The influence of earthquake gates on surface rupture length

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Abstract

Earthquake magnitude is controlled by the rupture area of the fault network hosting the event. For surface-rupturing large strike-slip earthquakes (~MW6+), ruptures must overcome zones of geometrical complexity along fault networks. These zones, or earthquake gates, act as barriers to rupture propagation. We map step-overs, bends, gaps, splays, and strands from the surface ruptures of 31 strike-slip earthquakes, classifying each population into breached and unbreached groups. We develop a statistical model for passing probability as a function of geometry for each group. Step-overs, and single bends are more predictable earthquake gates than double bends and gaps, and ~20% of ruptures terminate on straight segments. Based on our modeled probabilities, we estimate event likelihood as the joint passing probabilities of breached gates and straight segments along a rupture. Event likelihood decreases inversely with rupture length squared. Our findings support a barrier model as a factor in limiting large earthquake size.
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Key Points:

- We map step-overs, bends, gaps, splays, and strands from the surface ruptures of 31 strike-slip earthquakes at 1:50,000 scale.
- We estimate passing probabilities as a function of geometry for each earthquake gate type.
- Our results support a barrier model as a factor in controlling earthquake size.
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Plain Language Summary

Zones of geometrical complexity along faults, or earthquake gates, can halt propagating earthquakes. We map five types of geometrical complexities from historical surface rupture maps and regional fault maps: step-overs, bends, gaps, splays, and strands. We classify each mapped earthquake gate as breached (earthquake propagated past) or unbreached (earthquake halted) and measure the width of step-overs and strands, the length of gaps, and the angle of splays and bends. Based on these measurements, we model the probability that each gate will be breached given its geometry. Step-overs and single bends halt ruptures more predictably than double bends and gaps, and ~20% of the rupture ends occurred on straight fault segments. Using our probabilities, we show that the presence and geometry of earthquake gates plays a first-order control on the low likelihood of large surface rupturing earthquakes. The probabilities we estimate may be used in simulators to assess the hazard associated with multi-fault earthquakes.

Introduction

Earthquake surface ruptures are composed of fault segments bound by zones of geometrical complexity or earthquake gates (e.g., Wesnousky, 2006; Manighetti et al., 2007; Klinger, 2010; Perrin et al., 2016; Hamling et al., 2017). Earthquake gates can act as barriers to rupture propagation, where the history of past earthquakes, rupture dynamics, material properties, and the
availability and geometry of neighboring fault segments dictate the probability of throughgoing rupture. For earthquakes on vertically-dipping strike-slip faults, where the thickness of the seismogenic zone limits down-dip rupture propagation, earthquake gates have been proposed to exert an important control on rupture length, and thus on maximum magnitude (e.g., Wesnousky, 2006).

Historical earthquake rupture maps provide tests for geometrical controls on rupture propagation that serve as validation for rupture simulator forecasts and dynamic rupture models (e.g., Wesnousky, 2006; Wesnousky, 2008; Biasi and Wesnousky, 2016, 2017, 2021). For example, Wesnousky (2006) showed that rupture propagation through step-overs occurred in ~40% of the cases and step-overs wider than 3-4 km were never breached. Biasi and Wesnousky (2017) found that ruptures propagated past fault bends >25° less than half of the time. These studies relied on simplified rupture maps, limiting the minimum size of earthquake gates mapped to kilometer-scale. Earthquake gates in the hundreds of meters scale have not been characterized and may be of mechanical importance. For example, the 2014 Napa earthquake terminated in a 750-meter-wide step-over, too small to be included in previous studies. With new surface rupture maps from recent events, concurrent with ongoing efforts to standardize past rupture maps (e.g., Sarmiento et al., 2021; Nurminen et al., 2022) and improve regional fault maps, it is now possible to revisit and expand the analysis of the distribution of earthquake gates in size and space influences the probability of rupture propagation and final event size.

In this study, we map geometrical complexities at 1:50,000 scale, which corresponds with features >100-500 meters in length, from 31 strike-slip surface rupture maps in the unified Fault Displacement Hazard Initiative (FDHI) database (Sarmiento et al., 2021). We consider five types of earthquake gates: step-overs, bends, splays, gaps, and strands (Figure 1). Step-overs are spaces between neighboring, parallel, overlapping faults. Bends are locations where the fault changes strike. Bends may come in pairs (double bends) where the fault returns to its original orientation. Step-overs and double bends may be classified as a restraining (net contraction) or releasing (net extension), but single bends cannot be classified as such without knowledge of rupture propagation direction. Gaps are spaces between coplanar faults, distinct from step-overs, where faults are not coplanar. Splays are locations where the fault branches. We also consider fault strands that are parallel to subparallel of the main rupture that are activated without the rupture reaching the terminus of the main fault.
From our earthquake gate catalog, we estimate the passing probabilities of each earthquake gate class as a function of its geometry. Using these probability distributions, we analyze the joint probability of the observed breached gates and straight segments for each event and characterize the relationship of these probabilities to the observed earthquake magnitude and surface rupture length. Event joint probabilities may be applied to assess maximum rupture length for future earthquakes in mapped fault systems.

**Distribution of earthquake gates**

We map earthquake gates from the 31 strike-slip surface ruptures in the FDHI database (Sarmiento et al., 2021). We classify each mapped feature as breached or unbreached, depending on whether the rupture propagated past the earthquake gate (see methods). To consider the size and geometry distribution of the earthquake gates we map, we estimate empirical cumulative distribution functions (ECDFs) for each population (Figure 2), separated into breached and unbreached groups, and restraining and releasing categories when possible. We find that the ECDFs are well described by log-normal distributions. We use the two-sample Kolmogorov-Smirnoff (KS) test to assess whether different subset groups of an earthquake gate are statistically different. We use the p-value derived from the test, which is the probability of rejecting the null hypothesis that samples in the two subset groups were drawn from the same distribution. The convention for statistical significance is $p<0.05$.

