

Simulation of Large Earthquake Synchronization and Implications On North Anatolian Fault Zone

E. Sopaci¹, A. A. Özacar²

¹Laboratoire Géoazur, Centre national de la recherche scientifique (CNRS), Sophia Antipolis, France

²Department of Geological Engineering, Faculty of Engineering, Middle East Technical University, Ankara, Turkey

Key Points:

- Afterslip propagation in barriers controls fault synchronization and predictability of large earthquakes.
- Asperity size is less significant, contradicting previous studies, implying that rupture styles influence long-term stress interaction.
- Static stress changes can lead to immature small ruptures, complex slip deficits, and failure times.
- Simulations can mimic the migrating earthquakes along NAF and suggest the Cinarcik segment as a possible barrier, disrupting the synchrony.

Corresponding author: Eyüp Sopaci, sopaci@geoazur.unice.fr

Abstract

The North Anatolian Fault (NAF) has a history of large quasi-static large earthquake clusters. This study investigates the phenomenon with a model consisting of three strong velocity-weakening (VW) asperities separated by velocity-strengthening VS barriers in a 2.5D model governed by rate-and-state friction. The results show that the after-slips at the VS barrier control the stress interaction and synchronization; hence, the barrier strength and size are the most important parameters. The static stress transfer can lead to immature ruptures that arrest within the VW asperity, adding complexity to failure times. The asperity size appears insignificant, challenging previous theories linking barrier efficiency to the asperity-barrier size ratios. Such discrepancy suggests that slip type, e.g., slip-pulse or crack-growth, influences the long-term failure time distribution. Even though the state evolution (aging and slip laws) for frictional strength within the RSF framework differ significantly in co-seismic ruptures, they resemble each other for after-slip propagation, highlighting the importance of after-slip propagation and adding robustness to our conclusions. The results from various simulation scenarios suggest that the after-slip extents and duration with the peak slip rates and rupture speeds are the indicators for the synchronization and the predictability of large earthquakes. Despite the simplicity of the governed model, the results can mimic the synchrony of large earthquakes along the NAF, which are disrupted by aseismic creep and complex fault geometries such as releasing bend (e.g., Cinarcik segment), step-overs (e.g., Niksar) and slip partitioning (Duzce-Bolu segments) acting as barriers.

Plain Language Summary

North Anatolian Fault Zone (NAF) shows quasi-periodic failures of large strike-slip earthquakes that resemble a super-cycle pattern within which the characteristic earthquakes fail sequentially in a close interval. However, the super-cycle pattern and quasi-periodic failures mostly relate to the mega-thrust fault zones. More interestingly, a west migrating pattern appeared clearer in the seventieth century, elevating the hope of large earthquake predictability. This study investigated the earthquake synchronization and triggering phenomena on a 2.5D continuum model with three strong vertical asperities separated by barriers. The fault interface obeys rate and state friction. Simulation results imply how the barrier structure and after-slip propagation control the synchronization process, mimicking NAF observations. The results also reasonably imply the possible extent of future earthquakes expected to fail at the observed slip deficit along the NAF.

1 Introduction

The North Anatolian Fault Zone (NAF) has a historical record of large earthquake clusters that characteristic quasi-periodic earthquakes fail sequentially within close time intervals (Şengör et al., 2005). The following earthquake generally nucleates close to where the former stops in the cluster, where those points correspond to the step-overs along the NAF shown in Figure 1 (Pondard et al., 2007). The observations suggest those step-over areas have remarkable stress and strength heterogeneity can be attributed to "velocity-strengthening" barriers at the cluster edges, preventing ruptures from spreading from one segment to another or mitigating the transfer of stress (Kaneko et al., 2010; Lambert & Lapusta, 2021; Yıkılmaz et al., 2015; Cakir et al., 2014; Liu & Wang, 2023; Kondo et al., 2010; Kaya et al., 2009). In the recent situation, all segments of NAF from east to west have ruptured, except the locked segment(s) beneath the Marmara Sea, still building up strain for a large earthquake (Lange et al., 2019). This raises the question of what conditions synchronization happens and the large earthquakes become more predictable.

Studies of rock friction have established that a fault segment can undergo stick-slip motion if it is velocity weakening (VW) or tends to creep if it is velocity strength-

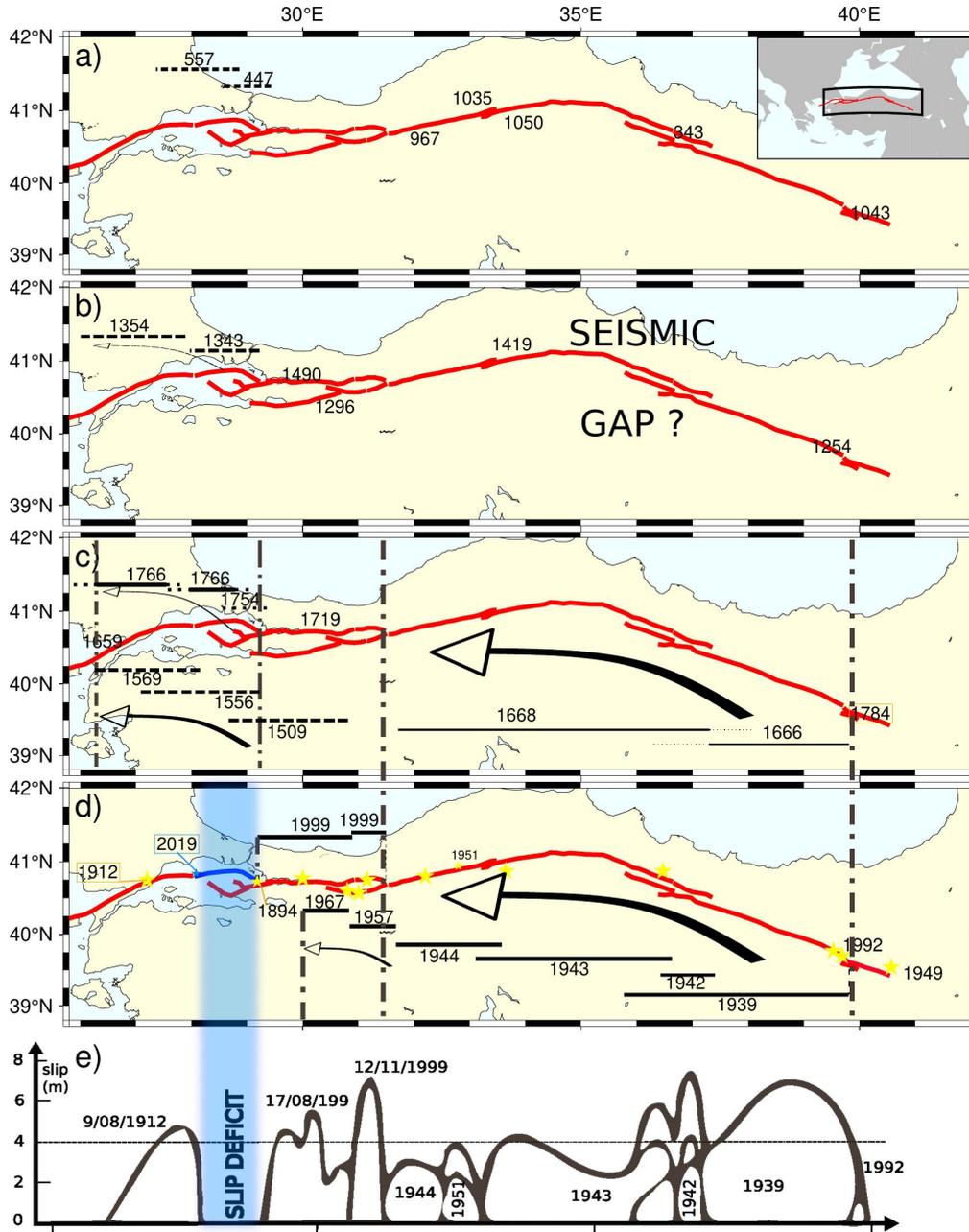


Figure 1. Map showing the historical earthquakes along North Anatolian Fault zone (a-d) and synchronized clusters, and its approximate recent situation (e). The historical earthquake catalog is compiled from studies (Şengör et al., 2005; Bulut & Doğru, 2021; Pondard et al., 2007; Fraser et al., 2009; Parsons, 2004)

66 ening (VS) (Dieterich, 1979; Ruina, 1983). The type of motion is determined by the crit-
 67 ical elastic stiffness relation within the framework of rate and state friction (RSF) in equa-
 68 1 (Ruina, 1983). If the stiffness is lower than the critical value $k < k_{cr}$, correspond-
 69 ing to the RSF parameter is $0 < a - b$, and the VW size is larger than a critical length
 70 (Ampuero & Rubin, 2008; Dieterich, 1992), the fault patch can nucleate earthquakes.
 71 The terms VW and VS patches refer to asperities and barriers, respectively.

$$72 \quad k_{cr} = \sigma_n(b - a)/d_c \quad (1)$$

73 Numerical simulations assuming that the frictional stress on the fault is RSF have
 74 revealed various aspects of earthquakes and fault synchronization, including the asperity-
 75 barrier sizes, frictional properties, and relative distances between patches (Kato, 2004;
 76 Kaneko et al., 2010; Dublanche et al., 2013; Cattania, 2019). The successive failure time
 77 delay between two VW patches embedded in VS medium increases as their separation
 78 distance increases (Kato, 2004). Simulation suggested that the VS barrier's effectiveness
 79 is related to the ratio between VW and VS sizes and the frictional properties of VS that
 80 control the probability of joint generation of a large earthquake (Kaneko et al., 2010).
 81 Also, the density of VW patches in a medium with the frictional properties of VS regions
 82 forms a threshold that determines the simultaneous failures of asperities and destabi-
 83 lization of the creeping region (Dublanche et al., 2013). Moreover, the analog models
 84 investigated the synchronization patterns of mega-thrust earthquakes in nature, finding
 85 that the ratio of the barrier and asperity patches (D_b/D_a) determines the barrier's ef-
 86 fectiveness (Corbi et al., 2017; Rosenau et al., 2019). Unlike the numerical simulations
 87 with RSF, Scholz (2010) argued that the synchrony of parallel faults necessitates sim-
 88 ilar intrinsic velocities to sustain a phase locking and classified the abutting fault syn-
 89 chronization into another category, likewise the pattern in NAF. However, Wei and Shi
 90 (2021) argued the role of the static stress transfer on fault synchronization by stating
 91 that static stress transfer leads to synchronization, unlike Scholz (2010). They also con-
 92 cluded that the barrier's width is more sensitive to synchronization than its frictional
 93 strength.

94 Our previous studies investigated the aftershock occurrence after the 30.10.2020
 95 Samos Mw7.0 earthquake (Sopaci & Özacar, 2021) and the triggering potential of a mod-
 96 erate earthquake on the locked segments of the NAF, remaining from a large earthquake
 97 (Sopaci & Özacar, 2023) using spring slider system. Here, we explore the issue of long-
 98 term spontaneous segment failures using a numerical model designed to be analogous
 99 to the North Anatolian Fault (NAF). Our numerical setup includes three strong, ver-
 100 tically oriented VW asperities separated by VS barriers. We use the numerical method
 101 described by (Lapusta et al., 2000) with the spectral FFT code (Sopaci, 2022). Numer-
 102 ous simulations mimicked synchronized, complex, or independent classes of fault zones.
 103 Most simulations are generated by the quasi-dynamic (QD) method, simplifying the in-
 104 ertial effects via radiation damping to reduce numerical costs. Some QD results are com-
 105 pared with the full inertial effects on identical setups to avoid numerical artifacts (Thomas
 106 et al., 2014; Lambert & Lapusta, 2021). Similarly, identical setups run using aging and
 107 slip state evolution laws to account for the distinct frictional strength evolution on the
 108 interface (Dieterich, 1979; Ruina, 1983).

109 This study first checks if numerical simulations can generate large earthquake syn-
 110 chronization analogous to NAF. Since the recurrence intervals of characteristic earth-
 111 quakes are generally long, there are a few well-documented ruptures with modern instru-
 112 mentation. Therefore, this study intended to assist in understanding the synchrony of
 113 large earthquakes and earthquake-triggering mechanisms. The natural indicator of syn-
 114 chronized fault zones is investigated by generating synthetic earthquake catalogs with
 115 a controlled setup. The study also intends to examine the progressive synchrony behav-

116 ior of NAF and its recent stress situation, where a large earthquake is expected (Şengör
 117 et al., 2005).

118 2 Simulation Set-up

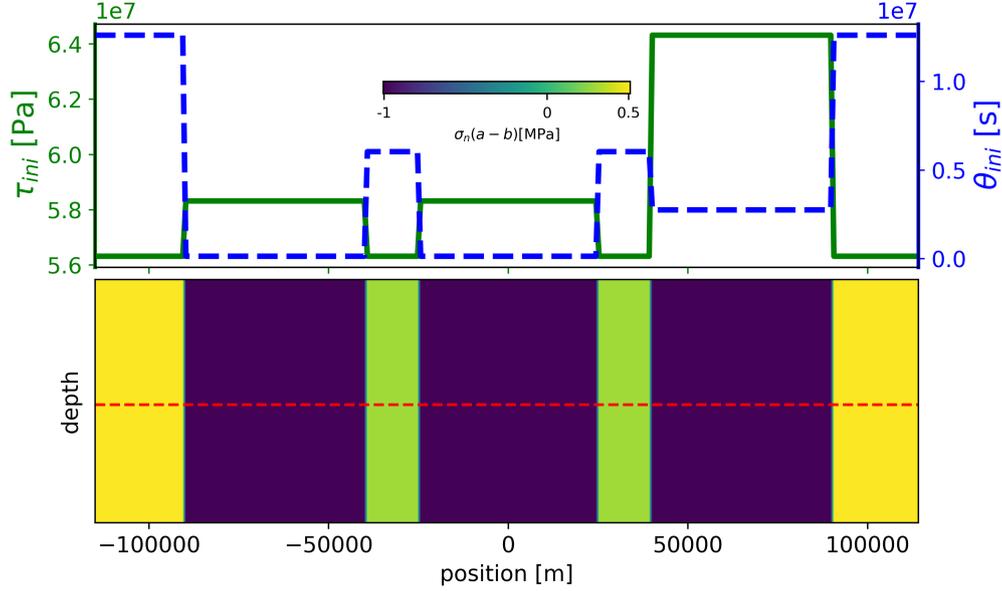


Figure 2. Simulation set-up: a) Initial values, b) a schematic representation of the fault in 2D medium.

