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Variable fault geometry suggests detailed fault slip-rate profiles and geometries are needed for fault-based probabilistic seismic hazard assessment (PSHA)

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Abstract

It has been suggested that a better knowledge of fault locations and slip-rates improves seismic hazard assessments. However, the importance of detailed along-fault slip-rate profiles and variable fault geometry has not yet been explored. We quantify the importance for modeled seismicity rates of using multiple throw-rate measurements to construct along-fault throw-rate profiles rather than basing throw-rate profiles on a single measurement across a fault. We use data from 14 normal faults within the central Italian Apennines where we have multiple measurements along the faults. For each fault, we compared strain-rates across the faults using our detailed throw-rate profiles and using degraded data and simplified profiles. We show the implied variation in average recurrence intervals for a variety of magnitudes that result. Furthermore, we demonstrate how fault geometry (variable strike and dip) can alter calculated ground shaking intensities at specific sites by changing the source-to-site distance for ground motion prediction equations (GMPEs). Our findings show that improved fault-based seismic hazard calculations require detailed along-fault throw-rate profiles based on well-constrained local 3D fault geometry for calculating recurrence rates and shaking intensities.

Key Words

Earthquake, fault, seismic hazard, recurrence intervals, geometry, PSHA, GMPEs, Apennines

Introduction

Active fault locations and slip-rates are the principal controls on earthquake locations and time-averaged recurrence rates, but fault data are currently under used within hazard assessments used to calculate earthquake risk. The need for long-term fault-derived slip-rates for probabilistic seismic hazard assessment (PSHA) has been noted (*e.g. Faure Walker et al., 2010; Stein et al., 2012; Papanikolaou et al. 2015; Blumetti et al., 2017*). In particular, multi-millennia fault slip-rates provide an opportunity to capture a long-term record of cumulative earthquake displacements covering multiple seismic cycles and avoiding the bias introduced by temporal earthquake clustering. From this average recurrence intervals can be inferred for individual faults. Some researchers are incorporating long-term fault slip-rates into hazard models for different regions of the world (e.g. California, USA: *Field et al., 2014*; Italy: *Valentini et al., 2017*; Greece: *Deligiannakis et al., 2018*) and tools have been developed to help researchers with such endeavors (e.g. FiSH, *Pace et al., 2016*). However, fault slip-rates remain one of the key uncertainties in calculating earthquake probabilities (*Field et al., 2014*) and the lack of detailed and accurate fault slip-rate data necessitates making assumptions regarding how to propagate data collected at a single site along the length of the fault.

The problem of propagation of data along strike is clearly important, because what is known from multi throw-rate and slip-rate measurements along single faults is that they are highly variable; however, current fault-based approaches for calculating earthquake hazard do not incorporate these detailed variations. Instead they use along-strike throw-rate or slip-rate profiles with artificially assigned simplified shapes extrapolated from one to a few measurements along simplified planar faults. This is in some ways inevitable because more detailed data are rarely available (e.g. *Field et al.*, *2014*). However, detailed data are available for active normal faults (e.g. *Cartwright and Mansfield, 1998; Contreras et al., 2000; Faure Walker et al., 2009; 2010; 2015; McClymont et al., 2009; Wilkinson et al., 2015; Mildon et al., 2016a; Reilly et al., 2016*) and this prompts the present study where we explore the effect of along-strike throw-rate variability for seismic hazard. Fortunately, locations where throw-rates vary dramatically along the strike of individual faults may be easy to identify, because along-strike profiles of throw-rates on active faults are altered where faults show non-planar fault geometry (*Faure Walker et al., 2009; 2015*). Additionally, the reasons for the throw-rate variations are well-understood due to development of quantitative relationships between throw-rate and fault geometry (*Faure Walker et al., 2009; 2015; Wilkinson et al., 2015; Mildon et al., 2016a; Iezzi et al., submitted*). Specifically, throw-rates are increased across bends in faults so that the strain-rates across the fault remain concomitant with their position along the fault (Figure 1). The geometry-dependent throw-rate model suggests active normal faults have local throw-rates governed by a combination of regional-scale external forces, displacement gradients along faults, and local 3D fault geometry which are inter-related (*Faure Walker et al., 2009).* The model may further explain much of the scatter and variations in shape of along fault displacement profiles (e.g. *Manighetti et al., 2005*) and the scatter seen in maximum slip against rupture length graphs of *Wells and Coppersmith (1994)* (*Iezzi et al., submitted*). In this paper we demonstrate the effect of spatial variations in throw-rate along individual faults for implied average recurrence intervals.

Another factor that has not been demonstrated is the compounded impact of including detailed fault geometry and throw-rate measurements for calculating modeled shaking intensities. These will change because along-strike bends in the map traces of faults change the distance to sites where shaking intensity is of interest; where brought closer to the fault, the intensity will increase and the recurrence time will decrease due to higher slip-rate, compounding the threat. We emphasize that shaking intensities at given locations are a critical input for earthquake risk assessment - the first step towards the development of risk reduction strategies - and performance-based earthquake design. For instance, the design peak ground acceleration (PGA) value for the 'ultimate limit state' or ‘life-safety’ performance objective is typically based on the annual rate of exceedance of 1/475 (corresponding to a mean return period of 475 years) (e.g., the current Italian Building Code, or IBC08, see *Iervolino et al., 2011*) and this will be affected by distance to the fault traces that rupture. This is because GMPEs, also known as ground-motion models and attenuation relations, are typically used to model the intensity of shaking at individual sites and across an area, within the framework of PSHA. GMPEs are empirical models estimating the probability distribution of ground-motion intensity measures (IMs) - such as PGA and SA (spectral acceleration) - occurring at a given site as a function of magnitude, source-to-site distance between the seismic source (the fault) and the site of interest, soil properties at the site, focal mechanism, and other parameters (e.g. *Bindi et al., 2011*). The source-to-site distance can be measured using a variety of metrics, such as R_{jb} ("Joyner-Boore" distance), R_{rup} (slant distance), R_{cent} (centroid distance), R_{hyp} (hypocentral distance), and R_{epi} (epicentral distance), see for instance *Bommer and Akkar (2012)*. To be computed in practice and be used in hazard assessments, these metrics require knowledge of the fault location and dip. For example, R_{jb}, is the closest horizontal distance from the site to the vertical projection of the rupture surface, which is dependent on the surface trace of the fault and the dip of the fault. Even if most modern GMPEs use definitions of the source-to-site distance that reflect the dimensions of the fault rupture for larger earthquakes rather than using point-source measures relative to the epicenter or hypocenter, the role of variable fault strike and a change of dip along strike are generally not considered in GMPEs used for hazard calculations or in the other steps of PSHA. In this paper we show that detailed knowledge of strike-variable fault geometries changes calculated shaking intensities, a critical input for PSHA.

