001). This plate convergence rate varies in relation to the dip vector on the fault sur-



98 **Figure 1.** Left: A map showing the location of the Cascadia fault mesh, the topography in
 99 the general vicinity and the locations of Seattle and Portland. Middle: The friction parameters, a
 100 and b and the difference, $a - b$ as a function of depth. $a - b$ is negative and thus the fault is ve-
 101 locity weakening between 5 km depth and 40 km depth. In the shallower and deeper portions of
 102 the fault, $a - b$ is positive and the fault is velocity strengthening. Right: a profile of the baseline
 103 effective normal stress as a function of depth.

108 face. We allow the slip rake to vary freely in accordance with the direction of highest shear
 109 stress at each point on the fault surface.

110 We impose an effective normal stress profile following Saffer and Tobin (2011) in
 111 assuming very high fluid overpressure at shallow and deep depths with somewhat less
 112 overpressure in the middle depths (Figure 1c). Unlike many previous earthquake cycle
 113 simulations, we allow the normal stress on the fault to vary as a result of nearby slip.
 114 With purely shear slip on a planar fault, there is no normal stress perturbation on the
 115 fault surface. However, due to the continuity of slip, the slip at a bend in the fault sur-
 116 face cannot be purely tangential to two different planes. As a result, there is a small com-
 117 ponent of tensile motion that perturbs the normal stress on the fault.

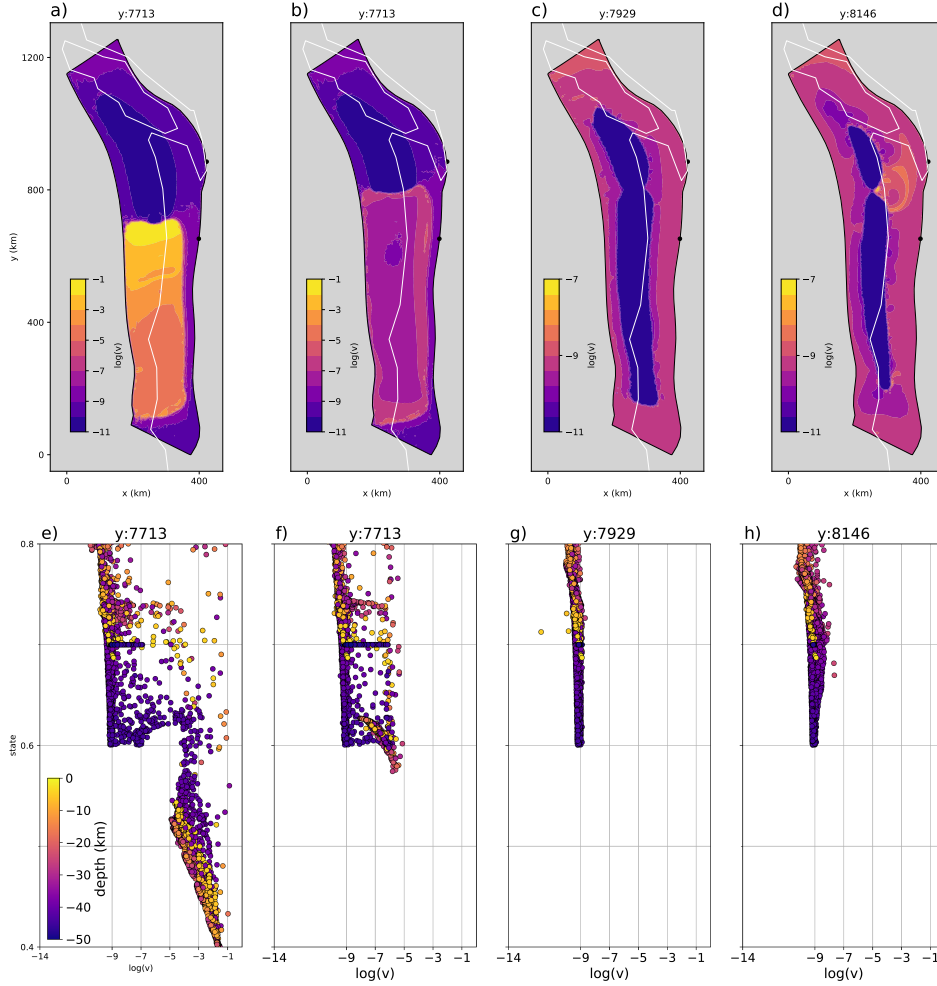
118 We run the primary model for 100,000 time steps or 10,864 years. To solve for the
 119 stress at each time step, we use a new continuous-slip boundary element method that
 120 accurately represents both stress and slip on the fault surface without any stress singu-
 121 larities (Thompson & Meade, 2019a). To update the fault slip and state variables in time,
 122 we use an adaptive Runge-Kutta 2(3) algorithm (Bogacki & Shampine, 1989) with a time