119 We assumed three large asperities embedded in a 2D medium, where simulations
 120 correspond only to the red dashed line in Figure 2, and the width information is added
 121 with (Luo & Ampuero, 2018). The shear stress on the interface τ is assumed to be rate
 122 and state friction computed by:

$$123 \quad \tau = \sigma_n \mu = \sigma_n \left[\mu_0 + a \ln \left(\frac{v}{v_0} \right) + b \ln \left(\frac{v_0 \theta}{d_c} \right) \right] \quad (2)$$

124 where σ_n denotes the effective normal stress, μ and μ_0 are the friction and refer-
 125 ence friction at the reference velocity v_0 . The second and third terms on the right-hand
 126 side (2) contribute as velocity v (dynamic) and state θ (static) dependence of friction,
 127 where d_c is the critical slip distance. a and b are constitutive parameters for direct ve-
 128 locity and state evolution. Two empirical state evolution formulas for θ to complete equa-
 129 tion 2, namely aging and slip laws, are given by (Dieterich, 1979; Ruina, 1983).

$$130 \quad \dot{\theta} = 1 - \frac{v\theta}{d_c} \quad (3)$$

$$131 \quad \dot{\theta} = -\frac{v\theta}{d_c} \ln \left(\frac{v\theta}{d_c} \right) \quad (4)$$

133 The elastic stress is defined by:

$$134 \quad \tau(x, t) = \tau^0(x) + f(x, t) - \frac{G}{2c_s}(v(x, t)) \quad (5)$$

135 where τ^0 is the loading stress, assuming no displacement discontinuity on the fault
 136 plane (Lapusta et al., 2000). The last term in equation 5, $G/2c_s(v(x, t))$ is the radiation
 137 damping to sustain a solution during rupture, where G and c_s are shear moduli, and speed
 138 (Rice, 1993). The second term is the stress transfer functional $f(x, t)$ due to the slip dis-
 139 continuity, for which we applied the spectral FFT method Perrin et al. (1995); Lapusta
 140 et al. (2000):

$$141 \quad \delta(x, t) - v_{PL}t = \sum_{n=-N_{ele}/2}^{N_{ele}/2} D_n(t)e^{ik_n x}$$

$$142 \quad f(x, t) = \sum_{n=-N_{ele}/2}^{N_{ele}/2} F_n(t)e^{ik_n x} \quad (6)$$

$$143 \quad k_n = \frac{2\pi n}{\lambda} + \frac{2\pi}{W}$$

144 where k_n is the spatial frequencies along the periodic domain λ and W is the width
 145 of the fault (depth) and N_{ele} is the number of elements over space domain. D_n and F_n
 146 are the complex Fourier coefficients of slip $\delta(x, t) - v_{PL}t$ and stress transfer functional
 147 $f(x, t)$, where v_{PL} is mean driving plate velocity. The Fourier coefficients of the stress
 148 transfer function are computed by:

$$149 \quad F_n(t) = -\frac{G|k_n|}{2}D_n(t) + \int_0^{T_w} W(|k_n|c_s t')\dot{D}_n(t-t') dt' \quad (7)$$

150 The first term is the so-called "static" term that contributes most during the slow
 151 phase. The second term contributes as the dynamic term, computed with truncated con-
 152 volution integral within a window $(t_i, t_i - Tw)$ over coefficients history of $(dD_n(t)/dt)$
 153 (Lapusta et al., 2000). In this study, we conducted most analyses by ignoring the sec-
 154 ond "dynamic" term for computational efficiency corresponding to QD approximation.
 155 We solved the equation of motion explicitly using Adams' multi-step predictor-corrector
 156 method by setting equations 2 and 5 equal and using a state evolution formula 3 or 4
 157 (Hairer et al., 1993). We searched for synchronization patterns using the following sim-
 158 ulation parameters.

Table 1. Simulation Parameters

Params	min	max	default
a_{asp}	0.005	0.015	0.01
$a_{bar} - b$	0.000	0.005	0.005
$d_c[mm]$	8	24	8
$L_{asp}[km]$	30	100	50
$L_{bar}[km]$	5	20	15
$v_{PL}=0.02\text{m/yr}$, $G=30\text{GPa}$, $c_s=3\text{km/s}$, $\mu_0=0.6$			
$W=50\text{km}$, $\sigma_n=100\text{MPa}$, $a_{asp} - b=-0.01$			

159 As mentioned, the simulation outcomes obeying RSF depend drastically on the spa-
 160 tial resolution or length scales. We set the minimum number of cells per the cohesive zone
 161 to $\Lambda_0/dx \geq 9$ for $a_{asp} \geq 0.01$ and $\Lambda_0/dx \geq 12$ for $a_{asp} < 0.01$, where a_{asp} and dx de-
 162 note minimum direct velocity effect parameter at the asperity and cell size. The cohe-
 163 sive zone is computed by:

$$164 \quad \Lambda_0 = C_1 \frac{Gd_c}{b\sigma_n} \quad (8)$$

165 where C_1 is a constant around 1 (Erickson et al., 2020). The setting resolution accord-
 166 ing to equation 8 makes $h^*/dx \gtrsim 20$ according to Lapusta et al. (2000), which is nec-
 167 essary to prevent cells from becoming unstable and failing independently where critical
 168 cell size h^* is computed by.

$$169 \quad h^* = \frac{\pi}{4} \frac{Gd_c}{(b-a)\sigma_n} \quad (9)$$

170 **3 Simulation Results**

171 **3.1 Classification of Results**

172 We performed sensitivity analyses on parameters listed in Table 1 using initial con-
 173 ditions shown in Figure 2.

174 The fault zone is considered synchronized if all asperities fail sequentially within
 175 a close time. We first identify the failure times of full ruptures (a slip event covers the
 176 whole VW asperity). Then, we calculate the failure time difference between neighbor as-
 177 perities during full ruptures and normalize them using the mean recurrence time for com-
 178 parison. The status is set to synchronize if the normalized failure time differences con-
 179 verge to the value less than 10% percent of the mean recurrence time. For larger values,
 180 it is "independent," and the status is "complex" if failure time differences diverge.

181 The failure time differences of the synchronized fault zones are fitted to an expo-
 182 nential model $\beta_0 \exp(\beta_1 x)$ as a function of its cycle count using the Gauss-Markov model
 183 with a constraint by forcing the model passes through the tangent line corresponding to
 184 the failure time difference between the successive events becomes stably short enough
 185 (it is converged to a value) (Koch, 1999). The fitting procedure allows a unique compar-
 186 ison by obtaining the synchronization rate and stability of the convergence. The fitted
 187 β_1 parameter represents the convergence rate (Schatzman & Schatzman, 2002). Let us
 188 now present examples of converged, complex, and independent cases.

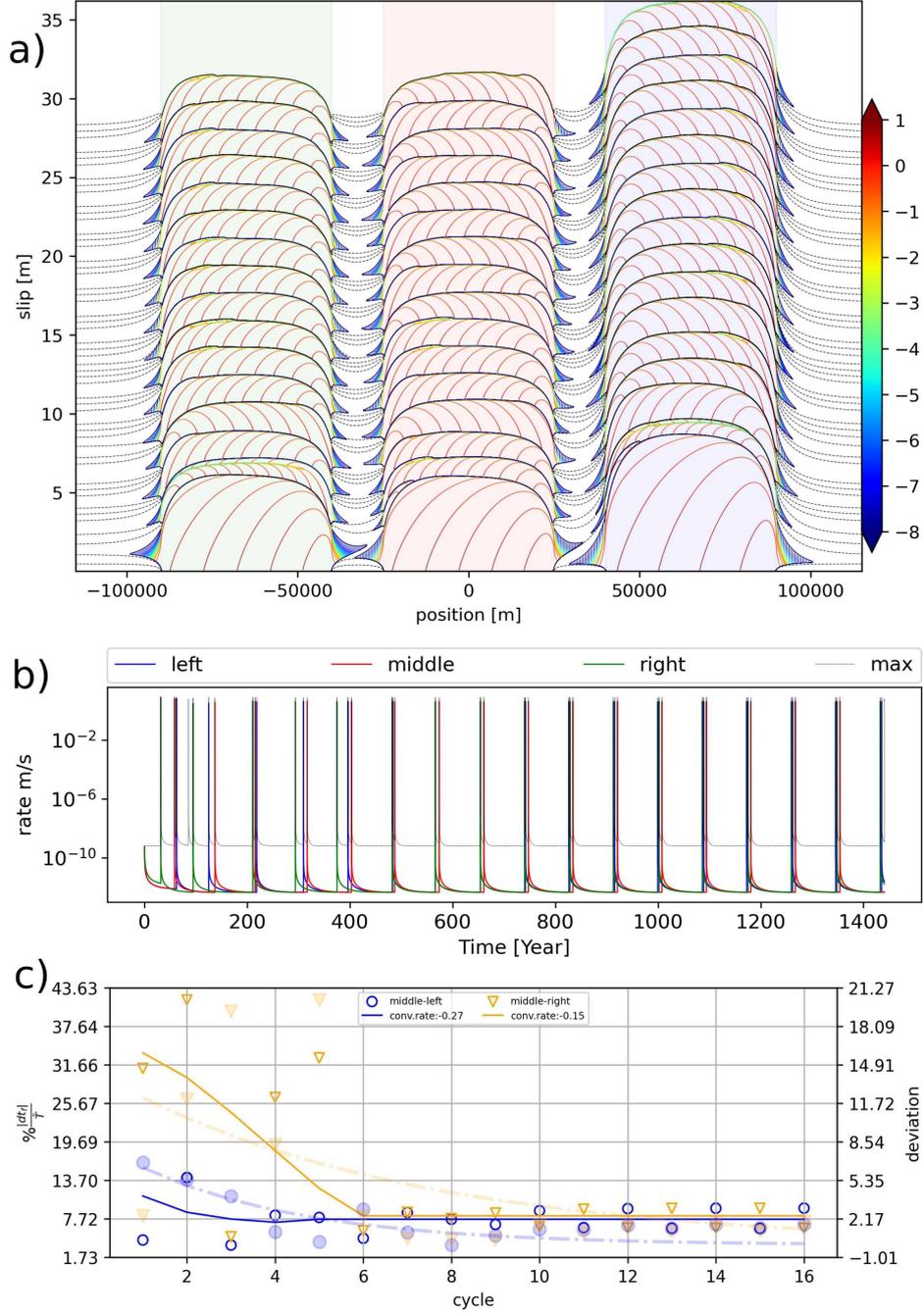


Figure 3. A synchronization example using slip law and default parameters in Table 1. a) slip profile: slip velocities are plotted in the logarithmic scale defined in the color bar on the right side. The dynamic rupture is plotted in two-second intervals, and post- or pre-seismic events are plotted with scatter plot until they reach a critical value $v_c = 10^{-8} m/s$. The inter-seismic times are plotted with black dashed lines every 20-year interval. b) time series of the middle of each asperity. The colors are given in the legend. c) Synchronization status of adjacent segments. Solid thin lines and scatters without face color denote constraint fit to normalized adjacent segment's failure time differences. The filled color scatters and bold dashed lines denote the deviations from the constraint fit.

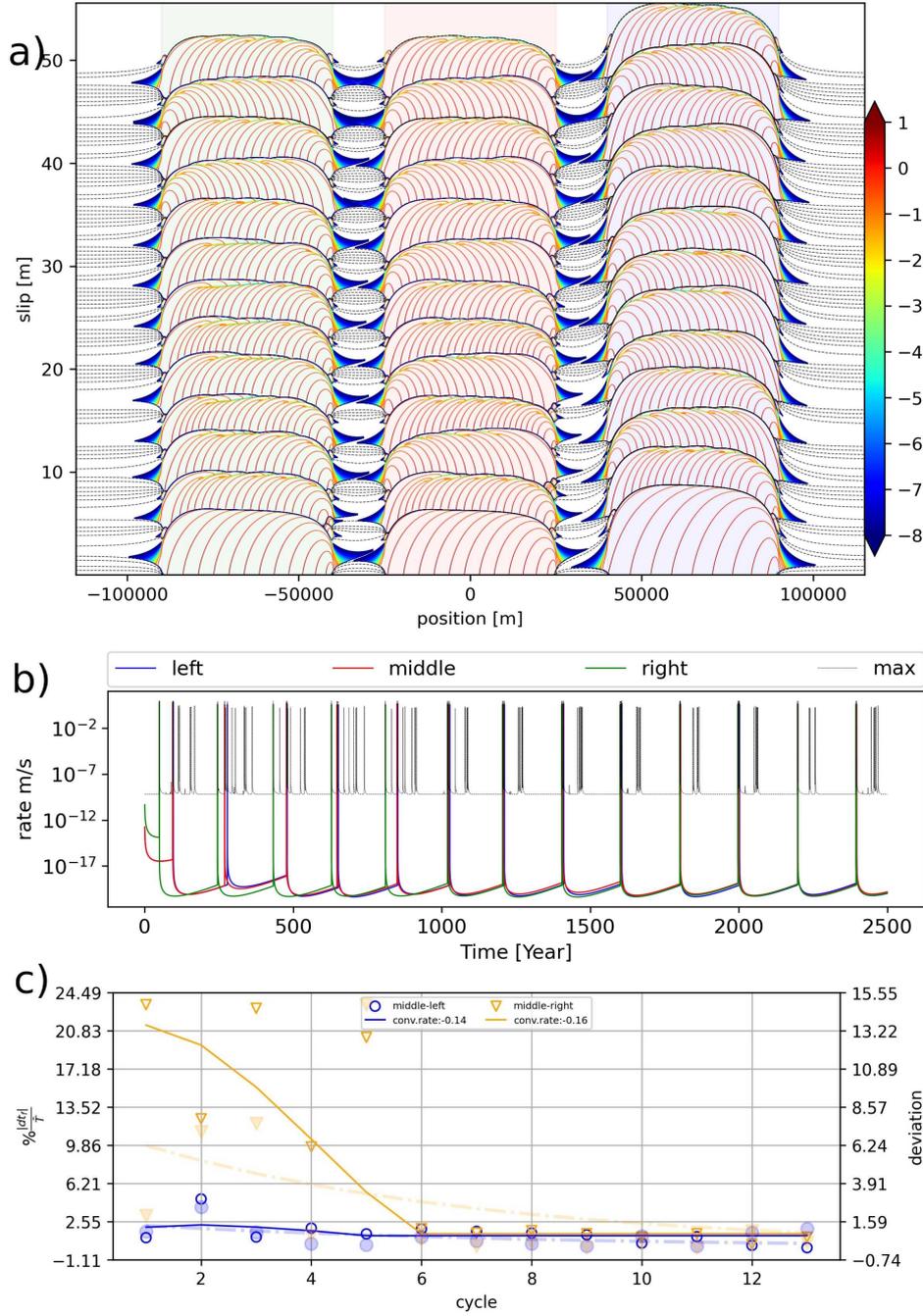


Figure 4. A synchronization example using aging law with default parameters in Table 1. a) slip profile: slip velocities are plotted in the logarithmic scale defined in the color bar on the right side. The dynamic rupture is plotted in two-second intervals, and post- or pre-seismic events are plotted with scatter plot until they reach a critical value $v_c = 10^{-8} m/s$. The inter-seismic times are plotted with black dashed lines every 20-year interval. b) time series of the middle of each asperity. The colors are given in the legend. c) Synchronization status of adjacent segments. Solid thin lines and scatters without face color denote constraint fit to normalized adjacent segment's failure time differences. The filled color scatters and bold dashed lines denote the deviations from the constraint fit.

