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Along-strike stress delays the ordering of slip on a fixed-length fault

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Abstract

The size of a large earthquake depends on how far the rupture runs and how much the fault slips. An early correlation with magnitude can appear while those two contributions are still mixed. Patches at both ends stop every rupture on a 120 km fault, so the length no longer varies and the early order is an order of slip. One background stress is a single value along the fault, and the other also varies along strike. Slip at 20 s is ordered by 2 s for 259 ruptures in the first case, and by 8 s (7–9 s) for 230 ruptures in the second. The extra seconds are not a slower rupture front. Where the stress varies along strike, stations beside the fault and around it show that order when the waves arrive. Stations ahead of the rupture do not lead the waves, and where the stress is one value, stations around the fault are later than the waves. The calculations are an idealized two-dimensional dynamic simulation, with one friction law and no field record.

Non-technical summary

How large an earthquake becomes depends on the length of the break and on how far the two sides of the fault slide. An early record can match the final size even while those two contributions are still mixed. In these calculations the rupture is stopped at both ends, so the length is the same for every event and the early order can only be an order of slip. After about 2 s, when the stress is one value for the whole fault, the events are in the rank order of the slip at 20 s, whereas that rank order is reached at about 8 s when the stress also varies along the fault and the spacing perpendicular to the fault is 400 m. Those extra seconds are not a slower rupture front.

Where the stress varies along strike, seismometers beside the fault and around it show this order when the waves arrive, whereas seismometers around the fault are a few seconds later than the waves when the stress is one value for the whole fault. Two measurements from the first 3 s after the predicted P arrival agree less well with the slip at 20 s than the full seismogram does. On a finer grid along the fault, the two times are again about 2 s and 8 s. When the spacing perpendicular to the fault is also 200 m, the times are about 2 s and 7 s, and three of the ruptures with varying stress do not propagate.

1 Introduction

The size of a large earthquake depends on how far the rupture runs and how much the fault slips. An early correlation between waveforms and magnitude can appear while those two contributions are still mixed, so it can be read as a determined size even when the length has not yet been fixed. Warning would need that size before the rupture is over. The calculations below stop every rupture at both ends of the same fault, so the length is shared and the early order can only be an order of slip.

One group of studies asks whether the early signal already contains the final magnitude. Catalog studies have reported a correlation between early signals and magnitude [Olson and

Allen, 2005, Colombelli et al., 2014, Melgar and Hayes, 2019, Longobardi et al., 2025]. That correlation has been read as a size that is fixed early, and a nucleation phase that grows with magnitude has been proposed [Ellsworth and Beroza, 1995]. However, large and small earthquakes can share the same onset [Meier et al., 2016, Ide, 2019], so the shared onset does not show that those first seconds determine the magnitude [Rydelek and Horiuchi, 2006]. For large subduction earthquakes, the early moment-rate growth does not predict the final magnitude [Meier et al., 2017]. In contrast, a reported increase of growth rate with final magnitude can be produced by selection bias [Meier et al., 2021]. Different final sizes separate only after about half of the rupture has been observed [Münchmeyer et al., 2022], and the P -wave onset does not determine the final size [Ide and Yoshida, 2026]. A second group asks what a network can see before the strong motion arrives, which is a different question from whether the magnitude is already fixed on the fault. Warning studies therefore have to separate rupture on the fault from the waves that reach a network [Allen and Kanamori, 2003, Minson et al., 2018, Allen and Melgar, 2019], and simulated ruptures have been used to test a geodetic warning magnitude [Solares-Colón et al., 2025]. However, these comparisons can still report a high score while rupture length and final slip remain entangled, and on a heterogeneous fault the starting point can also change the final size [Yang et al., 2022].

An early correlation therefore cannot be read as slip alone, because a change in length can produce the same correlation. Holding the length fixed, and then changing only the along-strike stress, is the comparison those studies do not make.

The calculations here make that comparison. Strong patches stop the ruptures at both ends of a 120 km fault, so the length does not vary, while the slip at 20 s does. Because the length is the same in both calculations, the difference between 2 s and 8 s is a delay in the ordering of slip. In the whole-fault draw the background stress is one value for the entire fault, and slip at 20 s is rank-ordered by 2 s; in the 10 km field a 1.3 MPa fluctuation correlated over 10 km is added along strike, and that ordering is reached at 8 s. The stations are compared with the arrival of the waves, as in warning studies, but the calculations are not

an operational warning product or a fit to one earthquake. With the spacing perpendicular to the fault also at 200 m, the whole-fault time is 2 s and the 10 km time is 7 s, and on that mesh, three of the 230 ruptures do not propagate.

2 Methods

2.1 Fault, friction, and resolution

The parameters below are idealized so that the rupture length can be held fixed while the slip still varies. The friction and the stress are not calibrated to a field record. The solver is `fdfault` [Daub, 2020], and the calculation is plane strain with the slip in that plane, so each rupture is mode II. The fault is 120 km long and lies between two elastic blocks, each 28 km thick. Each block has density $\rho = 2.67 \text{ g cm}^{-3}$, shear-wave speed $v_s = 3.464 \text{ km s}^{-1}$, and compressional-wave speed $v_p = 6 \text{ km s}^{-1}$. Along strike the spacing is 500 m (241 nodes), and across each block there are 71 nodes, so the spacing perpendicular to the fault is 400 m. The time step follows a Courant number of 0.3 relative to the shear-wave speed, which is how `fdfault` defines that number. The step is 0.0346 s when the smallest spacing is 400 m and 0.0173 s when it is 200 m. Relative to the compressional-wave speed the Courant number is 0.52. Normal stress σ_n is 120 MPa. Friction is linear slip weakening [Ida, 1972, Andrews, 1976], with static and dynamic coefficients $\mu_s = 0.677$ and $\mu_d = 0.525$, so the strengths are 81.2 MPa and 63 MPa. The mean initial shear stress is 70 MPa, which is a stress drop of 7 MPa on a slipped patch and a strength excess of 11.2 MPa ahead of the rupture. Nucleation is an overstress of 12 MPa on a 5 km patch, and the critical slip distance D_c is 0.4 m. The shear modulus is $\mu = \rho v_s^2$. $\Lambda = \mu D_c / [(\mu_s - \mu_d) |\sigma_n|]$ is about 703 m. This is a static length computed from the parameters, so $N_{cz} \approx 1.4$ points along strike is not a width measured on the propagating rupture. Day et al. recommend at least three grid points across the cohesive zone [Day et al., 2005].

