Effects of fault roughness on coseismic slip and earthquake locations

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Key Points:

- We simulate 10,000 year earthquake catalogs on faults with varying degrees of fractal roughness using rate-and-state friction
- The fractal fault properties control earthquake properties including hypocenter location and coseismic slip distribution
- These results explain many features observed in real faults, such as clustered seismicity, fractal co-seismic slip, and asperities
Abstract

Fault zone structure is well known to exert strong controls on earthquake properties including coseismic slip distribution, rupture propagation direction, and hypocenter location. It has also been well established that the principal slip surface, which accommodates the majority of earthquake displacement, exhibits roughness at all scales following self-affine fractal distributions. Here we explore the relationship between fault roughness and specific earthquake properties including slip, hypocenter location, and directivity based on long-term simulations of earthquake catalogs on fractally rough faults. We begin by using the von Kármán autocorrelation function to procedurally generate faults with fractal roughness, which we place in a homogeneous elastic solid and apply pure right-lateral shear at a constant rate with the earthquake simulator RSQSim. Running the simulations for 10,000 years each, we generate millions of earthquakes including thousands of events with Mw>6.0 which rupture the surface. We show that the patterns of surface rupture in these large events follow self-affine fractal distributions with consistent fractal dimension related distinctly to the fractal dimension of the fault. In addition, the hypocenters of these large events occur in very specific predictable locations where the longest wavelength structure produces a stress asperity (i.e., restraining bend). The resulting patterns can explain many features observed on real fault systems, including clustered hypocenter locations, spatially variable coseismic slip distributions, preferred rupture directions, and characteristic slip recurrence behavior. These results demonstrate a quantitative link between a directly-measurable fault property – roughness – and the properties of future earthquakes.
1. Introduction

Fault structure plays a crucial role in major fault processes including earthquake nucleation (e.g., Campillo et al., 2001), rupture propagation (Shi and Ben-Zion, 2006; Shi and Day, 2013), damage zone formation (e.g., Mitchell and Faulkner 2009), localization (e.g., Chester and Chester, 1998), and evolution (Sagy et al., 2007). A critical aspect of fault structure is the geometry of the principal slip surface (Chester et al., 2005), the narrow zone (typically < 10 cm thick) which accommodates most of the motion along the fault during large earthquakes (Sibson, 2003). The roughness of the principal slip surface can be measured in terms of amplitude and wavelength of the topography (Power et al., 1988). Understanding the role of fault roughness (e.g., Candela et al., 2011) is key to understanding the seismic behavior of faults. Laboratory studies suggest a complex feedback relationship between fault roughness and gouge formation due to slip (Amitrano and Schmittbuhl, 2002). Previous seismic observations suggest that roughness controls the first-order distribution of coseismic slip (Peyrat and Olsen, 2004). Additionally, local geometrical complexities may cause the fault to be unfavorably oriented for slip, which will concentrate stress (Marsan, 2006; Schmittbuhl et al., 2007) and therefore may control earthquake nucleation (Lay et al., 1981; Scholz, 2002), rupture propagation (Harris and Day, 1993; Lozos et al., 2011) or arrest (Aki, 1984; Bletery et al., 2016). Fault geometry has also been shown to control the seismic radiation patterns that result from large events (e.g., Madariaga, 1983). In the following sections, we review field geological measurements of fault roughness and geophysical observations of earthquake properties which relate to roughness. Finally, we examine the effect of roughness on the slip distribution and hypocentral density of earthquakes using multicycle earthquake simulations.
1.1 Measurement of Fault Roughness

The highest resolution images of roughness along the principal slip surface come from field and laboratory measurements. Although natural weathering processes alter exposed slip surfaces (Power et al., 1988), several decades of work have been done measuring roughness of a variety of fault types. Initial 1D profilometer measurements along normal faults at the outcrop scale (Power et al., 1988) found that the topography of fault surfaces is anisotropic (i.e. much smoother in the direction of slip), scale-invariant, and can be characterized as self-similarly fractal. Later, higher-resolution images that included a larger range of spatial wavelengths (Schmittbuhl et al. 1993; Lee and Bruhn, 1996) produced models that suggested surface roughness is self-affine rather than self-similar. More recent 2D lidar images of fault surfaces (Renard et al., 2006; Sagy et al., 2007; Jones et al., 2009; Candela et al., 2011) have validated the paradigm of faults as fractal surfaces, although they disagree about the fractal parameters. Some studies have suggested that the fractal dimension of fault surfaces is the same for multiple faults and spans eleven orders of magnitude (e.g., Renard et al., 2013), while other work suggests that fault roughness smooths as a function of cumulative slip (Sagy et al., 2007), as expected from the progressive wear of brittle earthquake processes (Brodsky et al., 2011). More recent observations show that roughness anisotropy disappears at the micrometer scale (Candela & Brodsky, 2016), possibly due to a transition from brittle to plastic deformation. These observations have led to the formulation of empirical scaling relations between fault roughness and scale-dependent rock strength (Brodsky et al., 2016).

