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Key Points:

- Strike-slip fault zone relative maturity is inferred from cumulative fault slip and from individual event surface rupture segment geometry.
- Maturity measures are compared with relative aftershock productivity, rupture velocity, and moment-scaled radiated energy.
- Less mature faults have higher relative aftershock productivity and lower rupture velocity than mature faults.
- Moment-scaled radiated energy is low for very new faults, increases with modest maturation, and then decreases for very mature faults.

Abstract

Variations in fault maturity have intermittently been invoked to explain variations in some seismological observations for large earthquakes. However, the lack of a unified geological definition of fault maturity makes quantitative assessment of its importance difficult. We evaluate the degree of empirical correlation between field measurements indicative of fault zone maturity and remotely measured seismological source parameters of 34 large shallow strike-slip events. Metrics based on fault segmentation, such as number of primary rupture segments and surface rupture azimuth, correlate best with seismic source attributes and the correlations with cumulative fault slip are somewhat weaker. Average rupture velocity shows the strongest correlation with metrics of maturity, followed by relative aftershock productivity. Mature faults have relatively lower aftershock productivity and higher rupture velocity. A more complex relation is found with moment-scaled radiated energy. There appears to be distinct behavior of very immature events with no prior mapped fault and < 1 km cumulative slip, which radiate modest seismic energy, while moderately mature faults have events with higher moment-scaled radiated energy and very mature faults with increasing cumulative slip tend to have events with reducing moment-scaled radiated energy. We also explore qualitative and composite assessments of maturity and arrive at similar trends. This empirical approach establishes that there are relationships between remote seismological observations and fault system maturity that can help to understand variations in seismic hazard among different fault environments and to assess the relative maturity of blind fault systems for which direct observations of maturity are very limited.

Plain Language Summary

Faults evolve from irregular fracture networks that progressively localize and accumulate slip on growing segments with increasing total fault displacement. Roughness of the boundary smooths with accumulating slip and gouge and damage zones accumulate. Fault zone maturity is an assessment of where a fault zone lies in this process. Earthquakes occurring on evolving faults are influenced by the geological features, and it is plausible that seismological attributes of individual large events may be indicative of the degree of maturation of the fault system. This is tested by empirical comparison of geological and geometrical aspects of strike-slip fault zones and surface ruptures of large events on them with seismological attributes of the events. While there is no agreed upon measure of fault zone maturity, we consider cumulative slip of shallow strike-slip faults and field observations of number of fault segments, step-over offsets between segments, and changes in angle between segments for a given rupture as maturity indicators. These are compared with relative aftershock productivity, rupture velocity, and moment-scaled radiated energy measures that can be made for all large earthquakes. Less mature faults have higher relative aftershock productivity and lower rupture velocity. Radiated energy is relatively low for newly forming faults, increases with modest cumulative slip and then decreases as maturity further increases. These relationships help elucidate seismic hazard for fault systems of different maturity and can indicate maturity for fault systems not exposed at the surface.

1. Introduction

Understanding how earthquake dynamic rupture process is affected by complex fault geometry and distinguishing this from frictional complexity and rheological properties of the fault is an important frontier in earthquake science (e.g., Klinger et al., 2018; Thomas et al., 2017; Wibberley et al., 2008). The complexity of the fault geometry reflects whether the fault network is mature or immature in terms of structural evolution. The structural maturity of the fault zone has been related to the seismic activity rate inferred from modern, historical and ancient seismic data (e.g., Cowan et al., 1996; Wesnousky, 1988; Wibberley et al., 2008) and plausibly may have significant impact on individual earthquake characteristics, such as the distribution of slip, rupture velocity, and number of ruptured segments (Perrin et al., 2021). Mature fault zones in strike-slip tectonic settings may serve as highly anisotropic permeability channels through the brittle crust making some regions more likely to produce slow events than immature fault zones (Thakur et al., 2020), while immature fault zones may exhibit more complex ruptures and distributed coseismic damage that can be observed seismologically.

Surface rupturing events provide important, albeit incomplete, characterizations of the fault systems producing large earthquakes for which seismic source parameters can be determined. For example, the 2019 M_W 7.1 Ridgecrest earthquake involved an immature surface-rupturing fault system with small cumulative slip (< 70 m) and multiple segments that could be mapped in the field at many

scales (e.g., DuRoss et al., 2020; Hudnut et al., 2020; Rodriguez-Padilla et al., 2022). Various seismic source attributes of the 2019 Ridgecrest mainshock have also been determined, indicating overall slow average rupture velocity, low moment-scaled radiated seismic energy, and relatively high aftershock productivity (e.g., Goldberg et al., 2020; Liu et al., 2019; Ross et al., 2019). These seismological characteristics contrast with the rupture of mature, large cumulative slip faults, such as those that produced the Kunlun (Tibet) earthquake in 2001 and the Denali (Alaska) earthquake in 2002. The latter ruptures include long, well-localized faults with high rupture velocity, including intervals of supershear rupture (Bhat et al., 2007; Bouchon & Vallée, 2003; Dunham & Archuleta, 2004; Perrin, Manighetti, Ampuero, et al., 2016; Vallée & Dunham, 2012; Walker & Shearer, 2009; Wang, Mori, et al., 2016), low aftershock productivity (especially in the supershear regions, e.g., Bouchon & Karabulut, 2008), and relatively high moment-scaled radiated energy overall.

Fault maturity is variably defined on different scales and may relate to the evolution of the fault core, the damage zone and the shear deformation zone, which reflect the regions controlled by wear processes (Perrin et al., 2021). A qualitative definition of fault maturity can also be the degree of evolution of its macroscopic structural properties, which may be related to the fault age, slip rate, and total accumulated slip, as adopted in various studies (Dolan & Haravitch, 2014; Manighetti et al., 2007; Perrin, Manighetti, Ampuero, et al., 2016). In this study, our usage refers to the general tendency for fault systems to evolve from complex fracture systems into localized through-going faults as displacement accumulates. Evolving faults intrinsically have variable amounts of slip, and hence maturity, along their length, being most mature near the middle of the fault length and least mature at the ends (e.g., Perrin et al., 2016); no single measure of maturity is valid over the entire fault. Persistence of fault segmentation even for large cumulative displacements may reflect controls of crustal thickness and geological structures that compete with the tendency to progressively localize onto a single surface (e.g., Klinger, 2010; Jiao et al., 2021). Thus, maturation is not self-evidently linear with time or cumulative slip. Broadening of damage zones around faults may saturate at relatively modest displacements (e.g., Savage & Brodsky, 2011). Related tendencies to have or lack shallow slip deficit and afterslip may indicate varying degrees of fault maturity (e.g., Li et al., 2020), but surficial sediments may obscure the degree of deeper localization for a wide range of fault maturity.

In this study, we explore the extent to which remotely observable source parameters of large shallow strike-slip earthquakes, specifically relative aftershock productivity, rupture velocity, and moment-scaled radiated elastic energy, are influenced by and indicative of the maturity of the fault system that hosted the event. We focus on shallow continental strike-slip faults with well-documented context and assemble data on several geological candidate metrics for measuring maturity: cumulative displacement, segment number, azimuth change and stepover offset. We then compare the correlation between each of these geological and geometric variables to the seismological ones for both the full dataset and

subsets with the most robust geological data. After identifying some preliminary trends, we then explore the power of a more heuristic assessment of maturity as well as a composite measure. In the end, we conclude that some seismological variables, such as rupture velocity and to a lesser degree aftershock productivity, are correlated with maturity metrics that include information about segmentation, especially number of segments or azimuth change. Seismic radiated energy has a more complex and potentially non-monotonic relationship to maturity.

2. Data

Continental earthquakes provide geological information that can not be as well observed for oceanic earthquakes. Specifically, shallow continental earthquakes with magnitudes larger than 6 are often quantitatively characterized by geological and seismological studies. Shallow crustal strike-slip earthquakes in particular provide field and geophysical observations that allow the maturity of the associated fault system to be evaluated. Detailed studies of continental strike-slip events with $M_W \geq 6.0$ over the past few decades provide multiple examples of ruptures with well-determined source parameters in tandem with an observational field study basis for evaluating the maturity of their fault system. For example, the segmented rupture determined for the M_W 6.5 Idaho earthquake in 2020 occurred on immature faults that were not previously mapped and lack large cumulative displacement (Yang et al., 2021). Recognizing the challenge of defining and measuring fault maturity with the available data, we assembled summary fault zone properties for regions hosting recorded large ($M_W \geq 6.0$) shallow strike-slip earthquakes to provide a preliminary basis for defining relative maturity. In total, we select the 34 strike-slip earthquakes shown in Figure 1. Except for the Ridgecrest sequence, which includes both the M_W 6.4 foreshock and the M_W 7.1 mainshock, all other utilized earthquakes are single events.