The background to our emphasis on using detailed fault slip-rate and fault geometry data is that most seismic hazard models currently used by government civil protection agencies to inform building codes and emergency planning, and by the (re)insurance industry, are driven by historical earthquake data and by the definition of seismic source zones, or areal sources, i.e., all the points within the considered area can be the epicenter of earthquakes with the same probability (e.g. *Stucchi et al.*, *2011*). This is in spite of it being known that historical and seismological records are of insufficient length relative to average fault recurrence intervals to be representative of longer time periods and capture the geography of seismic hazard (e.g. *Camelbeeck et al., 2007; Stein et al., 2012; Liu and Stein, 2016; Blumetti et al., 2017*). In particular, in continental settings, faults exist that are capable of producing large magnitude earthquakes that have not ruptured in historical times (e.g., *Liu et al., 2011; Mildon et al., 2017; Hintersberger et al. 2018*). For instance, in the central Apennines, Italy, the historical records are restricted to hundreds of years, but individual faults have recurrence intervals of hundreds to thousands of years (e.g. *Pace et al., 2006; Galli et al., 2008*). In August and October 2016, three earthquakes Mw 5.9 - 6.5 ruptured the Mt. Vettore fault (e.g. *Livio et al., 2016; Cheloni et al., 2017; Pucci et al., 2017; Civico et al., 2018; Villani et al., 2018*), a known active mapped fault that had not ruptured within the historical record but had clear evidence of meter-scale Holocene slip events (*Galadini and Galli, 2003; Mildon et al., 2017*; *Wedmore et al., 2017*). PSHA based on the historical record prior to these events would not explicitly include the hazard from this fault, or others that have not ruptured during historical times. Other examples worldwide such as the 2011 Great East Japan Earthquake and the 2010 Haiti Earthquake have had their probability underestimated because the fault displacement-rates were not properly considered (*Stein et al., 2012*). At a scale larger than individual faults, the pitfalls of using only shorter-term historical and seismicity data or deformation rates derived from geodesy to infer hazard have been highlighted in continental settings such as the central Italian Apennines *(Faure Walker et al., 2010)* and North China (*Liu et al., 2011*). For example, in the central Italian Apennines, calculated long-term (15±3kyr) fault-derived strain-rates in polygons with areas in the order of 1,000km^2 do not match short-term strain-rates inferred from historical moment tensors (700yrs) and geodesy (126yrs) (*Faure Walker et al., 2010*). The short-term (700yr) strain-rates are lower than long-term (15±3kyr) strain-rates in some areas but higher in others (*Faure Walker et al., 2010*). This leads to dramatic underestimations and overestimations of hazard for those areas respectively if calculated solely from historical records (*Faure Walker et al., 2010*). Without the longer-term view, hazard assessments will continue to be biased by the most recent events and hence risk from faults that have not ruptured in recent or historical times will not be communicated (e.g. *Liu and Stein, 2016*).

In this paper, we first calculate strain-rates and average recurrence intervals for a fault where data on detailed along-strike variations in throw-rate are available, and then demonstrate how degrading detailed along-strike throw-rate profiles to simplified idealized along-strike throw-rate profiles affects the calculated strain-rate across a single fault. We then expand this investigation to 14 individual faults for which we have moderately detailed data. For our example fault we show how the simplifications to the throw-rate profile affect average recurrence intervals calculated using FiSH software (*Pace et al., 2016*). For another example fault, we investigate the effect of simplifying fault map geometry and throw-rate profiles on expected shaking intensities. We find that detailed fault throw-rate profiles and fault geometries can have significant impact on calculated recurrence rates and ground shaking intensities at specific sites. Therefore, we argue that such variations should be considered within uncertainties of fault-based probabilistic seismic hazard assessments.

Geological Background

The studied faults are located in the central Apennines, Italy, a region of extending continental crust where offset 15±3ka landforms and sediments can be used to constrain throw-rates across normal faults (Figure 2) (e.g. *Piccardi et al., 1999; Roberts and Michetti, 2004*). Evidence for the age of the offset landforms and sediments comes from tephrachronology, ^{36}Cl cosmogenic exposure dating of fault scarps and upper slopes, the timing of a change from periglacial processes dominating slopes along active faults to slopes controlled by surface fault slip, and shifts in δ^{18}O from Tyrrhenian and other Mediterranean sea cores (*Giraudi and*

Frezzotti, 1986; Giraudi & Frezzotti, 1997; Allen et al., 1999; Cowie et al., 2017). Average 15±3ka fault throw-rates can be derived from topographic profiles across the offset slopes (e.g. *Roberts and Michetti, 2004*). This time period covers multiple seismic cycles (e.g. *Palumbo et al., 2004; Galli et al., 2008; Cowie et al., 2017*). 15ka throw-rates are representative of even longer time periods demonstrated by calculated strain-rates averaged over 15±3ka correlating with total fault throws across the faults developed since 2-3Ma, mantle SKS splitting delay times, and elevation above sea-level via a power law with exponent ~3 (*Faure Walker et al., 2012; Cowie et al., 2013*). This supports the idea that average recurrence intervals derived from 15±3ka rates are stable for even longer time periods. A map of the active faults in the region is shown in Figure 3 with the 14 faults investigated in this study highlighted.

Methods

We show the relevance for earthquake hazard calculations of using detailed or degraded data for a single fault, and then for 14 studied normal faults in the central Italian Apennines. We calculate strain-rates across each of these faults using detailed measurements of fault strike, dip and throw-rate. We compare the results to strain-rates calculated across the same 14 faults, but assuming planar fault geometry and taking a single measurement of the throw-rate and using this value to create assumed, simplified along-strike throw-rate profiles assuming either a ‘boxcar’ or ‘triangular’ profile (examples shown in Figure 4b). Using an example fault for each, we compare the detailed and degraded data cases for modeled average recurrence intervals and annual rates of exceeding specified ground shaking intensities.

Previously published data, supplemented by new fieldwork data (Table 1), of fault throws, and slip vector azimuths and plunges were used for the fault geometry, slip vectors and throw-rates needed as inputs to strain-rate calculations (Figure 2) (*Morewood and Roberts, 2000; Roberts and Michetti, 2004; Papanikolau et al., 2005; Papanikolau and Roberts, 2007; Faure Walker et al., 2009; 2010; 2012; Wilkinson et al., 2015; Cowie et al., 2017; Mildon, 2017; Wedmore, 2017*). The selected faults were mapped using field mapping, digital elevation models, satellite imagery, SRTM (Shuttle Radar Topography Mission) data, geological maps and paleoseismic trench data (*Roberts and Michetti, 2004; Roberts, 2008; Faure Walker et al., 2009; 2010; 2012; Cowie et al., 2017*). Topographic profiles across exposed fault scarps constraining the throw-rate at multiple sites along the faults have been constructed using slope angles measured directly in the field (Figure 2, see *Faure Walker et al., 2010* for a review of the method). At selected sites topography profiles have been extracted from DEMs constructed from terrestrial LiDAR scanning (see *Wilkinson et al., 2015* and *Cowie et al., 2017* for a review of the method). Slip vectors were determined by averaging measurements of multiple slickensides at each site on the exposed limestone fault planes (Figure 2).

The strain-rate across each of the 14 individual faults was calculated building on methods developed by *Faure Walker et al. (2009, 2010)*. The method combines measurements of fault strike, dip, throw, length and slip vector azimuth and plunge to calculate moment tensors using adaptations of the *Kostrov (1974)* equations. To capture the local variations in fault geometry and throw-rates, we discretized each non-planar fault on a regular grid with individual grid boxes having dimensions of 1km x 2km and calculated strain-rates on planar segments confined within each grid box. For the strain-rate across each whole fault (which vary in length between 5.5km and 46km) we combine grid squares to model the non-planar fault.

