2013 SCEC Annual Report

The Length to Which an Earthquake Will Go to Rupture: Information Gathering

PI's: Steven G. Wesnousky and Glenn P. Biasi

Summary

Empirical observations are a critical tool for placing observational bounds on physical models of the earthquake process and on estimates of the length of rupture expected to occur on mapped faults. We have previously used published maps to define the size and number of fault discontinuities at the ends and within historical earthquakes. The work resulted in (1) an empirical upper limit for strike-slip earthquakes of about 4-5 km step-over dimension (2) and the observation that the number of strike-slip ruptures is a decreasing function of the number of step-overs spanned by the rupture. The latter observation provides a statistical basis to estimate the likelihood of an earthquake spanning step-overs in fault trace. In this research we use published accounts of earthquakes that post-dated the previous work and earthquakes not previously included to extend the dataset of strike-slip earthquakes and to gather enough observations to apply the same approach to normal and reverse type earthquakes. We find that the same upper limit of 4-5 km step-over is observed among the newly added strike-slip earthquakes, but that ruptures are observed to propagate across step-overs of 7-8 km for dip-slip earthquakes. As for strike-slip earthquakes, the relative frequency of normal and reverse earthquake ruptures is a decreasing function of the number of step-overs spanned by the rupture. A manuscript summarizing these new data and relations is being prepared.

Intellectual Merit

The primary method for studying the macroscopic mechanics of earthquakes is through the use of physics-based computer models. These models are increasingly being used to understand the physical role of fault geometry in limiting the length of earthquake ruptures. Model results, however, span a wide range, because of the number of adjustable parameters, and the parameterization itself. The *intellectual merit* of this research stems from the development of empirical observations to constrain inputs and help evaluate results from physics-based computer model intended to describe the earthquake source.

Broader Impacts

SCEC focuses on earthquake systems science for understanding earthquake physics and applying that understanding to risk reduction in California, with extensions worldwide. Empirical relations from this research will contribute to evaluation of current earthquake rupture forecasts (e.g., UCERF 3), and to the development of future earthquake rupture models. Hazard analysis requires understanding the likely sizes of earthquakes that may occur, and their propensity to jump from fault to fault. This understanding will contribute directly not just to the study of fault physics, but to reducing the uncertainties and improving the quality of seismic hazard estimates in California.

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Abstract

Empirical observations that can statistically quantify the role of fault geometry in limiting rupture propagation are a critical tool for placing observational bounds on physical models that attempt to describe the earthquake process and the assessment of the length of rupture expected to occur on mapped faults. We have previously used published maps to define the size and number of fault discontinuities at the ends and within historical earthquakes. The work resulted in (1) an observed upper limit for strike-slip earthquakes of about 4-5 km step-over dimension (2) and the observation that the fraction of strike-slip ruptures in our sample decreases with as the number of step-overs spanned by the rupture increases. The latter observation provides a statistical basis to estimate the likelihood of an earthquake spanning step-overs in a fault trace or at a fault-to-fault juncture. We here use accounts of earthquakes in the literature to extend the dataset of strike-slip earthquakes and gather enough observations to apply the same approach to normal and reverse type earthquakes. Newly added strike-slip earthquake ruptures follow the previously observed upper limit of 4-5 km maximum step-over distance. However, dip-slip ruptures are observed to propagate across larger step-overs, up to 7-8 km. Like the strike-slip earthquakes, the number of normal and reverse earthquakes spanning steps is a decreasing function of the number of step-overs spanned by the rupture.