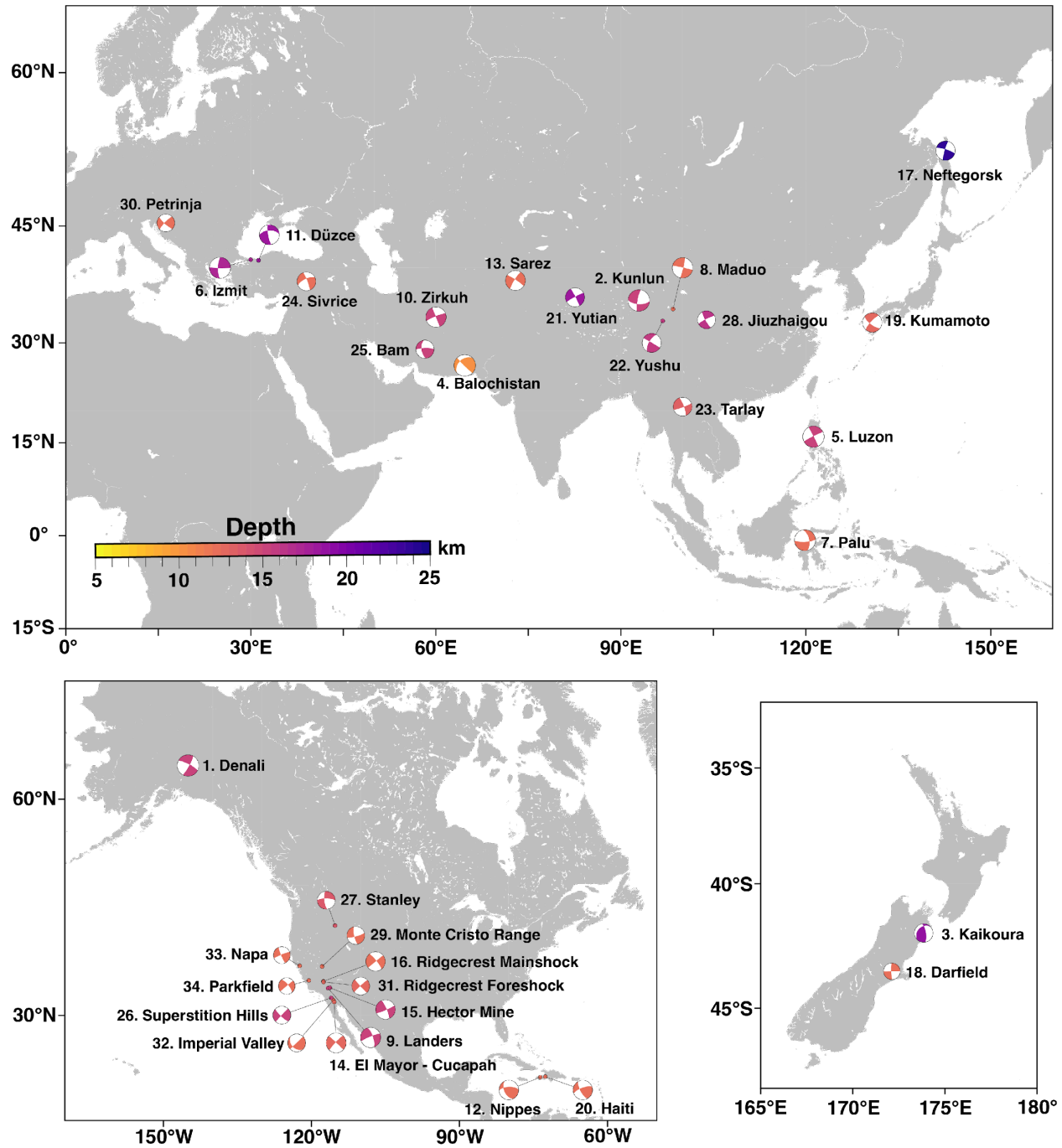


Figure 1. Maps showing locations and focal mechanisms of the 34 selected shallow strike-slip earthquakes, with the focal mechanisms color-coded by hypocen-

tral depth. Events are sorted by magnitude and labeled with numbers used as their event ID (Table 1) in the following discussion.

2.1 Geological and Geometric Measurements

Maturity is a qualitative property of fault systems and a basic challenge for this study is to establish field-based attributes of fault systems that provide a consistent assessment of relative maturity. The properties considered in this study include the total slip along the fault and segmentation related measurements (Figure 2).

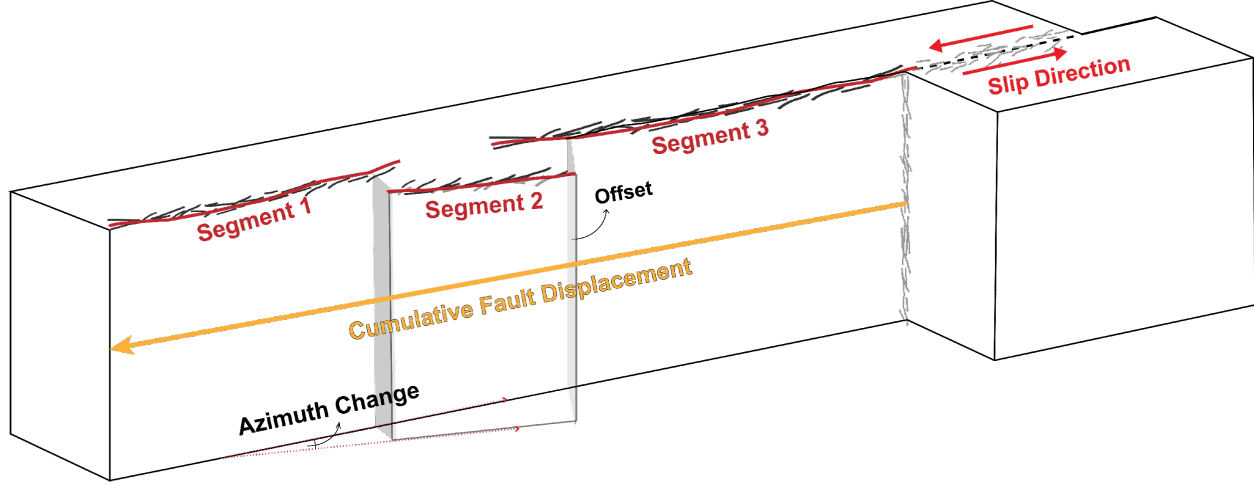


Figure 2. Schematic model of some geologic field measurements for a surface-rupturing fault, including cumulative fault displacement and fault segmentation related parameters such as number of primary segments and surface stepover offsets between segments.

2.1.1 Slip-based measures of maturity

A key issue for maturity is total slip of the fault involved in a particular rupture, related to both the slip rate and the fault age. If the fault has large cumulative displacement (from hundreds to thousands of kilometers), it can be considered overall mature, in terms of localization, gouge accumulation, etc., but maturity varies along the fault, so local properties where a rupture occurs are also important. Immature faults have small cumulative displacement (from hundreds of meters to a few tens of kilometers). We compile estimates of cumulative fault displacement in the literature for each of the faults in our study; these sometimes span a large range for a given fault due to observational limitations (Table1).

Another potential candidate metric of maturity is the ratio of surface slip to slip at depth on a fault. Surface fault slip during earthquakes is often smaller than the slip at depth determined from geodetic and seismologic data (e.g., Thatcher & Bonilla, 1989; Xu et al., 2016; Liu et al., 2021). Recent studies show

that the zone of maximum co-seismic slip in continental strike-slip earthquakes commonly occurs at about 3–6 km depth while the surface coseismic slip is often lower and afterslip and distributed deformation often do not add up to match the deep slip. Li et al. (2020) argue that a shallow slip deficit and lack of early afterslip indicates that the fault system is immature. We then expect a complex rupture geometry with distributed coseismic failure in the uppermost part of the brittle crust during the fault zone development. As faults mature, they straighten, develop a localized fault zone core, and the shallow slip deficit tends to diminish. Fault structural maturity and the percentage of total surface displacement that occurs on narrow zones of surface rupture relative to more distributed deformation have been revealed to have a consistent correlation (Dolan & Haravitch, 2014). Specifically, structurally immature fault zones (~ 25 km of total displacement) have lower percentage of the total surface deformation in earthquakes than mature faults. Although shallow slip deficit is potentially a useful factor for assessing maturity, the common lack of slip measurements and dependence on the estimates of slip at depth make it hard to quantify this property. Therefore, shallow slip deficit is ultimately not utilized in our set of geological measurements for all events, but it can provide extra assessment for some events when the data constraints are suitable.

2.1.2 Segmentation-based measures of maturity

Geological faults are segmented at large scale, and this is a property independent of the slip mode (Manighetti et al., 2007; 2021). As a fault grows with time, linkage between its large-scale segments increases and the geometry of the fault zone simplifies and becomes more continuous. The inter-segment zones commonly involve distributed, disorganized, secondary fissuring and faulting and therefore, can have higher overall strength on young, immature faults, and lower strength on mature features (Ben-Zion & Sammis, 2003). Earthquake ruptures on mature faults have been observed to have the ability to overcome the resistance of large scale stepovers while for immature faults, it is relatively harder for the earthquake to propagate across the disorganized, high-strength inter-segment zones (e.g., Gong et al., 2022; King & Nábělek, 1985; Liu et al., 2019; Sibson, 1985). Advances in fault mapping techniques have provided increasing details and more reliable rupture models, helping to characterize recent large earthquakes for the coseismic time-varying slip distribution of multiple fault segments involved in each rupture. For example, the 2019 Ridgecrest strike-slip earthquake sequence is a component of a developing large-scale fault system in the Eastern California shear zone (Goldberg et al., 2020; Liu et al., 2019; Ross et al., 2019; Shelly, 2020 and many others). The field attributes determined for the Ridgecrest mainshock indicate the rupture of a highly segmented immature fault zone that is not yet strongly localized. The degree of small-scale segmentation may influence seismological properties due to high fracture energy consumption, imposing slow average rupture velocity due to rupture hiatus as stepovers are negotiated, and high number of aftershocks due to stress concentration near segment transitions.

We therefore compile observations of field observations of surface ruptures in the

literature for each of the events in our study using multiple metrics based on segmentation (Figure 2). For instance, strike azimuth changes and stepovers are common features used to define segment boundaries along strike-slip ruptures (Bilham & Williams, 1985). Minor variation in the fault azimuth can produce significant rupture limitations while small stepovers of up to several kilometers do not necessarily prevent through-going rupture whereas stepovers larger than 5 km often do (Wesnousky, 1988; King et al., 2005; Klinger, 2010). In addition, the total number of segments is potentially an important aggregate measure of maturity.

Segmentation measures are, however, challenging to evaluate as the observed rupture must be long enough to capture the general features of the fault segmentation during an earthquake rupture without being biased by multiple segments located at the ends of the rupture (Klinger, 2010). Detailed and accurate rupture mapping is needed for resolution of the degree of segmentation. Our selected events are all large continental strike-slip events, most of which have well-documented surface ruptures. However, reported segmentation measures vary for each event due to different strategies in field mapping and counting of fault segments on a variety of scales.

A semi-automatic procedure with uniform criteria and scale can provide additional self-consistent segmentation measures to supplement our compiled results from prior studies. Therefore, we use a dataset compiled by Natural Hazards Risk and Resiliency Research Center (NHR3) that contains the digitized primary surface rupture of 21 earthquakes among our selected 34 events. The Sarez earthquake (earthquake ID13 in Figure 1) is an additional large earthquake that occurred in recent years and has well mapped surface rupture traces. We include this earthquake together with the 21 events from NHR3 to perform a systematic segmentation analysis to provide self-consistent constraints on segmentation of these local fault systems.