1.2 Relationship of Fault Roughness to Earthquake Properties

Seismological evidence of fault roughness is much more limited. Previous studies of along-strike seismicity streaks from relocated earthquakes along creeping faults in California (e.g., Rubin...
et al., 1999) were attributed to regions of localized stick-slip behavior. Similar work on other faults (e.g., Schaff et al., 2002) have interpreted the seismicity patterns as the result of large-scale roughness patterns (asperities) impeding slip locally. However, these patterns are not universally observed on all faults, even where highly accurate relocated seismicity catalogs are available (e.g., Hauksson et al., 2012). In general, hypocenter locations tend to become more localized and planar on some faults when more accurate techniques are applied (Waldhauser and Ellsworth, 2000; Zhang and Thurber, 2003), though seismicity on other faults may retain its diffusive pattern (Eberhart-Phillips, 1995; Graymer et al., 2007; Allam and Ben-Zion, 2012; Allam et al., 2014).

Even for well-resolved near-planar seismicity, low-magnitude earthquakes may represent brittle failure on subsidiary structures, making it difficult, if not impossible, to infer principal slip surface geometry from seismicity patterns.

It has previously been hypothesized that coseismic slip variability is linked to fault roughness through the mechanism of stress concentration (Candela et al., 2011). It is well-known that a rough fault surface creates strong heterogeneity in the stress field (e.g., Dieterich and Smith, 2009; Shi & Day, 2013; Duru & Dunham, 2016). It follows that a heterogeneous stress distribution on a fault surface will lead to variability in coseismic slip (Ampuero et al., 2006). Because of these relationships, it has been suggested (Candela et al., 2011) that the Hurst exponent, a parameter which controls the scaling between wavelength and amplitude of roughness variability, is the same for both coseismic slip and fault structure; i.e., fault roughness directly controls slip distribution.

The development of optical image cross-correlation techniques (Leprince et al., 2007; Ayoub et al., 2009) allows for the full characterization of co-seismic surface slip. These new methods include off-fault deformation which has been difficult to quantify due to its distributed nature.

Analysis of the 1992 Landers and 1999 Hector Mine earthquakes (Milliner et al., 2015; 2016)
found self-affine fractal distributions of surface slip for both events with Landers having a higher fractal dimension attributed to a rougher, more complex fault structure. The main limitation of these geodetic methods is that they can only be applied to the handful of events for which high-resolution pre- and post-event optical images are available, which poses a challenge for assessing the relationship between fault structure and coseismic surface slip.

1.3 Numerical Earthquake Simulations

The relationship between fault roughness and coseismic slip has been observed numerically for a few single-event simulations (e.g., Dunham et al., 2011), but has not been established for multiple earthquake cycles with evolving stress states. The present work seeks to address this limitation using numerical simulations of co-seismic slip on faults with prescribed roughness. Such simulations fall on a scale between two end-members: static, wherein the effects of earthquakes are neglected, and dynamic, wherein the complicated feedbacks among seismic radiation, friction, and stress are considered. The distinction is important because dynamic faulting has been shown to cause additional heterogeneity in earthquake properties, including induced self-similarity in the stress field (Cochard and Madariaga, 1994). However, dynamic rupture simulations are also more computationally intensive, thus few existing methods are capable of simulating multiple earthquake cycles (e.g. Lapusta and Liu, 2009). Nevertheless, both quasi-static (Dieterich and Smith, 2009) and fully dynamic earthquake rupture simulations (Shi and Day, 2013; Duru and Dunham, 2016) have shown that a fractally rough fault surface induces a fractal stress field, which in turn causes a highly variable slip distribution. In the present work, we evaluate the relationship between patterns of seismicity and fault roughness using a multicycle earthquake simulation technique. We use the quasi-dynamic earthquake simulator, RSQSim (Dieterich and Richards-
Dinger, 2010; Richards-Dinger and Dieterich, 2012), to compute the full slip distributions of millions of earthquakes on individual faults with various degrees of fractally distributed roughness. Large seismicity catalogs obtained with this method allow us to determine the statistical relationships between fault structure and earthquake parameters. Specifically, we show that (1) the fractal dimension of the slip at the surface is related to the fractal dimension of the fault itself, (2) patterns of high and low slip amplitude are consistent from event to event, and are controlled by the fault structure, (3) earthquakes in a given magnitude range have preferred hypocenter locations, with the largest events (Mw>6) especially nucleating only in a few regions that contain local asperities, and (4) because of their preferred hypocenter location, large events have a dominant rupture propagation direction and thus directivity, with (5) a characteristic pattern of slip for the largest events.