We mapped a total of 68 step-overs, where 25 are releasing and 43 are restraining. The widest breached step-over is 1.4 km wide and restraining. The breached and unbreached step-over populations are distinct, though the restraining and releasing groups are statistically indistinguishable ($p$-values of 0.7 and 0.4 for breached and unbreached populations respectively). We also map 43 strands, the bulk of which are within 2 km of the rupturing fault.

We mapped a total of 153 gaps, where only 6 were unbreached. The largest breached gap is ~15 km long. Despite the low number of unbreached gaps mapped, the breached and unbreached CDFs are statistically distinct ($p$-value of 0.02). Mapping an unbreached gap requires the rupturing fault and faults of parallel strike ahead of it to have been mapped in the regional map to a sufficient resolution to include gaps in the fault system. The low number of unbreached gaps we map may reflect the limited resolution of candidate, unactivated faults on available regional fault maps.
Figure 1. Earthquake gates mapped in this study. (a) Simplified cartoon showing the features characterized in this study. The black lines denote the surface rupture whereas the light gray lines represent the regional faults that did not rupture during the event. The widths, lengths, and angles measured are shown in green for the breached features and in red for the unbreached features. (b) Examples of breached earthquake gates from the FDHI rupture database (Sarmiento et al., 2021).

We map a total of 708 bends and analyze these separated into restraining and releasing, and single and double categories (Figure 2). The largest breached single bend is 52° and the largest breached double bend is 47°. The breached and unbreached single and double bends are statistically different (p=3x10^{-16} and p=0.001), but the restraining and releasing populations are not (p-values of ~0.2 for breached and unbreached).
We map 71 splays. The angles of splays that were ruptured versus splays that were bypassed cannot be separated by the KS test (p=0.07). In most cases where a splay was activated, the rupture propagated less than 3 km. Modeling studies suggest a link between rupture arrest at splays related to the kinematics of the junction and the length of the fault branch (Poliakov et al., 2002; Kame et al., 2004). Though we do not classify our splays into transpressional or transtensional because the direction of rupture propagation is not known, the fact that we only observe two complete rupture arrests at splays suggests that the presence of a splay plays a small role in the behavior of the rupture on the principal fault, despite the fact that most splay branches mapped were relatively short, which should hinder rupture propagation by allowing the two fault segments to interact as the rupture stops on the shorter one (Bhat et al., 2007). Overall, our results suggest that splays do not play an important role in rupture arrest at the mapping scale.

An important difference between characterizing earthquake gates from simplified rupture maps and the detailed rupture maps in the FDHI database is that the simplified rupture maps tend to overestimate the size of the earthquake gate. For example, the restraining step-over in the center of the Borrego earthquake rupture (Figure 1B) was mapped as 1.5 km wide from a simplified map in Wesnousky (2006) whereas we measure a width of ~800 meters. Breached step-overs wider than 2 km in previous work are hard-linked in the more detailed rupture maps. We classify these as breached double bends or splays, depending on what feature achieves the linkage. This is the case for the steps along the Landers earthquake which are hard linked by splay faults and were previously described as “complex step-overs” (Biasi and Wesnousky, 2016).

As part of their evolution, step-overs can become hard-linked by fault segments, evolving into double bends (Figure S1). We analyze our bend population by looking at two additional geometrical characteristics, a bend length (Lozos et al., 2011), and a proxy step-over width (Figure S1). When we parameterize bends by length or proxy step-over width, we find no differences between the breached and unbreached populations (Figure S2). This suggests that step-overs that evolve into double bends become mechanically different features with higher passing probability. An important implication of this observation is that the hard linkage we observe at the surface may persist at depth. This supports that earthquake gates of small dimensions can span the entire seismogenic zone and play a role in modulating rupture dynamics.
Rupture termination sometimes occurs on a straight portion of a fault, absent an observed earthquake gate, where the active fault continues for at least one kilometer past the rupture tip. This is the case for ~20% of the rupture termini in this study, comparable to the 10% of Biasi and Wesnousky (2016).

**Figure 2.** Empirical cumulative distribution function for the earthquake gates mapped in this study (solid) and log-normal cumulative distribution fit for each ECDF (dotted). Top left: Restraining and releasing step-overs, parameterized based on width. Top right: Gap length. Middle left: Strands. Middle right: Restraining and releasing double bends, parameterized based on angle. Bottom left: Distance to strand. Bottom right: Splays, separated into ruptured or unruptured.

**Passing probabilities**
For the earthquake gates that have statistically significantly different breached and unbreached populations, we estimate passing probability as a function of geometry using a logistic model. This model describes the probability of a binary outcome (breached versus unbreached) as a continuous function of the geometrical properties of an earthquake gate, without requiring arbitrary binning of the data (see supplementary methods). We use unweighted logistic regressions despite the number of features in the breached and unbreached classes being different in the gaps and bends groups. We do this because, especially for the bends, the range of breached and unbreached bend angles largely overlaps, so that the relative frequency of breached and unbreached features is what distinguishes the two groups (Biasi and Wesnousky, 2016). Weighting the data inversely by frequency would obscure this effect.

Because restraining and releasing features are not statistically different, we combine these groups when estimating passing probabilities. Our logistic models (Figure 3) suggest that step-overs wider than ~1.1 km will be breached less than half of the time. Step-overs >5 km will be breached <3% of the time, consistent with the fact that they are not observationally documented in the rupture maps without linking structures. The logistic models predict that gaps longer than ~19 km will be breached less than half of the time. This distance is considerably larger than for stepovers, which we interpret as evidence that the absence of sufficient unbreached gap measurements precludes a robust estimate of passing probabilities for gaps. Double bends >46° and single bends >38° are predicted to be breached less than half of the time.