123 step tolerance of 10^{-4} . Because we initiate the model with no slip deficit and thus no
124 stress, the fault is slowly evolving towards a steady state zone of behavior for the first
125 6,500 years. To be conservative and avoid the influence of the initial conditions, we fo-
126 cus our discussion on the evolution of slip after model year 7,000. There are 14 major
127 ruptures during this period along with frequent SSEs including three “fast” SSEs.

128 4 Discussion

129 The results of our simulations are most easily visualized as animations available
130 on YouTube (Thompson & Meade, 2019b). However, we present summary figures of a
131 representative earthquake cycle beginning with a rupture at year 7,713 (Figure 2a). This
132 rupture initiates in the southern half of the subduction zone and is propagating north-
133 wards. The rupture spans all the way to the trench and 6 km down dip into the deep
134 velocity strengthening zone. The rupture is slipping fastest (> 0.1 m/s) near its prop-
135 agation front, while earlier portions of the rupture slow to 1 mm/s. The state variable
136 drops to 0.4 in the fastest moving portions of the rupture representing a decrease in the
137 frictional resistance to slip. The rupture eventually arrests at approximately the latitude
138 of Portland.

139 Immediately after the rupture, afterslip continues around the edges of the ruptured
140 area (Figure 2b). The afterslip asymptotically decreases in velocity over the next 10 years.
141 While the afterslip slows it also spreads outward spatially, eventually extending more than
142 100 km along strike from the area that ruptured. The afterslip eventually extends all the
143 way to the deepest portions of the fault, accelerating those strongly velocity strength-
144 ening regions to almost 20 times the plate motion rate. In a different earthquake cycle
145 beginning with a rupture at model year 8,180, the last remnants of the afterslip zone spreads
146 over 200 km south of the main rupture and triggers a second rupture 61 years later.



147 **Figure 2.** In the first row (a-d) the base 10 log slip velocity on the fault is shown at four
 148 different snapshots in time during a single representative earthquake cycle. For reference, a slip
 149 velocity of $10^{-9}m/s$ is approximately equal to 32 mm/yr and thus is similar to the rate of plate
 150 motion. The two black dots show the locations of Seattle and Portland and the white line in-
 151 dicates the coastline. In the second row (e-h), the distribution of slip velocity against state is
 152 shown for the same points in time. a,e) a rupture propagating from south to north. b,f) postseis-
 153 mic afterslip. c,g) a period of interseismic locking. d,h) a slow slip event propagating bilaterally.
 154 Note that the color scale bar is different between panels a), b) and panels c), d).

155 At 216 years after the rupture, most of the middle depths of the fault are locked,
 156 while the deeper and some portions of the shallow fault are creeping at approximately
 157 the plate rate (Figure 2c). The outlines of the previous rupture define the most locked
 158 portion of the subduction zone. Another locked zone further north outlines the extent

159 of the penultimate ruptures. This spatial mosaicing is indicative of the historical con-
160 trol on the extent of future ruptures.