We follow the segmentation method described in Klinger (2010) to parameterize the earthquake surface rupture. This method is based on an l_1 trend filtering which performs a piecewise linear fit achieved by minimizing the equation, $\frac{1}{2} \sum_{i=1}^n (y_i - x_i)^2 + \lambda \sum_{i=2}^{n-1} |x_{i-1} - 2x_i + x_{i+1}|$, where y represents the data, x represents the model and n is the number of points. We follow the same strategy as Klinger (2010) by consistently resampling the surface rupture data to 1pt/100m to smooth the data to avoid biases caused by local minor wiggles and secondary strands along the rupture trace. This method is sensitive to fault azimuth changes and therefore can be a robust and useful tool in large-scale fault segmentation. The parameter λ controls the smoothness of the model and therefore affects the fit error between the data and model and the number of segments determined. Figure 3 shows the suite of possible combinations of RMS-misfit and number of segments with each point on this graph corresponding to a different choice of λ . The RMS-misfit drops drastically when the number of segments is lower than a threshold, therefore we select the preferred segment number as the minimum number of segments for which misfit no longer drops rapidly. As

a secondary criterion, we also consider a direct manual count from the rupture maps and verify that the semi-automatic method is consistent with visual inspection of the map (See Figures S1-S22 for direct visualization of the maps). The estimated number of segments is only for the main surface rupture while distributed ruptures or minor branches are not considered, so the segmentation measure is intrinsically a conservative one. Figures S1-S22 only present one possible realization of this semi-automatic segmentation method corresponding to the chosen λ . As Klinger (2010) points out, the specific segmentation is not unique, and we include uncertainty estimates on the number of segments.

We also use the segmentation on the NHR3 maps (Figures S1-S22) to determine maximum azimuth change and segment offset. Once again, we compare the results to published values in the literature for the specific earthquake where possible and report the full range of estimates as the range of possible values for the parameter in Table 1.

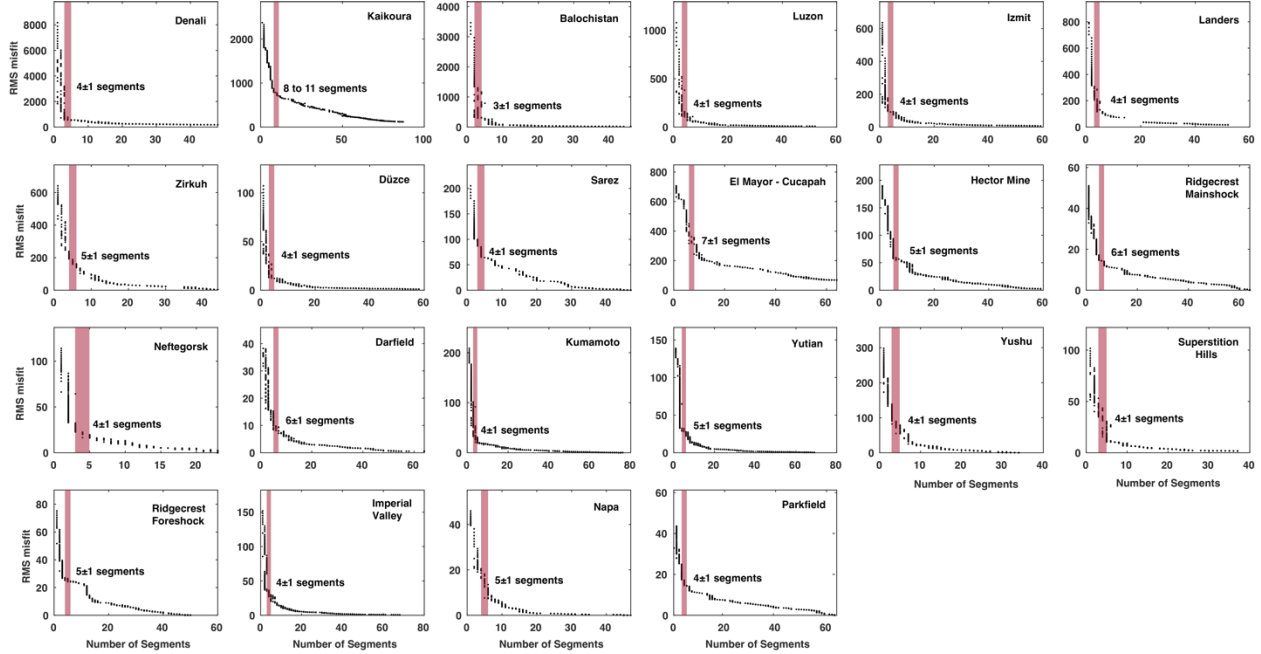


Figure 3. The l_1 trend filtering analyses for events with digitized surface rupture data. The number of segments listed in the figure is determined from the main surface rupture following the systematic segmentation method, and distributed branches are not counted. Figures S1-S22 present the final parameterizations for the number of segments for each event.

2.2 Seismic Source Attributes

Prior studies have suggested that geophysically determined earthquake characteristics, such as rupture velocity, stress drop, ground motion amplitude, and

slip distribution may be related to structural maturity of the local fault system (e.g., Dolan & Haravitch, 2014; Perrin et al., 2021; Stirling et al., 1996). We usually cannot robustly analyze the structural complexity of a blind fault but seismic source characteristics can be determined if it experiences a large earthquake. Seismology and geodesy now provide systematic characterizations of faulting for large earthquakes around the world, a subset of which do rupture the surface in fault zones for which we can estimate overall fault maturity. If we can establish relationships between the observed maturity of a fault and the seismic source attributes of earthquakes that rupture it, this would contribute to understanding variations in seismic hazard among different fault environments and could provide a probe of maturity of blind fault systems that are not exposed at the surface and cannot otherwise be characterized.

Among the 34 events in this study, only two well-studied and documented earthquakes, the 1979 Imperial Valley earthquake and the 1987 Superstition Hills earthquake, occurred earlier than 1990. We focus on events after 1990 because they have both more extensive field investigations and higher completeness of the main seismic parameter attributes that we consider: relative aftershock productivity, rupture velocity, and moment-scaled radiated elastic wave energy.

2.2.1 Aftershock Productivity

Aftershock productivity adjusted for scaling relative to mainshock magnitude has been related to both geological setting and focal mechanism (Dascher-Cousineau et al., 2020; Page et al., 2016; Tahir et al., 2012; Wetzler et al., 2016) and provides a measure of the distributed deformational process associated with an earthquake. For continental strike-slip events at shallow depth, we explore whether variability in aftershock productivity is influenced by fault zone maturity.

We use the ratio between the observed and predicted aftershock productivity as a readily measurable source parameter. Considering the variation in the completeness of magnitude for catalogs in different regions, the observed aftershock productivity (NA_{obs}) for each selected earthquake is determined using a fixed 45-day time window for aftershocks with magnitude 4.5 in the ANSS Comprehensive Earthquake Catalog (Comcat). A magnitude-dependent spatial search is used, which involves a circular search for shallow events centered on the mainshock epicenter with radius $R = 2 \times 10^{-2.44+0.59*M}$ by twice the empirical rupture length from Wells & Coppersmith (1994), following Ye et al. (2016). Here, M is the magnitude of the mainshock.

Ye et al. (2020) found a general relation for the predicted aftershock productivity for globally shallow major earthquakes with magnitude 7.0 using the same space-time window. The overall predicted productivity (NA_{pred}) is $NA_{pred} = 10^{0.99M-5.83}$, which specifies a typical aftershock productivity for each magnitude. The ratio between NA_{obs} and NA_{pred} provides a consistent measurement for each selected large strike-slip earthquake with a given magnitude (Table 1). Other clustering methods for identifying aftershocks can be used (e.g., Dascher-

Cousineau et al., 2020; Wetzler et al., 2022), and specific values vary, but the procedure here is simple and reproducible using global catalogs with a moderate magnitude of completeness. It is sufficient for our purpose of exploring basic relationships with fault zone maturation.

2.2.2 Rupture Velocity

Both observations and dynamic rupture simulations have shown that faster rupture velocity and the potential for supershear transition on faults surrounded by damaged zones are more likely on mature, well-localized and relatively straight segments of shallow faults (Huang et al., 2016; Perrin et al., 2016; Thakur & Huang, 2021; Zhang & Chen, 2006). Less mature segmented faults with offsets tend to experience rupture hiatus and slowing of average rupture speed (Bruhat et al., 2016; Goldberg et al., 2020; Hetland & Hager, 2006). Therefore, earthquake rupture velocity is a possible source property indicative of fault maturity.

The determination of rupture velocity requires very good regional seismic and geodetic constraints on the finite-fault rupture model for smaller events augmented by high-frequency back projections and surface wave measurements for larger events. Observations after 1990 tend to be more comprehensive for these measurements, but resolution varies regionally. We compile estimates of the average rupture velocity for each event from prior literature and present the information in Table 1.

2.2.3 Radiated Energy

Earthquakes occurring on immature (low cumulative displacement) faults are more likely to have more roughness at short fault wavelengths and, hence, may radiate more short-period energy per unit of moment than earthquakes occurring on smoother, more mature faults. But the radiated energy budget is in tension with fracture energy consumed in propagating the rupture along the rough surface, with plastic yielding and other dissipative processes consuming some of the available potential energy, particularly for newly emerging fault zones. As a fault matures it localizes and accumulates gauge, which may lower its strength and fracture energy (Perrin, Manighetti, & Gaudemer, 2016), with radiated energy being relatively high. While routine measures of radiated energy are routinely available from seismic recordings of our large events, as listed in Table 1, any plausible relationship to maturity is uncertain.

3. Correlations Between Each Maturity Measure and Seismological Parameters

We combine information from both the previous literature (including rupture velocity, cumulative fault displacement and segmentation results) and our systematic segmentation analysis (number of rupture segments, maximum azimuth changes, offsets of stepover between segments) and list the ranges of these parameters in Table 1. The large ranges indicated for some parameters reflect a mix of measurement procedures and uncertainty in the measurements.