2. Methods

To simulate long-term earthquake catalogs, we employ the 3D physics-based, quasi-dynamic, multicycle, boundary element earthquake simulator, RSQSim which is based on rate-and state-dependent friction. RSQSim has been shown to accurately reproduce rupture time histories, stress changes, and slip distributions similar to fully dynamic simulations (Dieterich and Richards-Dinger, 2010; Richards-Dinger and Dieterich, 2012). Simulations in RSQSim are driven by a one-time backslip calculation to compute fault element stressing rates that are equivalent to slipping the simulated fault system backwards at the long-term average (prescribed) slip-rate (Richards-Dinger and Dieterich, 2012). Once loaded, nucleation occurs spontaneously which generates ruptures that form a catalog of earthquakes. The timing and location of event nucleation is controlled by rate-state friction. The distributions of stress on the modeled faults evolve naturally
due to tectonic loading and earthquake stress field interaction. Though the fault geometry is fixed in each simulation, the stress state is constantly evolving, making each event unique. This type of simulation has been shown to reproduce many realistic earthquake properties, including frequency-magnitude statistics, earthquake clustering (i.e., foreshocks and aftershocks), and slip distributions (e.g., Tullis et al., 2012). Though fault interaction has been shown to play crucial role in earthquake behavior (e.g., Bürgmann et al., 1994, Stein, 1999), the present work examines the simplified case of a single vertically-dipping fault. This simplification allows us to explore the relationship between fault roughness and observable earthquake properties without the additional complexity of fault interaction.

We place the procedurally-generated faults (described below) in a homogeneous elastic solid with a homogeneous initial stress state and apply pure right-lateral boundary slip. The peak slip rate is 10 mm/yr in the upper center of the fault and is cosine-tapered towards the edges to reduce boundary artifacts in earthquake and slip distributions. Stress and failure on the fault elements are controlled by standard laboratory values of the rate- and state-dependent frictional parameters, $a = 0.01$, $b = 0.014$, and $D_c = 10 \mu m$ (see Richards-Dinger and Dieterich, 2012 for details). We run each simulation for 10,000 years, producing millions of stick-slip earthquakes, including hundreds of surface-rupturing events on the randomly-generated fractal fault geometries (Fig. 1). We compute all of the event moment magnitudes (Mw) based on the sum of the seismic moment of each element. We subsequently analyze the resulting earthquake catalogs in terms of the fractal dimension of coseismic surface slip ($D_s$) (Figs. 2-3) and correlation of hypocenter locations with fault structure in different magnitude ranges (Figs. 4-6).

