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Invited Review

Fault slip and earthquake recurrence along strike-slip faults — Contributions of high-resolution geomorphic data

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ABSTRACT

Understanding earthquake (EQ) recurrence relies on information about the timing and size of past EQ ruptures along a given fault. Knowledge of a fault's rupture history provides valuable information on its potential future behavior, enabling seismic hazard estimates and loss mitigation. Stratigraphic and geomorphic evidence of faulting is used to constrain the recurrence of surface rupturing EQs. Analysis of the latter data sets culminated during the mid-1980s in the formulation of now classical EQ recurrence models, now routinely used to assess seismic hazard. Within the last decade, Light Detection and Ranging (lidar) surveying technology and other high-resolution data sets became increasingly available to tectono-geomorphic studies, promising to contribute to better-informed models of EQ recurrence and slip-accumulation patterns.

After reviewing motivation and background, we outline requirements to successfully reconstruct a fault's offset accumulation pattern from geomorphic evidence. We address sources of uncertainty affecting offset measurement and advocate approaches to minimize them. A number of recent studies focus on single-EQ slip distributions and along-fault slip accumulation patterns. We put them in context with paleoseismic studies along the respective faults by comparing coefficients of variation *CV* for EQ inter-event time and slip-per-event and find that a) single-event offsets vary over a wide range of length-scales and the sources for offset variability differ with length-scale, b) at fault-segment length-scales, single-event offsets are essentially constant, c) along-fault offset accumulation as resolved in the geomorphic record is dominated by essentially same-size, large offset increments, and d) there is generally no one-to-one correlation between the offset accumulation pattern constrained in the geomorphic record and EQ occurrence as identified in the stratigraphic record, revealing the higher resolution and preservation potential of the latter. While slip accumulation along a fault segment may be dominated by repetition of large, nearly constant offset increments, timing of surface-rupture is less regular.

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1. Motivation and Background

One of the fundamental goals of earthquake geology and seismology is to identify earthquake (EQ) recurrence characteristics that enable probabilistic estimates of timing and size of future earthquakes along a given fault (e.g., Burbank and Anderson, 2012; McCalpin, 2009; Stein and Wysession, 2002). While already of distinct scientific interest, the main motivation behind this line of work is to improve assessments of seismic hazard, providing the means to mitigate the eventual destruction that is associated with large earthquakes (e.g., Allen, 2007; Allen et al., 2009; Field et al., 2013). Shedlock and Tanner (1999) reported that 60% of the fatalities from natural hazards are related to catastrophic earthquakes (Allen, 2007). This percentage does not include the devastating earthquakes that occurred within the last 15 years for example in Turkey (1999), India (2002), Iran (2003), Indonesia (2004), Pakistan (2005), China (2008), Haiti (2010), and Japan (2011). Furthermore, many fast-growing megacities are located in seismically hazardous regions. While there has not yet been a large earthquake directly beneath one of these megacities, occurrence of such an event may cause fatalities to exceed 1 million (Bilham, 2004). It is therefore of substantial interest to the public and policy makers to anticipate the type, location, and timing of an earthquake. One approach is to analyze a fault's earthquake rupture history, assuming that this history is a reflection of likely future behavior (Hutton, 1785). Following this assumption, statistical analysis of past EQ record may reveal patterns in EQ recurrence that could be used to make more accurate estimates of the potential timing and size of future EQs. The goal is therefore to reconstruct a fault's EQ rupture history to extract information from that history that enables improved estimates of future behavior of that fault and potentially of faults in general through an improved physical understanding of the rupture process.