Table 1. Estimated Parameters of the 34 Utilized Earthquakes

Event ID	Earthquake Information	M_{obs} NA_{obs}	Rupture NA_{pred} Loc- ity (km/s)	Radiated En- ergy (J), Moment scaled (km) Ra- di- ated En- ergy (J N ⁻¹ m ⁻¹)	Cumulative Fault Dis- place- ment (km)	Number of Seg- ments	Maximu Az- imuth Change (De- grees)	Stepover Off- set (km)	Reference
	/11/03 M_W 7.9 De- nali (United States)	0.56	-3.5	$\times 10^{16}$, 1.57×10^{-5}	-250	-6	-48	-4.2	Amand, 1957; Frankel, 2004; Grantz, 1967; Haeus- sler et al., 2004; Ozacar & Beck, 2004

/11/14	0.28	-3.6	$\times 10^{15}$, -150	-5	-35	-10	Der Wo- erd et al., 2002; Fu et al., 2005; Gau- der- mer et al., 1989; Ozacar & Beck, 2004; Wen et al., 2009; Xu et al., 2006
M_W			8.88×10^{-6}				
7.8							
Kun-							
lun							
(China)							
/11/13	1.76	-2	$\times 10^{16}$, -19	-17	~ 90	-4	Cesca et al., 2017; Litch- field et al., 2018; Nicol et al., 2018; Stir- ling et al., 1996; Xu et al., 2018
M_W			2.85×10^{-5}				
7.8							
Kaik-							
oura							
(New							
Zealand)							

/09/24	0.35	-4	$\times 10^{15}$, -460 1.54×10^{-5}	-4	-20	-1.3	Avouac et al., 2014; Valdiya & San- wal, 2017; Wang et al., 2016; Zinke et al., 2014
M_W							Barrier et al., 1991; Klinger, 2010; Ve- lasco et al., 1996
7.7							
Balochis- tan (Pak- istan)							
/07/16	2.51	-3.5	$\times 10^{16}$, -200 6.49×10^{-5}	-5	-10	NA	
M_W							
7.7							
Lu- zon (Philip- pine)							
/08/17	0.57	-4.8	$\times 10^{15}$, -88 1.11×10^{-5}	-5	-29	-0.5	Akbayram et al., 2016; Bou- chon et al., 2001; Lan- gridge et al., 2002; Sunal & Ertu- raç, 2012; Tibi et al., 2001
M_W							
7.6							
Izmit (Turkey)							

/09/28 M_W 7.5 Palu (Indonesia)	1.42	-4.3	$\times 10^{15}$, -250 1.65×10^{-5}	-4	-15	-5	Bao et al., 2019; Natawid- jaja et al., 2021; Soc- quet et al., 2019
/05/21 M_W 7.3 Maduo (China)	1.00	-3.5	$\times 10^{15}$, ~50 1.25×10^{-5}		-17	~2	Ren et al., 2022; Yuan et al., 2022; Yue et al., 2022
/06/28 M_W 7.3 Landers (United States)	1.88	-2.9	$\times 10^{15}$, -40 1.43×10^{-5}	-7	-30	-3	Cohee & Beroza, 1994; Dreger, 1994; Jachens et al., 2002; Klinger, 2010; Wes- nousky, 2006

/05/10	0.76	-3.5	$\times 10^{15}$, -105	-7	-30	-2.8	Ansari, 2021; Berbe- rian et al., 1999; Marchan- don et al., 2018; Tan et al., 2019; Walker & Jack- son, 2004
M_W			2.94×10^{-5}				
7.3							
Zirkuh							
(Iran)							
/11/12	0.60	-4.8	$\times 10^{15}$, -88	-5	-25	-2	Akbayram et al., 2016; Birgören et al., 2004; Bou- chon et al., 2001; Du- man et al., 2005; Sunal & Ertu- raç, 2012
M_W			1.26×10^{-5}				
7.2							
Duzce							
(Turkey)							

/08/14 M_W 7.2 Nippes (Haiti)	0.65	NA	NA, NA	-12.8	-5	-10	NA	Maurer et al., 2022; Pren- tice et al., 2010; Saint Fleur et al., 2020
/12/07 M_W 7.2 Sarez (Tajik- istan)	1.21	-5	$\times 10^{15}$, 2.77×10^{-5}	-100	-5	-22	-2	Elliott et al., 2020; Met- zger et al., 2017; Rutte et al., 2017; Sangha et al., 2017
/04/04 M_W 7.2 El Mayor- Cucapah (United States)	1.56	-2.5	$\times 10^{15}$, 1.89×10^{-5}	-5	-8	-85	-3	Fletcher et al., 2014; Teran et al., 2015; Uchide et al., 2013; Wei et al., 2011

/10/16 M_W 7.1 Hector Mine (United States)	1.33	-2.2	$\times 10^{15}$, -3.4 5.33×10^{-5}	-9	-60	-2	Jachens et al., 2002; Ji et al., 2002; Kaverina et al., 2002; Treiman et al., 2002
/07/06 M_W 7.1 Ridge- crest Main- shock (United States)	2.09	-2	$\times 10^{14}$, -0.1 8.54×10^{-6}	-12	-90	-1.7	Amos et al., 2013; DuRoss et al., 2020; Goldberg et al., 2020; Liu et al., 2019; Thompson Jobe et al., 2020
/05/27 M_W 7.1 Neftegorsk (Russia)	1.01	-2.1	$\times 10^{15}$, -50 3.91×10^{-5}	-7	-15	-1.3	Arefiev et al., 2000; Fournier et al., 1994; Kraeva, 2004

/09/03 M_W 7.0 Darfield (New Zealand)	3.02	-2.5	$\times 10^{15}$, NA 2.51×10^{-5}	-7	-35	-0.95	Elliott et al., 2012; Quigley et al., 2012; Quigley et al., 2019
/04/15 M_W 7.0 Ku- mamoto (Japan)	3.42	-2.5	$\times 10^{15}$, -1.4 4.52×10^{-5}	-10	-50	-1.2	Asano & Iwata, 2016; Kobayashi et al., 2017; Scott et al., 2018; Toda et al., 2016
/01/12 M_W 7.0 Haiti (Haiti)	4.85	-3.3	$\times 10^{15}$, -10 1.00×10^{-4}	-5	-20	~ 5	Koehler et al., 2013; Meng et al., 2012; Mercier de Lépinay et al., 2011; Pren- tice et al., 2010; Saint Fleur et al., 2020

/02/12	1.30	NA	$\times 10^{14}$, <65 3.19×10^{-5}	-7	-40	-3.4	Li et al., 2016; Ritts & Biffi, 2000; Stirling et al., 1996; Zhang & Ge, 2017
M_W							
6.9							
Yu-tian (China)							
/04/13	1.00	-5	$\times 10^{14}$, ~ 60 1.42×10^{-5}	-5	-10	-2	Li et al., 2012; Lin et al., 2011; Wang & Mori, 2012; Yan & Lin, 2015; Yokota et al., 2012
M_W							
6.9							
Yushu (China)							

/03/24 M_W 6.9 Tar- lay (Myan- mar)	1.63	-3.5	$\times 10^{14}$, -30 1.28×10^{-5}	-4	-20	-3	Feng et al., 2013; La- cassin et al., 1998; Orn- tham- marath, 2013; Tun et al., 2014
/01/24 M_W 6.7 Sivrice (Turkey)	1.26	-2.2	$\times 10^{14}$, -22 2.48×10^{-5}	-4	-10	NA	Bayrak & Ozer, 2021; Gallovič et al., 2020; Mel- gar et al., 2020; Tatar et al., 2020
/26 M_W 6.6 Bam (Iran)	0.59	~ 2.8	$\times 10^{14}$, -12 1.50×10^{-5}	-5	-10	NA	Jackson et al., 2006; Maleki Asayesh et al., 2020; Naka- mura et al., 2005; Walker & Jack- son, 2004

/11/24 M_W 6.6 Su- per- sti- tion Hills (United States)	0.59	~ 2.5	NA, NA	-43	-5	-20	-0.6	Hwang et al., 1990; Klinger, 2010; Stir- ling et al., 1996; Wes- nousky, 2006
/03/31 M_W 6.5 Stan- ley (United States)	0.25	-4	$\times 10^{14}$, ~ 1 1.55×10^{-5}		-4	~ 6	~ 10	Liberty et al., 2021; Yang et al., 2021
/08/08 M_W 6.5 Ji- uzhaigou (China)	0.99	~ 2.4	$\times 10^{13}$, ~ 1 1.29×10^{-5}		~ 2	~ 21	~ 4	Li et al., 2018; Y. Li et al., 2020; Zhang et al., 2021
/05/15 M_W 6.5 Monte Cristo Range (United States)	3.72	-2.6	$\times 10^{14}$, ~ 1 1.98×10^{-5}		-3	~ 23	NA	Li et al., 2021; Liu et al., 2021; Zheng et al., 2020

/12/29 M_W 6.4 Petrinja (Croatia)	0.94	-2	$\times 10^{14}$, -1.4 2.19×10^{-5}	-5	-70	NA	Baize et al., 2022; Markušić et al., 2021; Tondi et al., 2021
/07/04 M_W 6.4 Ridge- crest Fore- shock (United States)	1.56	-2	$\times 10^{13}$, -0.1 1.08×10^{-5}	-10	~ 85	-1.6	Amos et al., 2013; DuRoss et al., 2020; Gold- berg et al., 2020; Thomp- son Jobe et al., 2020
/10/15 M_W 6.4 Im- pe- rial Val- ley (United States)	2.81	-3.1	$\times 10^{14}$, -43 2.59×10^{-5}	-6	-50	-0.9	Archuleta, 1984; Pow- ers & Jor- dan, 2010; Stir- ling et al., 1996; Wes- nousky, 2006

/08/24 0	-3	$\times 10^{13}$, -175	-7	-30	-1.2	Dreger et al., 2015; Ji et al., 2015; Lan- gen- heim et al., 2010
M_W		1.85×10^{-5}				
6.02						
Napa						
(United						
States)						
<hr/>						
/09/28 1.66	-3.1	$\times 10^{13}$, -315	-5	-10	-1.5	Allmann & Shearer, 2007; Ma et al., 2008; Pow- ers & Jor- dan, 2010
M_W		9.69×10^{-6}				
5.97						
Park-						
field						
(United						
States)						

We now assess whether there are any trends between the seismic attributes (relative aftershock productivity, rupture velocity and moment-scaled radiated energy) and the geological fault complexity measurements in Figures 4 and 5, including the ranges on the parameters. Circular symbols represent the average value spanning the minimum to maximum range of each measurement.