To compare results from our synthetic catalogs with observations of surface slip and roughness, we model earthquakes on a fault with similar dimensions to the Landers and Hector
Mine ruptures previously studied by Milliner et al., (2015, 2016). The 60 km by 15 km faults used in this study are discretized into 75-m elements for a total of $1.6 \times 10^5$ fault elements. We use the von Kármán autocorrelation function (Goff & Jordan, 1988, Mai & Beroza, 2002) to create three fault realizations with three sets of fractal parameters for a total of nine individual fault structures (Fig. S1; a subset shown in Fig. 1). For the three parameter sets, we use constant $\alpha$ of 0.2 and $D_f$ equal to 1.1, 1.3, and 1.5, where $\alpha$ is the root-mean-square of the ratio between the amplitude of the fault topography and the length of the fault, and $D_f$ is the fractal dimension. In the wavenumber domain, $D_f$ controls the slope and $\alpha$ controls the intercept. The values of $D_f$ used in this study are similar to the values measured from the surface traces of the Landers and Hector Mine faults (Milliner et al., 2015, 2016). In line with previous studies of fault roughness, we generate anisotropic patterns of roughness, where faults are smoother in the direction of slip (e.g. Candela et al., 2011). The fractal dimension is linearly related to the Hurst exponent with the simple expression $D_f = 2 - H$. Because we find that the fractal dimension is a more intuitive value (i.e., representative of complexity varying between the end-members of 1 and 2 dimensions), we will generally discuss the scale-invariant variation in this paper in terms of fractal dimension. In addition, for simplicity, we will employ the terms ‘rougher’ and ‘smoother’ to mean ‘higher fault fractal dimension’ and ‘lower fault fractal dimension’, respectively.

For subsequent analysis of each simulation, we divide the seismicity into three size bins: a) $M<4$, b) $4<M<6$, and c) $Mw>6$. For the largest bin ($Mw>6$), we retrieve the surface slip for each event and measure the fractal dimension thereof ($D_s$) using the Thomson (1982) multi-taper method. This type of measurement is analogous to recent geodetic work in Southern California (Milliner et al., 2016), and allows for direct comparison to real earthquake surface slip distributions. This method requires a linear fit in the wavenumber domain which is illustrated for
two events (Fig. 2) and allows the creation of full distributions of $D_s$ for each fault realization (Fig. 3).

For each magnitude category, we also measure earthquake density as a function of along-fault distance and depth (Figs. 4-6 left); these are simply two-dimensional histograms with bin size of 150m in both dimensions. To explore the relationship between the cluster location and the fault structure, each density map is then correlated with the fault topography, which is done via a normalized inner product (Figs. 4-6 right). Finally, to compare the overall patterns from our simulated catalogs to observed seismicity, we use the same method to compute hypocentral densities for three southern California fault zones (Figs. S3-S5) using the relocated earthquake catalog from Hauksson et al. (2012).

3. Results

For each of the nine faults with differing roughness (Fig. S1) we obtain $>10^6$ earthquakes over the 10,000-year simulation period, ranging in size from a single element ($M_w \sim 1.3$) to ruptures spanning most of the fault. Fig. 1 shows the procedurally-generated roughness on the fault surface, examples of coseismic slip distributions for large ($M_w > 6$) events, and the surface slip distributions for all $M_w > 6$ events on each fault realization. Because the faults used in these simulations only differ in fractal dimension, the variation in seismicity and slip patterns are solely related to changes in $D_r$.

Figure 1 also shows a typical coseismic slip distribution (middle row) for each value of the fault roughness and surface slip profiles (bottom row) for every event in the simulation larger than $M_6$. For the roughest fault (Fig. 1d, $D_r = 1.5$), the coseismic slip distributions are highly spatially variable and discontinuous, though the longest wavelength pattern is generally elliptical with the
largest slip near the center of the fault towards the surface. As the fault structure becomes smoother (i.e. decreasing \(D_f\)), the coseismic slip distribution becomes more continuous and average slip increases. This is further evident in the surface slip profiles, which also decrease in variability for smoother faults. For example, the amplitude of the slip heterogeneity is larger for rougher faults (Figure 1g) than for smoother faults (Figure 1i) and the overall shape of the profile becomes more elliptical, as expected for ruptures along single planar faults with homogeneous stresses (Scholz, 2002). Comparing individual slip profiles from the same simulation shows that some regions of the fault result in higher- or lower-than-average slip that persist throughout the simulation. This indicates that while surface slip is highly variable, it is non-random. The extent to which these patterns are correlated with fault structure (i.e., can be statistically forecast) is examined in Figs. 4–6 and the discussion below.