Introduction

Estimating the size of an earthquake that will rupture in a system of mapped active faults is a fundamental step in probabilistic seismic hazard analysis (e.g. Field et al., 2009). Estimates of the size earthquakes on mapped faults generally consider the length of the fault and its discontinuities, and are estimated from empirical regression of historical earthquake rupture length versus earthquake magnitude (or seismic moment) (e.g. Wells and Coppersmith, 1994). Though simple in concept, significant uncertainty arises in estimating the length to which a rupture will propagate because historical earthquake ruptures have been observed to jump across discontinuities along fault strike and break more than one fault or fault segment in a single event (e.g. Sieh et al., 1993). We have in past years worked to collect, organize, and analyze the mapped fault geometries and surface slip distributions of a number of large historical continental surface rupture earthquakes (**Table 1**). The work has yielded observations and boundary conditions pertinent to SCEC's efforts to understand the physics of the earthquake rupture process and insights fundamental for predicting the future endpoints and thus lengths of earthquakes on mapped fault systems (Hillers and Wesnousky, 2008; King and Wesnousky, 2007; Shaw and Wesnousky, 2008; Wesnousky, 2006, 2008; Wesnousky and Biasi, 2011). More specifically, the work provided initial limits on the size of steps in fault trace through which an earthquake can rupture and statistics to estimate the likelihood of an earthquake rupturing through a step discontinuity in fault trace. That work was limited to a data set of about three dozen large strike-slip and a half-dozen each of normal and reverse continental earthquakes. For these earthquakes, there existed (1) maps of the surface rupture trace, (2) maps of the nearby active faults that did not rupture, and (3) measurements of coseismic offset at many points along the strike of the rupture to define the surface slip distribution. It was recognized that there are than twice this many earthquakes listed in the early paper of Wells and Coppersmith (1994) reported to have produced surface rupture but not necessarily satisfying all three of these characteristics. This year we were provided the opportunity to gather and assess whether or not these older earthquake data could provide a meaningful addition to the initial analysis. The study has resulted in a doubling of observations for normal and reverse faults, sufficient to allow developments of statistics bearing on the likelihood of faults rupturing through steps. Likewise, the data set of strike-slip earthquakes has increased ~30%.

Approach

The maps of the 1943 M7.6 Tosya (Figure 1a) and 1970 Gediz earthquakes of Turkey (Figure 1b) illustrate the manner in which are gathering and documenting observations. The mapped rupture is shown by a bold trace. Nearby fault traces that displace Quaternary and younger deposits but did not rupture during the earthquake are shown as thinner lines. Locations and dimensions of fault steps (≥~1 km) along and at the ends of the earthquake ruptures and the distances to nearest neighboring active fault traces from the endpoints of surface rupture traces are annotated. For many ruptures there is no information reported on the presence or possibility of nearby active fault traces and thus focus has been on identifying discontinuities within the ruptures. For strike-slip faults, steps in the fault trace are labeled as restraining or releasing depending on whether fault slip would produce contractional or dilational strains within the steps, respectively. The epicenters of the earthquakes, where known, are plotted as a star. With the increase in number of available earthquakes to study, we have also begun to compile statistics on the size and presence of other types of complexities. The Gediz rupture (Figure 1b) illustrates complexities such as gaps in the fault trace, parallel fault ruptures, and potential ambiguity in the definition of rupture length.

Results

The results of our research for strike-slip, reverse, and normal faulting earthquakes are summarized in Figures 2 a, b, and c, respectively. The figures on the left show synoptically the relationship between geometrical discontinuities along fault strike and the end points of the earthquake ruptures. In each, the events in red are those that we have added in this project. On the lower axis are arranged the historical earthquake ruptures arranged according to rupture length. Above the label of each earthquake on the horizontal axis is a vertical line along which symbols are placed to represent the dimension (vertical axis) of the discontinuities through which the respective earthquake ruptured through (open symbols) or at which it stopped (closed symbols). The new data support the idea that there is a limiting dimension of fault step (4-5 km) above which strike-slip earthquake ruptures have not propagated. The size of discontinuities through which earthquakes rupture appears not to increase for larger earthquakes (Figure 2a). The observations imply a physical limit on the dimension of process zone or volume significantly affected by stress changes at the rupture front. Though a number of new normal and reverse ruptures maps were gathered, published sources did not yield new information on the size of step discontinuities at the endpoints of such ruptures (left side of Figures 1 b, c). Dip-slip ruptures appear to be more capable of crossing steps, with the largest in our sample being 7-8 km. Fault separation at depth is, in general, unknown.