Figure 4 shows cumulative fault displacement determined from previous geological studies versus the seismic variables. Several earthquakes on short faults among our 34 cases do not have clear documentation of the total slip along the fault. Specifically, the two Ridgecrest earthquakes (event ID 16&31), Stanley earthquake (event ID 27), Jiuzhaigou earthquake (event ID 28), and Monte Cristo Range earthquake (event ID 29) occurred on newly mapped faults without extensive prior seismicity (Goldberg et al., 2020; Liu et al., 2019; Sun et al., 2018; Yang et al., 2021; Zheng et al., 2020). We assume that these earthquakes nucleated on young faults for which the total slip is relatively small. Although no systematic approach to assess the regional fault activity for the rupture area of the 2019 Ridgecrest earthquakes had been completed at the time of the earthquakes, previous studies have mapped the right-lateral displacement of the faults at the southern end of the rupture area to be tens of meters to hundreds of meters (Amos et al., 2013; Thompson Jobe et al., 2020). Therefore, we estimated the cumulative slip of the faults nucleating the two Ridgecrest

earthquakes to be ~ 100 m. As there are no robust total fault slip values for other fault systems listed above, we approximate their total slip to be ~ 1 km. To visually distinguish these events from other events in the figure, we depict them in gray.

Apart from the Stanley earthquake, cumulative fault displacement shows scattered, but systematic trends with relatively aftershock productivity and rupture velocity. Larger cumulative fault displacement is accompanied with relatively lower aftershock productivity and higher rupture velocity. Data for the variation with radiated energy in Figure 4c is yet more scattered, with the group of very new fault ruptures deviating from a reduction in energy with increasing slip. While there is not a clear reason for any of these trends to be linear, one interpretation is that the very new ruptures of unmapped faults have particularly strong energy dissipation (high fracture energy), which evolves quickly with modest cumulative slip, and then increasing smoothness of the fault results in decreasing radiation of short period energy.

In order to quantify the strength of the trends, we use p-values, which measure the probability that the observed correlation can be created by a random trend in uncorrelated datasets. A low p-value implies a strong significance to the result. We recognize that the use of p-values in this way does not rigorously correspond to a probability of correlation, but rather merely provides a convenient tool to quantify and compare the visually apparent trends in the data.

We bootstrap 1000 times to determine the p-value ranges for a linear model in log scale using datasets with and without the gray dots. Cumulative fault displacement for data with error bars are randomly selected between the lower and upper bounds in log scale for each bootstrap. The p-values determined from red dots (excluding outliers with no measured total slip) in Figure 4a-4c suggest the rupture velocity ($p = 0.0024$) and the moment-scaled radiated energy ($p = 0.041$) yield statistically significant loglog fits to the cumulative fault displacement. Relative aftershock productivity ($p = 0.082$) has a modestly significant trend with total slip.

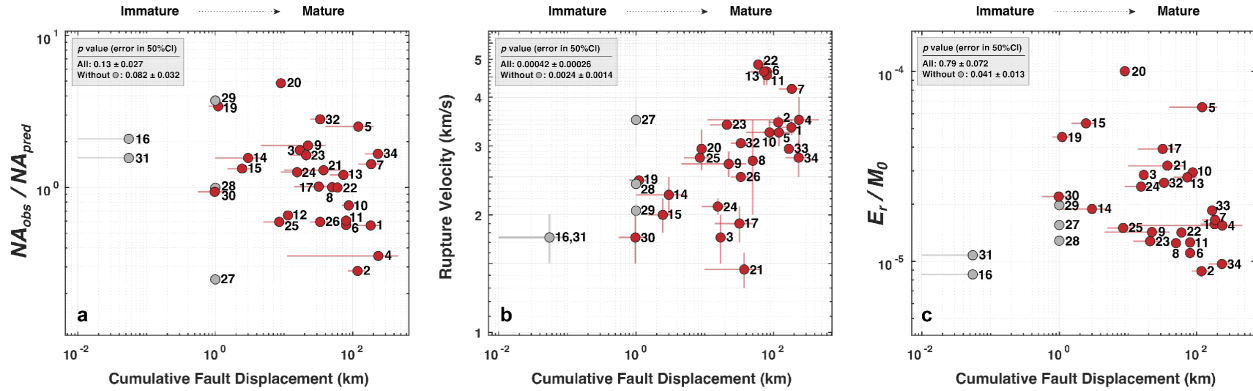


Figure 4. Cumulative fault displacement versus three seismic attributes of the

strike-slip event population. Event ID is used to identify events in Table 1 and Figure 1. Gray circles indicate ruptures of previously unmapped faults for which the cumulative displacement is set to 1 km, while other events with measured fault displacement estimates are marked in red. The strength of the trend in each panel is quantified with p-values, which are calculated both from the full dataset and the dataset without faults that do not have a total displacement.

Figure 5 shows comparisons between seismic parameters and the geological measurements of the segmentation. We generally need to be cautious with the segmentation estimates for smaller earthquakes ($M_W < 6.5$) when there is limited, or no available surface rupture measured in the field. Among the 34 studied events, the Haiti earthquake (event ID 20), Sivrice earthquake (event ID 24), Stanley earthquake (event ID 27) and Jiuzhaigou earthquake (event ID 28) do not have clear surface deformation or recognized slip (Hayes et al., 2010; Politz et al., 2020; Sun et al., 2018; Taymaz et al., 2021), so their segmentation estimates are from geophysical inversions and are correspondingly uncertain.

We mark the smaller events ($M_W < 6.5$) and the events without observable surface rupture in gray, so they can be visually down-weighted in Figure 5 to better detect any trend between the segmentation factors and the seismic attributes. The number of segments has a clear trend with aftershock productivity (Figure 5a) which matches the expectation that a fault with lots of segments and stress concentrations may generate more aftershocks. The number of segments also shows a trend with rupture velocity in Figure 5d where more segments correspond to lower rupture velocity, as might be expected by the difficulty in rupturing through a highly segmented system. The maximum azimuth between segments (Figure 5b, e, h) only appears to show a weak trend when the less robust data (gray dots) are neglected. The offset of stepover between segments has some relationship with rupture velocity (Figure 5f), but in general visually appears to be the weakest predictor of seismic behavior. None of the fault geometry factors are simply related to the moment-scaled radiated energy (Figure 5g-i). This last result echoes the same lack of clear correlation between moment-scaled radiated energy and total fault displacement when very immature faults are included (Figure 4c).

Our analysis suggests that correlations of the number of segments with the relative aftershock productivity ($p=0.014$) and the rupture velocity ($p=0.00022$) are significant. In addition, the maximum azimuth change shows moderately significant relation with the relative aftershock productivity ($p=0.033$) and the rupture velocity ($p=0.0024$) while the p-values for the stepover offset comparisons are too large to resolve any correlation.

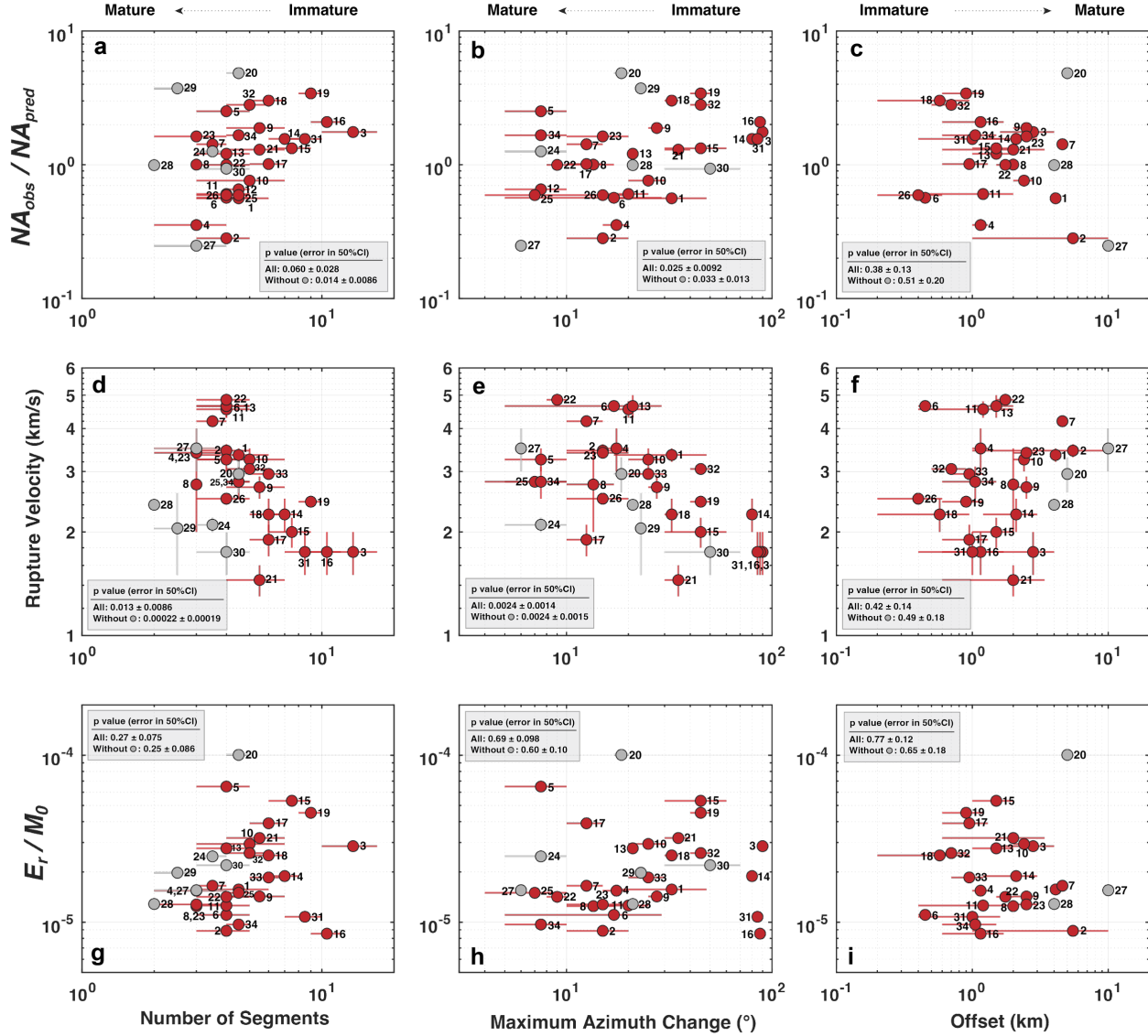


Figure 5. Estimated number of segments, azimuth changes and stepover offset between segments versus the three seismic attributes. Event ID is used corresponding to Table 1 and Figure 1. Gray circles indicate that these earthquakes either do not have documented surface rupture or the magnitudes are smaller than M_W 6.5. Other events are marked in red.