We assess the performance of our logistic regressions using an ROC score and confusion matrix (Pedregosa et al., 2011, Figures 3 and S4). Both metrics support that step-overs are the earthquake gates best described by a logistic model, with width being a strong predictor of rupture propagation. The logistic regressions struggle to predict unbreached bends well. This is because the populations of breached and unbreached bends largely span the same bend angles and are only separated by the changes in the breached and unbreached frequency of that angle, which makes it difficult to predict with a binary classifier. Therefore, at the mapping scale, bend angle is only an unequivocal predictor of whether a bend will be breached for very large angles.
Figure 3. Logistic regressions (gray) showing the passing probabilities of earthquake gates. The data are shown as beehive plots, which show all data points in each classification, breached in green and unbreached in red. Restraining and releasing features are combined (shown separately in Figure S3). Top left: Passing probability as a function of step-over width. Top right: Passing probability as a function of double bend angle. Bottom left: Passing probability versus gap length. Bottom right: Passing probability as a function of single bend angle. The gray shading shows the 95% C.I. calculated by bootstrapping.

Biasi and Wesnousky (2016) predict step-overs wider than 3 km will be breached <50% of the time, a value that exceeds our largest observed breached step-over. Biasi and Wesnousky (2017) found the probability of rupture propagation past a 25° bend was 50%, consistent with the estimate of Ozawa et al. (2023) using quasi-dynamic rupture models (Figure S5). We predict much larger passing probabilities of >75% for single and double bends of that size. The differences between our passing probabilities and those in previous work arise from the use of different rupture
maps (simplified versus not) and mapping at a finer scale.

In our work, double bend length is not a good predictor of whether a double bend will be breached (Figure S2). This may be a result of our map scale, such that large double bends are broken down into smaller constituent bends. Only 25 bends with length >2 km are contained within our dataset. Lozos et al. (2011) found bends shorter than 2 km were always breached in dynamic rupture models. For larger bends, trade-offs between bend angles and lengths result in a limiting size and angle at which bends are breached. Therefore, at a larger scale, double bends are effective earthquake gates.

A barrier model for earthquake size

For each of the events examined, we model an event likelihood that reflects the pre-existing geometrical complexity in the hosting fault system. We model event likelihood as the joint likelihood of continuing past the collective straight fault segments, \( p(L) \), and breaching \( n \) gates each with \( p_i \) in an event: \( p_{\text{EQ}} = p(L) \prod_{i=1}^{N} p_i \). We assume a constant chance of arrest at any point along without barriers such that \( p(L) = e^{-\lambda L} \) is the survival function of the exponential distribution where \( L \) is the rupture length, and \( \lambda = 8.16 \times 10^{-6} \text{ arrests/m} \) is calculated by dividing the total number of arrests by the total length of straight segments. We derive passing probabilities for each gate and its geometry from our logistic models.

Figure 4 (top) shows the distribution of modeled event likelihoods versus magnitude for the 31 strike-slip earthquakes in the FDHI database. Event likelihood decreases with increasing magnitude, as expected based on the model design, though there is significant scatter between events. We do not consider the M\(_W\) 5 events in our fit because M\(_W\) 5 events rarely cause surface ruptures (Wells and Coppersmith, 1993), and, when they do, the rupture is typically incomplete to the surface, resulting in the absence of a coherent rupture trace from which earthquake gates can be robustly mapped. We also exclude gaps from the likelihood estimates given the small number of unbreached gaps sampled, though including these would only change the scaling exponent by <0.2. If we chose to weight our logistic regressions by the frequency of points, the resulting passing probabilities would be substantially less where populations of breached and unbreached features overlap, resulting in a much steeper scaling relationship.

To investigate the relationship of rupture length to event likelihood, we compute
likelihoods as cumulative probabilities along each mapped rupture (Figure 4, bottom). Event likelihood decreases inversely with rupture length squared. As earthquake gates are traversed by rupture, the cumulative log-likelihood of each event decreases following a similar slope. The spacing between neighboring gates is log-normally distributed (Figure S6), with an average spacing of ~2 km.

Though our observations are limited by the magnitude range of observed surface rupturing earthquakes, the relationship between likelihood to surface rupture length, and to magnitude, suggests that earthquake scaling is at least in part controlled by the number and characteristics of the earthquake gates present along the hosting fault system. This supports a barrier model for earthquake size (e.g., Aki, 1979; Aki, 1989; Heaton, 1990), where geometrically simple segments of the fault are bounded by geometrically complex barriers that must be breached for the rupture to continue. Previous empirical studies have also argued in favor of this model based on the segmentation of surface ruptures and the distribution of displacements during an event (e.g., King and Nabelek, 1985; Klinger et al., 2006; Rockwell and Klinger, 2013).

An important subtlety in this study is that the definition of breaching as continuing for at least 1 km intrinsically limits the scale of gates considered. The earthquakes considered here had sufficient accumulated elastic energy to rupture kilometers of fault before stopping at earthquake gates. Therefore, while earthquakes in this dataset often stop at barriers, reaching those barriers in the first place was conditional on having sufficient elastic energy, an aspect that is asperity-controlled. This suggests that the size of large earthquakes is modulated by trade-offs between the location of asperities, which provide the elastic energy required for the event to continue growing, and the location and strength of barriers, which will bring the event to arrest when barrier strength exceeds the elastic energy available (Figure 5).
Figure 4. Top: Event likelihood versus magnitude for the strike-slip earthquakes in the FDHI database. The line shows the best fit for the evolution of event likelihood with magnitude. Bottom: Cumulative event likelihood versus distance along the surface rupture. Each colored line represents one event. The scattered dots indicate the event likelihood at its final rupture length. The rupture lengths are based on the FDHI event coordinate system (ECS) reference lines (Sarmiento et al., 2021). The orange line represents the best fit to the final event likelihoods.
Figure 5. Schematic cartoon of how an earthquake gate will bring rupture to arrest, conditional on the available elastic energy being lower than the strength of the barrier.