The fractal dimension of slip (\(D_s\)) is estimated from the slope of the power spectral density (PSD) of the surface slip distribution. In Figure 2, surface slip profiles from two, non-consecutive events on the same fault are shown along with their PSD. We find that estimates of the fractal dimension based on surface slip from both events are similar. In Figure 3, we show the distribution of \(D_s\)-values estimated in this manner for all events larger than M6 in each simulation. We find that each population of \(D_s\)-values estimated from surface slip is distinct and does not overlap with \(D_s\)-values made from faults with other roughness properties. The mean and standard deviation of each distribution are similar for each fault realization, but the fractal dimension of slip, \(D_s\), is systematically larger (20–30%) than the fractal dimension of roughness, \(D_f\). This suggests that the variability of coseismic slip is controlled directly by fault structure. This is potentially due to the ‘characteristic’ event behavior where the large events in all simulations tend to nucleate in the same location and lead to similar final slip distributions.
All faults, regardless of roughness, show significant persistent patterns of coseismic slip (Fig. 1 right) and repeating clusters of hypocenter locations (Fig. 4–6). To evaluate patterns in hypocenter locations, we measure the along-strike hypocenter distribution (Figs. 4–6 bottom right; Fig. S2 for all nine realizations) as well as the 2D hypocentral density compared to fault structure (Figs. 4–6) for the three different magnitude bins. The hypocentral distributions are non-random for all nine fault structures; each magnitude bin has a few preferred nucleation locations which each correlate to locally restraining fault topography. This preference decreases across all three magnitude bins with decreasing roughness; smoother faults allow for a larger variety of hypocenter locations. The smoothest faults ($D_f = 1.1$; Fig. 6) tend to have a looser concentration of large event hypocenters (i.e., weaker location preference), with more randomly distributed small events. The roughest faults ($D_f = 1.5$; Fig. 4) have very concentrated distributions of large events (i.e., strong preference) and also feature many complementary medium events that nucleate on the boundaries of the average large coseismic rupture (e.g. Fig. 1 middle row); the medium-sized events often fill in the slip deficits left by the large events.

In two dimensions, the hypocenters are extremely non-random, with focused patches dominating all three magnitude ranges (Figs. 4–6). Nearly every earthquake cluster correlates with local restraining topography, indicating that almost all of the simulated earthquakes nucleate in regions of high stress concentration. Interestingly, the patterns of hypocenter location do not correlate for faults of different roughness; even though the large-scale structure is the same for the three cases, small-scale heterogeneities lead to great differences in earthquake behavior.

4. Discussion
The results described above can explain a number of observations of real fault systems, specifically: along-fault variability of coseismic slip, characteristic large earthquakes, highly heterogeneous seismicity distributions, and rupture directivity. The degree of fault roughness directly affects these patterns by largely controlling the distribution of stress along the fault. These patterns are not due to inherent bias of the assumptions in the simulations, but are emergent behaviors arising strictly from the scale-dependent roughness properties.

4.1 Variability of Co-seismic Slip

High-resolution near-fault (<2 km) geodetic data of co-seismic surface motion have revealed that the amplitude of along-fault slip is variable at all observable scales. Milliner et al. (2016) found fractally distributed slip for both the 1992 M7.3 Landers and 1999 M7.1 Hector Mine earthquakes in southern California. Based on optical image correlation of before-and-after air photos, this variability was demonstrated to be much larger than the measurement uncertainty. Similar results were obtained from analyses of the 2001 M7.8 Kokoxili (Klinger et al., 2006) and the 1940 M7.0 Imperial Valley (Rockwell & Klinger, 2013) earthquakes, though the surface slip distributions were not quantified in fractal or power-law frameworks.

Geological field mapping and paleoseismic observations of coseismic slip measured from the offsets of surface features have also shown strong variability. Observations of slip variability in either space or time from the Dead Sea (Gomez et al., 2001), El Mayor-Cucapah (e.g., Gold et al., 2013; Fletcher et al., 2014), Landers (McGill & Rubin, 1999), and San Jacinto (e.g., Rockwell et al., 2014; Onderdonk et al., 2015) faults have all shown strong along-fault variation in amplitude for multiple earthquakes. Generally, this variability has been attributed to either measurement uncertainty, a change in the amount of off-fault distributed deformation (e.g., Manighetti et al.,
2005), or has simply been averaged out. However, in the case of the Landers earthquake, the field-observed variability was corroborated by the geodetic results as reflecting true rupture behavior (Milliner et al., 2015).