For each of the 14 studied faults we have at least four measurements of throw (one fault has 30 measurements while the remaining 13 faults have eleven or less) to contribute to the detailed or ‘all data’ case. We remove data points for the degraded data cases. For example, for the Parasano-Pescina fault, we have seven data sites along the fault with values for the 15ka throw, geometry (strike and dip) and slip-vector (Figure 4a). To investigate the effect of using degraded data, we compare calculations of strain-rate across this fault using (i) all data sites in the ‘all data’ throw profile with degraded data: (ii) leaving out the maximum throw point in the ‘no max’ profile but including the other measurements; (iii-) extrapolating a single throw along the whole fault in a ‘boxcar’ profile; and (iv) extrapolating throw along the fault by decreasing the maximum throw linearly to the fault tips in a ‘triangular’ profile (Figure 4b,c). We present three ‘boxcar’ scenarios: (iii-1) ‘boxcar-max’ which extrapolates the maximum throw along the whole fault; (iii-2) ‘boxcar-mean’ for which we integrate the throw profile to find the average displacement and extrapolate this along the whole fault; and (iii-3) ‘boxcar-min’ for which we extrapolate the minimum measured throw along the whole fault. For cases (i) and (ii) we use the detailed fault geometry, but for cases (iii) and (iv) we assume a planar fault geometry. We calculate strain-rates across a further 13 faults for the ‘all data’, ‘boxcar-max’, ‘boxcar-mean’, ‘boxcar-min’ and ‘triangular’ throw profiles.

To demonstrate the effect of using degraded data for calculating earthquake rates, we calculate recurrence intervals for two of the faults: the Parasano-Pescina Fault and the Pescasseroli fault. The earthquake magnitude-frequency distributions have been modeled with a truncated Gutenberg-Richter relationship using the FiSH software (*Pace et al., 2016*). In this distribution, the *b*-value describes how the number of events with magnitude $\geq M$, N, changes with magnitude up to a threshold magnitude, above which N decreases more rapidly (*Kagan, 2002; Jackson & Kagan; 2006*). For this study, b is assumed to be 1 (following *Bird and Kagan, 2004; Valentini et al., 2017*). The maximum earthquake magnitudes (*Mmax*) of the truncated

Gutenberg-Richter relationship for each fault have been calculated using empirical relationships based on fault length (*Wells and Coppersmith, 1994*).

To calculate activity rates at magnitudes given by the truncated Gutenberg-Richter relationship, we balanced the expected seismic moment rate of the truncated Gutenberg-Richter relationship with the seismic moment rate obtained by geometry and slip rates ($\dot{M}_g$):

$$M_g = \dot{\mu} LWV \qquad (1)$$

where μ is the shear modulus, V is the slip rate, and L and W are along-strike rupture length and downdip width, respectively. In this study, to include slip rate variability along strike, as well as detailed slip rate profiles, we assumed:

$$M_g = \mu \sum L_i W_i V_i \qquad (2)$$

where i indicates data of along-strike segments of a fault.

The effect of using degraded data on expected ground shaking at individual sites was investigated through a site-specific PSHA. We calculate annual rates of exceeding specified ground shaking intensities at a specified site. Earthquake rates for different earthquake magnitudes are calculated as described above using the ‘all data’, ‘boxcar-max’ and ‘triangular’ throw profiles. Shaking intensities for given magnitudes are calculated using GMPEs.

We use the widely-applied GMPEs for Italy (*Bindi et al., 2011*) to calculate the ground shaking from earthquakes on the Pescasseroli fault at a given site several kilometers from the fault. These GMPEs are derived for the geometrical mean of the horizontal components and the vertical, considering the latest release of the strong motion database for Italy. The regressions are performed over the magnitude range 4–6.9 and considering distances up to 200 km. The equations are derived for PGA, peak ground velocity (PGV) and 5%-damped spectral acceleration (SA) at periods between 0.04 and 2 s.

To test the effect of using simplified fault geometries on expected ground shaking intensities, we compare the GMPE results basing the source-to-site distance on detailed fault geometry and simplified planar fault geometries. Consistent with the used GMPEs, we use the R_{jb} source-to-site distance. For the ‘all data’ throw profile, we use R_{jb} based both on detailed fault geometry and simplified planar geometries. The simplified geometries use a planar fault strike projected between the two fault tips and two different fault dips: one using the fault dip measured at the site of maximum throw and the other using the fault dip measured at the fault tip. For the ‘triangular’ and ‘boxcar-max’ throw-profiles, the two planar fault geometries are modeled.

We account for uncertainty in the factors affecting ground motions by using a Monte Carlo simulation-based approach (e.g. *Assatourians and Atkinson, 2013*). To this aim, a 10,000yrs synthetically generated set of potential earthquakes across the Pescasseroli Fault, with their temporal distribution, is developed by drawing random samples from the assumed PSHA model components (and related probability distributions), i.e., magnitude-recurrence parameters and maximum magnitude, as defined above. 500 realizations of random numbers drawn from the standard normal distribution is multiplied by the given sigma value (variability of the GMPE model) and added to the median log-ground motions (from the GMPEs) to model the aleatory variability in ground motions. Site-specific hazard curves are displayed showing annual rates of exceedance against PGA and SA(1s). For the ‘all data’ throw profile with the strike-variable fault geometry, we show hazard curves of the PGA for each realization as well as the median, 16th and 84th curves (representing $\pm 1\sigma$). For all the simplified cases only the median curve is shown. In general, SA(1s) can be used as good predictor of the structural response and induced-damage of low-to-mid rise buildings, one of the most common construction types in Italy (e.g., *Rosetto et al., 2016*).

Results

The strain-rates within individual 1km x 2km grid boxes across the Parasano-Pescina fault are shown in Figure 4. Figure 4(i) shows the strain-rates calculated using all the data. Figures 4(ii-iv) show how the calculated strain-rates across the whole fault change for the 'no max', 'boxcar-max', 'boxcar-mean', 'boxcar-min' and 'triangular' throw profiles to 93%, 158%, 104%, 61% and 78% of the 'all data' profile respectively (the bars and errors of the 'all data' case are shown on each graph). The strain-rates calculated across the fault using the 'boxcar-max' (iii-1), 'boxcar-min' (iii-3) and 'triangular' (iv) throw profiles are outside the error margins of the calculated strain-rate across the fault using all the available data (i).

In Figure 5, the calculated strain-rates for the 'all data', 'boxcar-max', 'boxcar-mean', 'boxcar-min' and 'triangular' throw profiles are compared for each of the 14 studied faults. The strain-rates for each fault are normalized to the 'all data' case to allow comparison between the calculated strain-rate and the scenarios modeled with simplified throw-rate profiles. For the simplified 'boxcar-max', 'boxcar-mean', 'boxcar-min' and 'triangular' throw profiles, only one, nine, two and three of the faults have strain-rates within the 'all data' case errors respectively (errors for strain-rates across entire faults using 'all data' vary between 6% and 20%). Strain-rates across faults for the simplified cases vary from 51% to 303% relative to the 'all data' cases and half of them have calculated strain-rates <0.5 or >1.5 times the 'all data' cases. The results in Figures 4 and 5 demonstrate that one measurement of throw extrapolated along strike in either a 'boxcar' or 'triangular' profile is insufficient to characterize strain-rates across a fault.

The effect of using degraded data on calculated recurrence intervals is shown for the Parasano-Pescina fault in Figure 6. The different throw profiles modify the implied ≥M_w5.1 average earthquake recurrence intervals from 420yrs (‘all data’) to 465yrs, 262yrs and 524yrs for the ‘no max’, ‘boxcar-max’, and ‘triangular’ throw profile cases respectively.