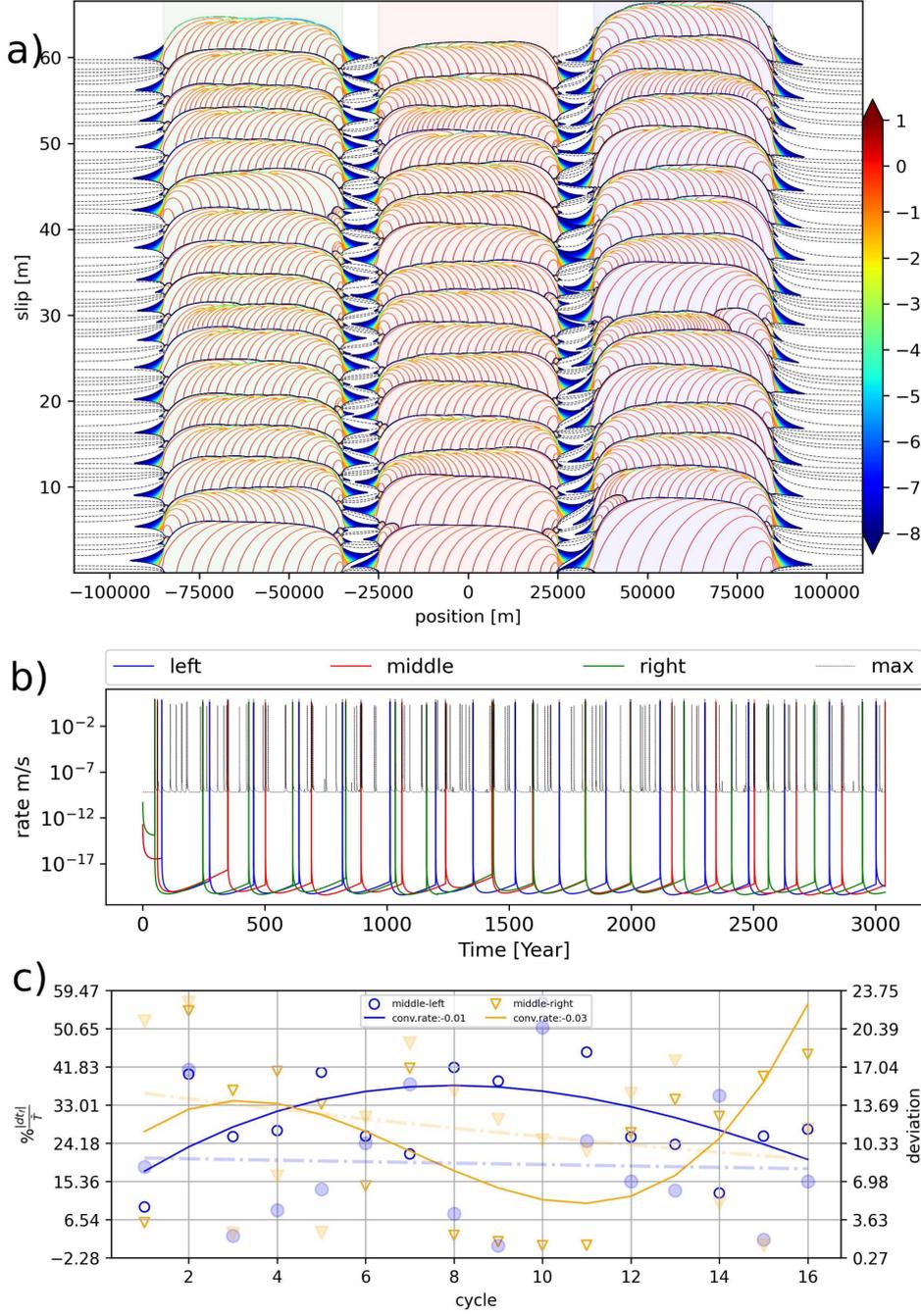


Figure 5. A complex example using aging law with default parameters in Table 1, except the barrier length decreased to 10km. a) slip profile: slip velocities are plotted in the logarithmic scale defined in the color bar on the right side. The dynamic rupture is plotted in two-second intervals, and post- or pre-seismic events are plotted with scatter plot until they reach a critical value $v_c = 10^{-8} m/s$. The inter-seismic times are plotted with black dashed lines every 20-year interval. b) time series of the middle of each asperity. The colors are given in the legend. c) Synchronization status of adjacent segments. Solid thin lines and scatters without face color denote constraint fit to normalized adjacent segment's failure time differences. The filled color scatters and bold dashed lines denote the deviations from the constraint fit.

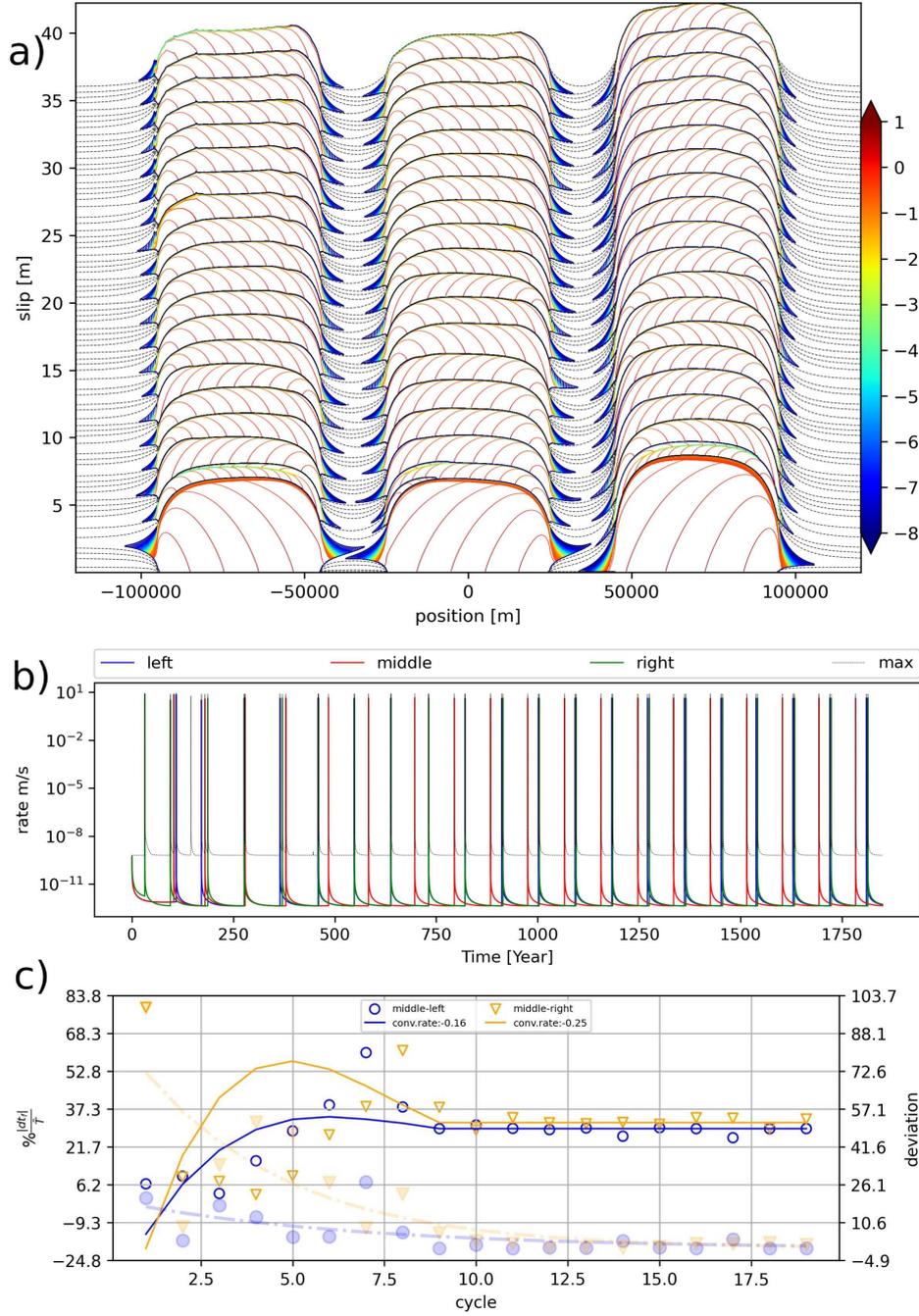


Figure 6. An independent status example using slip law with default parameters in Table 1, except the barrier length increased to 20 km and $a_{bar} - b = 0.003$. a) slip profile: slip velocities are plotted in the logarithmic scale defined in the color bar on the right side. The dynamic rupture is plotted in two-second intervals, and post- or pre-seismic events are plotted with scatter plot until they reach a critical value $v_c = 10^{-8} m/s$. The inter-seismic times are plotted with black dashed lines every 20-year interval. b) time series of the middle of each asperity. The colors are given in the legend. c) Synchronization status of adjacent segments. Solid thin lines and scatterers without face color denote constraint fit to normalized adjacent segment's failure time differences. The filled color scatterers and bold dashed lines denote the deviations from the constraint fit.

189 Figures 3 and 4 demonstrate a gradual decrease in failure time differences between
 190 neighboring asperities, leading to synchronization. Both setups have the same param-
 191 eters, except different state laws govern the frictional interface. Although synchroniza-
 192 tion patterns are similar (as seen in Figures 3-b and c and 4-b and c), the dynamics of
 193 the state laws are vastly different. The wave speed of the slip law is twice as fast as the
 194 aging law (Figures 3-a and 4-a). The aging law sustains quasi-true stationary contact
 195 during slow loading with near-zero slip rates and twice the recurrence times and slip amounts
 196 per cycle compared to the slip law. The slip profiles (Figures 3-a and 4-a) also show that
 197 the slip extension and duration at the VS region is higher for the aging law. As we will
 198 see later, the aging law’s generated peak stress is almost twice the slip law with the same
 199 setup. Still, due to higher fracture energy, the aging law can generate smaller events at
 200 the asperity edges by arresting the rupture within the VW region; the slip law tends to
 201 slip fully, exhibiting a vast difference in synchronization and triggering.

202 The studies previously stated that closer asperities and smaller barrier-asperity ratios
 203 mainly control synchronization processes (Kaneko et al., 2010; Corbi et al., 2017;
 204 Rosenau et al., 2019). However, the results in our simulations show otherwise that de-
 205 creasing the barrier size from 15 km (Figure 4) to 10 km (Figure 5) leads to desynchro-
 206 nization of the fault zone. More variable-sized events emerge for closer asperities due to
 207 the triggering by the neighbor asperity, leading to immature events. These immature slips
 208 can not propagate fully, are arrested within the asperity, and leave stress further het-
 209 erogeneity. On the other hand, weaker coupled asperities due to the longer barrier length
 210 and stronger velocity strengthening barriers sustain better synchronization. Still, too weakly-
 211 coupled asperities due to the barrier length (Figure 6) converge to a value higher than
 212 a threshold; they generate regular cycles but are classified as independent slip events.

213 3.2 Sensitivity Analyses

214 Figures 3 - 6 display how barrier length significantly changes the fault zone’s syn-
 215 chronization pattern. Wei and Shi (2021) pointed out in a model with two asperities that
 216 the barrier’s length is more important than its frictional properties. We examine the bar-
 217 rier’s impact on synchronization by visualizing the barrier length change (with colors)
 218 and VS behavior ($a_{bar}-b$) change in different subplots in Figure 7. The extremely short
 219 (5km) and weak barrier ($a_{bar}-b < 0.003$) synchronizes very fast, regardless of the state
 220 law they govern. The slip law generally exhibits more regular cycles, either synchronized
 221 or independent failures. Yet, if the barrier is extremely weak $a_{bar} - b = 0.0$, it may
 222 generate complex earthquake cycles, as shown in Figure 7. The simulation with the ag-
 223 ing law favors more partial ruptures; as a result, many simulations are classified as com-
 224 plex. On the other hand, it shows two distinct synchronization patterns depending on
 225 the barrier length and frictional strength. While the weak VS barrier ($a_{bar}-b < 0.003$)
 226 synchronizes very fast for short barrier lengths (blue color line in Figure 7), longer bar-
 227 riers require stronger VS $a_{bar} - b > 0.003$ so that neighbor events do not lead to trig-
 228 gered immature partial ruptures. For example, the 15 km barrier length with aging law
 229 (orange color at top subplots) can not synchronize unless the barrier is strong enough
 230 $a_{bar} - b = 0.005$ to inhibit the immature triggered rupture.