Every rupture also carries two fixed patches, each 4 km wide and centred 18 km on either

side of the hypocentre. One patch is +7 MPa, and the other is −7 MPa, which lowers that patch to the dynamic strength. A friction coefficient of 10^4 is assigned to the outer 8 km at each end, so propagating ruptures stop near 8 and 112 km, and the outer boundaries are absorbing. Figure 1 shows the geometry.

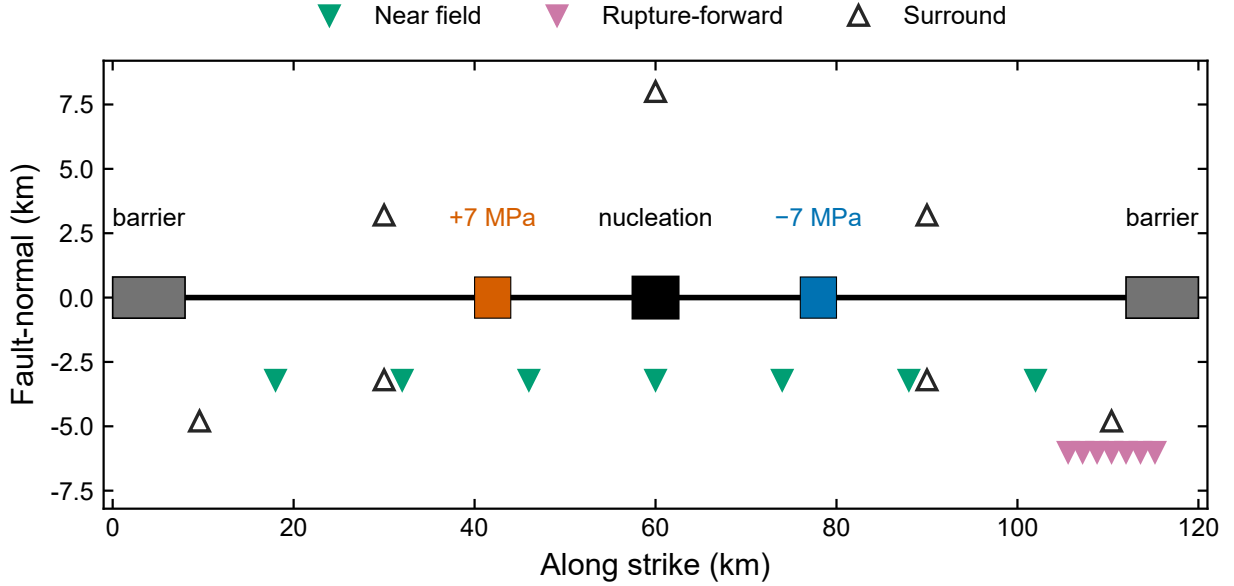


Figure 1: Fault and stations, drawn for a hypocentre at 60 km. Grey bars are the end patches that stop the rupture. The black box is the nucleation patch. The two coloured boxes are the fixed ± 7 MPa patches that every rupture carries, 18 km on either side of the hypocentre. Symbols are the three station layouts. Only the central part of the 28 km blocks is shown.

Five ruptures were rerun with each block widened from 28 km to 56 km. The median ratio of energy at the stations ahead of the rupture, wide domain over the original, is 1.00, 0.99, and 1.11 in the windows 0–14 s, 14–28 s, and 28–50 s. Slip at 20.8 s differs by less than 0.7%, while slip at the end of the record differs by 11.5%. The slip used below is therefore the first stored sample at or after 20 s, not the last sample.

2.2 The two prestress calculations

The two calculations share the length, the friction, and the two fixed patches, and they differ only in the along-strike background stress, so a difference in ordering time is not a difference in rupture length. In both calculations the hypocentre is drawn within 0.08 times the fault length on either side of the centre. The nucleation overstress is drawn from a normal distribution of standard deviation 0.5 MPa about the 12 MPa overstress. The whole-fault draw and the 10 km field each begin with 300 draws. Ruptures with fewer than five ruptured nodes, or with no slip at 20 s, are left out. The whole-fault draw has no along-strike field beyond the two fixed patches. Its background shear stress is one sample for the whole fault, from a normal distribution of mean 70 MPa and standard deviation 0.4 MPa. The 10 km field keeps the mean at 70 MPa and adds a zero-mean Gaussian field of standard deviation 1.3 MPa, with covariance $\sigma^2 \exp[-\Delta x^2/(2\ell^2)]$ and $\ell = 10$ km. Ripperger et al. used heterogeneous prestress; the covariance used here is squared-exponential [Ripperger et al., 2007]. Correlation lengths of 5 km and 20 km were each started from 36 draws, to test whether the ordering time moves by 3 s or more.

The 10 km field is also run at 250 m, and both calculations are run again at 200 m along strike, on 601 nodes, so the static length Λ spans about 3.5 grid points. The stored stress is interpolated onto that mesh, and the spacing perpendicular to the fault stays 400 m. On the 10 km field, two along-strike meshes count as the same ordering when both times lie in 7–9 s and the rank correlation of slip at 20 s is at least 0.9. On the whole-fault draw they count as the same ordering when the finer time is no later than 2 s and that correlation is at least 0.9. A further mesh uses 141 nodes across each block, so the spacing perpendicular to the fault is 200 m. The stress is interpolated in the same way, and the ordering time on that mesh is compared with the 200 m along-strike ruptures.