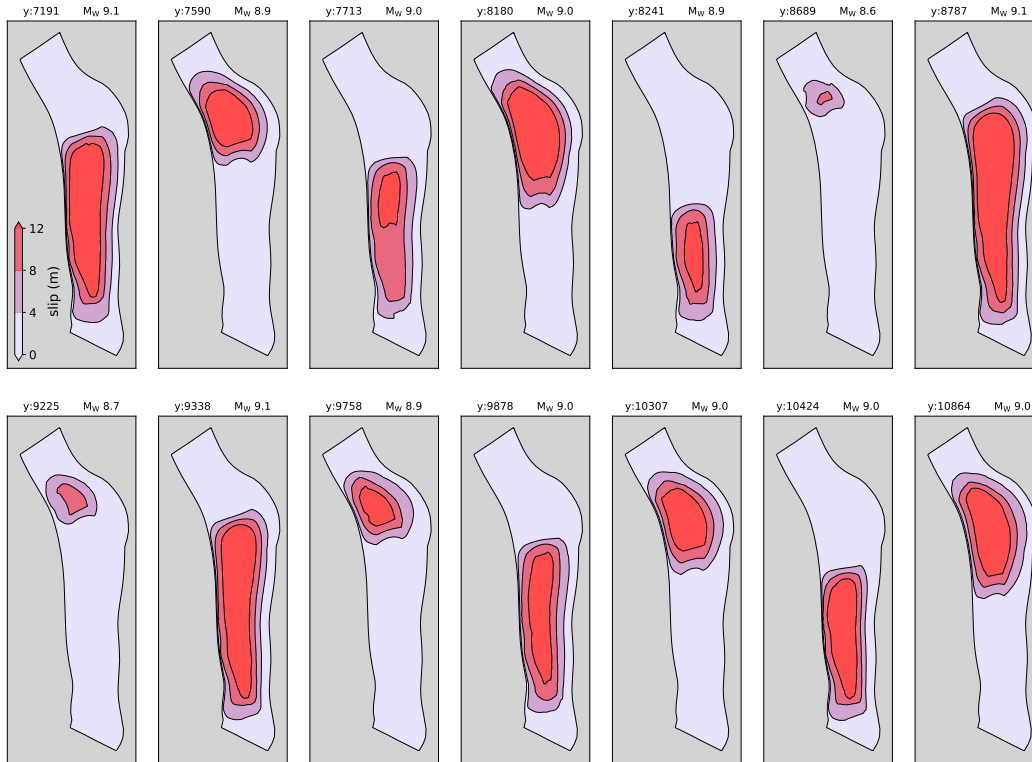
161 At 433 years after the rupture, there is slow slip event propagating bilaterally un-
162 derneath the Olympic Peninsula (Figure 2d). Simultaneously, the most strongly coupled
163 region decreased in down-dip width by nine km. Seven more slow slip events will occur
164 before the fault eventually ruptures again at year 8,180.

165 The coupling erosion of the locked zone (Figure 2c and Figure 2d) is a general fea-
166 ture of these earthquake cycle models (Segall & Bradley, 2012; Mavrommatis et al., 2015).
167 Immediately after a rupture, the entire ruptured area will become locked. During the
168 interseismic phase, the locked zone will shrink in size. Once the locked zone is small enough,
169 slow slip events will begin nucleating along the edges until eventually enough stress has
170 accumulated to trigger the initiation of another rupture.

171 Importantly, with are 14 ruptures in our model over 3,800 years (Figure 3), the re-
172 currence interval of 271 years in this model is similar to paleoseismic estimates of recur-
173 rence (Clague, 1997). The ruptures range from unlocking 20% to 80% of the fault sur-
174 face with most only rupturing either the northern or southern half of the fault. The mag-
175 nitudes range from $M_W = 8.7$ to 9.1 with maximum slip of almost 20 meters and along
176 strike lengths up to 900 km.

177 Much work has been dedicated to the causes of real world rupture barriers (Noda
178 & Lapusta, 2013; Protti et al., 2014; Loveless & Meade, 2015). In the model we present
179 here, there are clear boundaries at which the ruptures arrest (Figure 3). These bound-
180 aries persist over several earthquake cycles, but are not permanent. These ephemeral bound-
181 aries are controlled by the stress field with a recently ruptured patch not rupturing in
182 the next event because the stress level has not yet risen sufficiently to continue propa-
183 gation. The barriers are eventually eliminated by a rupture crossing the barrier. Over
184 the next one or two earthquake cycles, a new barrier evolves. Thus, it is possible that
185 many real world rupture barriers are due to the remnant stress shadow from previous
186 slip events and may not persist over several earthquake cycles.

189 In addition to this primary model, we have run several other models with slightly
190 different parameter sets. In particular, we have a model with a planar free surface and
191 planar megathrust. While most of the same slip behaviors are present in that model, the



187 **Figure 3.** The extent and slip magnitude during each rupture. The year and model magni-
 188 tude for each rupture are displayed above the diagrams.

192 ruptures have simpler patterns and behave in a more consistently cyclic pattern. The
 193 nonplanar geometry is introducing some acyclic behavior into the model that is not present
 194 in the planar equivalent.

195 We have also run models with a reduction in the degree of velocity weakening be-
 196 havior. These models behave as expected, with a lower propensity to rupture and larger
 197 regions of decoupled creep. We have run models with a normal stress profile that is per-
 198 fectly linear with depth rather than having higher effective normal stress at middle depths.
 199 Those models behave almost identically except the nucleation point of ruptures is 2-6
 200 km shallower.