Figure 7 shows site-specific spectral shaking for an example fault can be altered beyond the 1σ uncertainty if a simplified fault geometry is assumed that does not include strike-variable geometry. We show the shaking derived from using our measured, detailed fault geometry and two examples of simplified planar fault geometry to demonstrate this point. We use an example site, which has Rjb distance to the Pescasseroli fault of 4.6km when utilizing the detailed fault trace and measurements of dip. However, this distance in increased to 6.4km and 11.3km if the fault is simplified to having planar geometry between the tips with the dip projected from the maximum throw site and tip respectively (see Figure 7a). Figure 7b shows how degrading the fault geometry - so that the fault becomes planar - changes calculated ground shaking from that fault at the specified example site by altering the source-to-site distance (solid line compared to dashed and dotted lines). Figure 7c shows the combined effect of degrading both the fault geometry and throw profiles (dotted and dashed lines). For this fault, the 475yr return period PGA for a given site varies from 0.23g (±1σ: 0.21-0.24g) given the actual fault geometry to 0.20g or 0.13g when relying on simplified tip-to-tip planar fault geometries with the dip projected from the maximum throw data site or from the fault tip respectively. If the simplified throw profiles are added to the simplified planar fault geometries for this example fault, this reduces the 475yr PGA to as low as 0.12g (52% of the ‘all data’ case using detailed geometry) compared to the 0.23g (±1σ: 0.21-0.24g) for the actual fault geometry and detailed throw dataset, a difference that is bigger than the uncertainty on the latter. This is because a fault’s non-planarity alters the fault-to-site distance and simplified throw profiles change calculated rates of occurrence. A similar result can be observed in terms of SA(1s) (Figure 7). The observed discrepancies in the observed shaking intensities between simplified and detailed fault geometry further increase at higher mean return periods (lower annual rates of exceedance) (Figure 7c).

Discussion

Constraining slip-rate has been cited as one of the key uncertainties in earthquake probability calculations (*Field et al., 2014*). For example, in California UCERF3 slip-rates are directly constrained for less than half the fault segments (*Field et al., 2014*). Detailed data showing how throw-rates and fault geometry vary along a fault are rarely available. Therefore, how these parameters change along the length of a fault generally needs to be inferred from just one or a few measurements. For fault-based PSHA the importance of using such extrapolations needs to be known. In this paper we show that key outputs from fault-based PSHA vary dramatically if the inferred along-strike throw-rate (and hence slip-rate) profile is in error.

For our degraded data sets used for calculating recurrence intervals and ground shaking, we included the data we considered most likely to be present in a less detailed dataset, in other words, the long-term throw data most likely to be collected when only one or a few measurements are taken to represent the throw along the entire fault. We considered the case where only one data site exists along the fault and extrapolated this using ‘boxcar-max’ and ‘triangular’ throw profiles. In these two scenarios, we assumed that the most likely location where data may be collected would be the site of maximum offset due to it being the most likely site to have identifiable and preserved offset features. In addition, for an example fault we studied the effect of a scenario where detailed data has been collected, but not from the site of maximum throw: the ‘no max’ case (ii). In the studied fault, the maximum offset occurs across a bend in the fault, as expected from the geometry-dependent throw-rate model in *Faure Walker et al. (2009, 2015)*, so this degraded data scenario represents a case where the bend is not identified, leading to exclusion of a site of higher throw. We show this example to highlight the importance of ensuring data is not excluded along locations with variable geometry. The strain-rate calculated using the integrated average throw does lie within the ‘all data’ case error for nine of the 14 faults, however, for five of the faults an average throw is insufficient. We emphasize that in general fewer measurements than what we have are available for calculating an average throw and hence using average throw-rates or slip-rates will likely cause worse results than shown. We have not determined a general rule as to whether using average throw-rates would more likely overestimate or underestimate the strain-rate across a fault because it is dependent on which throw-rate measurements are incorporated in the calculation of the average throw-rate. We show the ‘boxcar-min’ and ‘boxcar-max’ scenarios to demonstrate the range of possible values that could be obtained from using an “average” throw-rate when this is calculated from fewer data points. Therefore, we argue that using an “average” throw or slip projected along the fault is also insufficient for modeling hazard.

If the problems with extrapolating data are not recognized, this can lead to large errors in recurrence interval calculations. To put this into perspective we discuss how this compares to the effect of temporal variability in the recurrence intervals due to earthquake clustering. Values of the coefficient of variation (CV, standard deviation of the recurrence interval divided by the mean recurrence interval) generally used in PSHA are <0.5 as this is consistent with values computed (e.g. 0.38 (*Gonzalez et al., 2006*); 0.14-0.34 (*Pace et al., 2006*); 0.48 (*Lienkaemper and Williams, 2007*); 0.2-0.39 (*Visini and Pace, 2014*)). Half our strain-rates calculated using the simplified throw-rate scenarios lead to values <0.5 or >1.5 times the ‘all data’ case; this demonstrates that using detailed throws changes probability calculations beyond the uncertainty due to intrinsic natural variability.

We also demonstrate that if the compounded effect of using simplified planar fault geometry and simplified throw profiles on calculated ground shaking exceedance probabilities is not considered, this will lead to errors in values that inform building code regulations. For the example Pescasseroli fault, the 475yr return period PGA is altered beyond 1σ error and thus our results are significant, for instance, to building code 'ultimate limit state' and ‘life-safety’. The observed differences further increase at higher mean return periods, for instance for the 2475yr PGA or SA(1s), corresponding to collapse prevention in several international building codes and in the IBC08. For other faults, whether ground shaking calculated from simplified throw-rates and planar geometries is higher or lower than the ‘all data’ case will depend on both the impact on the recurrence intervals and changes in modeled source-to-site distances. To what extent and to how far from a fault the calculated ground shaking could be impacted by performing calculations based on simplified planar fault geometry and a simplified throw or slip profile is likely to be a function of how variable the actual fault geometry is. Note that local calculations in shaking intensities near faults could be further altered where there are dramatic local variations in fault strike. For instance, along a strongly non-planar fault such as the Fiamignano fault (Figure 3), planar fault models could underestimate local shaking intensities by mislocating a site from the hangingwall onto the footwall. Therefore, the non-planarity of faults, detailed changes in throw-rates along faults and local dramatic changes in fault strikes could have significant impact for local planning and disaster management through building regulation impacts. At a regional scale, changes in implied exceedance probabilities of implied shaking (PGA or SA) will have impact on the calculated damage state and hence calculated losses in catastrophe models used within the insurance industry. To achieve high-resolution risk mapping, detailed fault parameters need to be included.

We note that a full hazard analysis could use a combination of GMPEs, through a logic-tree approach (e.g. *Bommer et al., 2005*). These should include epistemic uncertainties such as site-specific properties and dip propagation with depth. However, in this paper we use just one set of GMPEs to demonstrate the relevance of geometry. The *Bindi et al. (2011)* GMPEs were chosen because they perform well in the region. Specifically, they performed better than older GMPEs for calculating predicted shaking intensities at stations following the 24th August 2016 Amatrice earthquake (*Meletti et al., 2016*; *EEFIT, 2017*).