2.3 Ordering time

The ordering time is the moment when slip accumulated so far has the same ranking, across ruptures, as the slip at 20 s. The slip at 20 s, denoted Y , is the sum of absolute slip on ruptured nodes at the first stored sample at or after 20 s, multiplied by the node spacing. $M(T)$ is the same sum using only the slip accumulated by time T , and slip on the fault is stored every 50 time steps: 1.73 s at 500 m, 1.08 s at 250 m, and 0.87 s at 200 m along strike and at 200 m perpendicular to the fault. $M(T)$ is interpolated linearly between those samples. T_C^{85} is the first time, on a 1 s grid from 1 to 21 s, at which the absolute Spearman correlation of $M(T)$ with Y reaches 85% of its peak. The interval is the 5th and 95th percentiles of 1000 bootstrap resamples of the ruptures. The rupture time of a node is the first time its slip rate exceeds 0.001 m s^{-1} , and the rupture speed between 12 and 108 km is the median of distance increments divided by the corresponding time increments. A set of ruptures is supershear when the median of those speeds exceeds v_s . The shading in Fig. 2 uses 200 draws.

2.4 Stations and early measures

The calculation asks how much of the on-fault order is visible at the stations after the waves have traveled. At each of three layouts of seven stations, the same rank correlation with slip at 20 s is computed. The near-field layout lies along strike between 18 and 102 km, 3.2 km from the fault. The rupture-forward layout is clustered between 106 and 115 km, 6 km from the fault, ahead of the rupture. Stations in the surround lie on both sides of the fault at 3.2–8 km. Slip that could have reached the stations is the on-fault slip, delayed at each node by the straight-line travel time at v_p to the nearest station. T_{vis}^{85} is the ordering time of that delayed slip, and T_R^{85} is the ordering time of the station records. The lag $T_R^{85} - T_{\text{vis}}^{85}$ is the delay after the waves. An interval that contains zero and ends by 3 s means the records arrive with the waves, an interval that stays positive is a delay after the waves, and any other interval is unresolved.

The logarithm of each station’s energy is also fit with a ridge regression of penalty 1 in ten folds. T_R^{85} uses the summed energy, while this fit uses each station on its own. Peak displacement P_d and a characteristic period τ_c [Kanamori, 2005, Wu and Kanamori, 2005] are taken in a 3 s window after the predicted P arrival, with earlier samples set to zero. Both use the two in-plane components together, neither is filtered, and that arrival is the straight-line distance from the hypocentre to the station divided by v_p . A ridge regression with the same penalty and the same ten folds predicts Y from the two measures. The error is the root-mean-square error divided by the standard deviation of Y . An error of 1 is no better than predicting the mean slip for every rupture.

2.5 Earlier calculations

The supplement reports earlier calculations on other geometries, not the 259 and 230 ruptures above: an older reading moved the reported time from 12 s to 1 s, and energy alone, on 23 ruptures of that 120 km fault, did not repeat a 16 s delay.

2.6 Ruptures without the end patches

The 10 km field was rerun without the end patches, the mean stress was then moved toward the dynamic strength, and the nucleation overstress was raised so that nucleation still exceeds 81.2 MPa. Six stress settings are plotted, and each has at least four propagating ruptures.

3 Results

3.1 Slip falls into order later when stress varies along strike

Figure 2 shows the absolute Spearman correlation between slip accumulated by time T and slip at 20 s. Of 300 whole-fault draws, 259 rupture, and $T_C^{85} = 2$ s, with a bootstrap interval of 1–3 s, where the correlation is 0.83 at 1 s and 0.88 at 2 s. Of 300 draws in the 10 km field,

179 230 rupture, and every one stops at both end patches; $T_C^{85} = 8$ s, with a bootstrap interval
 180 of 7–9 s, where the correlation is 0.63 at 2 s and 0.87 at 8 s. Length does not differ between
 181 the two calculations. Draws with correlation lengths of 5 km and 20 km reach this order at
 182 7 s and 6 s, on 26 and 29 of each set of 36. These times differ from the 8 s of the 10 km field
 183 by 1 s and 2 s, less than the 3 s shift used as the test. The 6 s between the ordering times of
 184 2 s and 8 s is the contrast between the two calculations, which differ only in the along-strike
 185 stress. Between 12 and 108 km, the median time from the first ruptured node to the last is
 186 9.94 s on the 10 km field and 9.77 s on the whole-fault draw. The difference is 0.17 s, less
 187 than 3 s, so the later ordering is not a slower front. Between 12 and 108 km, the median
 188 rupture speed is 4.81 km s^{-1} on the 500 m grid in both calculations. The rupture speeds
 189 exceed v_s in 80% of the 10 km ruptures and in 87% of the whole-fault ruptures, and on that
 190 grid none exceeds $\sqrt{2}v_s$. The median is 5.77 km s^{-1} for the 10 km field at 250 m, for both
 191 calculations at 200 m along strike, and for the 10 km field with 200 m spacing perpendicular
 192 to the fault. On that perpendicular mesh the whole-fault median is 2.89 km s^{-1} , below v_s ,
 193 and the ordering time remains 2 s. On this definition, both calculations at 500 m and at
 194 200 m along strike are supershear, as are the 10 km field at 250 m and the 10 km field with
 195 200 m spacing perpendicular to the fault, whereas the whole-fault calculation with 200 m
 196 spacing perpendicular to the fault is not. For most nodes, stored slip is already past D_c at
 197 the first nonzero sample, so those samples do not resolve the cohesive zone.

Table 1: Ordering time of slip at 20 s. T_C^{85} is that time on the fault. The 200 m along-strike row keeps 400 m spacing perpendicular to the fault. The count 230/300, and the fact that all of them stop at both ends, refers to the 500 m set. The perpendicular 200 m entry is one time, with no bootstrap interval, computed on 227 of those 230. Three of the 230 ruptures do not propagate. Lags are from the 500 m grid. Stations ahead of the rupture are in Appendix A.