On the right side of Figure 2 are histograms for strike-slip, reverse, and normal earthquake ruptures. Here we have limited attention to only those steps that occur within the rupture traces. The number of earthquake used to produce each histogram is labeled in the figures. Each histogram shows the number of earthquake ruptures as a function of the number of step-overs spanned by the rupture. The histograms show that the number of occurrences of earthquake ruptures is a decreasing function of the number of steps through which the respective earthquakes have propagated. Fitting these data with a simple probability model quantify these observations and yield relative likelihoods of similar ruptures in the future. These data are fit to Geometric distributions (e.g. Larson, 1982). The Geometric distribution model assumes that each step-over has a random probability of stopping the rupture and that rupture extension reflects the compounding improbability of passage. The Geometric model is in concert with the idea that step-overs have a causal role in impeding rupture propagation as is also suggested in computer models (e.g. Harris and Day, 1999; Oglesby, 2008).

Summary

We have significantly increased the number of observations bearing on the role of fault geometry on fault rupture through a careful review of older fault rupture data. As well, we have added earthquake rupture observations arising from earthquakes more recent than our earlier published work. The observations and approach embodied in **Figures 1 and 2** are important for ultimately reducing uncertainty attendant to estimating the endpoints of ruptures and rupture lengths on mapped multi-segment faults and fault systems and, in this way, directly pertinent to the goals of SCEC and UCERF3.

Figure Captions

Figure 1. Illustration of data synthesis. a) 1943 Tosya, Turkey Earthquake. b) 1970 Gediz Earthquake, Turkey. See text for details.