Most hazard assessments (for earthquakes and other natural hazards) are at a lower spatial resolution than would be desirable for planners (e.g. *Pile et al., 2018*); this is particularly pertinent in areas with critical infrastructure and highly populated areas. Fault-derived hazard maps allow seismic hazard to be calculated at a high spatial resolution (e.g. *Deligiannakis et al., 2018*). However, a balance has to be achieved between increasing resolution and any accompanying increases in uncertainty, so understanding how a lack of detailed fault knowledge affects fault-based hazard calculations and associated uncertainties is needed. We have shown herein that calculating exceedance probabilities of shaking intensities at a high spatial resolution requires detailed throw-rate and geometry measurements as simplifying these can create results beyond 1σ uncertainty. Therefore, we advocate the use of fault data to increase resolution, but with caution of including appropriate uncertainties where detailed data is lacking. In contrast to fault-based hazard assessments, those based solely on historical shaking or instrumental seismicity data have a restricted resolution because they divide the catalogue of earthquakes amongst seismic source zones (e.g., *Meletti et al.*, *2008*). These are polygons drawn on maps enclosing large areas with similar historical seismicity. Fault traces are not used, but instead the polygons represent areas that enclose one or more suspected seismic sources. Earthquake probabilities are calculated in each polygon using the rate of historical seismicity (e.g. *Meletti et al.*, *2008*). It is the size of these polygons that limits the spatial resolution of the hazard maps, which in turn is limited by the available historical or seismicity data.

We have not determined herein what spatial resolution of throw-rate data is required for resolving the along-strike throw-rate profiles of faults with sufficient detail to capture the variations in throw-rates such that more measurements do not change inferred recurrence intervals. In terms of resolving individual paleoearthquake magnitudes along a fault from trench sites, *Hintersberger and Decker (2015)* found that 4-6 observation sites were required. We have used at least 4 sites along each fault in our analysis to represent the 'all data' cases for the 14 faults studied, equivalent to measurements with average inter-site spacing of 200m to 6km. The geometry-dependent throw-rate model (*Faure Walker et al., 2009; 2015*) suggests that faults with a higher along-strike variation in geometry would likely have a corresponding greater variation in throw-rate along the strike. This might suggest that using simplified throw-rate profiles is sufficient if faults are relatively planar (e.g. *D'Amato et al., 2017*), but not if the fault has more variable fault geometry. This has not been tested, but intuitively it is clear that more sites are needed for faults with greater non-planarity. To determine the required spatial resolution, we need a greater number of examples of faults with multiple data sites.

Currently such detailed geometry and throw-rate data with multiple data points on each fault is not available and in some areas it may be difficult to obtain it by ground-based field methods. However, we note that techniques to capture such data - such as TLS (terrestrial laser scanning), ALS (airborne LiDAR scanning) and structure from motion photogrammetry - are making the data acquisition increasingly possible (e.g. see *Telling et al. (2017)* for a review of improvements in modeling fault geometries with TLS). With increasing capabilities to measure such detail we argue that as such data become available they should be used. In addition, throw-rates can be constrained from paleoseismic trench studies. However, such studies need to use multiple sites along a fault and consider fault geometry when extrapolating point data along a fault or input into calculations like those in *Faure Walker et al. (2009)* so that along strike variations in throw-rate can be calculated relative to constrained sites.

In addition to including detailed geometry for calculating earthquake rates and ground shaking intensities, we suggest that it should also be used for other aspects of hazard calculations. For example, the effect of Coulomb stress transfer is sometimes included in earthquake probability calculations (e.g. *Pace et al., 2014*). We note that there are increasing capabilities to input fault geometry detail in Coulomb stress transfer calculations, with existing studies demonstrating the need for strike-variable geometry (*Mildon et al. 2016b; 2017*).

Overall, we argue that fault slip-rates are needed to inform seismic hazard calculations rather than relying on historical records alone, however we have demonstrated herein the importance of using detailed along-fault throw-rate profiles and detailed fault geometry for these. Without such data, hazard calculations used to inform government, industry, and residents may misinform about the geography of seismic hazard and hence not trigger appropriate action to mitigate against future events. Our results highlight that local 3D fault geometry and local throw-rates must be considered when extrapolating data from individual sites along a fault for use in fault-based PSHA. We have demonstrated the importance of detailed data for calculating strain-rates and hence earthquake moment release across faults (*Faure Walker et al., 2009; 2010; Wilkinson* *et al., 2015*), earthquake recurrence intervals averaged over multiple earthquake cycles, and expected shaking calculated using GMPEs. For individual towns, multiple faults will affect the probabilities of different shaking intensities so the changes for the individual faults shown here will be compounded. Therefore, we are advocating a change in how fault slip-rates and geometry are considered in PSHA calculations.

Conclusions

We find that using detailed fault throw profiles and fault geometries that vary along strike can have significant impact on calculated hazard calculations by altering recurrence rates and ground shaking intensities at specific sites respectively. We show that probability calculations change beyond the uncertainty due to intrinsic natural variability and site-specific shaking intensities change beyond the uncertainty bounds of GMPEs. Therefore, we argue that either detailed data should be used when calculating hazard or that such variations should be considered within uncertainties of fault-based PSHA.

We studied 14 active normal faults within the central Apennines for which we have four or more sites constraining the post 15ka throw-rate. Calculating strain-rates across these faults from simplified 'boxcar-max', 'boxcar-mean', 'boxcar-min' and 'triangular' throw profiles resulted in only one, nine, two and three of the faults having strain-rates lie within 1 sigma error of the 'all data' case respectively. For the simplified cases, calculated strain-rates vary from 51% to 303% relative to the 'all data' cases with half of them having calculated strain-rates <0.5 or >1.5 times the 'all data' cases. These results demonstrate how far from the actual rates simplifications can cause the strain-rates to be.

For an example fault, the Parasano-Pescina fault, using simplified throw-rate profiles modifies the implied $\geq M_w 5.1$ average earthquake recurrence intervals from 420yrs (‘all data’) to 465yrs, 262yrs and 524yrs for the ‘no max’, ‘boxcar-max’, and ‘triangular’ throw profile cases respectively.

For another example fault, the Pescasseroli fault, the 475yr return period PGA for a given site a few kilometers (R_{jb} 4.6km) from the fault varies from 0.41g (±1σ: 0.37-0.44g) given the actual fault geometry and throw-profile to 0.34g or 0.24g when relying on simplified tip-to-tip planar fault geometries with the dip projected from the maximum throw site or from the fault tip respectively. Using simplified throw profiles and planar fault geometries for this example fault alters the 475yr PGA to as low as 0.19g (46% of the ‘all data’ case using detailed geometry).

Data and Resources

The data used in this paper came from published sources listed in the references and new data in Table 1. Figure 3 was made using the Generic Mapping Tools version 5.2.1 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998).

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Tables

Table 1: Fieldwork data used within calculations that have not been previously published.