	Whole-fault	10 km field		
	259/300	230/300 at 500 m		
T_C^{85} , 500 m (s)	2 (1–3)	8 (7–9)		
T_C^{85} , 200 m along strike (s)	2	8 (7–9)		
T_C^{85} , perpendicular 200 m (s)	2	7		
Layout	lag (s)	T_{vis}^{85}	T_R^{85}	lag (s)
Near field	0 to 1	9	8	−1 to 0
Surround	1 to 4	9	9	−2 to 0

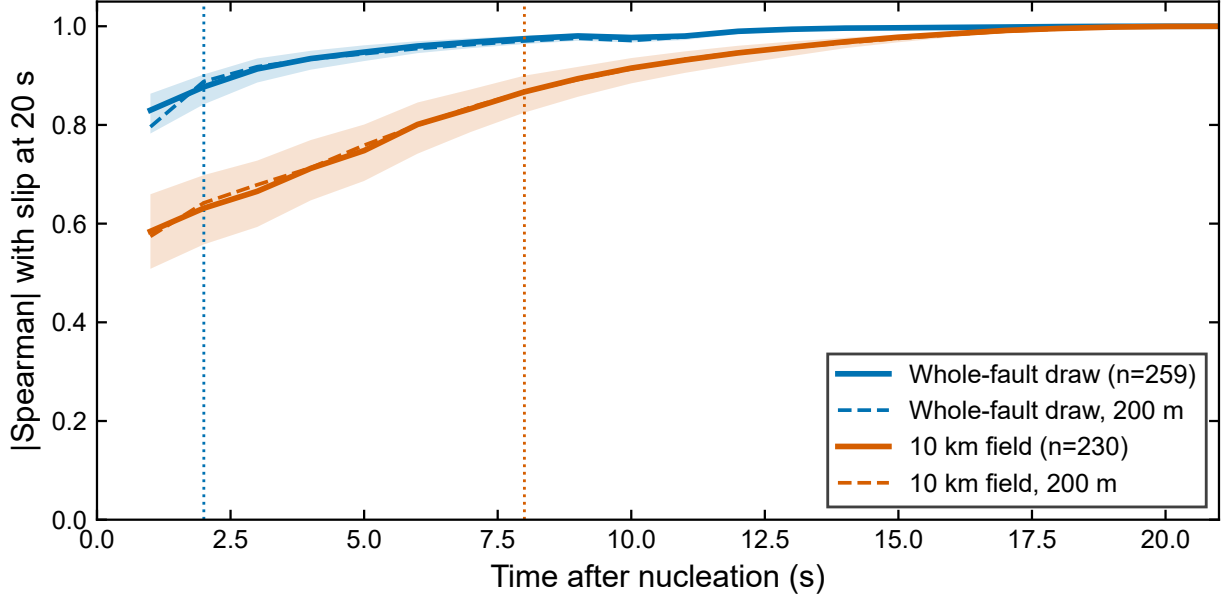


Figure 2: Absolute Spearman correlation between slip accumulated by time T and slip at 20 s. Shading is the 5–95% range of 200 bootstrap draws over the ruptures. Dotted lines mark 85% of the peak correlation: 2 s for the whole-fault draw and 8 s for the 10 km field. Dashed curves are the same ruptures at 200 m along strike.

3.2 Station lags relative to the arriving slip

Figure 3 and Table 1 give the lags between the station records and the slip that could have reached them. On the 10 km field the near field and the surround arrive with the waves, and the same intervals hold at 200 m along strike. A separate fit to each station gives 8 s beside the fault and 9 s for the surround, on both grids. On the whole-fault draw the near field arrives with the waves on both grids, and the surround is later. The ordering time of slip that could have reached the stations, and the ordering time of station energy, are 4 s and 4 s in the near field, and 7 s and 8 s in the surround. At 200 m along strike the surround times are 4 s and 8 s. A separate fit to each station on that surround reaches 85% at 5 s on both grids. Its lag on the 500 m grid is -2 to 1 s, so the fit arrives with the waves, ahead of the summed energy. Stations ahead of the rupture are described in Appendix A.

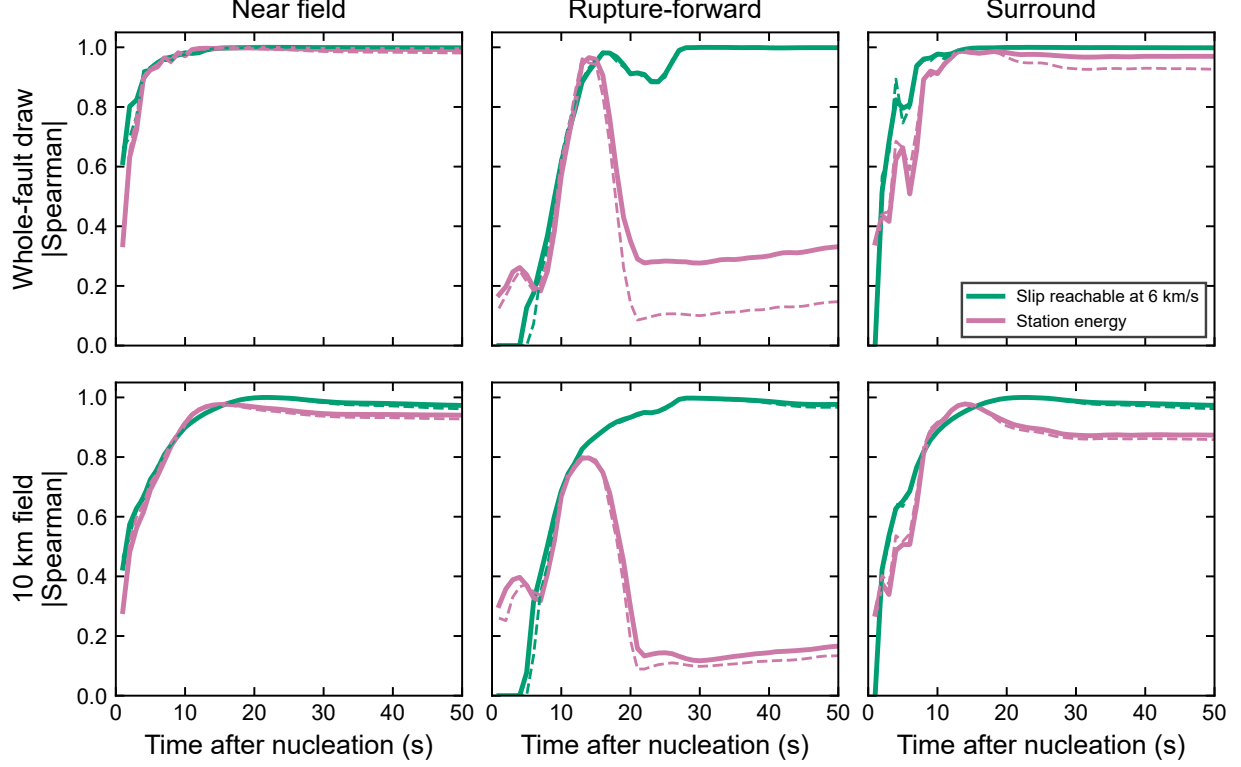


Figure 3: Station energy (pink) and slip that could have reached the stations at $v_p = 6 \text{ km s}^{-1}$ (green), each as the absolute Spearman correlation with slip at 20 s. Top: whole-fault draw, 259 ruptures. Bottom: 10 km field, 230 ruptures. Columns are the three layouts of Fig. 1. Dashed curves are the same ruptures at 200 m along strike. The right-hand column is discussed in Appendix A.