When an earthquake terminates at a barrier, elevated residual stresses, if not relaxed, can promote rupture propagation past the barrier in a subsequent event. This behavior is observed in multi-cycle rupture models (e.g., Duan and Oglesby, 2006) and inferred from the occurrence of aftershocks at barriers where ruptures terminate (Aki, 1979). Earthquake gates may therefore act as a barrier in one event, and as an asperity in a subsequent event. Large earthquakes are thought to preferentially nucleate at asperities. Thus, earthquake gates behaving as asperities would be in proximity to the epicenter of the event. As one test of this prediction, we evaluate the distribution of breached and unbreached gates with respect to the epicentral location (Figure S7, top). We find no relationship between the location of an earthquake gate and whether it was breached. Earthquake gates and their geometry, as well as whether they were breached, are also not correlated with their position along the surface rupture (Figures S8 and S9).
Earthquake gates behaving as asperities are also expected to overlap with locations with large displacements on the fault, where the elastic energy available is high. To test this hypothesis, we measure the distance between breached and unbreached earthquake gate and the location of peak slip in that event (Figure S7, bottom). We find no relationship between whether a gate was breached or not and its distance from the location of maximum slip. The absence of these spatial correlations suggests that, while earthquake gates may also act as asperities, this relationship is not frequent enough or the effect sufficiently large to stand out in our surface-rupture dataset. Our results instead demonstrate that the geometry of earthquake gates, acting as barriers to rupture propagation, influences the growth of ruptures and the final magnitude an earthquake achieves.

Conclusions

We map step-overs, bends, gaps, splays, and strands along the surface rupture maps of 31 strike-slip earthquakes at 1:50,000 scale. We characterize these earthquake gates as breached and unbreached based on whether the rupture propagated. We use these measurements to fit a logistic model to each earthquake gate type that estimates passing probabilities as a function of gate geometry. We find that step-over width is an excellent predictor of whether a step-over will be breached. Bend angle is a limited predictor of whether a bend will be breached, although the ratio of unbreached to breached bends increases consistently with increasing bend angle. We find double bends behave differently than step-overs with the same geometry, suggesting step overs persist as discrete unlinked fault strands at depth. These empirically determined passing probabilities can be used to calibrate long-term rupture simulators (e.g. Field et al., 2015; Milner et al., 2022).

The fact that the mapped gates are preferred stopping points provides strong evidence that the surficially mapped features are indicative of fault structure that persists to depth. In addition, we use the passing probabilities of the breached earthquake gates in each event to estimate a retrospective event likelihood that captures the likelihood of that earthquake given the complexity of the hosting fault system. The cumulative event likelihood tabulated along rupture strike supports a barrier model as a factor in controlling earthquake size, where relatively straight fault segments are bounded by geometrical barriers that must be breached for the rupture to continue growing.

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Open Research
The data and code required to reproduce our analysis are available from https://github.com/absrp/passing_probabilities_EQgates. They will be transferred to a Zenodo repository for permanent storage following acceptance.

References


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Introduction

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Figure 1. Earthquake gates mapped in this study. (a) Simplified cartoon showing the features characterized in this study. The black lines denote the surface rupture whereas the light gray lines represent the regional faults that did not rupture during the event. The widths, lengths, and angles measured are shown in green for the breached features and in red for the unbreached features. (b) Examples of breached earthquake gates from the FDHI rupture database (Sarmiento et al., 2021).

We map a total of 708 bends and analyze these separated into restraining and releasing, and single and double categories (Figure 2). The largest breached single bend is 52° and the largest breached double bend is 47°. The breached and unbreached single and double bends are statistically different (p=3x10^{-16} and p=0.001), but the restraining and releasing populations are not (p-values of ~0.2 for breached and unbreached).
We map 71 splays. The angles of splays that were ruptured versus splays that were bypassed cannot be separated by the KS test (p=0.07). In most cases where a splay was activated, the rupture propagated less than 3 km. Modeling studies suggest a link between rupture arrest at splays related to the kinematics of the junction and the length of the fault branch (Poliakov et al., 2002; Kame et al., 2004). Though we do not classify our splays into transpressional or transtensional because the direction of rupture propagation is not known, the fact that we only observe two complete rupture arrests at splays suggests that the presence of a splay plays a small role in the behavior of the rupture on the principal fault, despite the fact that most splay branches mapped were relatively short, which should hinder rupture propagation by allowing the two fault segments to interact as the rupture stops on the shorter one (Bhat et al., 2007). Overall, our results suggest that splays do not play an important role in rupture arrest at the mapping scale.

An important difference between characterizing earthquake gates from simplified rupture maps and the detailed rupture maps in the FDHI database is that the simplified rupture maps tend to overestimate the size of the earthquake gate. For example, the restraining step-over in the center of the Borrego earthquake rupture (Figure 1B) was mapped as 1.5 km wide from a simplified map in Wesnousky (2006) whereas we measure a width of ~800 meters. Breached step-overs wider than 2 km in previous work are hard-linked in the more detailed rupture maps. We classify these as breached double bends or splays, depending on what feature achieves the linkage. This is the case for the steps along the Landers earthquake which are hard linked by splay faults and were previously described as “complex step-overs” (Biasi and Wesnousky, 2016).