Our present results can explain this slip variability simply as the result of a heterogeneous stress field (where the strength or resistance to applied loading varies along-strike) which itself results from fractally rough fault topography. It has previously been established through numerical simulations that fractal roughness yields a fractal stress field (Dieterich and Smith, 2009) and, independently, that heterogeneous stress fields lead to variability in coseismic slip (Ampuero et al., 2006). Our present results provide the next step, in which a fractal stress field created by fractal roughness gives rise to fractal coseismic slip. In addition, we show that the fractal dimension of the slip ($D_s$) is tightly constrained by the fault fractal dimension ($D_f$); fault realizations with the same $D_f$ produce similar distributions of $D_s$ (Fig. 5), albeit $D_s$ is systematically larger than $D_f$. Though it has been suggested that the Hurst exponent for fault structure and coseismic slip is the same (Candela et al., 2011), we show that there is a non-linear relationship; the variability of the slip is always much greater than that of the fault which created it. In principle, one could develop an empirical scaling law between the fault and slip fractal dimensions, wherein we expect smoother, more mature faults produce smoother coseismic slip distributions. With effectively only three different data points, our present simulations are inadequate for such a task, which we leave for future work.

### 4.2 Characteristic Earthquakes

In addition to having a consistent fractal dimension for all events, each fault realization also shows a characteristic pattern of co-seismic slip, hypocenter location, and magnitude for all large
events. It is a long-standing debate in seismology whether earthquakes follow a strict Gutenberg-Richter distribution in frequency-magnitude space, or if there is a “characteristic” earthquake magnitude for each fault (e.g., Wesnousky, 1994; and response from Kagan, 1996). The characteristic interpretation has been bolstered by paleoseismic field studies in southern California which show similarity of the slip characteristics of large events (e.g., Rockwell et al., 2014; Scharer et al., 2014; Rittase et al., 2014; Rockwell et al., 2016). Though the debate centers around the frequency-magnitude statistics of faults, the physical question that needs to be answered is: do properties of the fault geometry lead to a preferred spatial pattern of earthquake rupture? In the simulation results, it is clear that there are several features of the coseismic rupture of large events that are consistent from event to event. First, the magnitudes of the largest events are all in a similar range from 6.1 to 6.3. This, in turn, leads to a relative reduction in the number of M5.0 to M6.0 events. Second, the patterns of low and high coseismic slip along the fault vary consistently among events and correlate to directly to local fault geometry (i.e. the slip distribution is characteristic of a given fault geometry). Specifically, in large events local restraining topography leads to higher amounts of coseismic slip, while local releasing topography leads to low coseismic slip (Fig. 1). This pattern becomes more pronounced at higher $D_f$, which produces larger variability in coseismic slip patterns. This suggests that the spectral properties of slip ($D_s$) are directly related to the spectral properties of the fault surface ($D_f$). Finally, these large earthquakes have very strongly preferred nucleation locations that are controlled by fault roughness (Figs. 8-10). This preference is also more highly constrained at higher fractal dimensions.

Thus, the existence of a fractally rough fault structure leads to similar large earthquakes with preferred magnitude, hypocenter location, and even coseismic slip patterns. A preferred nucleation location will generally lead to a preferred rupture direction which, in turn, leads to enhanced
directivity properties. Though the simulations feature nucleation biased towards central locations
due to the imposed cosine-tapered plate motion, this need not be the case in real fault systems. In
nature, faults do not act independently, but respond to stress changes due to slip on neighboring
faults. Simulating a system of faults leads to more realistic and heterogeneous stress distributions
on an individual fault, in addition to those created by roughness on the fault itself. These variations
in the stress field due to fault interaction are also expected to give rise to a power-law distribution
of event magnitudes that is not well represented by the current simulations. Such system-scale
fault interaction is beyond the scope of this study and could change the distributions of the features
examined here.

4.3 Clustered Hypocenters

The locations of earthquake hypocenters are observed to be clustered along strike and with
depth on virtually every fault that has been studied in high resolution. Recent well-studied
examples with precise earthquake locations include the San Andreas fault at Parkfield (e.g.,
Lippoldt et al., 2017), the San Jacinto fault (Allam et al., 2014), the Denali fault (e.g., Allam et al.,
2017), the Dead Sea fault (Begin et al., 2015), the Irpinia fault (de Landro et al., 2015), and the
Marmara fault (e.g., Schmittbuhl, 2016). In all of these cases, the hypocenters are strongly
clustered at all magnitude ranges, with prominent gaps and clusters which vary in density along
strike and with depth. Figs. S3–S5 illustrate the clustered nature of seismicity using three Southern
California faults; though there are fewer events than in the simulated catalogs, the clustered
patterns are similar to those shown in Figs. 4–6.