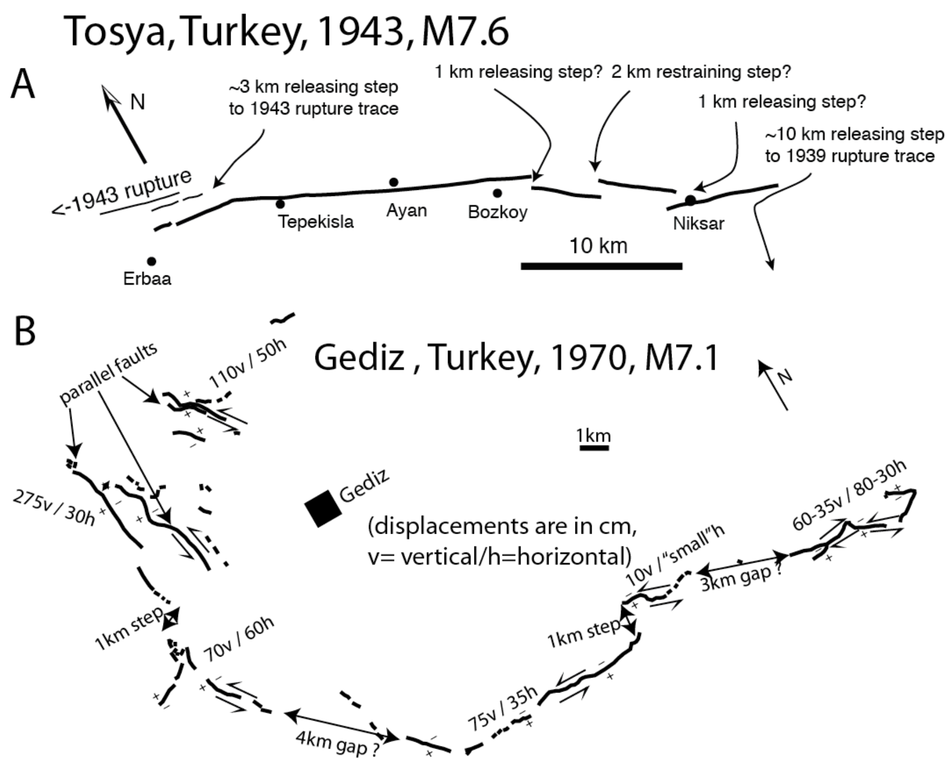
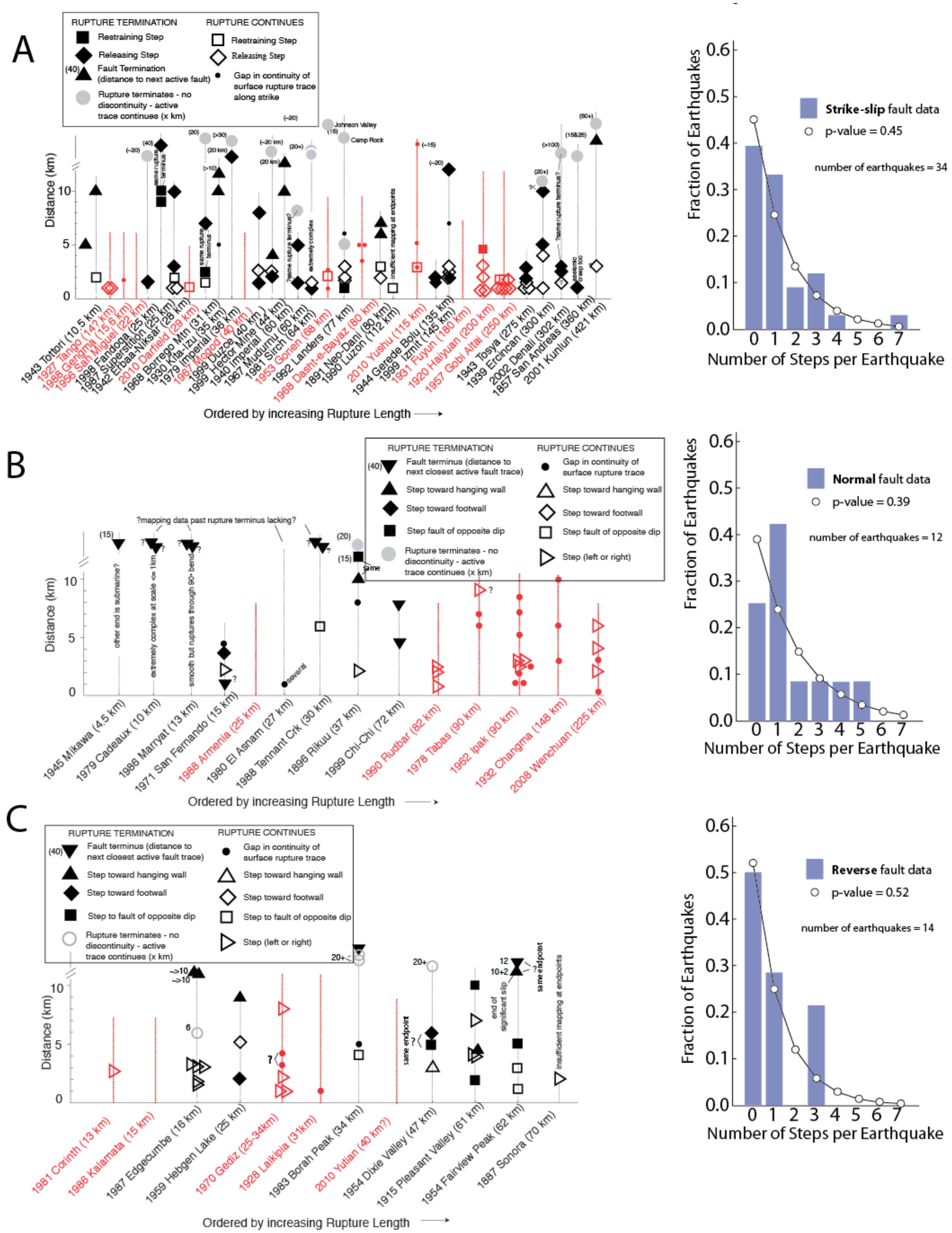


Figure 2. (next page) Results from a) strike-slip, b) normal and c) reverse type earthquakes. Text in red indicates new observations uncovered in this study. Left side of each figure: Earthquakes are labeled and arranged on the lower axis according to rupture length. Above the label of each earthquake there is a vertical line along which symbols are placed to represent the dimension (vertical axis) of the discontinuities through which the respective earthquake ruptured through (open symbols) or at which it stopped (closed symbols). Right side of figure: Histograms showing the number of earthquake ruptures as a function of the number of step-overs spanned by the rupture. Each is fit to a geometric probability density function.