As part of their evolution, step-overs can become hard-linked by fault segments, evolving into double bends (Figure S1). We analyze our bend population by looking at two additional geometrical characteristics, a bend length (Lozos et al., 2011), and a proxy step-over width (Figure S1). When we parameterize bends by length or proxy step-over width, we find no differences between the breached and unbreached populations (Figure S2). This suggests that step-overs that evolve into double bends become mechanically different features with higher passing probability. An important implication of this observation is that the hard linkage we observe at the surface may persist at depth. This supports that earthquake gates of small dimensions can span the entire seismogenic zone and play a role in modulating rupture dynamics.
Rupture termination sometimes occurs on a straight portion of a fault, absent an observed earthquake gate, where the active fault continues for at least one kilometer past the rupture tip. This is the case for ~20% of the rupture termini in this study, comparable to the 10% of Biasi and Wesnousky (2016).

**Figure 2.** Empirical cumulative distribution function for the earthquake gates mapped in this study (solid) and log-normal cumulative distribution fit for each ECDF (dotted). Top left: Restraining and releasing step-overs, parameterized based on width. Top right: Gap length. Middle left: Strands. Middle right: Restraining and releasing double bends, parameterized based on angle. Bottom left: Distance to strand. Bottom right: Splays, separated into ruptured or unruptured.

**Passing probabilities**
For the earthquake gates that have statistically significantly different breached and unbreached populations, we estimate passing probability as a function of geometry using a logistic model. This model describes the probability of a binary outcome (breached versus unbreached) as a continuous function of the geometrical properties of an earthquake gate, without requiring arbitrary binning of the data (see supplementary methods). We use unweighted logistic regressions despite the number of features in the breached and unbreached classes being different in the gaps and bends groups. We do this because, especially for the bends, the range of breached and unbreached bend angles largely overlaps, so that the relative frequency of breached and unbreached features is what distinguishes the two groups (Biasi and Wesnousky, 2016). Weighting the data inversely by frequency would obscure this effect.

Because restraining and releasing features are not statistically different, we combine these groups when estimating passing probabilities. Our logistic models (Figure 3) suggest that step-overs wider than ~1.1 km will be breached less than half of the time. Step-overs >5 km will be breached <3% of the time, consistent with the fact that they are not observationally documented in the rupture maps without linking structures. The logistic models predict that gaps longer than ~19 km will be breached less than half of the time. This distance is considerably larger than for stepovers, which we interpret as evidence that the absence of sufficient unbreached gap measurements precludes a robust estimate of passing probabilities for gaps. Double bends >46° and single bends >38° are predicted to be breached less than half of the time.

We assess the performance of our logistic regressions using an ROC score and confusion matrix (Pedregosa et al., 2011, Figures 3 and S4). Both metrics support that step-overs are the earthquake gates best described by a logistic model, with width being a strong predictor of rupture propagation. The logistic regressions struggle to predict unbreached bends well. This is because the populations of breached and unbreached bends largely span the same bend angles and are only separated by the changes in the breached and unbreached frequency of that angle, which makes it difficult to predict with a binary classifier. Therefore, at the mapping scale, bend angle is only an unequivocal predictor of whether a bend will be breached for very large angles.
Figure 3. Logistic regressions (gray) showing the passing probabilities of earthquake gates. The data are shown as beehive plots, which show all data points in each classification, breached in green and unbreached in red. Restraining and releasing features are combined (shown separately in Figure S3). Top left: Passing probability as a function of step-over width. Top right: Passing probability as a function of double bend angle. Bottom left: Passing probability versus gap length. Bottom right: Passing probability as a function of single bend angle. The gray shading shows the 95% C.I. calculated by bootstrapping.

Biasi and Wesnousky (2016) predict step-overs wider than 3 km will be breached <50% of the time, a value that exceeds our largest observed breached step-over. Biasi and Wesnousky (2017) found the probability of rupture propagation past a 25° bend was 50%, consistent with the estimate of Ozawa et al. (2023) using quasi-dynamic rupture models (Figure S5). We predict much larger passing probabilities of >75% for single and double bends of that size. The differences between our passing probabilities and those in previous work arise from the use of different rupture
maps (simplified versus not) and mapping at a finer scale.

In our work, double bend length is not a good predictor of whether a double bend will be breached (Figure S2). This may be a result of our map scale, such that large double bends are broken down into smaller constituent bends. Only 25 bends with length >2 km are contained within our dataset. Lozos et al. (2011) found bends shorter than 2 km were always breached in dynamic rupture models. For larger bends, trade-offs between bend angles and lengths result in a limiting size and angle at which bends are breached. Therefore, at a larger scale, double bends are effective earthquake gates.

**A barrier model for earthquake size**

For each of the events examined, we model an event likelihood that reflects the pre-existing geometrical complexity in the hosting fault system. We model event likelihood as the joint likelihood of continuing past the collective straight fault segments, \( p(L) \), and breaching \( n \) gates each with \( p_i \) in an event: \( p_{EQ} = p(L) \prod_{i=1}^{N} p_i \). We assume a constant chance of arrest at any point along without barriers such that \( p(L) = e^{-\lambda L} \) is the survival function of the exponential distribution where \( L \) is the rupture length, and \( \lambda = 8.16 \times 10^{-6} \text{ arrests/m} \) is calculated by dividing the total number of arrests by the total length of straight segments. We derive passing probabilities for each gate and its geometry from our logistic models.