Fault	UTM X	UTM Y	Slip vector azimuth (°)	Slip vector plunge (°)	15ka throw (m)
Barisciano	369075	4698111	194	51	7.0
	383475	4689190			6.5
	392297	4679321	226	44	6.5
Fucino	393474	4644538	229	52	
	393493	4644535	233	58	
	393541	4644520	209	56	
	393583	4644506	210	58	
	393594	4644503	219	59	
	393636	4644489	220	50	
	393736	4644447	218	40	
Liri	364529	4648418	168	65	

	364554	4648395	173	61	
	364628	4648319	178	67	9
	364633	4648332	189	71	
	364671	4648294	197	64	
	364683	4648271	189	66	
	364722	4648213	177	58	
Ocre	367652	4682645	197	66	
	367884	4682479			6.4
	368647	4681804	211	58	
	368775	4681715	213	46	
	368838	4681676	217	56	
	368939	4681589			2.8
	369008	4681532	260	62	
	369048	4681494	255	55	6.3 ±3.0 *(eye estimate)*
	369068	4681487			4.0
	369251	4681334	217	54	
Roccapreturo	392123	4672914	185	62	
	393537	4671944	237	47	

	393541	4671945			6.5
	393554	4671926	231	50	
	393665	4671836	225	57	
	393699	4671804	215	55	
	393781	4671481	215	59	
	393785	4671635	211	44	
	393791	4671445	213	56	
	393799	4671404	212	53	
	393971	4671229			8.47
	393995	4671211	258	45	
	394004	4671182	258	55	
	395036	4670693	253	52	
Scanno	406678	4642989	209	41	
	406796	4643001			4.5
	406929	4642938	217	47	10.6
	407154	4642786			12.6
	407413	4642561	224	58	
	407452	4642544	217	52	12.3

	407462	4642521	228	54	
	407571	4642414	212	52	
	410765	4637903			4.0

Figure captions

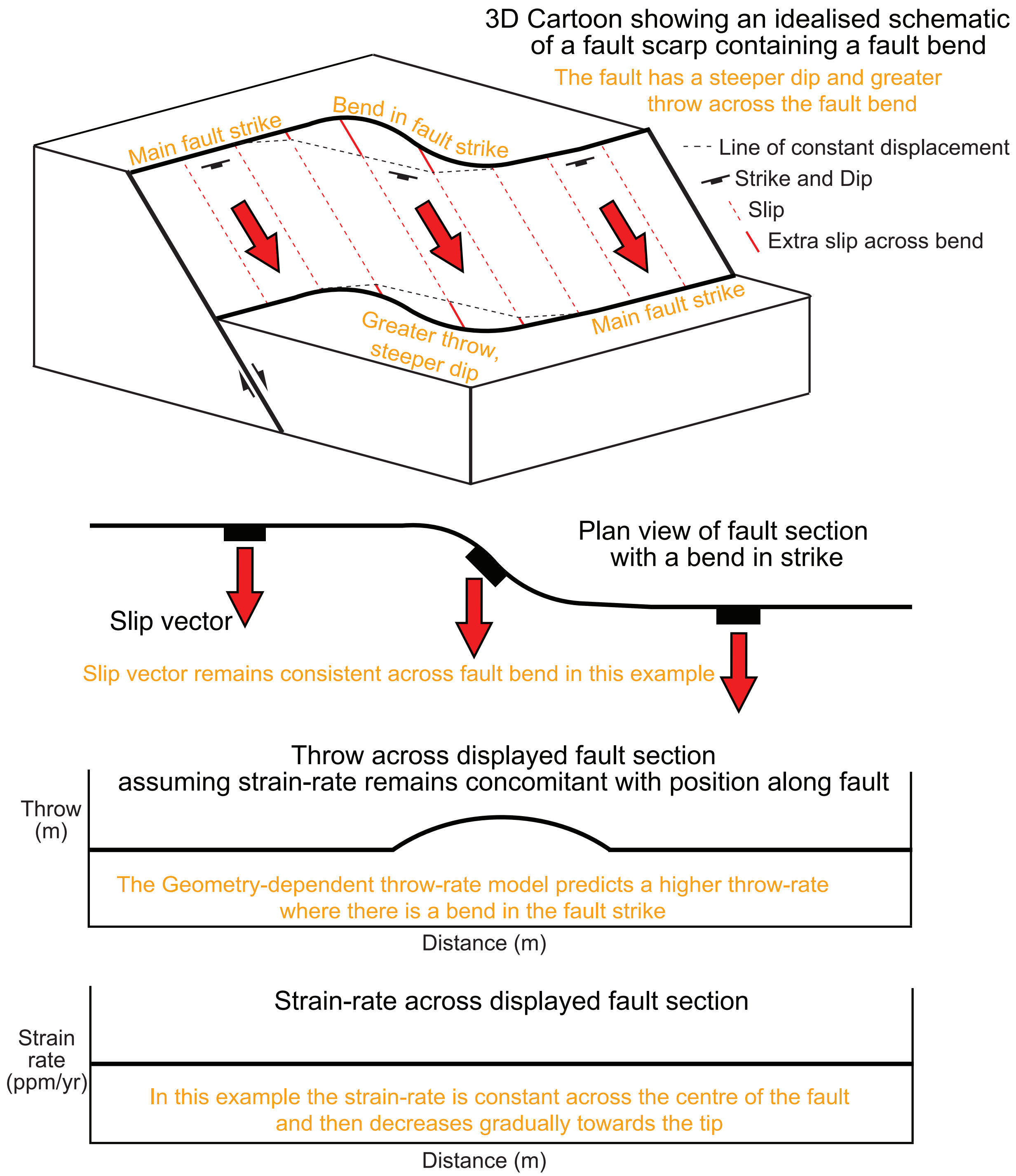

Figure 1: Geometry-dependent throw-rate model. The figure shows how, for a given strain-rate profile, the throw-rate across the fault changes with a change in strike along the fault. In order to keep the strain-rate concomitant with its position along a fault, the throw-rate varies where there are changes in fault strike and dip. How the strain-rate changes along the fault is shown

here for one idealized example. The figure has been adapted from Faure Walker et al. (2015).