231 Figure 8 examines the parameters related to asperity. Decreasing the direct veloc-
 232 ity effect parameter makes the asperity prone to triggering. For the aging law (Figure
 233 8 upper-left subplot), all simulations display complex failure times as a_{asp} changes for
 234 the default barrier strength $a_{bar} - b = 0.003$. Inset Figure 8 (upper-left) for the aging
 235 law emphasizes how barriers’ frictional properties significantly change the results; increas-
 236 ing barriers strength $a_{bar} - b = 0.005$ leads to synchronization of asperities. A similar
 237 pattern also emerges for the slip law (Figure 8 lower-left), showing the barrier’s strength
 238 significantly affects the synchronization. While moderate barrier strength ($a_{bar} - b =$
 239 0.003) exhibits synchronization for higher direct velocity effect parameter a_{asp} , higher
 240 barrier strength in the inset $a_{bar} - b = 0.005$ leads to synchronization for lower a_{asp} .

241 In other words, the asperity that is more prone to triggering synchronizes better with
 242 the strong barrier and vice-versa.

243 Subplots in the middle column of Figure 8 shows the effect of d_c on synchroniza-
 244 tion. According to the results for $d_c = 8 - 16mm$, no direct influence on synchroniza-
 245 tion is visible. We also tested $d_c = 24mm$, which can lead to bilateral rupture propa-
 246 gation due to increasing the nucleation zone (Dieterich, 1992; Ampuero & Rubin, 2008),
 247 but this does not change our conclusion on the synchronization. The asperity size is gen-
 248 erally large enough to mimic the NAF’s large strike-slip segments so that large earth-
 249 quakes can nucleate at the VS-VW edge and fully slip. On the other hand, the larger
 250 d_c can change the post-slip slip pattern on the barrier, but it does not change our con-
 251 clusion.

252 The change in the asperity size L_{asp} displays no significant influence on the syn-
 253 chronization pattern (right sub-figures 8). Our result on L_{asp} contradicts some studies
 254 relating the barrier efficiency to the asperity barrier length ratios (Kaneko et al., 2010;
 255 Corbi et al., 2017). One reason for such an exact opposite result is the rupture propa-
 256 gation type. Our model is specifically designed for the large strike-slip faults along NAF,
 257 with larger length-to-width ratio L_{asp}/W , so that slip generally nucleates at the one edge
 258 and slips over the domain with a self-healing pulse as observed from previous earthquakes
 259 (Konca et al., 2010). Therefore, we apply the 2.5D model (Luo & Ampuero, 2018), as-
 260 suming that the slip averaged over the width. This assumption changes the rupture pat-
 261 tern to a self-healing pulse so that the slip does not grow as a crack-like pattern, lead-
 262 ing to the maximum slip amount independent of the asperity length.

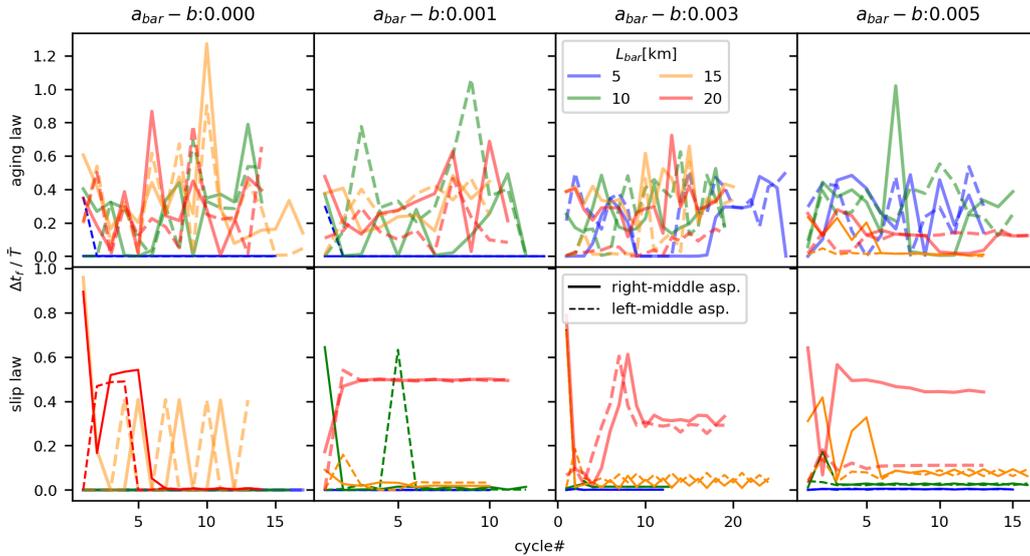


Figure 7. The figure shows the effects of barrier length and its frictional properties on syn-
 chronization. The horizontal and vertical axes are the earthquake cycle and the normalized
 (divided by the mean recurrence time) failure time differences between adjacent asperities. The
 effects of a change in the barrier’s frictional properties ($a_{bar} - b$) and state types are plotted in
 vertical and horizontal orders, respectively. The failure time differences between right-middle and
 left-middle asperities are plotted with solid and dashed lines, and their colors indicate barrier
 lengths, given in the legends. The synchronized and complex setups are also distinguished by their
 line transparency to improve readability. Unless otherwise stated, the parameters are set to the
 default values in table 1.

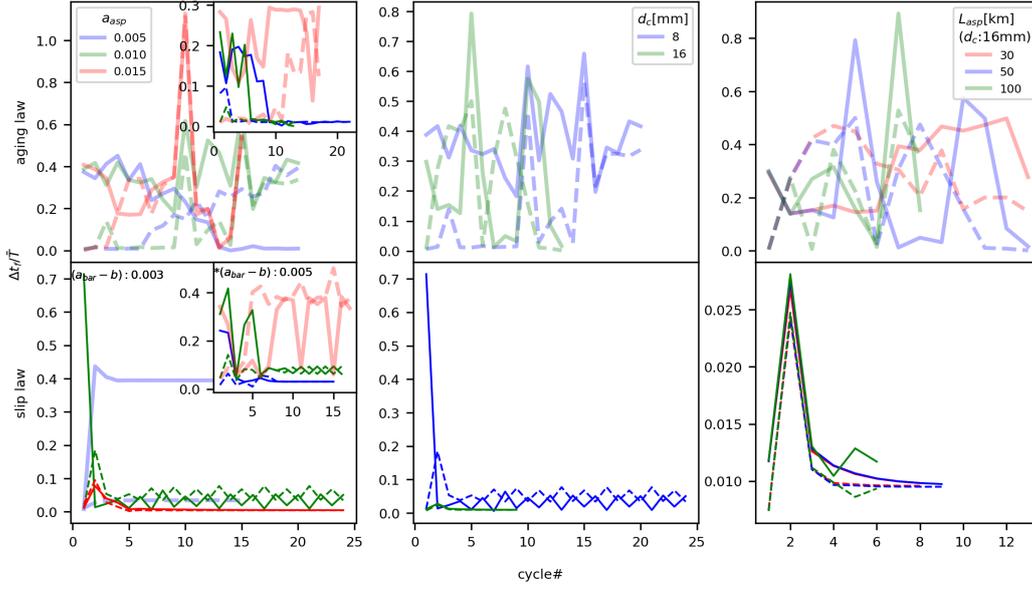


Figure 8. Figure shows the effects of asperity’s frictional properties, size, and critical slip distance changes on the synchronization. The horizontal and vertical axes are the earthquake cycle and the normalized failure time differences between adjacent asperities. The effects of a change in the asperity’s direct velocity effect parameter a_{asp} , critical slip distance d_c , and asperity length L_{asp} are plotted vertically for aging and state laws, respectively. The failure time differences between right-middle and left-middle asperities are plotted with solid and dashed lines. Changes in parameters are plotted with different colors, given in the legends. The synchronized and complex setups are also distinguished by their line transparency to improve readability. Also, in the inset figures, the barrier’s frictional property is set to $a_{bar} - b = 0.005$ to visualize the effect of the barrier’s strength. Unless otherwise stated, the default parameters are in table 1.

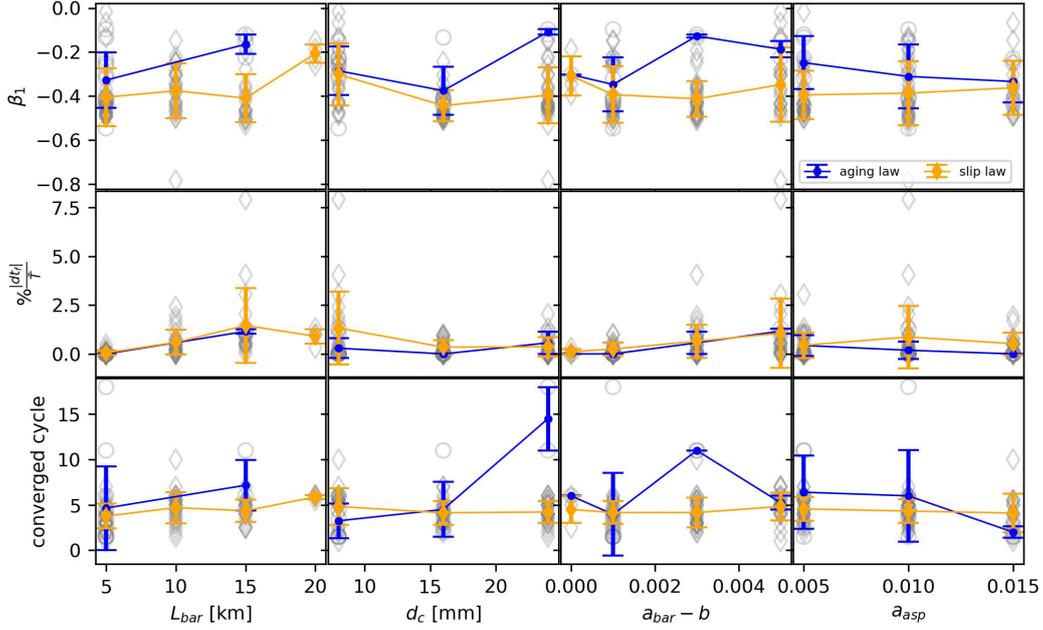


Figure 9. The plot shows how fast the faults are synchronized with changing certain parameters. The so-called convergence rates (β_1 of fitted deviance) are plotted on the top. The middle row shows the converged values, defined by the failure time differences in percentage between two successive large earthquakes of adjacent faults normalized by mean recurrence time. The lower row is the converged cycle defined, after which cycle faults synchronize.

263 Next, we order the convergences in Figure 9. The parameters that are sensitive to
 264 synchronization are grouped (the horizontal axes of Figure 9), and the results are compared for the β_1 parameter, the convergence value, and the converged cycle (the vertical
 265 axes of Figure 9). According to the exponential model, the convergence is faster and
 266 more stable for negative values of β_1 because it deviates less from the fitted model to
 267 residuals. The smaller converged value means the failure time difference is shorter, and
 268 lower converged cycles indicate a quicker synchronization. Figure 9 demonstrates that
 269 the slip law sustains a better synchronization than the aging law. The mean converged
 270 values (the difference between the full ruptures on the adjacent asperities) are similar
 271 for both laws unless the barrier is extremely large or strong ($L_{bar} = 20km$, $a_{bar} - b =$
 272 0.005). The first column in Figure 9 demonstrates that lower barriers lead to faster syn-
 273 chronization, closer failure times, and higher deviations due to the strong coupling be-
 274 tween asperities. Increasing critical slip $d_c = 8mm$ and $d_c = 16mm$ does not change
 275 the convergence, but a further increase to $d_c = 24mm$ leads to higher deviations. This
 276 deviation is not because d_c is a sensitive parameter to synchronization but because in-
 277 creasing d_c increases the nucleation half-length (Ampuero & Rubin, 2008) for nucleation
 278 of a slip event. For $d_c = 24mm$, slip events can nucleate closer to the asperity center
 279 rather than its VS-VW transition. The weaker barrier ($a_{bar} - b$) generally sustains bet-
 280 ter synchronization. The aging law shows a better synchronization for larger a_{asp} , which
 281 leads to a weaker triggering potential. On the other hand, the slip law shows less sig-
 282 nificance in its synchronization rate to the asperity's frictional because of its smaller frac-
 283 ture energy.
 284

285

3.3 The role of static triggering

286

287

288

289

290

291

292

293

294

295

296

297

298

299

300

Figure 10 displays the five full rupture events on the middle asperity and their propagation over time. The state laws differ significantly during co-seismic ruptures but resemble each other in the post-seismic phase. The aging law's instantaneous stress increase on the barrier is twice the slip law's. Hence, the after-slip duration and peak slip values are larger, so the significant stress can reach the neighbor asperity for the aging law. If the barrier is short enough, the co-seismic rupture can propagate through the barrier and increase the stress level significantly at the asperity edge, so-called static stress triggering. Suppose the stress levels or slip deficits are close to each other. In that case, the rupture on one asperity can lead to another full rupture at the neighbor asperity, which we call synchronization. Otherwise, the static triggering leads to an immature event that can not fully rupture, generating further stress heterogeneity between the asperities. Here, the slip law is more inclined to synchronization because it can rupture with smaller fracture energy (Ampuero & Rubin, 2008). Even though two asperities have different slip deficits, an immature rupture can continue rupturing with smaller slip values, still able to equalize the stress balance.

301

302

303

304

305

306

307

308

To further emphasize our conclusion that static stress transfer leads to complex failures, the snapshots of slip propagation for complex and synchronized fault zones are shown in figure 11. Three successive slip events on the middle asperity and after-slips at the surrounding barriers are shown. The figure shows that three successive co-seismic rupture propagation are considerably similar, regardless of fault zone is synchronized or not. However, synchronized fault zones show remarkably smaller slip propagation, thus weaker triggering effects, justifying our conclusion that static stress transfer leads to complex failures.