Figure 4 (top) shows the distribution of modeled event likelihoods versus magnitude for the 31 strike-slip earthquakes in the FDHI database. Event likelihood decreases with increasing magnitude, as expected based on the model design, though there is significant scatter between events. We do not consider the \( M_w 5 \) events in our fit because \( M_w 5 \) events rarely cause surface ruptures (Wells and Coppersmith, 1993), and, when they do, the rupture is typically incomplete to the surface, resulting in the absence of a coherent rupture trace from which earthquake gates can be robustly mapped. We also exclude gaps from the likelihood estimates given the small number of unbreached gaps sampled, though including these would only change the scaling exponent by <0.2. If we chose to weight our logistic regressions by the frequency of points, the resulting passing probabilities would be substantially less where populations of breached and unbreached features overlap, resulting in a much steeper scaling relationship.

To investigate the relationship of rupture length to event likelihood, we compute
likelihoods as cumulative probabilities along each mapped rupture (Figure 4, bottom). Event likelihood decreases inversely with rupture length squared. As earthquake gates are traversed by rupture, the cumulative log-likelihood of each event decreases following a similar slope. The spacing between neighboring gates is log-normally distributed (Figure S6), with an average spacing of ~2 km.

Though our observations are limited by the magnitude range of observed surface rupturing earthquakes, the relationship between likelihood to surface rupture length, and to magnitude, suggests that earthquake scaling is at least in part controlled by the number and characteristics of the earthquake gates present along the hosting fault system. This supports a barrier model for earthquake size (e.g., Aki, 1979; Aki, 1989; Heaton, 1990), where geometrically simple segments of the fault are bounded by geometrically complex barriers that must be breached for the rupture to continue. Previous empirical studies have also argued in favor of this model based on the segmentation of surface ruptures and the distribution of displacements during an event (e.g., King and Nabelek, 1985; Klinger et al., 2006; Rockwell and Klinger, 2013).

An important subtlety in this study is that the definition of breaching as continuing for at least 1 km intrinsically limits the scale of gates considered. The earthquakes considered here had sufficient accumulated elastic energy to rupture kilometers of fault before stopping at earthquake gates. Therefore, while earthquakes in this dataset often stop at barriers, reaching those barriers in the first place was conditional on having sufficient elastic energy, an aspect that is asperity-controlled. This suggests that the size of large earthquakes is modulated by trade-offs between the location of asperities, which provide the elastic energy required for the event to continue growing, and the location and strength of barriers, which will bring the event to arrest when barrier strength exceeds the elastic energy available (Figure 5).
Figure 4. Top: Event likelihood versus magnitude for the strike-slip earthquakes in the FDHI database. The line shows the best fit for the evolution of event likelihood with magnitude. Bottom: Cumulative event likelihood versus distance along the surface rupture. Each colored line represents one event. The scattered dots indicate the event likelihood at its final rupture length. The rupture lengths are based on the FDHI event coordinate system (ECS) reference lines (Sarmiento et al., 2021). The orange line represents the best fit to the final event likelihoods.
Figure 5. Schematic cartoon of how an earthquake gate will bring rupture to arrest, conditional on the available elastic energy being lower than the strength of the barrier.

When an earthquake terminates at a barrier, elevated residual stresses, if not relaxed, can promote rupture propagation past the barrier in a subsequent event. This behavior is observed in multi-cycle rupture models (e.g., Duan and Oglesby, 2006) and inferred from the occurrence of aftershocks at barriers where ruptures terminate (Aki, 1979). Earthquake gates may therefore act as a barrier in one event, and as an asperity in a subsequent event. Large earthquakes are thought to preferentially nucleate at asperities. Thus, earthquake gates behaving as asperities would be in proximity to the epicenter of the event. As one test of this prediction, we evaluate the distribution of breached and unbreached gates with respect to the epicentral location (Figure S7, top). We find no relationship between the location of an earthquake gate and whether it was breached. Earthquake gates and their geometry, as well as whether they were breached, are also not correlated with their position along the surface rupture (Figures S8 and S9).
Earthquake gates behaving as asperities are also expected to overlap with locations with large displacements on the fault, where the elastic energy available is high. To test this hypothesis, we measure the distance between breached and unbreached earthquake gate and the location of peak slip in that event (Figure S7, bottom). We find no relationship between whether a gate was breached or not and its distance from the location of maximum slip. The absence of these spatial correlations suggests that, while earthquake gates may also act as asperities, this relationship is not frequent enough or the effect sufficiently large to stand out in our surface-rupture dataset. Our results instead demonstrate that the geometry of earthquake gates, acting as barriers to rupture propagation, influences the growth of ruptures and the final magnitude an earthquake achieves.

Conclusions

We map step-overs, bends, gaps, splays, and strands along the surface rupture maps of 31 strike-slip earthquakes at 1:50,000 scale. We characterize these earthquake gates as breached and unbreached based on whether the rupture propagated. We use these measurements to fit a logistic model to each earthquake gate type that estimates passing probabilities as a function of gate geometry. We find that step-over width is an excellent predictor of whether a step-over will be breached. Bend angle is a limited predictor of whether a bend will be breached, although the ratio of unbreached to breached bends increases consistently with increasing bend angle. We find double bends behave differently than step-overs with the same geometry, suggesting step overs persist as discrete unlinked fault strands at depth. These empirically determined passing probabilities can be used to calibrate long-term rupture simulators (e.g. Field et al., 2015; Milner et al., 2022).

The fact that the mapped gates are preferred stopping points provides strong evidence that the surficially mapped features are indicative of fault structure that persists to depth. In addition, we use the passing probabilities of the breached earthquake gates in each event to estimate a retrospective event likelihood that captures the likelihood of that earthquake given the complexity of the hosting fault system. The cumulative event likelihood tabulated along rupture strike supports a barrier model as a factor in controlling earthquake size, where relatively straight fault segments are bounded by geometrical barriers that must be breached for the rupture to continue growing.