3.3 Peak displacement and a characteristic period in the first 3 s after the predicted P arrival

Figure 4 shows the error of P_d and τ_c for the 10 km field at 500 m. With samples before the predicted P arrival removed, the error of P_d and τ_c is 0.60 and 0.77 of the standard deviation of slip at 20 s in the near field, 0.66 and 0.87 ahead of the rupture, and 0.62 and 0.86 for the surround. On the same ruptures at 200 m along strike the errors are 0.66 and 0.78, 0.66 and 0.85, and 0.66 and 0.86.

At 500 m, most of the drop in the error is within 3 s of the ordering time of slip that could have reached the stations. At 200 m along strike the drop is also within 3 s of that ordering time, except for peak displacement ahead of the rupture. There the error falls at 10 s, and the ordering time of slip that could have reached those stations is 14 s. The station lag at that end remains -5 to -2 s, which stays unresolved.

A ridge regression on the energy of each station up to 50 s, at 500 m, has a relative error of 0.17 in the near field and 0.15 for the surround.

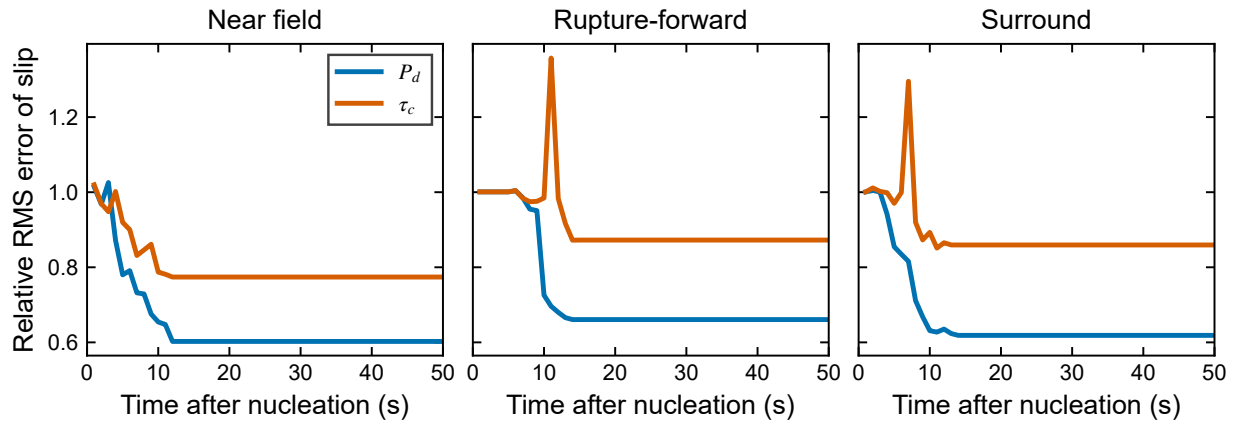


Figure 4: Relative root-mean-square error of the slip at 20 s predicted from peak displacement P_d (blue) and characteristic period τ_c (orange) in the first 3 s after the predicted P arrival. The curves are the 230 ruptures of the 10 km field at 500 m. The slip at 20 s of each rupture is estimated from the other ruptures.

3.4 The length remains fixed

Figure 5 shows the lengths of the ruptures run without the end patches. Without those patches, 24 of 36 ruptures in the 10 km field propagate, and every one spans 120 km. At 70 MPa, fluctuations of 3 and 7 MPa still leave lengths of 119.5–120 km. At 66, 65, and 63 MPa the lengths fall into two groups. One rupture in each group stops within about 40 km (Fig. 5a) and the majority reach the end (Fig. 5b), so the standard deviation is large while more than half still span the fault. That split is the one expected near the threshold

230 between arrest and runaway [Galis et al., 2017, Xu et al., 2015, Ripperger et al., 2007]. The
 231 2 s and 8 s times are measured on the ruptures that the end patches stop.