A
RUPTURE TERMINATION
Restraining Step
Releasing Step
Fault Termination (distance to next active fault)
Rupture terminates - no discontinuity - active trace continues (x km)
RUPTURE CONTINUES
Restraining Step
Releasing Step
Gap in continuity of surface rupture trace along strike
Distance (km)
1943 Tottori (10.5 km)
1927 Tango (14? km)
1988 Gengma (15.6 km)
1956 San Miguel (22 km)
1999 Fandoga (25 km)
1987 Superstition (25 km)
1942 Erbaa-Niksar (28 km)
2010 Darfield (29 km)
1968 Borrego Mtn (31 km)
1930 Kita-Izu (35 km)
1979 Imperial (36 km)
1967 Mogod (40 km)
1999 Duzce (40 km)
1940 Imperial (60 km)
1999 Hector Mine (44 km)
1967 Mudurnu (60 km)
1981 Sirch (64 km)
1953 Gonen (68 km)
1992 Landers (77 km)
1968 Dasht-e-Bayaz (80 km)
1891 Neo-Dani (80 km)
1990 Luzon (112 km)
2010 Yushu (115 km)
1944 Gerede Bolu (135 km)
1999 Izmit (145 km)
1931 Fuyun (180 km)
1920 Haiyuan (200 km)
1957 Gobi Altai (250 km)
1943 Tosya (275 km)
1939 Ercincan (300 km)
2002 Denali (302 km)
1857 San Andreas (360 km)
2001 Kunlun (421 km)
Johnson Valley
Camp Rock
Ordered by increasing Rupture Length
Fraction of Earthquakes
Strike-slip fault data
p-value = 0.45
number of earthquakes = 34
Number of Steps per Earthquake
B
RUPTURE TERMINATION
Fault terminus (distance to next closest active fault trace)
Step toward hanging wall
Step toward footwall
Step fault of opposite dip
Rupture terminates - no discontinuity - active trace continues (x km)
RUPTURE CONTINUES
Gap in continuity of surface rupture trace
Step toward hanging wall
Step toward footwall
Step fault of opposite dip
Step (left or right)
?mapping data past rupture terminus lacking?
other end is submarine?
extremely complex at scale <= 1km
smooth but ruptures through 90° bend
Distance (km)
1945 Mikawa (4.5 km)
1979 Cadeaux (10 km)
1986 Maryat (13 km)
1971 San Fernando (15 km)
1988 Armenia (25 km)
1980 El Asnam (27 km)
1988 Tennant Crk (30 km)
1896 Rikuu (37 km)
1999 Chi-Chi (72 km)
1990 Rudbar (82 km)
1978 Tabas (90 km)
1962 Ipak (90 km)
1932 Changma (148 km)
2008 Wenchuan (225 km)
Ordered by increasing Rupture Length
Fraction of Earthquakes
Normal fault data
p-value = 0.39
number of earthquakes = 12
Number of Steps per Earthquake
C
RUPTURE TERMINATION
Fault terminus (distance to next closest active fault trace)
Step toward hanging wall
Step toward footwall
Step to fault of opposite dip
Rupture terminates - no discontinuity - active trace continues (x km)
RUPTURE CONTINUES
Gap in continuity of surface rupture trace
Step toward hanging wall
Step toward footwall
Step to fault of opposite dip
Step (left or right)
Distance (km)
same endpoint
end of significant slip
insufficient mapping at endpoints
1981 Corinth (13 km)
1986 Kalamata (15 km)
1987 Edgecumbe (16 km)
1959 Hebgen Lake (25 km)
1970 Gediz (25-34km)
1928 Laikipia (31km)
1983 Borah Peak (34 km)
2010 Yutian (40 km?)
1954 Dixie Valley (47 km)
1915 Pleasant Valley (61 km)
1954 Fairview Peak (62 km)
1887 Sonora (70 km)
Ordered by increasing Rupture Length
Fraction of Earthquakes
Reverse fault data
p-value = 0.52
number of earthquakes = 14
Number of Steps per Earthquake

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