Table 2 P-values reported in Figure 4 and Figure 5

Cumulative fault displacement (Figure 4)	Number of Segments
All	Most Robust Data

Relative Aftershock Productivity	0.13±0.027	0.082±0.032
Rupture Velocity	4.2×10⁻⁴ ±2.6×10⁻⁴	0.0024±0.0014
Moment-scaled Radiated Energy	0.79±0.072	<i>0.041±0.013</i>

a. Earthquakes with measurable cumulative fault displacement.

b. Earthquakes with documented segmentation of the surface rupture.

Bolds indicate p-values less than 0.01, i.e., very significant. *Italics* indicate p-values between 0.01 and 0.05, i.e., marginally significant.

We summarize p-values in Table 2 and present their distributions in Figure S23. In general, rupture velocity shows the most robust behavior with the geological parameters, which suggests that it might be appropriate to use as a preliminary representation of fault maturity. The main exception is stepover width, which has no relationship with rupture velocity or anything else in this study. The correlation between the relative aftershock productivity and cumulative fault displacement is moderately significant, and there is a relationship with two of the surface rupture parameters related to segmentation: the segment number and maximum azimuth change. It is reasonable that segmentation affects aftershock production, perhaps through increasing the availability of activated faults and local stress concentrations at the ends of segments (Dascher-Cousineau et al., 2020). The moment-scaled radiated energy is relatively uncorrelated with the geological measurements from both the p-value statistical analysis and visual inspection.

4. Composite Measures of Maturity

As this discussion makes clear, fault maturity is difficult to quantify by any single measurement of a fault system. Therefore, it is also useful to consider alternative, composite approaches that combine information from more than one indicator of maturity. One such approach is to simply classify each fault system as either mature or immature based on a qualitative reading of all available data. We reach such a judgment for the fault involved in each earthquake in the supplementary text based on a reading of the available literature for each case (See first section of supplementary text). Given that maturity is intrinsically a continuous rather than binary property of fault systems, this qualitative approach must be limited in its scope, but it lends itself to a simple distinction of mature versus immature.

Figure 6 shows the resulting relationship between the qualitatively defined maturity and each seismic parameter. The result reinforces the trends noted in individual comparisons above, with higher aftershock productivity and lower rupture velocity for less mature systems.

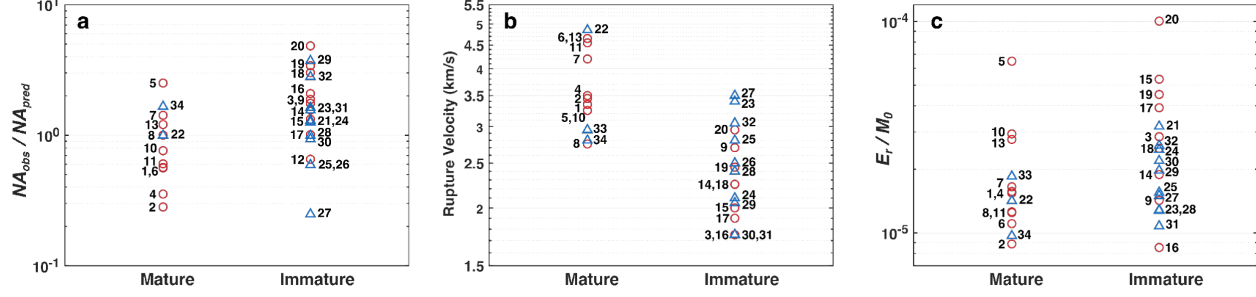


Figure 6. Qualitative bimodal fault zone maturity categorization compared with seismic parameters: (a) relative aftershock productivity, (b) rupture velocity, and (c) radiated energy normalized by moment. Red circles represent earthquakes with $M_W > 7$ while blue triangles are smaller events. Event ID is used for each individual event corresponding to Table 1 and Figure 1.

We also consider a more quantitative combination of the three field measurements that individually showed promising trends with seismic observables: cumulative fault displacement, number of segments and azimuth changes between segments. Here we define maturity based on a particular weighted linear combination of the three measures that is guided by our understanding thus far. Given that the cumulative fault displacement estimates are independent of the other two measurements and do not have a problem of lacking sufficient data, we assign the cumulative displacement values twice the weight of the other two measurements. Mature faults in our parameterization generally have larger net slip, relatively simple ruptures with few major segments and little variation in the along-strike azimuth. Immature faults have only a few kilometers of total slip and the ruptures occur on several segments with complex surface rupture traces.

This weighted combination of the fault maturity parameters gives a relative distribution from mature to immature systems that we can now compare with the seismic parameters (Figure 7). Note that p-values are provided again to help quantify the relative degree of correlation, but should not be interpreted as probabilities as the composite measure was designed to incorporate the parameters previously established to be most correlated. We see that once again mature faults again correspond to high rupture velocity and to a lesser degree high aftershock productivity while immature faults tend to have low rupture velocity and high aftershock productivity.

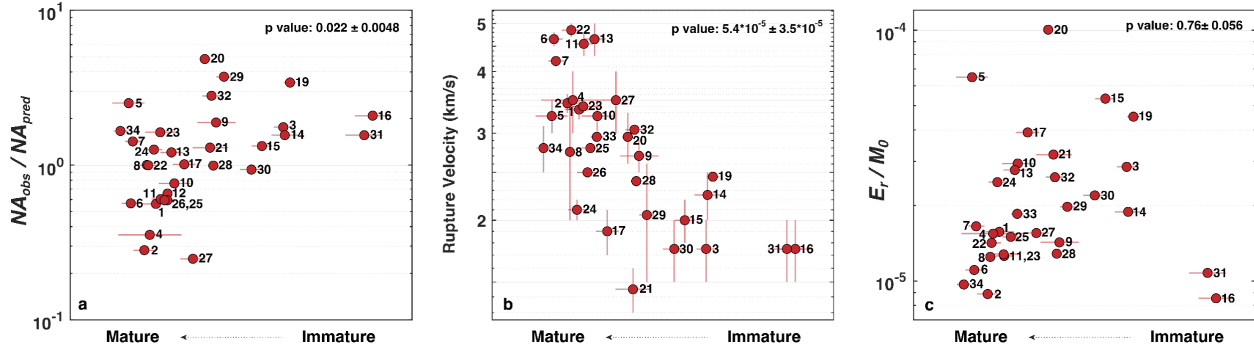


Figure 7. The linear composite measure of relative maturity from field measurements compared to (a) relative aftershock productivity, (b) rupture velocity, and (c) moment-scaled radiated energy. Event ID is used for each individual event corresponding to the legends in Figure 1.

As in the analysis of individual measures, scaled radiated energy has a high p-value and no clear correlation with maturity as quantified by the composite measure. However, there are two conspicuous outliers in the lower right-corner of Figure 7c, which are the two Ridgecrest earthquakes and without those outliers a visual trend seems evident. This is a problematic situation given that the Ridgecrest earthquakes are exceptionally well-mapped and documented and there is no reason to exclude them. They are also likely among the most extreme examples of very immature faults. This raises the intriguing possibility that the evolution of seismic radiated energy with maturity is non-monotonic.

The schematic model in Figure 8 illustrates a scenario that could lead to a non-monotonic trend in radiated energy. Fractures are relatively unaligned and distributed on very immature faults and a large earthquake in this system must dissipate more energy in breaking through to form a more continuous rupture surface. With evolution of maturity, faults become more localized and dissipation of strain energy in generating new cracks is reduced, allowing more short period energy to be radiated. For well-developed maturity faults become smooth enough that through-going ruptures have smoother moment rate-functions and comparatively little energy is radiated during the rupture process (Madariaga, 1977; Fang & Dunham, 2013). As a result, the maximum in radiated energy occurs for fault zones with intermediate maturity.

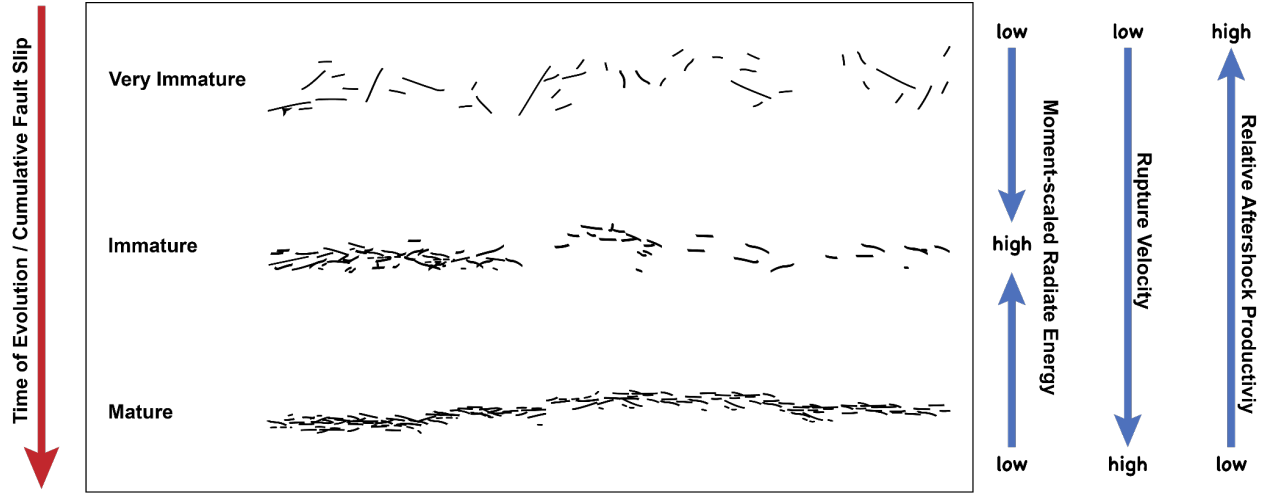


Figure 8. Schematic surface pattern of cracks in a fault system with evolving structural maturity with time or cumulative fault slip. When a large earthquake occurs in these systems, there is strong energy dissipation in the very immature case due to forming connecting cracks and overcoming stepovers; there is less consumption of fracture energy and strong radiation in the intermediate state where segments are localizing, and there is little reduced radiation from the smoother, localized mature case.