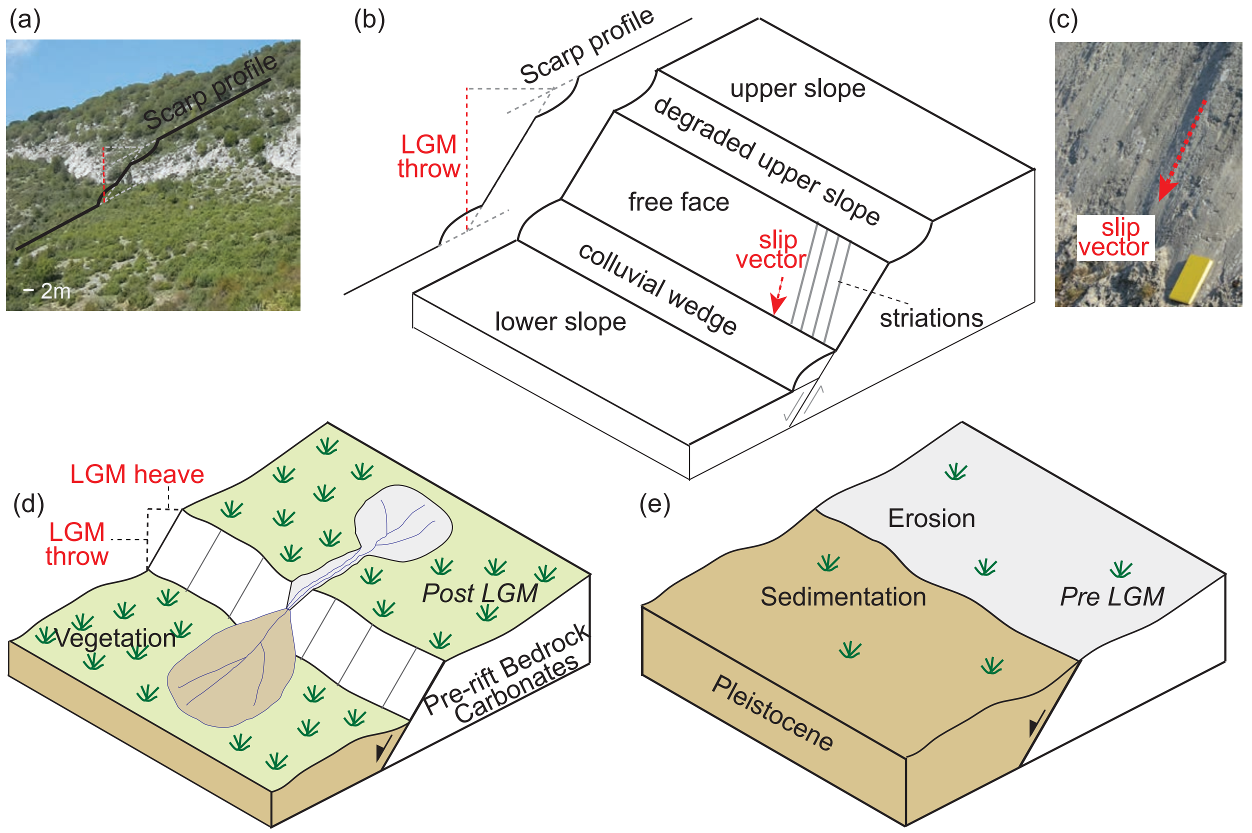

Figure 2: Fault scarps exposed at the surface in the central Italian Apennines formed since the end of the LGM (Last Glacial Maximum). (a) Photograph of a post glacial scarp with example of a scarp profile line. (b) Cartoon topographic scarp profile constructed across cartoon fault scarp showing how the throw since the LGM is constructed. (c) Striations on limestone fault plane revealing slip vector (d) Cartoon showing formation of surface scarp following the LGM, the scarp is exposed because fault slip-rates are faster than erosion and sedimentation rates; the LGM provides a time marker since the scarps were formed because during the glacial maximum, as shown in (e), scarps were generally not exposed as erosion and sedimentation rates outstripped fault slip rates. (b) adapted from Faure Walker et al. (2009), (d) and (e) adapted from Roberts and Michetti (2004) and Faure Walker (2010).

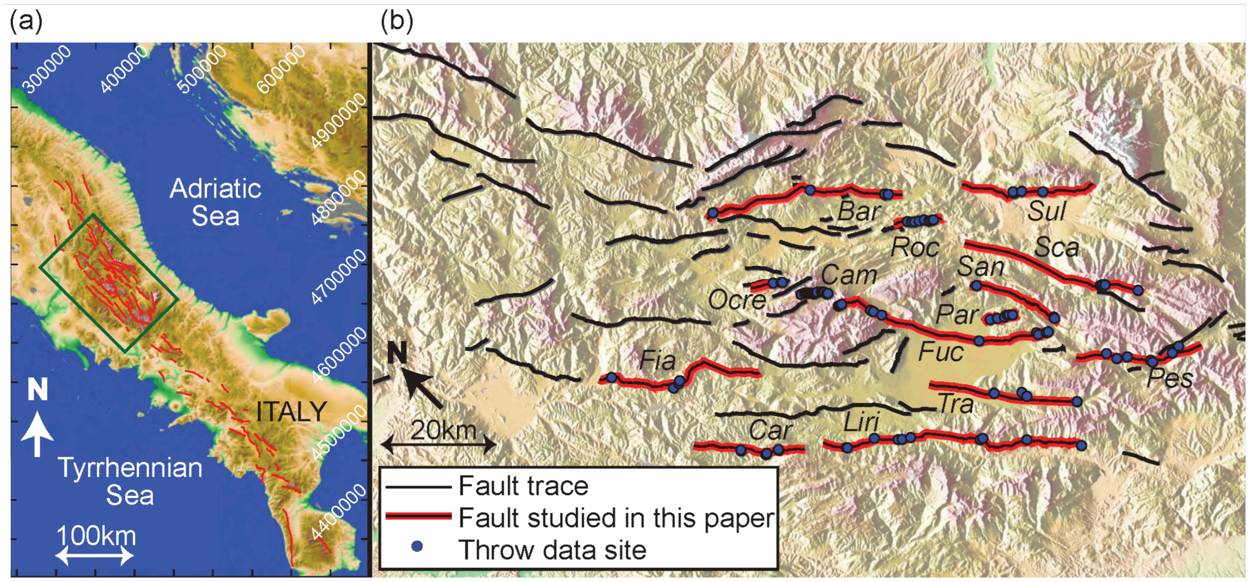

Figure 3: Map of the active faults in the central Apennines study region showing studied faults. The box in location map (a) shows the area covered by the more detailed map (b) of the 14 faults investigated in this study. Along the 14 faults, which are highlighted in red, sites with 15ka throw-rate measurements are shown with filled in circles. Bar=Barisciano, Cam=Campo Felice, Car=Carsoli, Fia=Fiamignano, Fuc=Fucino, Par=Parasano, Pes=Pescasseroli, Roc=Roccapreturo, San=San Sebastiano, Sca=Scanno, Sul=Sulmona, Tra=Trasacco. Liri and Ocre also marked. Figures produced using GMT (Wessel et al., 2013).