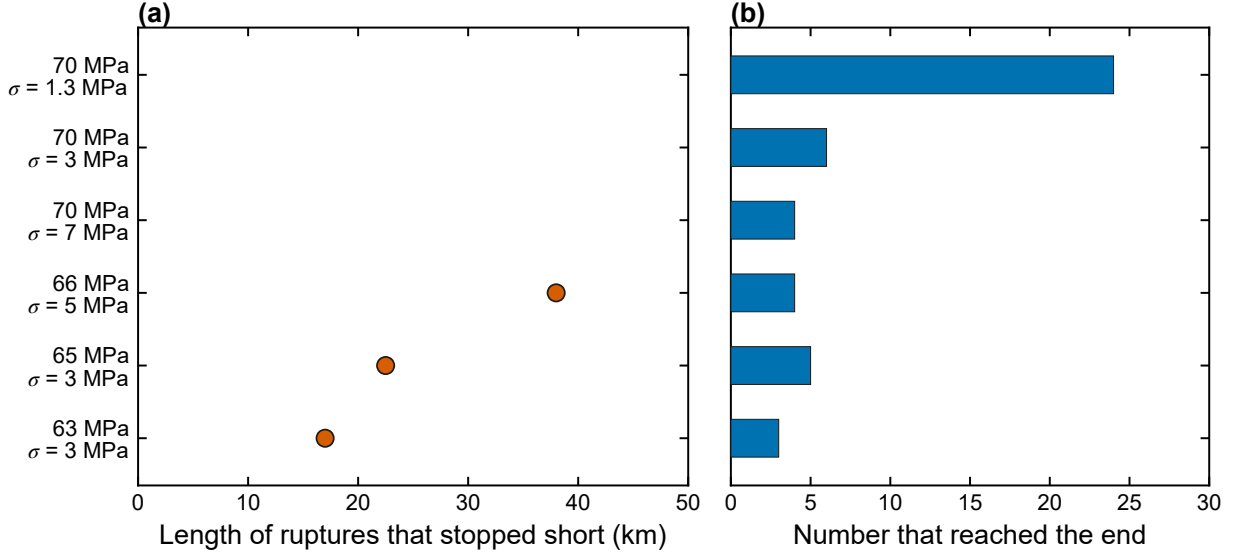


Figure 5: Rupture length without end patches, for the same groups in both panels. (a) Measured length of each rupture that stopped short of 100 km. A group with no circle had none. (b) Number of ruptures in that group that reached the end of the fault. Labels are the mean shear stress and the standard deviation of the along-strike fluctuation. The two fixed ± 7 MPa patches are present in every group.

232 3.5 Finer spacing along strike

233 The 2 s and 8 s times are measured where the static length Λ spans about 1.4 grid points.
 234 The first 72 ruptures that propagate in the 10 km field, rerun at 250 m, where Λ spans about
 235 2.8 grid points, give 11 s on both grids, and that 11 s is outside 7–9 s. The 8 s time comes
 236 from all 230 ruptures, not from these 72, whose rank correlation of slip at 20 s is 0.958.
 237 When all 230 ruptures are paired, both the 500 m grid and the 250 m grid give 8 s, and the
 238 rank correlation of slip at 20 s is 0.982 (Sect. 2.2). Neither the 500 m grid nor the 250 m
 239 grid puts three points across that static length, short of what Day et al. recommend [Day
 240 et al., 2005].

The 10 km field and the whole-fault draw were then rerun at 200 m along strike, with 601 nodes, so Λ spans about 3.5 grid points. Spacing perpendicular to the fault remains 400 m, and the 10 km stress from the coarser grid is interpolated onto the new nodes. On the 10 km field, T_C^{85} is 8 s at 200 m, the bootstrap interval is 7–9 s, and the rank correlation of slip at 20 s with the 500 m ruptures is 0.982. The correlation is 0.64 at 2 s and 0.87 at 8 s, against 0.63 and 0.87 at 500 m. On the whole-fault draw, T_C^{85} is 2 s at 200 m, every bootstrap resample on that grid gives 2 s, and the rank correlation of slip at 20 s is 0.998. The correlation is 0.80 at 1 s and 0.89 at 2 s, against 0.83 and 0.88 at 500 m. Between the 500 m grid and the finer grids, and between the two 200 m grids, the median root-mean-square difference in rupture time is at most 0.18 s, and the median relative difference in slip at 20 s is at most 0.011.

3.6 Spacing perpendicular to the fault

The same ruptures were run again with 200 m spacing perpendicular to the fault. On the whole-fault draw, all 259 ruptures propagate, and T_C^{85} is 2 s. The rank correlation of slip at 20 s with the 200 m along-strike ruptures is 0.975. On the 10 km field, 227 of the 230 ruptures propagate, and T_C^{85} on those 227 is 7 s. The rank correlation of their slip at 20 s with the 200 m along-strike ruptures is 0.976. Three of the 230 ruptures do not propagate, the 7 s time is still within 7–9 s, and the two ordering times on this mesh differ by 5 s. The front durations above were not recomputed here, and stations, P_d , and τ_c were not recomputed on this mesh.

4 Discussion

The early order in these calculations is an order of slip, because the rupture length does not change. With one background stress, that order is in place by 2 s when the spacing perpendicular to the fault is 400 m. When the stress also varies along strike, the same order

takes 8 s, and the later time is not a slower front. The front takes nearly the same time
 in both calculations, so slip on the patches that have already ruptured does not yet match
 the slip at 20 s. No further cause of the 6 s was measured. A reading consistent with the
 equal front times is that the fluctuation changes the local stress drop, which is 7 MPa at
 the mean stress, by amounts of order 1.3 MPa. Relative slip among ruptured patches can
 therefore keep changing after the front arrives, which a single background stress does not
 do. In the whole-fault draw the background stress is already inside the nucleation patch,
 and the correlation of slip is 0.83 at 1 s. When that spacing is 200 m, the whole-fault time
 is 2 s and the 10 km time is 7 s. Catalog magnitudes combine rupture length and slip. In
 these calculations the length does not vary, and removing the end patches does not produce
 a continuous range of lengths. Different final sizes separate only after about half of the
 rupture has been observed [Münchmeyer et al., 2022], and the 8 s and 7 s are not that half
 of the rupture.

The lags in Table 1 and Appendix A compare the station records with the arrival of the
 waves [Minson et al., 2018]. The relative error from peak displacement and the characteristic
 period [Kanamori, 2005, Wu and Kanamori, 2005], in the 3 s window after the predicted P
 arrival, is 0.60–0.87 on the 500 m grid and 0.66–0.86 at 200 m. Station energy over the 500 m
 record has a relative error of 0.15–0.17. An older comparison in the supplement, using ten
 waveform measurements, put a 16 s delay on stations ahead of the rupture; energy alone,
 on 23 ruptures of that 120 km fault, does not repeat it. On 40 other ruptures, describing
 the same waves with a more flexible fit moves the reported time from 12 s to 1 s (see the
 supplement). That shift is a change in the reading, not a change in the ruptures.

The calculations are plane strain and use one friction law, so a rupture front does not
 spread with depth and there is no free surface. The 2 s and 8 s are times for this geometry.
 They are not shown for a three-dimensional rupture, and the calculations include no field
 record. About 1.4 grid points span the static length Λ at 500 m, short of the three that Day
 et al. recommend [Day et al., 2005]. At 200 m along strike, Λ spans about 3.5 grid points,

which meets that count, and those ruptures still give 2 s and 8 s. For most nodes, stored slip is already past D_c at the first nonzero sample, so the cohesive-zone width was not measured. The 10 km time is 7 s only on the mesh with 200 m spacing perpendicular to the fault.