201 Finally, we have run a model with four times higher effective normal stress. This
 202 model demonstrates that the rupture and slip magnitudes depend linearly on the assumed
 203 effective normal stress on the fault surface. In this higher stress model, the recurrence
 204 interval is 1,100 years and the slip per event is four times larger with peak slip magni-
 205 tudes over 100 meters. These unrealistic results from a high stress model suggest that

206 the Cascadia subduction zone may have very low effective normal stress and is in agree-
207 ment with observational evidence (Hardebeck, 2015; Audet et al., 2009).

208 On the other hand, the main control on the recurrence interval in our models is the
209 fault strength. Decreasing effective normal stress decreases the fault strength, but de-
210 creasing the baseline friction coefficient (f_0 in the rate and state equations) would also
211 decrease the fault strength. Another way to reduce coseismic slip magnitudes is to have
212 a mix of velocity weakening and velocity strengthening zones or simply have a slightly
213 less velocity weakening friction parameters. It is also worth wondering whether these large
214 slip magnitudes are an artifact of the quasidynamic approximation. However, in a fully
215 dynamic model, total slip would likely be even higher than in these quasidynamic mod-
216 els due to higher dynamically supported slip velocities during rupture (Thomas et al.,
217 2014).

218 **5 Fast slow slip events**

219 A striking feature of the model is the occasional “fast” SSE occurring on the north-
220 ern most portion of the subduction zone. These events have slip rates over $1 \mu\text{m}/\text{s}$ but
221 below the $1 \text{ mm}/\text{s}$ characteristic of a seismic rupture. We see these events at year 9,059,
222 9,618 and 10,731. These events have the moment release equivalent to $M_W \approx 8$ rup-
223 tures. We believe it is unlikely that the quasidynamic approximation is affecting the pres-
224 ence of these events because the slip rates are several orders of magnitude below normal
225 seismic rupture velocities. Despite this, it should be confirmed that these fast SSEs also
226 occur in fully dynamic earthquake cycle models.

227 No such fast SSEs have been yet been observed during the geodetic era (~ 30 years).
228 However, these events are predicted to occur only every thousand years in our model and
229 would not produce significant ground shaking. So, it’s possible that no such fast SSEs
230 have occurred during our short window of modern geodetic observation. In the paleoseis-
231 mic record, uplift would occur in a short enough period of time that it might be confused
232 for a rupture, but there would be no evidence of a tsunami (Nelson et al., 2006). Sub-
233 duction zones that host fast SSEs may have less seismic hazard than otherwise predicted.

234 On the other hand, if these fast SSEs never occur in nature, that provides useful
235 constraints on frictional behavior. With improved regional modeling capabilities, we may
236 be able to rule out certain sets of rate and state frictional parameters because those pa-

237 rameters predict unrealistic events. More generally, with improved realism, we can use
238 earthquake cycle modeling techniques to identify likely models of frictional behavior and
239 stress states on faults. While there may be a large null space, many frictional behaviors
240 and parameter sets can be ruled out because they do not explain the shapes, sizes, range
241 or frequency of slip events that we observe.

242 **6 Conclusions**

243 Realistic earthquake cycle models including accurate fault geometry and surface
244 topography will lead to a better understanding of the crucial role played by these first
245 order nonlinearities in the evolution of earthquake cycles. Here, we discuss earthquake
246 cycle simulations on an high-fidelity geometric representation of the Cascadia subduc-
247 tion zone beneath true surface topography. Over the 3,800 years of spun-up model time,
248 we observe great 14 earthquakes. The boundaries of these ruptures are defined by ephemeral
249 rupture barriers. These barriers are defined by the stress field produced by previous rup-
250 tures and eventually are eliminated by a barrier crossing rupture. In addition to many
251 $M_W = 6 - 7$ slow slip events, we see occasional “fast” slow slip events with $M_W \approx 8$.
252 These are a new type of slip behavior, previously undiscussed. These “fast” slow slip events
253 may occur in nature and reduce the seismically available moment or they may be a spu-
254 rious feature of an unrealistic friction law. Regardless, these Cascadia earthquake cycle
255 models show the promise of a new generation of geometrically and physically realistic
256 fault modeling in understanding and quantifying fault slip behavior of all types in a uni-
257 fied setting.

258 **Acknowledgments**

259 The data and source code for this work is available at <https://github.com/tbenthompson/qd>.
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