While extrapolation of the Gutenberg–Richter relation (Gutenberg and Richter, 1954) may be appropriate to constrain large EQ occurrence probability on a global scale, it is not readily permissible for individual faults or fault sections (e.g., Schwartz and Coppersmith, 1984). Corresponding local-scale magnitude–frequency statistics often consist of a truncated inverse power-law distribution (i.e., the Gutenberg–Richter relation) for small to moderate size earthquakes, and a Gaussian-like distribution of large earthquakes (Fig. 1A; e.g., Ben-Zion, 2008; Wesnousky, 1994). Based on numerical simulations of multi-cycle earthquake rupture, Zielke and Arrowsmith (2008) provide a physical explanation for this bimodal magnitude–frequency distribution. They attribute it to a systematic depth-dependence of constitutive parameters that govern frictional behavior (e.g., Beeler et al., 1994; Blanpied et al., 1991; Dieterich, 1981; Stesky et al., 1974; Tullis, 2007; Tullis and Weeks, 1986) and by that affect down-dip earthquake rupture extent. In this conceptual framework, earthquakes may be grouped into full rupture and partial rupture EQs (FR and PR earthquakes respectively, e.g., Scholz, 1988; Pacheco et al., 1992) where the prior refers to EQs that rupture a fault's full down-dip extent of the seismogenic fault width whereas the latter only ruptures a portion of it (Fig. 1B). In other cases, faults are practically void of small to moderate size seismicity even though occurrence of large EQ ruptures has been historically documented. Small-moderate size event recurrence statistics may therefore not be representative for their larger relatives, thus limiting the value of those instrumental records to constrain large EQ recurrence characteristics.

Alternatively, historical accounts of seismically induced shaking and surface rupture may be used to reconstruct rupture histories (Nur, 2007 and references therein). An ideal historical earthquake record would a) include descriptions that enable constraining EQ size for example through the spatial distribution of shaking intensity levels (e.g., Guidoboni et al., 1994, Toppozada et al., 2002), b) associate the earthquake rupture with specific fault segments, c) give a sufficiently precise EQ age, and d) provide this information consistently through time and over multiple earthquake cycles. In many cases only a few of those requirements are met, distinctly impeding the ability to reconstruct fault rupture patterns from historical accounts (e.g., Nur, 2007).

In the absence of sufficient instrumental or historical records, other data sets are needed in order to determine earthquake recurrence characteristics. Paleoseismology and tectonic geomorphology provide those data sets. Sufficiently large earthquakes may rupture the ground surface

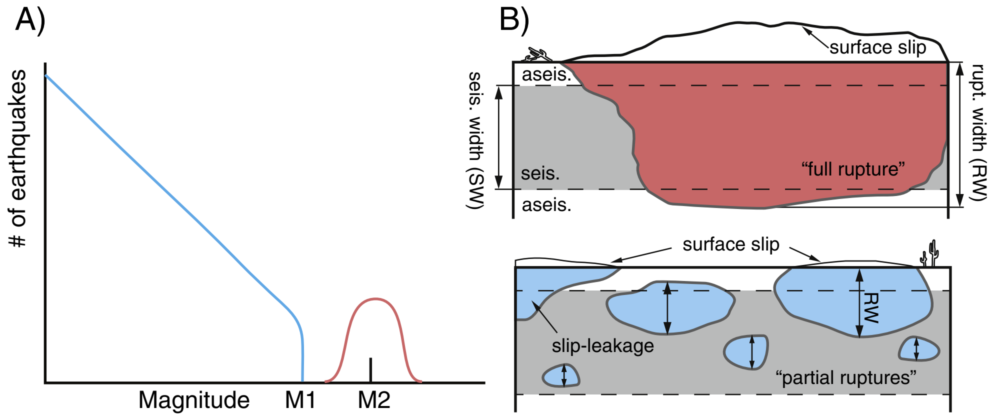

Fig. 1. A) Schematic representation of single-fault magnitude frequency relation (MFR) (e.g., Ben-Zion, 2008; Wesnousky, 1994). While the small to moderate size EQs (magnitude $M < M_1$) form a truncated Gutenberg-Richter (GR) distribution, larger EQs form a Gaussian-like distribution around M_2. EQs with $M < M_1$ may reflect the partial activation of a fault's seismogenic width (SW), whereas the latter (with $M \sim M_2$) reflect the full activation of a fault's seismogenic width (e.g., Pacheco et al., 1992; Scholz, 1988; Zielke and Arrowsmith, 2008). They termed the corresponding EQs to be partial rupture (PR) and full rupture (FR) earthquakes, respectively. B) Schematic representation of the down-dip rupture width (RW) of partial and full rupture EQs along a fault in relation to the extent of SW (e.g., Pacheco et al., 1992; Scholz, 1988; Zielke and Arrowsmith, 2008). While the rupture width of PR earthquakes is always smaller than SW, rupture width of FR earthquakes equals or exceeds SW (King and Wesnousky, 2007). Also shown is an example of slip leakage (Sieh, 1996) where a fault experiences partial rupture due to an EQ along a neighboring fault (segment). Rupture planes are color-coded in correspondence to the portions of the MFR to which they contribute.