5 Conclusions

With the rupture length held fixed, the early order is an order of slip. Slip at 20 s is rank-ordered by 2 s when the background stress is one value for the whole fault, and by 8 s (7–9 s) when a 1.3 MPa fluctuation varies along strike over 10 km and the spacing perpendicular to the fault is 400 m. With that spacing at 200 m, the whole-fault time is 2 s and the 10 km time is 7 s, and three of the 230 ruptures in the 10 km field do not propagate on that mesh. On the meshes with 400 m spacing perpendicular to the fault, stations beside the 10 km ruptures and around them show the 8 s order when the waves arrive. Stations ahead of the rupture do not lead the waves, and on the whole-fault draw, stations around the fault are later than the waves. In the 3 s window after the predicted P arrival, the relative error from peak displacement and a characteristic period is 0.60–0.87 on the 500 m grid and 0.66–0.86 at 200 m. Removing the end patches does not produce a continuous range of lengths. At 200 m along strike, Λ spans about 3.5 grid points, and those ruptures give 2 s and 8 s. Stations, P_d , and τ_c were not recomputed on the mesh with 200 m spacing perpendicular to the fault.

Data and code availability

The calculations, the list of ruptures, random seeds, prestress settings, and the scripts that compute the ordering times, the station lags, and the earlier calculations in the supplement will be deposited in a DOI-citable archive before submission. That deposit is not yet public. Until it is public, editors and reviewers receive a private link to the same archive. A GitHub repository alone will not be the archive of record.

Competing interests

The author declares no competing interests.

Author contributions

Wenjie Lyu: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of generative AI use

The author used AI-based tools for English language editing. No AI tool generated the calculations, the numerical results, or the figures. The author reviewed the text and takes responsibility for the final content.

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A Stations ahead of the rupture

The right-hand column of Fig. 3 shows these curves. On the 10 km ruptures the lag at stations gathered by that end is -5 to -2 s at 500 m and again at 200 m, so it does not arrive with the waves. Energy correlation on the 500 m records reaches 0.80 at 14 s and falls to 0.12 by 30 s, while slip that could have reached those stations stays near 1. The 85% time is taken from the peak of the energy curve, so it falls at 11 s at 500 m and at 10 s at 200 m, before the ordering time of that slip at 14 s, and why the correlation falls after 14 s is not known. The same fall occurs for the whole-fault draw, from about 0.97 at 14 s to 0.28

336 at 30 s on the 500 m records, but there the lag is -1 to 0 s on both grids and the records
337 do arrive with the waves. The early time on the 10 km ruptures is not information ahead of
338 the P wave, and a separate fit to each station reaches 85% at 13 s.

References

- Richard M. Allen and Hiroo Kanamori. The potential for earthquake early warning in southern California. *Science*, 300(5620):786–789, 2003. doi: 10.1126/science.1080912.
- Richard M. Allen and Diego Melgar. Earthquake early warning: Advances, scientific challenges, and societal needs. *Annual Review of Earth and Planetary Sciences*, 47:361–388, 2019. doi: 10.1146/annurev-earth-053018-060457.
- D. J. Andrews. Rupture velocity of plane strain shear cracks. *Journal of Geophysical Research*, 81:5679–5687, 1976. doi: 10.1029/JB081i032p05679.
- S. Colombelli, A. Zollo, G. Festa, and M. Picozzi. Evidence for a difference in rupture initiation between small and large earthquakes. *Nature Communications*, 5:3958, 2014. doi: 10.1038/ncomms4958.
- Eric G. Daub. fdfault: a finite-difference code for elastodynamic rupture problems. <https://github.com/edaub/fdfault>, 2020. Version 1.0.0, released 13 March 2020; accessed 2 September 2026.
- Steven M. Day, Luis A. Dalguer, Nadia Lapusta, and Yi Liu. Comparison of finite difference and boundary integral solutions to three-dimensional spontaneous rupture. *Journal of Geophysical Research: Solid Earth*, 110:B12307, 2005. doi: 10.1029/2005JB003813.
- William L. Ellsworth and Gregory C. Beroza. Seismic evidence for an earthquake nucleation phase. *Science*, 268:851–855, 1995. doi: 10.1126/science.268.5212.851.
- Martin Galis, Jean Paul Ampuero, P. Martin Mai, and Frédéric Cappa. Induced seismicity provides insight into why earthquake ruptures stop. *Science Advances*, 3:eaap7528, 2017. doi: 10.1126/sciadv.aap7528.
- Yoshiaki Ida. Cohesive force across the tip of a longitudinal-shear crack and Griffith’s

specific surface energy. *Journal of Geophysical Research*, 77:3796–3805, 1972. doi:
10.1029/JB077i020p03796.

Satoshi Ide. Frequent observations of identical onsets of large and small earthquakes. *Nature*,
573:112–116, 2019. doi: 10.1038/s41586-019-1508-5.

Satoshi Ide and Keisuke Yoshida. Predictable and unpredictable aspects of earthquakes from
P-wave onsets of acceleration seismograms. *Earth, Planets and Space*, 78:28, 2026. doi:
10.1186/s40623-025-02357-9.

Hiroo Kanamori. Real-time seismology and earthquake damage mitigation. *Annual Review*
of Earth and Planetary Sciences, 33:195–214, 2005. doi: 10.1146/annurev.earth.33.092203.
122626.

Valeria Longobardi, Simona Colombelli, and Aldo Zollo. The deterministic behaviour of
earthquake rupture beginning. *Communications Earth & Environment*, 6:883, 2025. doi:
10.1038/s43247-025-02814-z.

M.-A. Meier, J. P. Ampuero, and T. H. Heaton. The hidden simplicity of subduction megath-
rust earthquakes. *Science*, 357:1277–1281, 2017. doi: 10.1126/science.aan5643.

Men-Andrin Meier, Thomas Heaton, and John Clinton. Evidence for universal earthquake
rupture initiation behavior. *Geophysical Research Letters*, 43:7991–7996, 2016. doi: 10.
1002/2016GL070081.

Men-Andrin Meier, Jean-Paul Ampuero, Elizabeth Cochran, and Morgan Page. Apparent
earthquake rupture predictability. *Geophysical Journal International*, 225:657–663, 2021.
doi: 10.1093/gji/ggaa610.