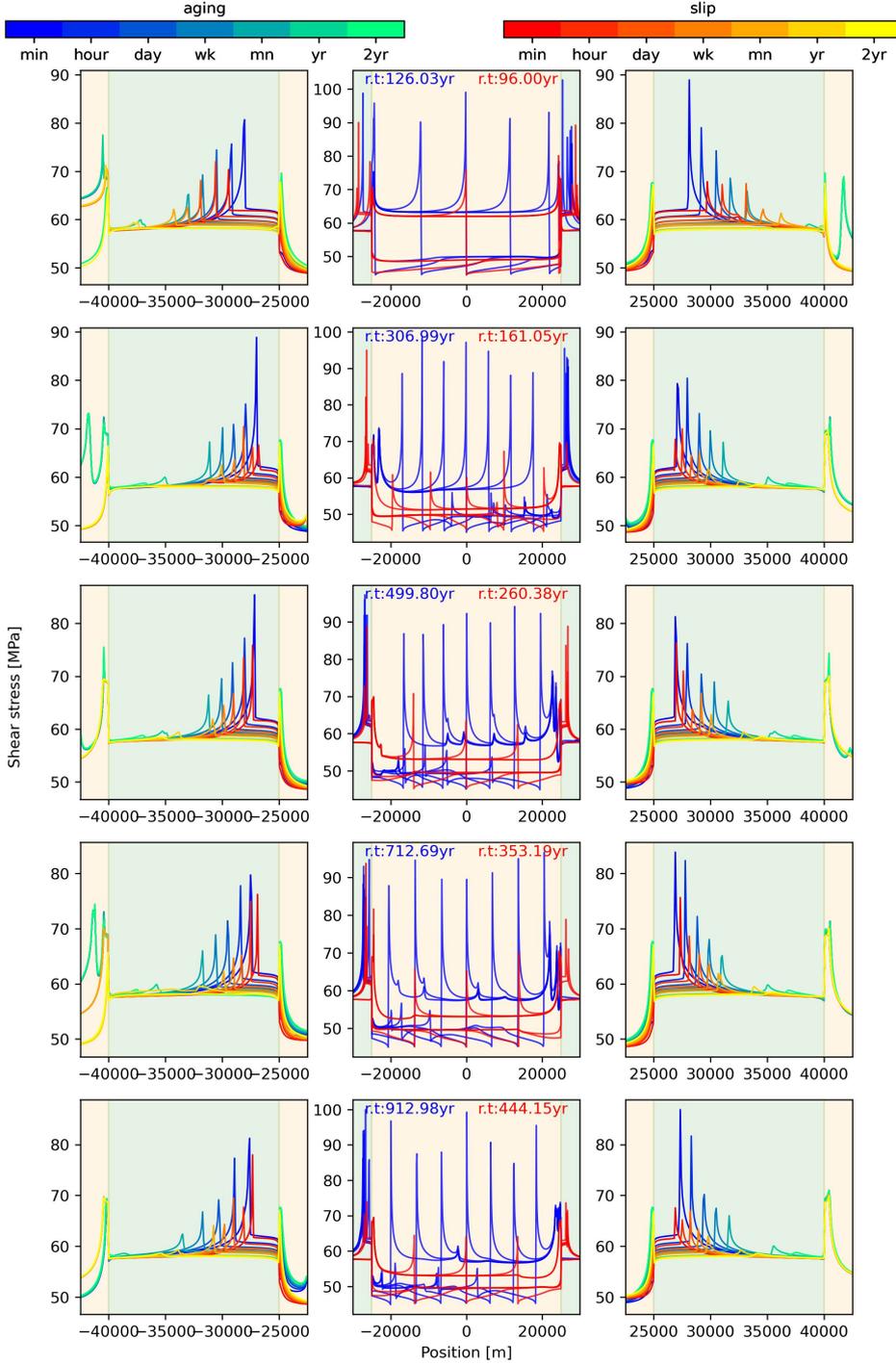


Figure 10. 5 full successive ruptures and post-seismic propagation of middle asperity are plotted. The default parameters in table 1 are used, except $a_{bar} - b = 0.003$. On the left and right, the propagation on the barrier is plotted with colored lines that define the time and state law, given in the color bar. The propagation on the middle asperity is plotted in the middle subplots with 5-second intervals. Rupture times are written in the middle plot for each state law with the color code defined in the color bar.

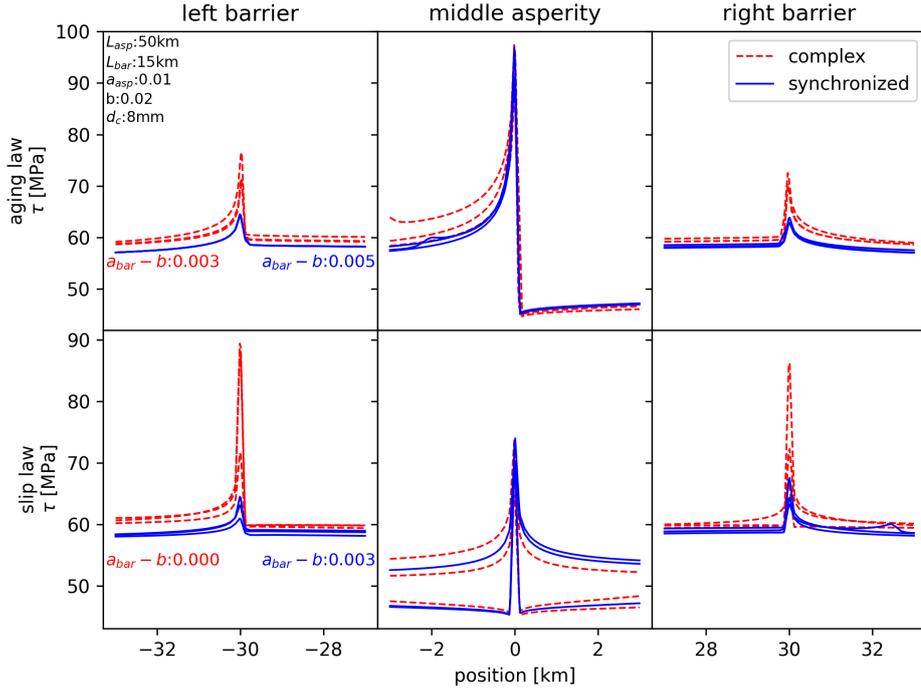


Figure 11. The stress propagation of complex and synchronized simulations are plotted for full ruptures on the middle asperity and continuation on the left and right barrier. The plotted waves correspond to the highest amplitudes of the first-fourth ruptures on the middle asperity and 5km away from it. The parameters for simulation are written on the first sub-plot (upper-left) and plotted with a color code for the synchronization status given in the legend. Complex and synchronized status simulations correspond to the $a_{bar} - b$ values given in the first column for aging and slip laws.

309

3.4 Indicator of synchronization and predictability of large earthquakes

310

311

312

313

314

315

316

317

318

319

320

321

Many scenarios generated synchronized, complex, and independent fault zones that can mimic characteristic earthquakes along major strike-slip fault zones like NAF. The simulation results show that the synchronized or independent fault zones exhibit higher velocities. Therefore, we plotted the clustered fault zones as peak velocities (PV) and concerning other observable in Figure 12. According to the results, fault zones with higher rupture lengths, shorter duration, and faster wave speeds are valuable indicators for large earthquakes' predictability. Besides, fault zones exhibiting shorter pre and post-seismic duration and length are more predictable. Also, the predictable earthquakes exhibit less co-seismic stress drop than the complex fault zones. On the other hand, the predictability is unrelated to the magnitude and maximum observed slip. The complex fault zones show a partial rupture ratio close to 1 (the rate between partial and full ruptures) due to the triggering of neighbor asperity, which leads to immature ruptures.

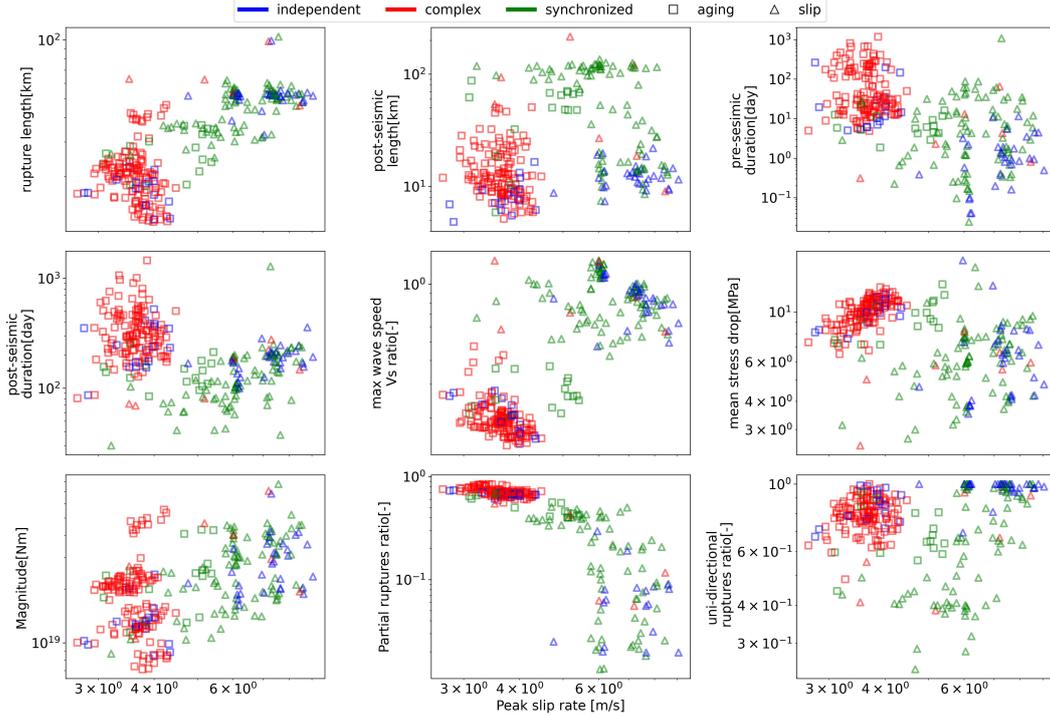


Figure 12. Peak Velocity (slip rate) [m/s] vs. Distribution stats of slip event

4 Discussion on results

We analyzed the spontaneous failure times of initially heterogeneous three vertical strong velocity weakening (VW) asperities separated by velocity strengthening (VS) barriers within the rate and state friction (RSF) framework. Our 2.5D numerical setup is designed for investigating the fault segments' synchrony along the North Anatolian Fault (NAF) Zone (Şengör et al., 2005). Still, the results will also shed light on other major fault zones. We extended previous studies using RSF (Wei et al., 2018; Shi et al., 2022) by considering different state laws, namely aging and slip laws (Dieterich, 1979; Ruina, 1983). The simplified inertial effect, the so-called quasi-dynamic (QD) method, was used in numerical simulations (Rice, 1993). Still, fully-dynamic (FD) effects with wave-mediated stress transfer were tested (Lapusta et al., 2000), in supplementary figures 1 and 2, which indicate despite the FD affects the co-seismic wave propagation significantly, FD has an insignificant effect on the synchronization. Therefore, we leave a detailed discussion on the FD effects on a later study.

We investigated the mechanisms of reciprocal earthquake triggering and synchronization. We applied analyses to determine fault synchronization's sensitive and insensitive parameters to reveal its possible mechanism. Examining the large data generated by the simulations led us to identify fault synchronization indicators that are observable in nature. This has important implications for understanding the predictability of large earthquakes, especially in major fault zones with limited reliable data like NAF due to long recurrence periods. Finally, this study aims to provide insights into the future seismic risks along NAF.

344

4.1 State laws

345

346

347

348

349

350

351

352

353

354

The simulation results reveal distinct dynamics for the aging and slip law. It is worth noting that the outcomes of numerical models with RSF depend on how well the grid points are resolved (Lambert & Lapusta, 2021). At least 9 or 12 grid points per the nucleation zone length Λ_0 are used (Equation 2) (Dieterich, 1992). The resolution is sufficient for the Aging law with the quasi-dynamic approximation (Lambert & Lapusta, 2021). Still, slip law requires denser grid points and necessitates indeed more computational resources (Ampuero & Rubin, 2008). However, we did not observe independently failing grids due to the coarse resolution with the slip law thanks to its weaker fracture energy, which tends to slip fully and thus reasonably generate robust solutions for the synchronization problem.

355

356

357

358

359

360

361

362

363

364

365

366

According to laboratory studies, aging law fails to fit large slip rates, while slip law performs better (Nakatani, 2001; Bhattacharya et al., 2015). Moreover, the Slip law promotes better transient triggering than the aging law due to its stronger weakening rate, but they show similar static triggering effects (Sopacı & Özacar, 2023). A significant divergence in the co-seismic dynamics emerges for both laws, but both laws resemble each other at the VS barrier (Figures 11, 10). Since we observed that the synchronization mechanism is mainly controlled by the barrier’s strength or frictional properties, the choice of the state law did not change our conclusion. So, despite the differences between aging and slip laws, our observations regarding fault synchronization and the role of barrier properties remained consistent across the two state laws. This adds robustness to our conclusions and further supports the significance of barrier strength in fault synchronization dynamics.

367

4.2 Triggering and Synchronization

368

369

370

371

372

373

374

375

376

377

378

379

380

381

382

383

384

385

386

387

388

389

We observed two kinds of static triggering in our simulations. For the first kind, the coseismic slip can propagate through the VS zone to the neighbor VW asperity, or it nucleates within the VW zone but can not propagate and arrest within the VW zone, as a result changing the stress level in the vicinity (Gomberg et al., 1998). This happens if the barrier can not fully stop the afterslip propagation within its domain depending on the amount of load and, most importantly, its strength and size. Or the triggered immature event can not propagate future. The barrier can yield the loaded stress in the VS domain in the second static triggering mechanism, temporarily increasing the creep speed. The latter can lead to synchronization, while the first generally generated complex failure times in our results, unlike the results suggested by (Wei & Shi, 2021; Shi et al., 2022). These contradicting conclusions with similar studies can be due to their milder simulation setup, which shows how the rupture dynamics can drastically change the results. Figures 6 and 7 of (Wei & Shi, 2021) show the creep can penetrate through the asperity, and the earthquake nucleates close to the asperity center. Such creep penetration accounts for a setup in which the nucleation phase requires a larger slip directly related to d_c and a/b parameters, supposed that the seismogenic width is large enough (Cattania, 2019). In our simulation setup, the earthquakes generally nucleate at the asperity edges and propagate unilaterally as a self-healing pulse along the VW asperity, diverging from their dynamics. More to the point, such large nucleation zones with the higher d_c were discussed as non-physical (Rubin & Ampuero, 2005); since then, the nucleation process should have been detectable from the earth’s surface. Therefore, we suggest static triggering leads to asynchronous failure times, justifying (Scholz, 2010).

390

391

392

393

394

Through temporary changes in stress due to waves passing by and under certain conditions, the external perturbations can lead to a self-acceleration of the locked patch (Sopacı & Özacar, 2023). The slip law’s sensitivity to an external perturbation is higher than the aging law’s due to its stronger weakening term (Nakatani, 2001; Sopacı, 2023). Nonetheless, the static triggering effects are several times higher than the transient ef-

395 facts (Sopaci & Özacar, 2023). Since the simulations started with initially heterogeneous
 396 stress, we do not think the transient effects are responsible for driving the segments into
 397 synchrony; instead, it is the afterslip propagation.