5. Summary and Conclusions

This study evaluates the degree of empirical correlation between the remotely measurable source parameters of large shallow strike-slip events and field-based estimates of maturity of the fault zone environment where these events occur. We collect geologic field measurements for 34 inland strike-slip earthquakes (M_W 6) indicative of fault system maturity from prior work to assess whether these properties are related with relative aftershock productivity, average rupture velocity, or moment-scaled radiated energy. Rupture complexity measurements are also made using a surface rupture digital dataset with an automatic segmentation procedure to provide consistency on the collected geological measurements.

We find that the cumulative fault displacement, number of rupture segments, and surface rupture azimuth changes correlate with rupture velocity. Number of segments and azimuth change also correspond to a lesser degree of aftershock productivity. Another measure of geological rupture, segment offset width, has no such correlation with any seismic parameter. No simple trend is found with moment-scaled radiated energy, but there may be distinct behavior of very immature events with no prior mapped fault and very small cumulative displacement having depressed radiated energy in addition to a separate trend of radiated energy decreasing with maturity once a through-going fault has been developed. We also explored composite measures of maturity both qualitatively

and quantitatively. A weighted linear combination of the three most important geological measurements reinforces the inference that mature faults are prone to relatively low aftershock productivity and high rupture velocity.

The empirical relationships found here provide a better understanding of variations in seismic hazard attributes of events in different fault systems. For example, less mature ruptures with lower overall rupture velocity may produce lower ground vibrations but more aftershocks than ruptures on more localized, larger-slip faults. In addition, if remote inferences of fault zone maturity are sufficiently reliable, they provide a means by which to characterize fault system complexity when there is a lack of accessible surface measurements. For oceanic, blind faulting, or isolated events in areas with poor instrument distributions, the empirical relations may improve our understanding of the evolutionary state of causal fault systems.

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Open Research

All data used in this study are provided in the text in summary form, with references to the original sources.

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Figure 1. Maps showing locations and focal mechanisms of the 34 selected shallow strike-slip earthquakes, with the focal mechanisms color-coded by hypocentral depth. Events are sorted by magnitude and labeled with numbers used as their event ID (Table 1) in the following discussion.

Figure 2. Schematic model of some geologic field measurements for a surface-rupturing fault, including cumulative fault displacement and fault segmentation related parameters such as number of primary segments and surface stepover offsets between segments.

Figure 3. The l_1 trend filtering analyses for events with digitized surface rupture data. The number of segments listed in the figure is determined from the main surface rupture following the systematic segmentation method, and distributed branches are not counted. Figures S1-S22 present the final parameterizations for the number of segments for each event.

Figure 4. Cumulative fault displacement versus three seismic attributes of the strike-slip event population. Event ID is used to identify events in Table 1 and Figure 1. Gray circles indicate ruptures of previously unmapped faults for which the cumulative offset is set to 1 km, while other events with measured fault displacement estimates are marked in red. The strength of the trend in each panel is quantified with p-values, which are calculated both from the full dataset and the dataset without faults that do not have a total displacement.

Figure 5. Estimated number of segments, azimuth changes and offset between segments versus the three seismic attributes. Event ID is used corresponding to Table 1 and Figure 1. Gray dots represent that these earthquakes do not have surface rupture or the magnitudes smaller than M_W 6.5 while other events are marked in red.

Figure 6. Qualitative bimodal fault zone maturity categorization compared with seismic parameters: (a) relative aftershock productivity, (b) rupture velocity, and (c) radiated energy normalized by moment. Red circles represent earthquakes with $M_W \geq 7$ while blue triangles are smaller events. Event ID is used for each individual event corresponding to Table 1 and Figure 1.

Figure 7. The linear composite measure of relative maturity from field measurements compared to (a) relative aftershock productivity, (b) rupture velocity, and (c) moment-scaled radiated energy. Event ID is used for each individual event corresponding to the legends in Figure 1.

Figure 8. Schematic surface pattern of cracks in a fault system with evolving structural maturity with time or cumulative fault slip. When a large earthquake occurs in these systems, there is strong energy dissipation in the very immature case due to forming connecting cracks and overcoming stepovers; there is less consumption of fracture energy and strong radiation in the intermediate state where segments are localizing, and there is little reduced radiation from the smoother, localized mature case.

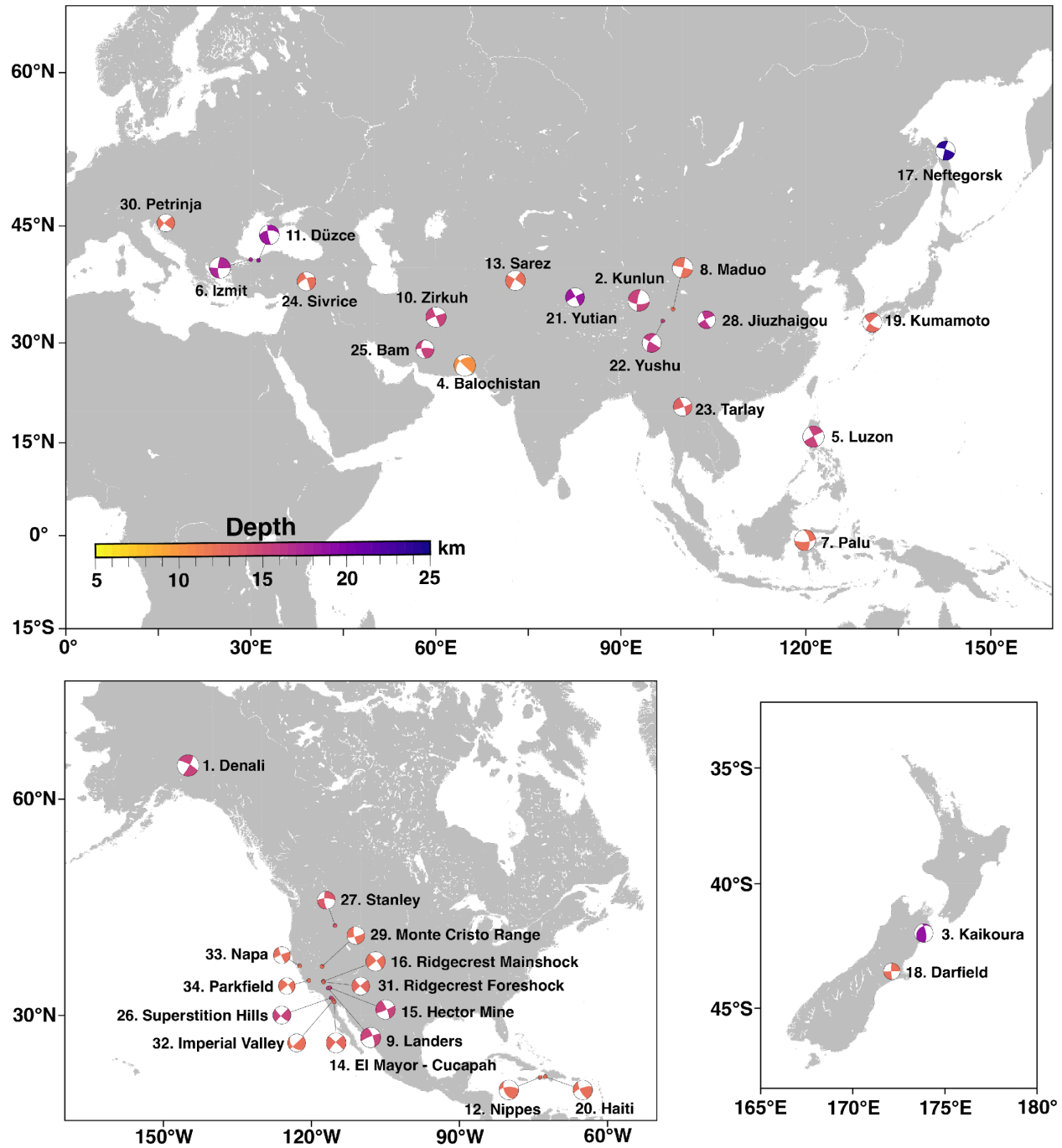


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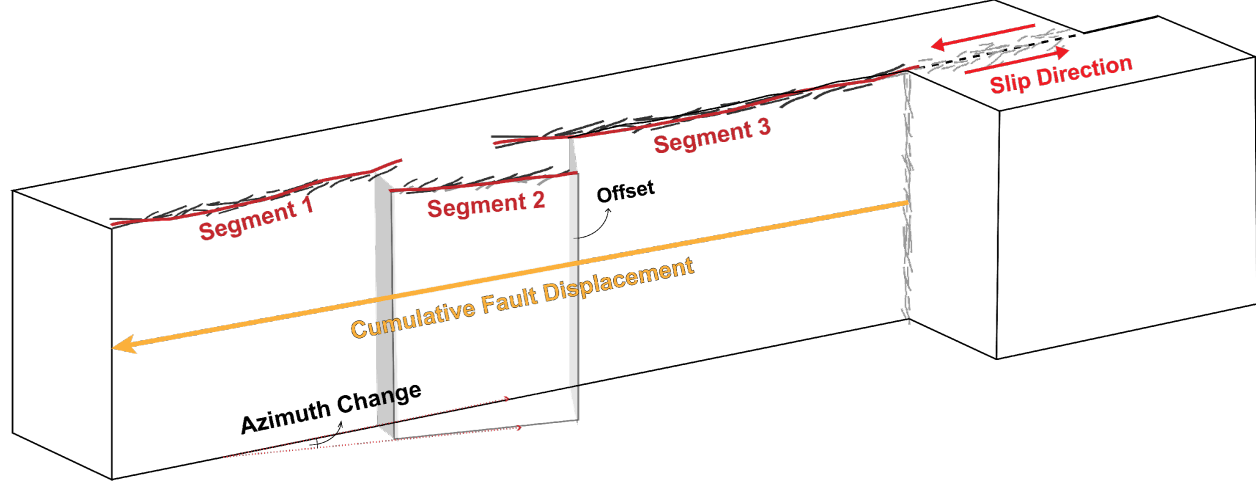