Diego Melgar and Gavin P. Hayes. Characterizing large earthquakes before rupture is com-
plete. *Science Advances*, 5:eaav2032, 2019. doi: 10.1126/sciadv.aav2032.

- Sarah E. Minson, Men-Andrin Meier, Annemarie S. Baltay, Thomas C. Hanks, and Elizabeth S. Cochran. The limits of earthquake early warning: Timeliness of ground motion estimates. *Science Advances*, 4:eaag0504, 2018. doi: 10.1126/sciadv.aag0504.
- Jannes Münchmeyer, Ulf Leser, and Frederik Tilmann. A probabilistic view on rupture predictability: All earthquakes evolve similarly. *Geophysical Research Letters*, 49(13):e2022GL098344, 2022. doi: 10.1029/2022GL098344.
- Erik L. Olson and Richard M. Allen. The deterministic nature of earthquake rupture. *Nature*, 438:212–215, 2005. doi: 10.1038/nature04214.
- J. Ripperger, J.-P. Ampuero, P. M. Mai, and D. Giardini. Earthquake source characteristics from dynamic rupture with constrained stochastic fault stress. *Journal of Geophysical Research: Solid Earth*, 112:B04311, 2007. doi: 10.1029/2006JB004515.
- Paul Rydelek and Shigeki Horiuchi. Is earthquake rupture deterministic? *Nature*, 442:E5–E6, 2006. doi: 10.1038/nature04963.
- Margarita M. Solares-Colón, Diego Melgar, Andrew Howell, Brendan Crowell, Elisabetta D’Anastasio, Emmanuel Caballero, and Bill Fry. Using ruptures from an earthquake cycle simulator to test geodetic early warning system performance. *Seismica*, 4(2), 2025. doi: 10.26443/seismica.v4i2.1769.
- Yih-Min Wu and Hiroo Kanamori. Rapid assessment of damage potential of earthquakes in Taiwan from the beginning of *P* waves. *Bulletin of the Seismological Society of America*, 95(3):1181–1185, 2005. doi: 10.1785/0120040193.
- Jiankuan Xu, Haiming Zhang, and Xiaofei Chen. Rupture phase diagrams for a planar fault in 3-D full-space and half-space. *Geophysical Journal International*, 202:2194–2206, 2015. doi: 10.1093/gji/ggv284.

408 Hongfeng Yang, Suli Yao, and Xiang Chen. Rupture propagation on heterogeneous fault:
409 Challenges for predicting earthquake magnitude. *Chinese Science Bulletin*, 67(13):1390–
410 1403, 2022. doi: 10.1360/tb-2021-1086.

Supplement: Earlier readings for “Along-strike stress delays the ordering of slip on a fixed-length fault”

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These notes are earlier calculations on smaller sets. An older reading moved the reported time from 12 s to 1 s, and energy alone did not repeat a 16 s delay. They are not part of the 2 s and 8 s results in the main text.

1 The reported time depends on the reading

On 40 other ruptures, a linear combination of waveform measurements, a small network, and a larger network put the reported time at 12, 3, and 1 s. The three estimates differ. The reported time moves from 12 s to 1 s as the fit to the same waves becomes more flexible. These times are separate from the 2 s and 8 s in the main text, and they are not delays for a warning network. The simplest reading still separates the waves from a phase-scrambled control late in the record [Theiler et al., 1992], and the gap between the data and that control is about 0.60. Resampling the ruptures moves the 12 s estimate, and that bootstrap is not confined to 12 s. The three point estimates remain 12, 3, and 1 s.

Table 1: Earlier station comparison on smaller sets. $\Delta T = T_R^{85} - T_C^{85}$ in seconds. Those columns use ten waveform measurements. The energy line replaces them for the 120 km ruptures. These ruptures are not the 259 and 230 in the main text.

	120 km $n = 10, T_C^{85} = 12$ s	80 km $n = 11, 18$ km off, $T_C^{85} = 3$ s
Near field ΔT	-4	0
Rupture-forward ΔT	+16	+9
Surround ΔT	0	+5
Energy only	14 s peak; 0.07 at 28 s	

2 An older station comparison

Table 1 is an earlier comparison on smaller sets. With ten waveform measurements, stations ahead of the rupture are 16 s later than the fault on ten ruptures on the 120 km fault ($T_C^{85} = 12$ s) and 9 s later on eleven ruptures on an 80 km fault, with stations 18 km off the fault ($T_C^{85} = 3$ s). Stations beside the fault are not later (-4 s and 0), and stations around the fault match the fault on the 120 km ruptures and are 5 s later on the 80 km ones. Energy alone, on 23 ruptures of the 120 km fault, peaks at 14 s (correlation 0.95) and is 0.07 at 28 s. The bootstrap of that 85% time lies between 10 and 14 s. Those 23 include the ten that could be loaded from the comparison above, plus later ruptures.

3 Earlier ruptures

The geometries and curve shapes below were calculated before the 259 and 230 ruptures. They do not explain the 2 s and 8 s. Far, long, and short are labels for that earlier set, and the labels overlap. On both far geometries, slip on the fault is ordered before the stations show that order (11 and 12 ruptures). Of the two long geometries, one on-fault curve rises gradually and the other is mixed. The comparison asked only that one of the two rise gradually, and one did. Short geometries with at least eight ruptures are not used to claim that their timing keeps changing. One short geometry has seven ruptures and is left out.

Each geometry uses twelve starting draws. The long geometries do not share one curve, and these stations are not the 10 km result in the main text.

An earlier set, with initial-condition perturbations of amplitude $\varepsilon = 1$, separated ruptures by whether the on-fault curve rises gradually or flattens early. The ruptures whose on-fault curve flattens early do not share one leave-one-out pattern. They were not part of the 2 s and 8 s calculations, and they are not used to explain those times.

References

James Theiler, Stephen Eubank, André Longtin, Bryan Galdrikian, and J. Doyne Farmer. Testing for nonlinearity in time series: the method of surrogate data. *Physica D: Nonlinear Phenomena*, 58:77–94, 1992. doi: 10.1016/0167-2789(92)90102-S.