398 4.3 Sensitive parameters

399 Our results suggest strong barriers can dampen the after-slip propagation; as a re-
 400 sult, the stress transfer occurs aseismically and sustains synchronization, whereas weak
 401 barriers allow triggered immature small events and lead to more variable-sized and com-
 402 plex failure distribution. The $\sigma_n(a-b)$ parameter of the barrier mainly controls the bar-
 403 rier’s strength. The length of the barrier is not directly related to the barrier’s strength,
 404 but the longer it is, the less the coseismic slips can reach the neighbor barrier and lead
 405 to immature earthquakes. More to the point, the inset subplots in figure 8 show how chang-
 406 ing the barrier’s strength changes the synchronization dependence on other parameters.
 407 In that sense, our sensitivity analyses diverge from the (Wei & Shi, 2021), stating that
 408 the barrier’s length is more important than its frictional properties.

409 The simulation results in this study show that the synchronization depends am-
 410 biguously on the asperity parameters. The numerical earthquake triggering studies with
 411 RSF state that the direct velocity effect parameter controls the response to an external
 412 perturbation; thus, the smaller a_{asp} , the more prone it is to be triggered. Sensitivity to
 413 a_{asp} in figure 8 shows how asperity that is prone to triggering $a_{asp} = 0.005$ can syn-
 414 chronize for strong barrier $b - a_{bar} = 0.005$ but shows complex failure with $b - a_{bar} =$
 415 0.003 . Figure 8 also shows that the change in the asperity size shows insensitivity to syn-
 416 chronization. Our conclusion contradicts the idea that the asperity barrier ratio quan-
 417 tifies the barrier efficiency and controls the asperity synchronization process (Corbi et
 418 al., 2017; Kaneko et al., 2010). In this study, the three asperities with identical proper-
 419 ties dictate pulse-like ruptures that unilaterally propagate along the strike, assuming the
 420 slip is the same within a finite width W (Luo & Ampuero, 2018). The rupture styles,
 421 such as crack-like growth or slip pulses, can change the recurrence patterns from chaotic
 422 to quasi-periodic (Nie & Barbot, 2022). Also, the 3D complex fault structure may lead
 423 to more complex failure sequences closer to statistical power laws in nature (Yin et al.,
 424 2023), thus may show more sensitivity to asperity properties. However, our main con-
 425 clusion states that the barrier strength mainly controls the synchronization, and thus,
 426 the predictability of earthquakes would not change.

427 Moreover, critical slip distance d_c is used several times larger than the laboratory
 428 experiments for the sake of the computational burdens (Ampuero & Rubin, 2008; La-
 429 pusta et al., 2000). The value of d_c also dictates the minimum nucleation length scales
 430 to generate seismic events (Dieterich, 1992; Rubin & Ampuero, 2005; Ampuero & Ru-
 431 bin, 2008). The values used in this study for d_c do not alter the synchronization results.
 432 However, different rupture styles emerge for the upper values of d_c , also affected by the
 433 constitutive parameters a and b , and effective normal stress, which can impact the com-
 434 plex failure time occurrences (Cattania, 2019), should be noted.

435 4.4 Predictability Of Large Earthquakes

436 Synthetic data generated by numerous scenarios fitting the NAF analogy reveal that
 437 the predictability of fault zones is correlated to the peak slip rate, after-slip propagation,
 438 and rupture speed. Predictable synchronized earthquakes generally exhibit relatively long
 439 silent periods and successive full ruptures resembling super-cycles. Super-cycles are gen-
 440 erally associated with subduction zones and thrust faults, showing quasi-periodic recur-
 441 rence intervals (Herrendörfer et al., 2015; Salditch et al., 2020). Even though not quite
 442 similar and quasi-regularly compared to subduction zones, the strike-slip fault zones show
 443 clustered and synchronized segments in time and space as observed along NAF (Şengör
 444 et al., 2005; Bouchon et al., 2021). The mature fault zones are generally less likely to pro-

445 duce smaller events and host pulse-like earthquake ruptures that can propagate through-
 446 out the seismogenic zone (Thakur & Huang, 2021; Lambert et al., 2021). Even though
 447 it has not been well established, the rupture speed and rupture type, i.e., crack growth
 448 or slip pulse, are interrelated (Huang & Ampuero, 2011). The synchronized fault zones
 449 in this study slip fully with faster propagation speed and higher peak slip rates, suggest-
 450 ing mature fault zones are likely to synchronize. Also, our results justify the importance
 451 of slow aseismic slip as a mechanism of large earthquake nucleation and triggering (Nie
 452 & Barbot, 2022; Bouchon et al., 2021; Nalbant et al., 2023). Identifying the creeping re-
 453 gions and tracking the aseismic motion are the keys to identifying future seismic risks.

454 5 Implications On North Anatolian Fault Zone

455 North Anatolian Fault Zone (NAF) is one of the most active strike-slip fault zones.
 456 The fault segments fail quasi-periodically with approximately 250-300 years of recurrence
 457 interval, exhibiting a super-cycle-like pattern; large earthquakes fail relatively quickly
 458 and proceed with a long seismic quiescence. This sequential failure pattern constitutes
 459 clusters, and discreteness appears between the clusters due to the failure time differences
 460 (Bulut & Dođru, 2021). The synchronized clusters became more regular after the sev-
 461 enteenth century, which was less clear before (Şengör et al., 2005). In the twentieth cen-
 462 tury, a new sequence of large earthquakes began with the MS7.9 Erzincan (1939) at the
 463 eastern edge of the NAF. It migrated towards the west following MS7.1 Niksar-Erba (1942),
 464 MS7.5-7.7 Tosya-Ladik (1943), MS7.4 Bolu-Gerede (1944) ruptures (Şengör et al., 2005)
 465 (see also Figure 1). Remarkably, the following earthquake nucleated near where the pre-
 466 ceding rupture stopped. The synchronization slowed down after the Bolu-Gerede seg-
 467 ment, where the NAF splits into two branches: the north branch that dives into the Mar-
 468 mara Sea, called the Main Marmara Fault Zone (MMF), and the south branch (Bulut
 469 & Dođru, 2021). The sequence continued with the 1955 and 1967 earthquakes along the
 470 southern branch, while the northern branch waited 55 years until the Mw7.6 Izmit rup-
 471 ture on 17.08.1999. Three months later, on 12.11.1999 Mw7.2 Duzce fault ruptured at
 472 the eastern edge of the Izmit rupture. This earthquake doublet was an example of a de-
 473 layed triggering, explained mostly by the conventional static stress transfer (Stein et al.,
 474 1997). The MMF segment lies on the western side of the Izmit segment, which is thought
 475 to be the last chain to complete the 1500 km-long cycle. Kumburgaz and Cinarcik sub-
 476 segments within MMF remain unbroken in this current situation and have been most
 477 likely loading for a $M > 7$ earthquake (Lange et al., 2019).

478 The static stress transfer computations can reasonably indicate the elevated stress
 479 buildups but can not fully explain further triggering. For example, the Mw7.2 Duzce (12.11.1999)
 480 event does not correlate the mapped stress distribution with the previous events; instead,
 481 the maximum slip corresponds to the stress shadow of two adjacent M7.4 (1944, Bolu-
 482 Gerede) and Mw7.6 (1999, Izmit) ruptures and the hypocenter stands at the stress neu-
 483 tral region $\Delta\tau \approx 0$ (King et al., 2001; Utkucu et al., 2003). The stress and frictional
 484 state heterogeneity and the effect of an an-elastic time-dependent process during the nu-
 485 cleation are proposed to explain this inconsistency (Bouchon et al., 2021; Lorenzo-Martín
 486 et al., 2006; Pucci et al., 2007). Further, the Duzce rupture plane shows distinctly higher
 487 electric resistivity for the eastern where high slip occurred but had the stress shadow from
 488 previous ruptures. In contrast, the western part closer to the Mw7.6 Izmit rupture show-
 489 ing high-stress load has remarkably weaker resistance, interpreted as possibly a circula-
 490 tion of hydro-thermal fluids (Kaya et al., 2009). Supporting the idea, the lower nor-
 491 mal stress in the western part is proposed to inhibit the Izmit rupture propagation as
 492 a barrier and lead to the three-month delayed triggering (Pucci et al., 2007). Suppose
 493 faults consist of VW asperities embedded in a VS barrier-like environment. In that case,
 494 co-seismic slip can jump from one asperity to the other, mainly controlled by the VS en-
 495 vironment, as an alternative view to geometric complexity (Kaneko et al., 2010). There-

496 fore, we argue that frictional stress heterogeneity and after-slip propagation at the west-
 497 ern part of the Duzce fault better explain the inconsistency of the static stress transfer.

498 The trench observations also suggest the Bolu-Gerede segment (1944, east to the
 499 Duzce segment) consists of multiple asperities. These asperities failed synchronously, at
 500 least for the previous four ruptures, generating regular quasi-periodic cycles with sim-
 501 ilar sizes (Kondo et al., 2010). Furthermore, recent INSAR observations suggest that five
 502 creeping segments along NAF correlate well with the nucleation and arrest of large earth-
 503 quakes (Liu & Wang, 2023). They are Izmit, Ismetpasa, and Destek creeping segments,
 504 which were also reported previously (Cakir et al., 2014), and two newly identified creep-
 505 ing segments: in the middle of the 1939 earthquake and the spatial gap between the 1939
 506 and Ms 6.8 Erzincan (1992) rupture to the east. Combined with the step-overs, these
 507 regions perhaps control the synchronized earthquakes along NAF. Let us investigate three
 508 remarkable possible barriers and discuss their roles.

509 The Izmit segment was the final destination of the earthquake sequences, and re-
 510 cent observations suggest the western part of the Izmit segment is still creeping (Aslan
 511 et al., 2019). Besides, the 30 km Cinarcik releasing bend forms a depression that sep-
 512 arates the Izmit and Kumburgaz strike-slip segments, generating a large zone of (~ 14
 513 km thick) fault complexity (Armijo et al., 2005; Pondard et al., 2007; Uçarkuş et al., 2011).
 514 According to our numerical simulations, barriers over 20km long generally prevent sig-
 515 nificant stress transfer, leading to more independent failures. This may provide a basis
 516 that two strike-slip fault segments (Izmit and Kumburgaz) did not fail synchronously
 517 due to the Cinarcik releasing bend acting as a barrier.

518 A small break of the Cinarcik segment with normal fault mechanism is probably
 519 correlated to the MS6.3 1963 event, while larger $M\sim 7$ 1894 is to the southern branch of
 520 NAF in Marmara according to the sea floor investigation (Armijo et al., 2005). There-
 521 fore, the Cinarcik segment can be considered overdue; the last rupture beneath Marmara,
 522 possibly including the Cinarcik segment, was either in 1766 or 1754 (Pondard et al., 2007).

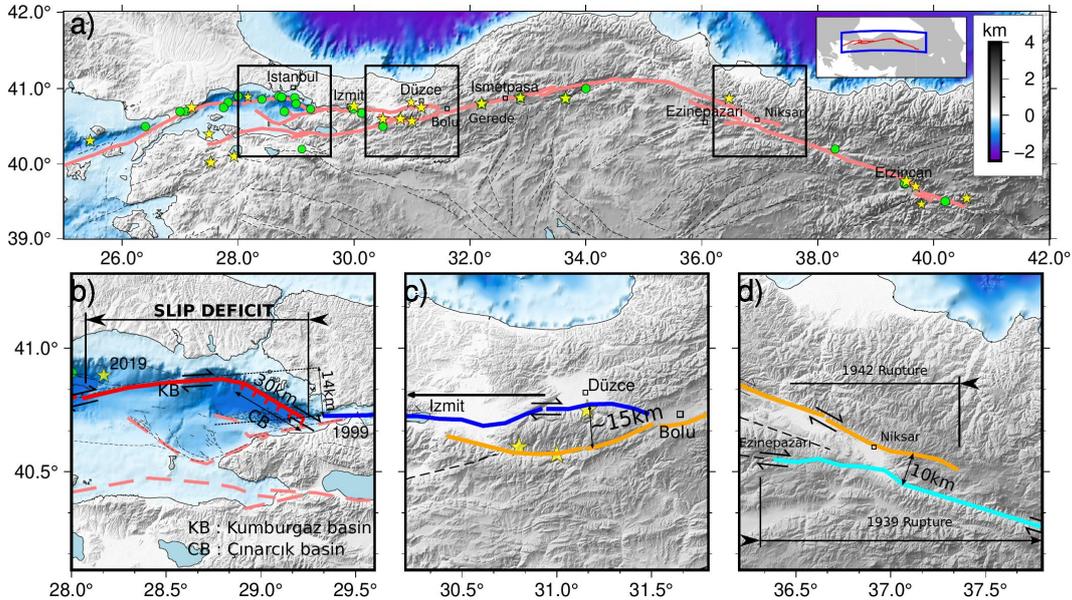


Figure 13. The Map (a) shows the synchronized segments along NAF in different color codes. The segment boundaries are highlighted with a black frame on map (a) and plotted on a larger scale in b-d.

523 However, there is still no satisfying proof during which earthquake the Cinarcik segment
 524 ruptured. On the western side, the Mw7.4 1912 Ganos earthquake is suggested to con-
 525 tinue to the Central Marmara basin and stop similar to the Izmit earthquake that stopped
 526 at the Cinarcik releasing bend (Aksoy et al., 2010). In this respect, Kumburgaz and Cinar-
 527 cik segments display slip deficits that can rupture during the next earthquake (Lange
 528 et al., 2019).

529 Recently, a moderate earthquake (Mw5.9 29.09.2019) occurred along a secondary
 530 fault near the Central Marmara Basin at the western tip of the Kumburgaz segment. It
 531 sparked a debate about whether it could trigger the expected large Marmara earthquake
 532 (Karabulut et al., 2021). According to our numerical investigations, the moderate event
 533 was not strong enough to trigger a large earthquake however, it could potentially advance
 534 the failure time (Sopacı & Özacar, 2023). However, the most important question still re-
 535 mains: where will the next earthquake nucleate, and what will be its extent?