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We thank Glenn Biasi, Coby Abrahams, and Will Steindhart for suggestions. We thank So Ozawa for sharing his data. S.W., V.H., and A.M.R.P. benefitted from mentoring from Gaby Noriega. A.M.R.P was funded by FINESST award 80NSSC21K1634.

Open Research

The data and code required to reproduce our analysis are available from https://github.com/absrp/passing_probabilities_EQgates. They will be transferred to a Zenodo repository for permanent storage following acceptance.

References


Supporting Information for

The influence of earthquake gates on surface rupture length

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Table S11
Earthquake gate maps for each event

Introduction
This file contains the detailed mapping method followed, supplementary figures S1 to S10, table S11, and the maps of each event and its corresponding earthquake gate. The maps are generated in 30 in x 30 in files at 300 dpi so that they can be easily zoomed into and examined.

Supplementary Methods
Earthquake Gate Mapping

The Fault Displacement Hazard Initiative (FDHI) database is hosted at and maintained by the Natural Hazards Risk & Resilience Research Center at the University of California, Los
The database contains rupture maps and displacement, lithology, and other information for sixty-six surface-rupturing crustal earthquakes, with moment magnitudes ranging from 5.0 to 8.0 (accessed June 2022). Thirty-one of these events are strike-slip (Figure S10). The database was compiled with a focus on rupture detail, completeness, accuracy, and consistency across datasets. Surface ruptures are mapped to 1-meter precision in the database, though individual maps differ in the level of detail captured in the surface rupture (e.g., Figure S10, B and C). This variability is in part related to the different degrees of complexity in the hosting fault system, and in part a result of differences in mapping methods and extent across ruptures. We map earthquake gates from the surface ruptures in the FDHI database at a 1:50,000 scale, which roughly corresponds to mapping features with lengths exceeding 100-500 meters. At this scale, we expect the level of detail across ruptures to be roughly comparable.

Prior work has either relied on simplified rupture maps (e.g., Wesnousky, 2006) or simplified ruptures to segments long enough (~7 km) to be bounded by earthquake gates representative of the full seismogenic zone (Biasi and Wesnousky, 2017). We map earthquake gates directly from the surface rupture maps, without simplifying the rupture traces. An important consequence of our scale of choice (1:50,000) is that larger features (for example, the large, regional-scale releasing bend in the Balochistan earthquake which spans 6 km) are mapped into its smaller constituents that occur at the mapping scale (i.e. several shorter bends that make up the regional one).

The surface rupture maps in the FDHI database include ruptures classified as primary and distributed. The Landers and Ridgecrest (foreshock and mainshock) earthquakes have a substantially larger amount of distributed ruptures mapped than the remaining events. For consistency between events in the analysis, we do not consider the distributed ruptures from these events in our earthquake gate mapping. We characterize gates as restraining or releasing when possible, depending on the volumetric deformation fostered by the type of slip and the geometry of the fault segments. To do this, we assume all fault segments involved in the rupture have strike-slip kinematics consistent with the focal mechanism for the event. This is a reasonable approximation for all the strike-slip ruptures in the FDHI database except for the Denali earthquake, from which we remove the portion of the rupture that occurred on the Susitna Glacier Thrust, where the earthquake initiated (e.g., Crone et al., 2004). We also do not consider the zone...
We characterize five different types of earthquake gates in this study: step-overs, gaps, bends, splays, and strands (Figure 1). We distinguish between breached features where the rupture transferred through and continued for at least 1 kilometer, and unbreached features, where the rupture halted immediately or within 1 km past the gate. For the case of splays, we classify cases where the rupture transferred onto a splay (regardless of whether it also continued on the main fault), as ruptured and instances where an available intersecting splay fault was foregone as unruptured. Note the use of different terminology from breached and unbreached to indicate that at least one fault strand was always active past the splay (Figure 1).

For each of the gates of interest, we measure the relevant geometrical attribute. For bends and splays, this is the bend angle, which is the difference between the fault strike as it enters the feature and the fault strike as it exits the feature. In the case of multi-stranded bends, we map the bend strand with the smallest angle. We distinguish between single bends, where the fault strike changes once, and double bends, where the fault strike changes for a segment and then returns to the original strike (see examples in Figure 1). Step-overs occur where a fault ends and the rupture is forced to jump onto a neighboring segment or come to arrest. We also map locations where the rupture activates parallel to subparallel neighboring fault strands without reaching the terminus of the principal fault. By definition, strands may only exist as breached features, as there was no fault terminus that forced a jump. For step-overs and strands, we measure the distance between parallel fault segments at their minimum, orthogonal to the fault segments when possible. For gaps, we measure the length of the gap between the active rupture and another fault, or between parts of the active rupture if breached, in the fault-parallel direction. Note that we do not have the ability to distinguish gaps that represent pauses on the rupture on the same fault versus gaps that represent the spacing between two sequential faults of parallel strike.