In many cases, this patchy distribution has been attributed to either aseismic slip (e.g., Ergintav
et al., 2014) or the inherent incompleteness of the historical seismicity record (e.g., Lorito et al.,
Instead, our results show that these observed patterns can arise as a result of fault roughness. In the simulations, nearly all earthquakes nucleate in regions of locally restraining fault topography, where the local geometry allows for a high concentration of stress before failure. The only exceptions are at the boundaries of large ruptures (Fig. 4 top left), which can be attributed to stress transfer. The relatively weaker sections of the fault with releasing or neutral topography also do not act as barriers to slip; thus, nearly all of the stress at these locations is released during events which nucleate elsewhere. Indeed, the majority of slip along the fault occurs only during the largest events (Figs. 4–6), and this effect becomes more significant with increasing fault fractal dimension (rougher fault geometry).

4.4 Fault Asperities

The idea that the large characteristic earthquakes on a given fault are controlled by locally strong regions which resist slip is not new. This “asperity” paradigm of earthquake recurrence has been explored for several decades (Lay & Kanamori, 1981; Aki, 1984; Ben-Zion & Rice, 1993) and has been most successful at explaining the slip properties of large subduction zone earthquakes (e.g., Inuma et al., 2011; Murotani, 2013). In the present simulations, asperities are simply an emergent phenomenon resulting from the statistical nature of the fault roughness. Regions of large coseismic slip are controlled by locally releasing topography. For example, the surface slip for the three examples shown (Figs. 2–4b) is most often low in the 38–40 km along-fault distance, corresponding to the most slip-favorable surface topography which are the sites of lower normal stress. Nevertheless, the short-wavelength topography leads to dramatic changes in coseismic slip behavior. This pattern agrees with both the geodetic studies (e.g., Milliner et al., 2015) and paleoseismic studies (e.g., Rockwell et al., 2014), which show that the slip patterns correlate to the
fault geometry. On the other hand, images of coseismic slip from the largest subduction zone earthquakes are too low in resolution to capture any but the largest-scale variations in slip (see Lay, 2017 and references therein). Nevertheless, the emergent nature of fault zone asperities in the present work is compatible with these previous observations of coseismic slip.

5. Conclusion

We have demonstrated direct, quantitative links between a measurable fault property, roughness, and various earthquake properties including hypocenter location, coseismic slip variability, and characteristic slip distributions. The relatively simple underlying assumptions—rate-and-state friction, fractal fault geometry, and constant plate motion—lead to simulation results that can explain many real observations of earthquake behavior. We have shown that hypocenter locations are increasingly clustered with increasing roughness and correlate well with the fractal geometry of the fault surface. Hypocenters of the largest earthquakes have strongly preferred locations, which leads to characteristic events with similar magnitudes and coseismic slip distributions. These slip distributions have fractal dimensions which are systematically (though non-linearly) related to the fractal dimension of the fault topography. All of these patterns are supported by recent geodetic observations, and several decades of paleoseismic and seismological observations. Our results suggest that rougher faults produce rougher slip distributions, more tightly clustered seismicity, and large events with preferred locations and directivity.