536 According to our results, the two adjacent segments act as synchronized for a few
 537 cycles due to triggering and stress interaction, but this synchronization can be tempo-
 538 rary (Figures 7 and 8). This result suggests that a failure of Kumburgaz and Cinarcik
 539 segments in one single earthquake is possible if two segments are considered overdue (Bohnhoff
 540 et al., 2013; Lange et al., 2019). In that scenario, once an earthquake is nucleated within
 541 the Kumburgaz or Cinarcik segment, wave propagation can trigger the other earthquake
 542 instantaneously (Sopacı & Özacar, 2023). On the other hand, two large segments can
 543 fail with a delayed time, possibly similar to 1776 and 1754 events (Parsons, 2004; Pon-
 544 dard et al., 2007). The Cinarcik segment is likely weaker with a shorter recurrence in-
 545 terval due to active normal faulting in comparison to the adjacent strike-slip segments
 546 (Kumburgaz and Izmit), which complicates the long-term failure times of NAF and is
 547 one of the main reasons why synchronization slows down (Bulut & Dođru, 2021).

548 Historical earthquakes exhibit the west migrating synchronization rate slowed down
 549 after the Bolu segment (1944 rupture) (Bulut & Dođru, 2021), where NAF splits into
 550 north and south branches constituting a 10-15 kilometer width step-over with remark-
 551 able stress transfer appeared to be between the branches (Lettis, 2003). According to
 552 our results, the stress transfer in such distances can affect the synchronization depend-
 553 ing on the barrier's frictional properties. Many of our results suggest that the static stress
 554 transfer breaks the synchronization pattern due to leading immature earthquakes. More
 555 to the point, the difference in the slip distribution of the Duzce (Mw7.2, 12.11.1999) rup-
 556 ture can originate from the mechanical interaction between the Duzce and Izmit segments
 557 joint (Pucci et al., 2007), further complicating the failure times.

558 The MS7.8 Erzincan (1939) earthquake started a series of large earthquakes (1942,
 559 1943, 1944), nucleated at the eastern edge of the Erzincan fault, and propagated unilat-
 560 erally approximately 250 km to the west. Instead of following the main path of NAF,
 561 it propagated along the Ezine Pazari fault, the southern branch of the Niksar pull-apart
 562 region, about 75 km (Cakir et al., 2014). The observed slip values were comparably low
 563 at the Niksar pull-apart region, and possibly, it acted as a barrier (Cakir et al., 2014; Zabcı
 564 et al., 2011). However, the previous 1668 earthquake *MS* 8 is thought to have broken
 565 the whole segments, jumping over the 10km length step over including the Erzincan fault
 566 (1939-1944 ruptures in the twentieth century) after a large seismic gap, (Şengör et al.,
 567 2005). The recent cycle did not break the whole segments as in the seventieth century
 568 and broke sequentially was explained by the rupture propagation driven by the geomet-
 569 rical frictional differences (Cakir et al., 2014). In 1939, once the rupture could not jump
 570 the 10 km length step over due to the higher stress level along the Ezine Pazari, it led
 571 to a stress shadow onto the Erbaa-Niksar segment, leading to 3 years of delay. There-
 572 fore, it can lead to a larger earthquake as in 1668 for the next cycle (Cakir et al., 2014),
 573 showing the significance of the barrier's frictional and geometric structures for the seis-
 574 mic risk assessments.

6 Conclusion

Motivated by the synchronized historical pattern along the North Anatolian Fault (NAF) Zone, we investigated the fault synchronization on a 2.5D physics-based asperity-barrier model in the rate and state friction (RSF) framework. The simulations started with initially heterogeneous conditions, and after several spontaneous ruptures with various scenarios, we investigated the conditions that the fault zone can adequately equalize the stress levels between the segments, leading to synchronization. Results reveal that static stress transfer can lead to immature triggered events, so the slip deficit or stress heterogeneity remains, leading to complex failure times. On the other hand, the strength and size of the aseismic zones control the synchronization process. Thus, determining the aseismic zones and examining their slow and silent dynamics have the uppermost importance for the predictability of large events. The asperity size did not show significance in synchronization in our study. However, it should be noted that the rupture style affects long-term synchronization patterns, which depend on the constitutive RSF parameters and the asperity size relative to nucleation length scales within the RSF framework. The different rupturing styles can account for why similar studies suggested that the barrier efficiency depends on the asperity size, while we suggested the opposite. Our simulation setup fits the mature fault zone with characteristic and quasi-periodic failures along earthquakes that nucleate at the transition zones and rupture unilaterally as slip-pulses, mimicking NAF. Even though the simulation setup is too simple for NAF, the results can explain the synchronized clusters along it, where the synchronization rates slow down, and where they behave independently.

Open Research

No data were used nor created in this study. The code is publicly available in GitHub-Zenodo (Sopaci, 2022). The maps are generated using GMT 6.0 (Wessel et al., 2019).

Acknowledgments

The numerical calculations reported in this paper were fully/partially performed at TUBITAK ULAKBIM, High Performance and Grid Computing Center (TRUBA resources).

References

- Aksoy, M. E., Meghraoui, M., Vallée, M., & Çakır, Z. (2010). Rupture characteristics of the ad 1912 mürefte (ganos) earthquake segment of the north anatolian fault (western turkey). *Geology*, *38*(11), 991–994.
- Ampuero, J. P., & Rubin, A. M. (2008). Earthquake nucleation on rate and state faults - Aging and slip laws. *Journal of Geophysical Research: Solid Earth*, *113*(1), 1–21. doi: 10.1029/2007JB005082
- Armijo, R., Pondard, N., Meyer, B., Uçarkus, G., Lépinay, B. M. D., Malavieille, J., ... Sarikavak, K. (2005, 6). Submarine fault scarps in the sea of marmara pull-apart (north anatolian fault): Implications for seismic hazard in istanbul. *Geochemistry, Geophysics, Geosystems*, *6*, 6009. doi: 10.1029/2004GC000896
- Aslan, G., Lasserre, C., Cakir, Z., Ergintav, S., Özarpaci, S., Dogan, U., ... Renard, F. (2019, 2). Shallow creep along the 1999 izmit earthquake rupture (turkey) from gps and high temporal resolution interferometric synthetic aperture radar data (2011–2017). *Journal of Geophysical Research: Solid Earth*, *124*, 2218–2236. Retrieved from <https://onlinelibrary.wiley.com/doi/abs/10.1029/2018JB017022> doi: 10.1029/2018JB017022
- Bhattacharya, P., Rubin, A. M., Bayart, E., Savage, H. M., & Marone, C. (2015). Critical evaluation of state evolution laws in rate and state friction: Fitting large velocity steps in simulated fault gouge with time-, slip-, and stress-

- 623 dependent constitutive laws. *Journal of Geophysical Research: Solid Earth*,
624 *120*(9), 6365–6385. doi: 10.1002/2015JB012437
- 625 Bohnhoff, M., Bulut, F., Dresen, G., Malin, P. E., Eken, T., & Aktar, M. (2013,
626 jun). An earthquake gap south of Istanbul. *Nature Communications* *2013* *4*:1,
627 *4*(1), 1–6. Retrieved from <https://www.nature.com/articles/ncomms2999>
628 doi: 10.1038/ncomms2999
- 629 Bouchon, M., Karabulut, H., Aktar, M., Özalaybey, S., Schmittbuhl, J., Bouin, M.-
630 P., & Marsan, D. (2021). The nucleation of the Izmit and Düzce earthquakes:
631 some mechanical logic on where and how ruptures began. *Geophysical Journal*
632 *International*, *225*(3), 1510–1517. doi: 10.1093/gji/ggab040
- 633 Bulut, F., & Dođru, A. (2021). Time frame for future large earthquakes near
634 İstanbul based on east-to-west decelerating failure of the north anatolian fault.
635 *Turkish Journal of Earth Sciences*, *30*(2), 204–214. doi: 10.3906/yer-2006-7
- 636 Çakir, Z., Ergintav, S., Akođlu, A. M., Çakmak, R., Tatar, O., & Meghraoui,
637 M. (2014, 10). Insar velocity field across the north anatolian fault (east-
638 ern turkey): Implications for the loading and release of interseismic strain
639 accumulation. *Journal of Geophysical Research: Solid Earth*, *119*, 7934-
640 7943. Retrieved from <http://doi.wiley.com/10.1002/2014JB011360> doi:
641 10.1002/2014JB011360
- 642 Cattania, C. (2019, sep). Complex Earthquake Sequences On Simple Faults.
643 *Geophysical Research Letters*, *46*(17-18), 10384–10393. doi: 10.1029/
644 2019GL083628
- 645 Corbi, F., Funicello, F., Brizzi, S., Lallemand, S., & Rosenau, M. (2017). Control
646 of asperities size and spacing on seismic behavior of subduction megathrusts.
647 *Geophysical Research Letters*, *44*, 8227–8235. doi: 10.1002/2017GL074182
- 648 Şengör, A. M., Tüysüz, O., Imren, C., Saking, M., Eyidođan, H., Görür, N.,
649 ... Rangin, C. (2005). The north anatolian fault: A new look. *An-*
650 *annual Review of Earth and Planetary Sciences*, *33*, 37–112. doi: 10.1146/
651 annurev.earth.32.101802.120415
- 652 Dieterich, J. H. (1979, 5). Modeling of rock friction 1. experimental results and con-
653 stitutive equations. *Journal of Geophysical Research: Solid Earth*, *84*, 2161-
654 2168. Retrieved from <http://doi.wiley.com/10.1029/JB084iB05p02161>
655 doi: 10.1029/JB084iB05p02161
- 656 Dieterich, J. H. (1992). Earthquake nucleation on faults with rate-and state-
657 dependent strength. *Tectonophysics*, *211*(1-4), 115–134. doi: 10.1016/
658 0040-1951(92)90055-B
- 659 Dublanchet, P., Bernard, P., & Favreau, P. (2013). Interactions and triggering in
660 a 3-d rate-and-state asperity model. *Journal of Geophysical Research: Solid*
661 *Earth*, *118*, 2225–2245. Retrieved from <http://doi.wiley.com/10.1002/jgrb.50187>
662 doi: 10.1002/jgrb.50187
- 663 Erickson, B. A., Jiang, J., Barall, M., Lapusta, N., Dunham, E. M., Harris, R., ...
664 Wei, M. (2020). The community code verification exercise for simulating se-
665 quences of earthquakes and aseismic slip (seas). *Seismological Research Letters*,
666 *91*, 874–890. doi: 10.1785/0220190248
- 667 Fraser, J., Pigati, J. S., Hubert-Ferrari, A., Vanneste, K., Avsar, U., & Altinok, S.
668 (2009, oct). A 3000-Year Record of Ground-Rupturing Earthquakes along
669 the Central North Anatolian Fault near Lake Ladik, Turkey. *Bulletin of the*
670 *Seismological Society of America*, *99*(5), 2681–2703. doi: 10.1785/0120080024
- 671 Gomberg, J., Beeler, N. M., Blanpied, M. L., & Bodin, P. (1998). Earthquake trig-
672 gering by transient and static deformations. *Journal of Geophysical Research:*
673 *Solid Earth*, *103*(10), 24411–24426. doi: 10.1029/98jb01125
- 674 Hairer, E., Wanner, G., & Nørsett, S. P. (1993). *Solving ordinary differential equa-*
675 *tions i* (Vol. 8). Springer Berlin Heidelberg. Retrieved from [http://link](http://link.springer.com/10.1007/978-3-540-78862-1)
676 [.springer.com/10.1007/978-3-540-78862-1](http://link.springer.com/10.1007/978-3-540-78862-1) doi: 10.1007/978-3-540-78862
677 -1

- 678 Herrendörfer, R., van Dinther, Y., Gerya, T., & Dalguer, L. A. (2015, 6). Earth-
679 quake supercycle in subduction zones controlled by the width of the seis-
680 mogenic zone. *Nature Geoscience*, *8*, 471-474. Retrieved from [https://](https://www.nature.com/articles/ngeo2427)
681 www.nature.com/articles/ngeo2427 doi: 10.1038/ngeo2427
- 682 Huang, Y., & Ampuero, J.-P. (2011, 12). Pulse-like ruptures induced by low-
683 velocity fault zones. *Journal of Geophysical Research*, *116*, B12307. Re-
684 trieved from <http://doi.wiley.com/10.1029/2011JB008684> doi:
685 10.1029/2011JB008684
- 686 Kaneko, Y., Avouac, J.-P., & Lapusta, N. (2010). Towards inferring earthquake pat-
687 terns from geodetic observations of interseismic coupling. *Nature Geoscience*,
688 *3*, 363-369. Retrieved from <http://www.nature.com/articles/ngeo843> doi:
689 10.1038/ngeo843
- 690 Karabulut, H., Güvercin, S. E., Eskiköy, F., Konca, A. Ö., & Ergintav, S. (2021).
691 The moderate size 2019 september m w 5.8 silivri earthquake unveils the
692 complexity of the main marmara fault shear zone. *Geophysical Journal Inter-*
693 *national*, *224*(1), 377–388.
- 694 Kato, N. (2004). Interaction of slip on asperities: Numerical simulation of seis-
695 mic cycles on a two-dimensional planar fault with nonuniform frictional
696 property. *Journal of Geophysical Research: Solid Earth*, *109*, 1-17. doi:
697 10.1029/2004JB003001
- 698 Kaya, T., Tank, S. B., Tunçer, M. K., Rokoityansky, I. I., Tolak, E., & Savchenko,
699 T. (2009, 8). Asperity along the north anatolian fault imaged by magnetotel-
700 lurics at düzce, turkey. *Earth, Planets and Space*, *61*, 871-884. Retrieved from
701 [https://earth-planets-space.springeropen.com/articles/10.1186/](https://earth-planets-space.springeropen.com/articles/10.1186/BF03353198)
702 [BF03353198](https://earth-planets-space.springeropen.com/articles/10.1186/BF03353198) doi: 10.1186/BF03353198/METRICS
- 703 King, G. C., Hubert-Ferrari, A., Nalbant, S. S., Meyer, B., Armijo, R., & Bow-
704 man, D. (2001, 11). Coulomb interactions and the 17 august 1999 izmit,
705 turkey earthquake. *Comptes Rendus de l'Académie des Sciences - Se-*
706 *ries IIA - Earth and Planetary Science*, *333*, 557-569. Retrieved from
707 <https://linkinghub.elsevier.com/retrieve/pii/S1251805001016767>
708 doi: 10.1016/S1251-8050(01)01676-7
- 709 Koch, K.-R. (1999). Parameter estimation in linear models. In *Parameter estimation*
710 *and hypothesis testing in linear models* (pp. 149–269). Springer.
- 711 Konca, A. O., Leprince, S., Avouac, J.-P., & Helmberger, D. V. (2010). Rupture
712 process of the 1999 m w 7.1 duzce earthquake from joint analysis of spot, gps,
713 insar, strong-motion, and teleseismic data: A supershear rupture with variable
714 rupture velocity. *Bulletin of the Seismological Society of America*, *100*(1),
715 267–288.
- 716 Kondo, H., Özaksoy, V., & Yildirim, C. (2010, apr). Slip history of the 1944 Bolu-
717 Gerece earthquake rupture along the North Anatolian fault system: Impli-
718 cations for recurrence behavior of multisegment earthquakes. *Journal of*
719 *Geophysical Research: Solid Earth*, *115*(4), 4316. doi: 10.1029/2009JB006413
- 720 Lambert, V., & Lapusta, N. (2021, 10). Resolving simulated sequences of earth-
721 quakes and fault interactions: Implications for physics-based seismic hazard
722 assessment. *Journal of Geophysical Research: Solid Earth*, *126*. Retrieved
723 from <https://onlinelibrary.wiley.com/doi/10.1029/2021JB022193> doi:
724 10.1029/2021JB022193
- 725 Lambert, V., Lapusta, N., & Perry, S. (2021, mar). Propagation of large earthquakes
726 as self-healing pulses or mild cracks. *Nature*, *591*(7849), 252–258. Retrieved
727 from <http://www.nature.com/articles/s41586-021-03248-1> doi: 10.1038/
728 s41586-021-03248-1
- 729 Lange, D., Kopp, H., Royer, J. Y., Henry, P., Çakir, Z., Petersen, F., ... Géli,
730 L. (2019). Interseismic strain build-up on the submarine North Ana-
731 tolian Fault offshore Istanbul. *Nature Communications*, *10*(1). Re-
732 trieved from <http://dx.doi.org/10.1038/s41467-019-11016-z> doi:

- 733 10.1038/s41467-019-11016-z
- 734 Lapusta, N., Rice, J. R., Ben-Zion, Y., & Zheng, G. (2000). Elastodynamic analysis
735 for slow tectonic loading with spontaneous rupture episodes on faults with
736 rate- and state-dependent friction. *Journal of Geophysical Research: Solid*
737 *Earth*, *105*(B10), 23765–23789. doi: 10.1029/2000jb900250
- 738 Lettis, C. A. H. E. A. A. B. J. B. W. (2003). Timing of late holocene earthquakes
739 on the eastern düzce fault and implications for slip transfer between the south-
740 ern and northern strands of the north anatolian fault system, bolu, turkey.
741 *Turkish Journal of Earth Sciences*, *12*.
- 742 Liu, Z., & Wang, T. (2023, 8). High-resolution interseismic strain mapping
743 from insar phase-gradient stacking: Application to the north anatolian fault
744 with implications for the non-uniform strain distribution related to coseis-
745 mic slip distribution. *Geophysical Research Letters*, *50*. Retrieved from
746 <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023GL104168>
747 doi: 10.1029/2023GL104168
- 748 Lorenzo-Martín, F., Roth, F., & Wang, R. (2006, 10). Elastic and inelastic trig-
749 gering of earthquakes in the north anatolian fault zone. *Tectonophysics*, *424*,
750 271–289. Retrieved from [https://linkinghub.elsevier.com/retrieve/pii/](https://linkinghub.elsevier.com/retrieve/pii/S0040195106002265)
751 [S0040195106002265](https://linkinghub.elsevier.com/retrieve/pii/S0040195106002265) doi: 10.1016/j.tecto.2006.03.046
- 752 Luo, Y., & Ampuero, J. P. (2018). Stability of faults with heterogeneous friction
753 properties and effective normal stress. *Tectonophysics*, *733*, 257–272. Retrieved
754 from <https://doi.org/10.1016/j.tecto.2017.11.006> doi: 10.1016/j.tecto
755 .2017.11.006
- 756 Nakatani, M. (2001). Conceptual and physical clarification of rate and state friction:
757 Frictional sliding as a thermally activated rheology. *Journal of Geophysical Re-*
758 *search: Solid Earth*, *106*(B7), 13347–13380. doi: 10.1029/2000jb900453
- 759 Nalbant, S. S., Bhloscaidh, M. N., McCloskey, J., İpek, C., & Utkucu, M. (2023, 1).
760 The role of stress barriers on the shape of future earthquakes in the mentawai
761 section of the sunda megathrust. *Turkish Journal of Earth Sciences*, *32*, 320-
762 329. Retrieved from [https://journals.tubitak.gov.tr/earth/vol132/iss3/](https://journals.tubitak.gov.tr/earth/vol132/iss3/7)
763 [7](https://journals.tubitak.gov.tr/earth/vol132/iss3/7) doi: 10.55730/1300-0985.1847
- 764 Nie, S., & Barbot, S. (2022, 8). Rupture styles linked to recurrence patterns in seis-
765 mic cycles with a compliant fault zone. *Earth and Planetary Science Letters*,
766 *591*, 117593. doi: 10.1016/J.EPSL.2022.117593
- 767 Parsons, T. (2004). Recalculated probability of $m \geq 7$ earthquakes beneath the sea of
768 marmara, turkey. *Journal of Geophysical Research: Solid Earth*, *109*, 1–21. doi:
769 10.1029/2003JB002667
- 770 Perrin, G., Rice, J. R., & Zheng, G. (1995). Self-healing slip pulse on a frictional
771 surface. *Journal of the Mechanics and Physics of Solids*, *43*(9), 1461–1495.
772 doi: 10.1016/0022-5096(95)00036-I
- 773 Pondard, N., Armijo, R., King, G. C. P., Meyer, B., & Flerit, F. (2007, oct). Fault
774 interactions in the Sea of Marmara pull-apart (North Anatolian Fault): earth-
775 quake clustering and propagating earthquake sequences. *Geophysical Journal*
776 *International*, *171*(3), 1185–1197. doi: 10.1111/j.1365-246X.2007.03580.x
- 777 Pucci, S., Pantosti, D., Barachi, M., & Palyvos, N. (2007, 10). A complex seis-
778 mogenic shear zone: The düzce segment of north anatolian fault (turkey).
779 *Earth and Planetary Science Letters*, *262*, 185–203. Retrieved from
780 <https://linkinghub.elsevier.com/retrieve/pii/S0012821X07004827>
781 doi: 10.1016/j.epsl.2007.07.038
- 782 Rice, J. R. (1993). Spatio-temporal complexity of slip on a fault. *Journal of Geo-*
783 *physical Research: Solid Earth*, *98*(B6), 9885–9907.
- 784 Rosenau, M., Horenko, I., Corbi, F., Rudolf, M., Kornhuber, R., & Oncken, O.
785 (2019). Synchronization of great subduction megathrust earthquakes: Insights
786 from scale model analysis. *Journal of Geophysical Research: Solid Earth*, *124*,
787 3646–3661. doi: 10.1029/2018JB016597

- 788 Rubin, A. M., & Ampuero, J. P. (2005). Earthquake nucleation on (aging) rate and
789 state faults. *Journal of Geophysical Research: Solid Earth*, *110*, 1-24. doi: 10
790 .1029/2005JB003686
- 791 Ruina, A. (1983, 12). Slip instability and state variable friction laws. *Jour-*
792 *nal of Geophysical Research*, *88*, 10359-10370. Retrieved from [https://](https://onlinelibrary.wiley.com/doi/full/10.1029/JB088iB12p10359)
793 onlinelibrary.wiley.com/doi/full/10.1029/JB088iB12p10359 doi:
794 10.1029/JB088iB12p10359
- 795 Salditch, L., Stein, S., Neely, J., Spencer, B. D., Brooks, E. M., Agnon, A., & Liu,
796 M. (2020, 1). Earthquake supercycles and long-term fault memory. *Tectono-*
797 *physics*, *774*, 228289. Retrieved from [https://linkinghub.elsevier.com/](https://linkinghub.elsevier.com/retrieve/pii/S0040195119304044)
798 [retrieve/pii/S0040195119304044](https://linkinghub.elsevier.com/retrieve/pii/S0040195119304044) doi: 10.1016/j.tecto.2019.228289
- 799 Schatzman, M., & Schatzman, M. (2002). *Numerical analysis: a mathematical intro-*
800 *duction*. Oxford University Press on Demand.
- 801 Scholz, C. H. (2010). Large earthquake triggering, clustering, and the synchroniza-
802 tion of faults. *Bulletin of the Seismological Society of America*, *100*, 901-909.
803 Retrieved from [https://pubs.geoscienceworld.org/bssa/article/100/3/](https://pubs.geoscienceworld.org/bssa/article/100/3/901-909/349641)
804 [901-909/349641](https://pubs.geoscienceworld.org/bssa/article/100/3/901-909/349641) doi: 10.1785/0120090309
- 805 Shi, P., Wei, M., & Barbot, S. (2022, 8). Contribution of viscoelastic stress
806 to the synchronization of earthquake cycles on oceanic transform faults.
807 *Journal of Geophysical Research: Solid Earth*, *127*. Retrieved from
808 <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022JB024069>
809 doi: 10.1029/2022JB024069
- 810 Sopaci, E. (2022). *eyupsopaci/sbiem: intial release (version v.0.1.0)[software]*. Zen-
811 odo. doi: 10.5281/zenodo.7419328
- 812 Sopaci, E., & Özacar, A. A. (2021, sep). Simulation of seismic triggering and failure
813 time perturbations associated with the 30 October 2020 Samos earthquake
814 (Mw 7.0). *TURKISH JOURNAL OF EARTH SCIENCES*, *30*(5), 653–664.
815 Retrieved from <https://journals.tubitak.gov.tr/earth/vol130/iss5/7>
816 doi: 10.3906/yer-2104-6
- 817 Sopacı, E. (2023). *Physics based earthquake triggering and fault interactions* (PhD
818 thesis). Middle East Technical University.
- 819 Sopacı, E., & Özacar, A. A. (2023, 7). Impact of 2019 mw 5.8 marmara sea earth-
820 quake on the seismic cycle of locked north anatolian fault segment. *Tectono-*
821 *physics*, *859*, 229888. Retrieved from [https://linkinghub.elsevier.com/](https://linkinghub.elsevier.com/retrieve/pii/S0040195123001865)
822 [retrieve/pii/S0040195123001865](https://linkinghub.elsevier.com/retrieve/pii/S0040195123001865) doi: 10.1016/j.tecto.2023.229888
- 823 Stein, R. S., Barka, A. A., & Dieterich, J. H. (1997). Progressive failure on the north
824 anatolian fault since 1939 by earthquake stress triggering. *Geophysical Journal*
825 *International*, *128*(3), 594–604.
- 826 Thakur, P., & Huang, Y. (2021, 9). Influence of fault zone maturity on fully dy-
827 namic earthquake cycles. *Geophysical Research Letters*, *48*. Retrieved from
828 <https://onlinelibrary.wiley.com/doi/10.1029/2021GL094679> doi:
829 10.1029/2021GL094679
- 830 Thomas, M. Y., Lapusta, N., Noda, H., & Avouac, J. P. (2014). Quasi-dynamic
831 versus fully dynamic simulations of earthquakes and aseismic slip with and
832 without enhanced coseismic weakening. *Journal of Geophysical Research: Solid*
833 *Earth*, *119*, 1986-2004. doi: 10.1002/2013JB010615
- 834 Uçarkuş, G., Çakır, Z., & Armijo, R. (2011, 1). Western termination of the mw
835 7.4, 1999 İzmit earthquake rupture: Implications for the expected large earth-
836 quake in the sea of marmara. *Turkish Journal of Earth Sciences*, *20*. Re-
837 trieved from <https://journals.tubitak.gov.tr/earth/vol120/iss4/2> doi:
838 10.3906/yer-0911-72
- 839 Utkucu, M., Nalbant, S. S., McCloskey, J., Steacy, S., & Alptekin, Ö. (2003). Slip
840 distribution and stress changes associated with the 1999 november 12, düzce
841 (turkey) earthquake (mw= 7.1). *Geophysical Journal International*, *153*(1),
842 229–241.

- 843 Wei, M., Kaneko, Y., Shi, P., & Liu, Y. (2018, 5). Numerical modeling of dy-
844 namically triggered shallow slow slip events in new zealand by the 2016 mw
845 7.8 kaikoura earthquake. *Geophysical Research Letters*, *45*, 4764-4772. doi:
846 10.1029/2018GL077879
- 847 Wei, M., & Shi, P. (2021). Synchronization of earthquake cycles of adjacent seg-
848 ments on oceanic transform faults revealed by numerical simulation in the
849 framework of rate-and-state friction. *Journal of Geophysical Research: Solid*
850 *Earth*, *126*, 1-15. doi: 10.1029/2020JB020231
- 851 Wessel, P., Luis, J., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H., & Tian, D.
852 (2019). The generic mapping tools version 6. *Geochemistry, Geophysics,*
853 *Geosystems*, *20*(11), 5556–5564.
- 854 Yin, Y., Galvez, P., Heimisson, E. R., & Wiemer, S. (2023, 3). The role of three-
855 dimensional fault interactions in creating complex seismic sequences. *Earth*
856 *and Planetary Science Letters*, *606*, 118056. doi: 10.1016/J.EPSL.2023
857 .118056
- 858 Yıkılmaz, M. B., Turcotte, D. L., Heien, E. M., Kellogg, L. H., & Rundle, J. B.
859 (2015, 8). Critical jump distance for propagating earthquake ruptures
860 across step-overs. *Pure and Applied Geophysics*, *172*, 2195-2201. doi:
861 10.1007/s00024-014-0786-y
- 862 Zabci, C., Akyüz, H. S., Karabacak, V., Sançar, T., Altunel, E., Gürsoy, H., &
863 Tatar, O. (2011, jan). Palaeoearthquakes on the Kelkit Valley segment of
864 the North Anatolian Fault, Turkey: Implications for the surface rupture of
865 the historical 17 august 1668 Anatolian earthquake. *Turkish Journal of Earth*
866 *Sciences*, *20*(4), 411–427. doi: 10.3906/yer-0910-48