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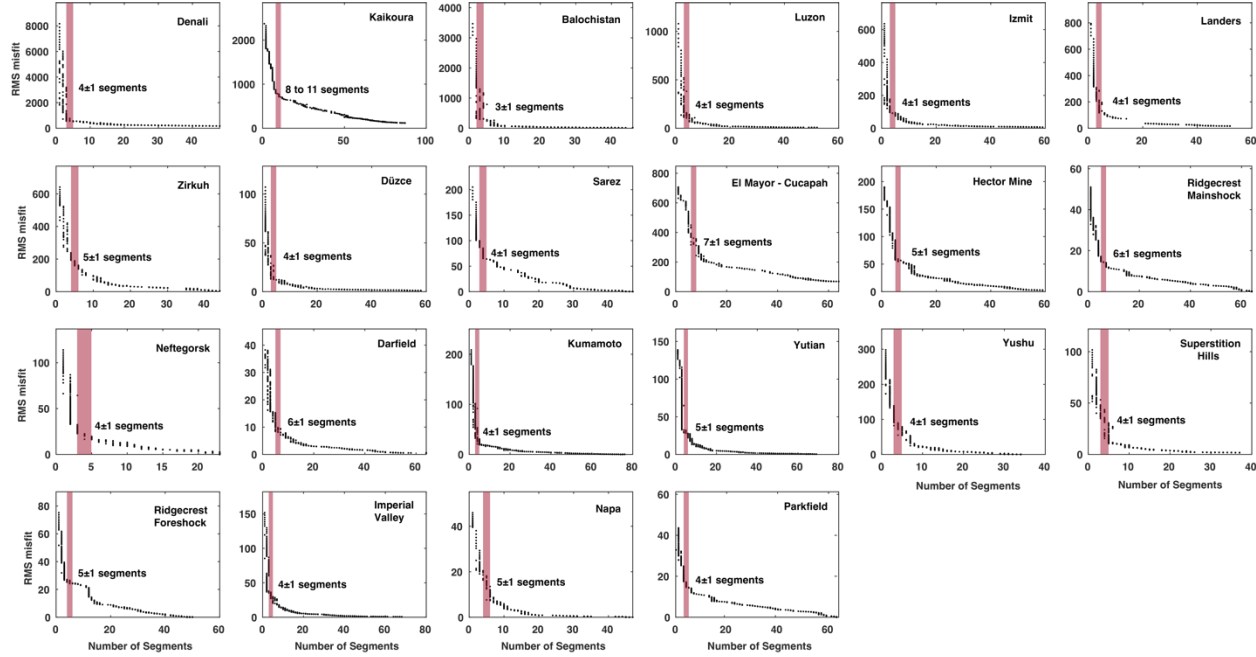


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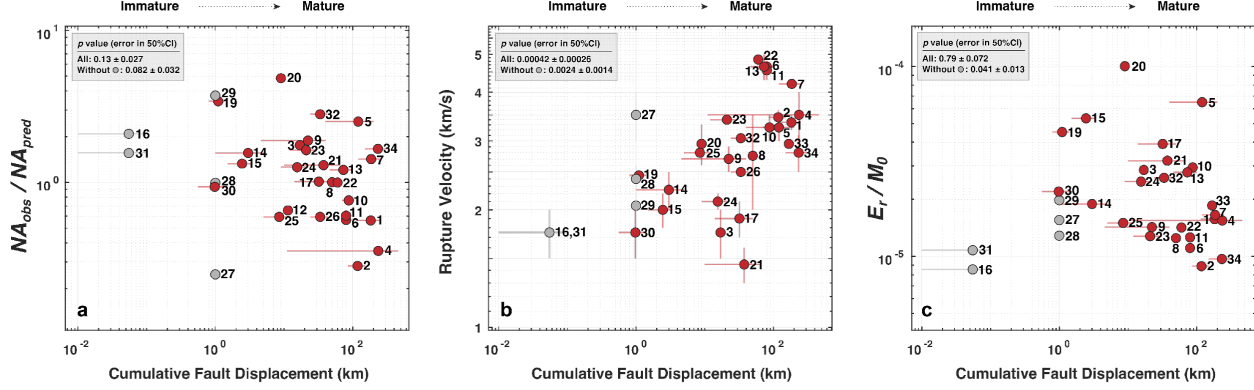


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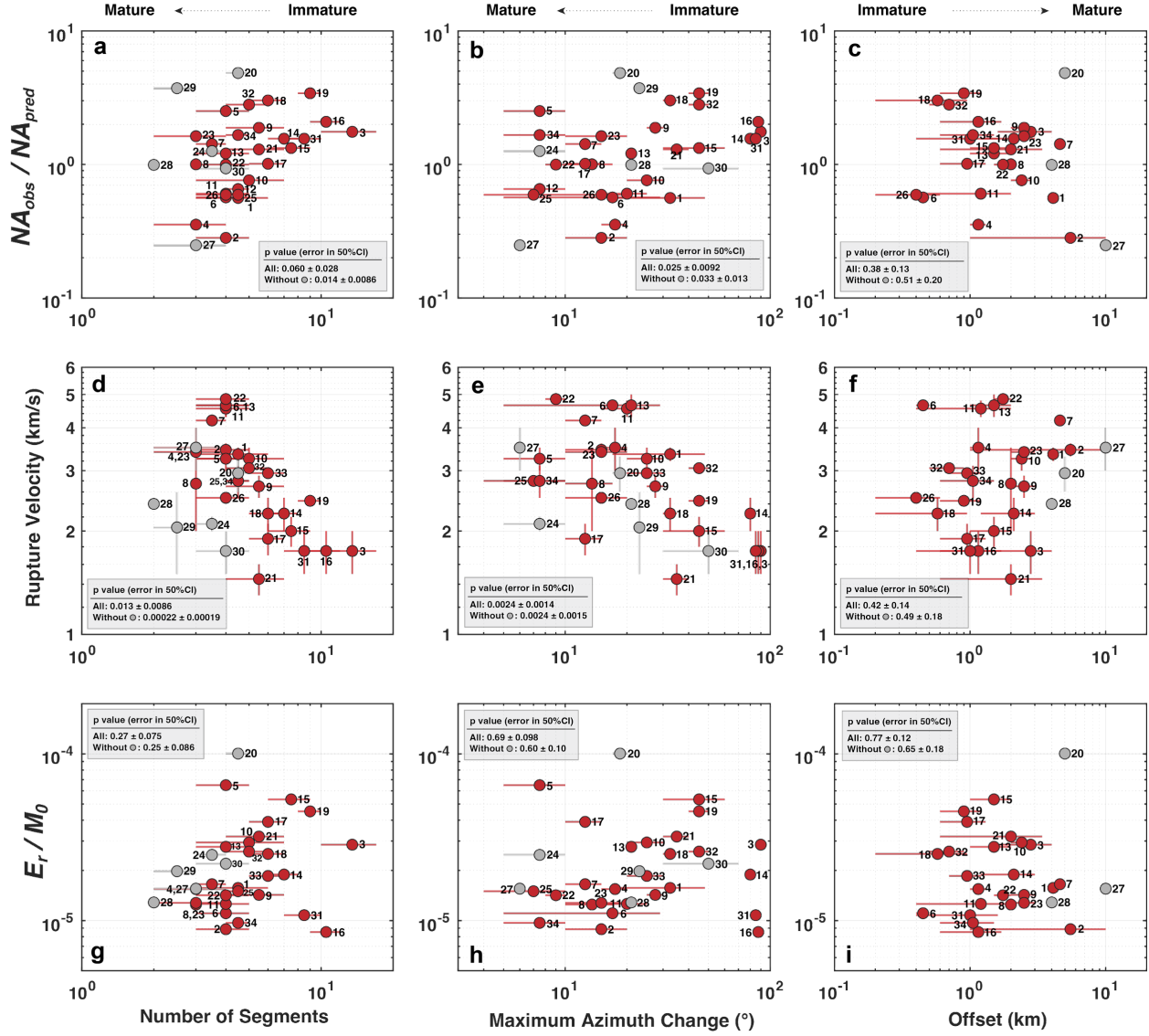


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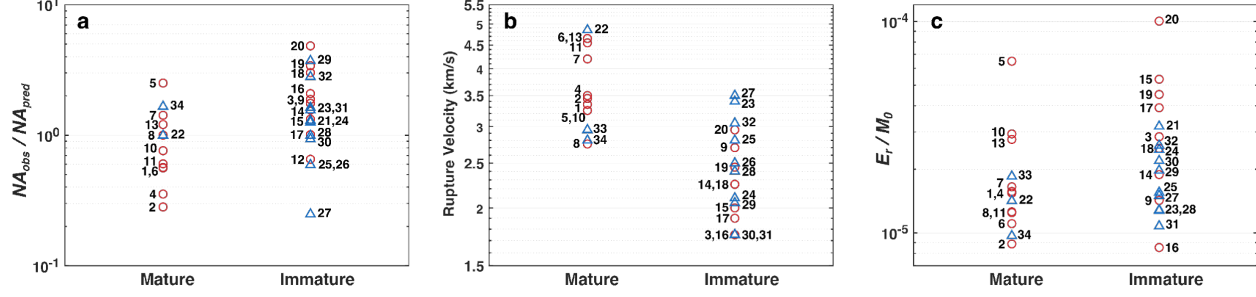


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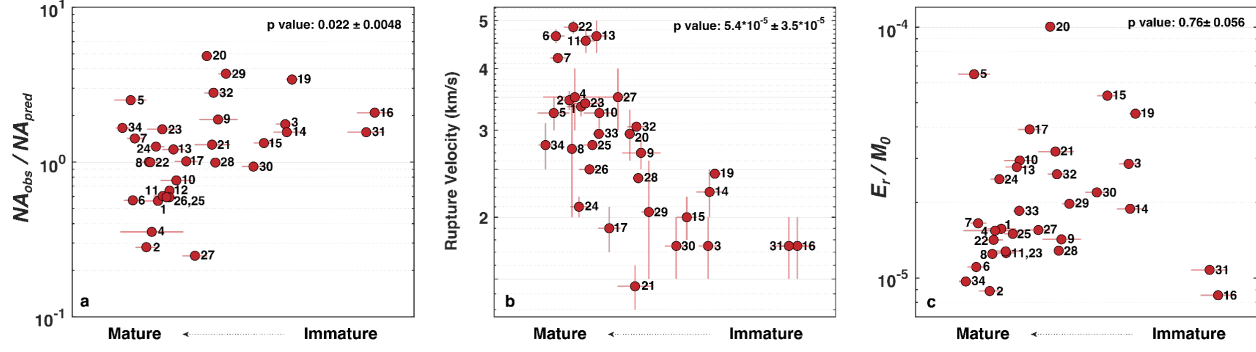


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