In principle, these results can be built into empirical scaling laws and statistical representations of likely earthquake nucleation locations. We save this or future work which will require many more simulations of different fault geometries. Nevertheless, we have demonstrated the power of the fractally-rough fault paradigm, which yields predictable results that are far from random.
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Figure 1: Summary figure comparing the roughness (top row), coseismic slip from three events (middle row), and surface slip for all events in each simulation (bottom row). Red colors indicate restraining topography, while blue indicates releasing topography. The three faults differ in fractal dimension but use the same random seed, giving them similar long-wavelength structure. The roughest fault (left column) has the most variable and discontinuous slip both at depth and at the surface. In all three simulations, the surface slip shows recurring patterns from event to event (colored lines), resulting in a characteristic average slip profile (bold red lines).
Figure 2: Comparison of the surface slip, power spectral density, and measured fractal dimension from slip (Ds) for two large (M>6.3) non-consecutive events in the Df 1.5 seed 10 simulation. There are differences in the patterns of variability between the two events, but there are persistent features such as low slip at ~28km and ~43km along-fault distance; these are persistent features in most of the large events for this simulation (Fig. 1 lower left). The two events have similar Ds, which is also fairly consistent for all events (Fig. 3).
Figure 3: Full distributions of surface slip fractal dimension (Ds) for all large events (M>6) in each of the nine simulations. Simulations with the same Df yield similar distributions of Ds with closely aligned mean (red lines) and standard deviation (green lines). Since these patterns hold even for very different fault realizations (Fig. S1), they suggest that the variability of the slip is controlled directly by fault structure.
Figure 4: (left) Hypocentral density for the Df 1.5 seed 10 simulation in three different magnitude ranges, with the fault topography shown for reference. All three magnitude bins produce seismicity clustered near the center of the fault. (right) Correlation of the hypocentral densities with the fault topography; this is the inner product of each of the left images with the fault roughness. All three magnitude ranges correlate strongly with high topography, indicating that hypocenters almost exclusively occur in locally restraining bends. (bottom right) The along-fault distribution of earthquake hypocenters. There is a pronounced seismic gap for the M>6 earthquakes from 35km to 45km along-fault distance.
Figure 5: Hypocentral density for the Df 1.3 seed 10 simulation. Compared to the results of the rougher fault (Fig. 4), the hypocenters are still clustered but more distributed in all three magnitude bins; a slightly smoother fault allows for a wider variety of nucleation sites. The M>6 events mostly start near 20km distance and rupture unilaterally. All other features are as described in Figure 4.
**Figure 6:** Hypocentral density for the Df 1.1 seed 10 simulation. This is the smoothest fault realization, and produces the most scattered distribution of seismicity. Nevertheless, the hypocenters in all three magnitude ranges are distributed in tight clusters around the fault. The largest events nearly always nucleate in the center of the fault and propagate bilaterally. All other features are as described in Figure 4.
Figure S1: Comparison of the fault topography for all nine fault realizations presented in the manuscript. Each column is based on the same random seed, giving it the same general structure, while each row represents a different fractal dimension. For simplicity, the manuscript focuses on a comparison of the results from the central column of faults, but the general patterns of hypocenter clustering, seismicity correlation to fault restraining bends, repeating surface slip patterns, and the slip spectral properties all hold for each suite of faults. This means that the differences between the realizations’ fractal properties are controlling the differences in observed seismic behavior; the specific realizations are not responsible for significant differences in these patterns (e.g., Fig. 3).
Figure S2: The epicentral distributions for all nine realizations. The placement corresponds to Fig. S1 (the Hurst exponent H is related to fractal dimension D via D=2-H). The roughest faults have the most peaked distribution (the strongest preference for epicentral location) in all three magnitude bins.
Figure S3: (top) A map of the Landers earthquake aftershock zone in Southern California. The 1992 M7.3 mainshock (blue triangle) produced 58267 aftershocks (grey) as low as M0.1 in a near-fault region we have arbitrarily chosen. (middle) Cross-sectional view of the same seismicity oriented approximately along strike of the Landers fault from SE to NW. (bottom) Cross-sectional density plot of the same seismicity, similar to Figs. 4-6 left. The bin sizes are 2km horizontally and 1.5km vertically, with a normalized colorscale as in Figs. 4-6. Even with nearly 60,000 hypocenters, the seismicity is strongly clustered and leaves significantly large gaps. A robust analysis of this data is outside the scope of the present work, but this clustered distribution strongly resembles the modeled data shown in Figs. 4-6. Earthquake data are from the 30-year relocated catalog of Hauksson et al. (2011).
Figure S4: Similar to Fig. S3 for the 1999 M7.1 Hector Mine earthquake with 21,255 earthquakes. The events are even more clustered than for Landers, with a prominent gap of seismicity visible even in map-view.
Figure S5: Similar to Fig. S4 for the San Jacinto fault, with 48,770 earthquakes. Unlike the previous examples which were dominated by aftershocks from fairly recent earthquakes, the San Jacinto fault hasn’t experienced an event with M>7.0 since 1800 (Rockwell et al., 2014). Nevertheless, the seismicity is similarly clustered with most regions lacking any discernible events, such as the prominent ‘Anza Gap’ (Sanders & Kanamori, 1984) near 0km along-fault distance.