We rely on different active fault databases to characterize unbreached features, where we measure the angle or distance between the ruptured fault and unruptured active faults in the database. The reference databases we use are listed in Supplementary Table S11. For the United States, the resolution of the regional faults associated with the events in this study in the Qfaults database is comparable to the resolution of the primary rupturing faults in the FDHI database. For the Darfield event in New Zealand, we use the NZAFD database, mapped at 1:250,000 (Langridge...
et al., 2016). The Active Faults of Eurasia Database (AFEAD) database for Eurasia, which we use for events in Turkey and Asia, is mapped at 1:500,000 scale (Bachmanov et al., 2021). Last, the GEM database, which we use only for the San Miguel and Pisayambo earthquakes in Mexico and Ecuador respectively, is mapped at 1:1,000,000 scale (Styron and Pagani, 2020). In the interest of classifying unbreached features as restraining or releasing, when the inactive fault kinematics are unknown, we assume these are the same as the rupturing faults’. When two unbreached step-overs may be measured at a fault’s terminus, we map both of them, following the choice of previous workers (e.g., Wesnousky, 2006). Note that some events (e.g., Galway Lake and Ridgecrest foreshock) have unbreached step-overs at both of their termini with the same fault (e.g., the faults in the Landers event and the Garlock fault respectively), in which case both unbreached step-overs are mapped. When a gap and a step-over of the same size exist, and one gets breached but the other one does not, we map both the breached and unbreached features. The same occurs where there is a bend but the rupture instead skips the bend and jumps ahead to a more straight portion of the fault. This only occurs in the case of very similarly sized earthquake gates available at the same location, otherwise, we only map the smallest gate present. We provide our mapped earthquake gates as shapefiles (see data availability section) and shown over the rupture maps and regional fault maps in the supplementary section.

Passing Probability and Event Likelihood Estimates

To determine whether the forms of geometrical complexity we map (Figure 1) act as barriers to rupture propagation, we analyze the distribution of breached and unbreached gates in terms of the geometrical attribute measured (angle or length). We look at the cumulative distribution functions of breached and unbreached gates and use a Kolmogorov-Smirnoff (KS) test to determine whether the breached and unbreached populations are statistically different.

For those features where the breached and unbreached populations are statistically different, we compute passing probabilities as a function of the geometrical characteristics of the gate. To do so, we use a logistic function, which describes the probability of a binary outcome (breached or unbreached) as a continuous function of the geometry of an earthquake gate. To fit logistic regressions through our data, we use the Python package scikit learn (Pedregosa et al., 2011). An advantage of using logistic regressions over past methods is that estimating probabilities does not rely on arbitrary binning of the data. We evaluate the performance of our logistic models
for each type of earthquake gate using Receiver Operating Characteristic (ROC) scores and confusion matrices, which is standard procedure for these models (Pedregosa et al., 2011). ROC scores can range from 0.5 to 1, with increasing numbers indicating that more data points have been correctly predicted by the logistic regression.

**Supplementary Figures**

Figure S1: Releasing double bend from the 2014 Yutian earthquake. The rupture map is shown in gray. The pink and purple lines show the bend length as defined by Lozos et al. (2011) and the proxy step-over width respectively.
Figure S2: Cumulative distribution function of the breached and unbreached proxy step-over width (top) and length (bottom) for double bends.
**Figure S3.** Logistic regressions (gray) showing the passing probabilities of restraining and releasing step-overs and double bends. The data are shown as beehive plots, which show all data points in each classification, breached in green and unbreached in red. The ROC score for each logistic regression is shown on the top right of each panel. Top and bottom left: Passing probability as a function of step-over width. Top and bottom right: Passing probability as a function of double
bend angle. The gray shading shows the 95% confidence intervals of the regressions calculated by bootstrapping.

Figure S4: Confusion matrices for the logistic models for step-overs, single and double bends, and gaps in Figure 3.
Figure S5: Comparison of the passing probabilities for different bend angles estimated in Biasi and Wesnousky (2017), Ozawa et al. (2023), and this study. Passing probability estimated as the number of breached bends per bin over the total number of bends in that bin in previous studies and with logistic regressions here. Note that the Biasi and Wesnousky (2017) passing probabilities
include both single and double bends without discriminating between them, and the Ozawa et al. (2023) passing probabilities only include double bends.

Figure S6: Empirical complementary cumulative distribution function (gray) of the distances to nearest neighbor for all breached earthquake gates. Complementary cumulative distribution functions for an exponential and a log-normal fit are shown in black and red, respectively.
Figure S7: Cumulative distribution function of breached and unbreached earthquake gates parametrized based on their distance to the epicenter (top) and distance to the location where the maximum slip occurred along the rupture (bottom).
Figure S8: Distribution of breached and unbreached earthquake gates along the normalized surface rupture lengths of the 31 strike-slip events. The rupture lengths are based on the FDHI database event coordinate systems (ECS) reference lines (Sarmiento et al., 2021). There are some unbreached gates not at the edge of the ruptures. This is because, at some locations, there were two
or more earthquake gates available, so that the gate the rupture continues past is mapped as breached and the remaining ones get mapped as unbreached (see methods for details).

Figure S9: Frequency of earthquake gates, breached and unbreached in green and red respectively, along the normalized surface rupture length for each earthquake gate type.
Figure S10: Surface rupturing strike-slip earthquakes in the FDHI database (Sarmiento et al., 2021). A: Epicentral locations of events, color-coded by moment magnitude. The insets show events in California, Baja California, and Japan. B: Surface rupture map of the Landers 1992 event in California. C: Surface rupture map of the 1995 Great Kobe earthquake in Japan, including a strand located 7 km from the main rupture. Note scale difference for these events.
Table S11: Reference maps of active faults to measure unbreached feature characteristics with respect to.

<table>
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<tr>
<th>Reference Fault Map</th>
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<td>United States</td>
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<td>New Zealand Active Faults Database (NZAFD)</td>
<td>New Zealand</td>
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<td>The Active Faults of Eurasia Database (AFEAD)</td>
<td>Europe and Asia</td>
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</tr>
<tr>
<td>GEM Global Active Faults Database</td>
<td>Central and South America</td>
<td>Styron and Pagani (2020)</td>
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</table>
Earthquake gate types

- stepover breached
- stepover unreached
- bend breached
- bend unreached
- strand breached
- splay breached
- splay unreached
- gap breached
- gap unreached