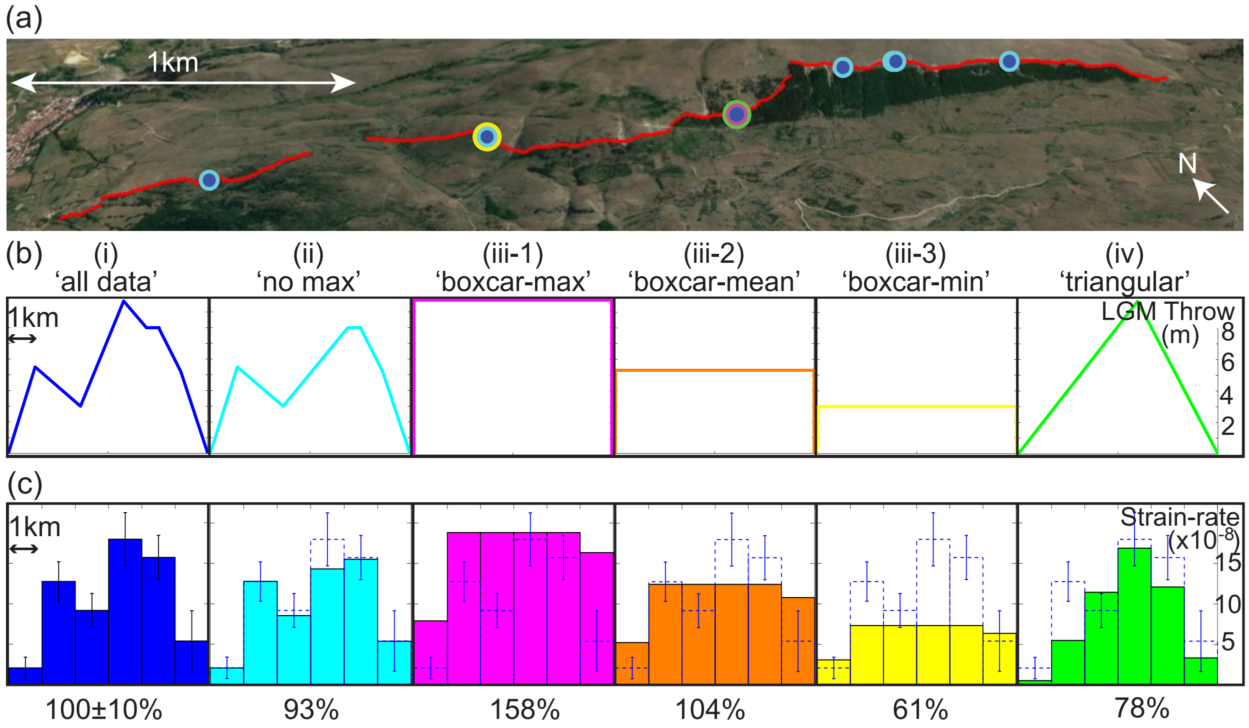

Figure 4: Plots show how 15kyr strain-rates in a regular 1x2km grid change along the Parasano-Pescina fault and how using degraded data for the throw profiles affects the calculated strain-rates across the fault. (a) Trace of Parasano-Pescina Fault from GoogleEarth^{TM}*. Circles show sites of post-glacial throw measurements, the colours correspond to which models (i-iv) the throw measurements were used in. (b) Throw profiles along the fault for each of the models and (c) strain-rates within 1km x 2km grid boxes along the fault. (i) 'all data' uses all the data from the seven data collection sites along the fault. (ii) 'no max' uses all the data except from the throw-rate data collected from the site of maximum 15ka throw. (iii-1) 'boxcar-max' only uses the data from the maximum throw-rate site, (iii-2) 'boxcar-mean' uses the average 15ka throw, slip vector azimuth and plunge, and (iii-3) 'boxcar-min' uses only data collected from the minimum throw-rate site (above zero). In each 'boxcar' scenario, the value of throw is projected along the entire length of the fault until near the fault tips where the throw rapidly decreases to zero. (iv) 'triangular', like 'boxcar-max' only uses the data from the*

maximum throw-rate site, but in this scenario the throw-rate decreases linearly from the maximum to zero at each tip forming a triangular throw-rate profile along the fault. Error bars and dotted bar plots shown in each plot are for the 'all data' case (i). Percentage values in the boxes give the total strain-rate across the fault relative to the 'all data' case (i). This shows that degrading data by excluding a single data point (ii) or extrapolating a single throw value along a fault (iii, iv) changes calculated strain-rates across the fault.

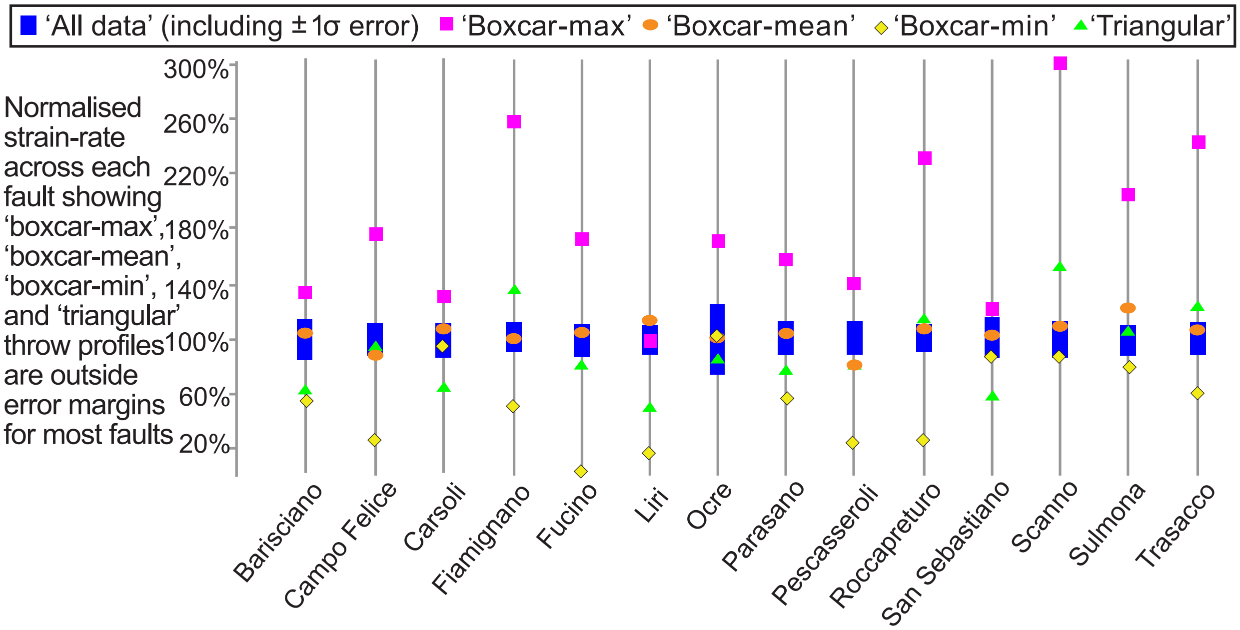

Figure 5: Strain-rates calculated across 14 faults using different throw-rate profiles: 'all data' case (blue rectangles including ±1σ), 'boxcar-max' (pink squares), 'boxcar-mean' (orange ovals), 'boxcar-min' (yellow diamonds) and 'triangular' (green triangles). The strain-rates calculated using simplified throw-rate profiles are shown relative to those calculated using the 'all data' throw-rate profiles. The inferred strain-rates calculated using simplified throw-rate profiles mostly lie outside ±1σ uncertainty of the 'all data' strain-rates, demonstrating that the simplified throw-rate profiles are insufficient for calculating strain-rates across faults.

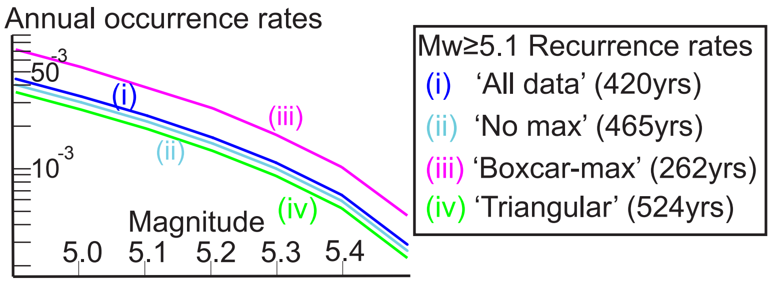

Figure 6: Frequency-magnitude semi-log plots for M_w 4.9-5.5 for the four throw-profile scenarios along the Parasano-Pescina fault. The graphs compare the (i) all data sites included in the 'all data' throw profile with three sets of degraded data. The three sets of degraded data are created by: (ii) leaving out the maximum throw point in the 'no max' profile but including the other measurements; (iii) extrapolating the maximum throw along the whole fault in a 'boxcar-max' profile; and (iv) extrapolating throw along the fault by decreasing the maximum throw linearly to the fault tips in a 'triangular' profile. Calculated earthquake ≥M_w5.1 recurrence intervals are 420yrs, 465yrs, 262yrs and 524yrs for cases (i) – (iv) respectively. This example shows that using simplified throw-rate profiles can change calculated recurrence intervals that are used to inform PSHA.

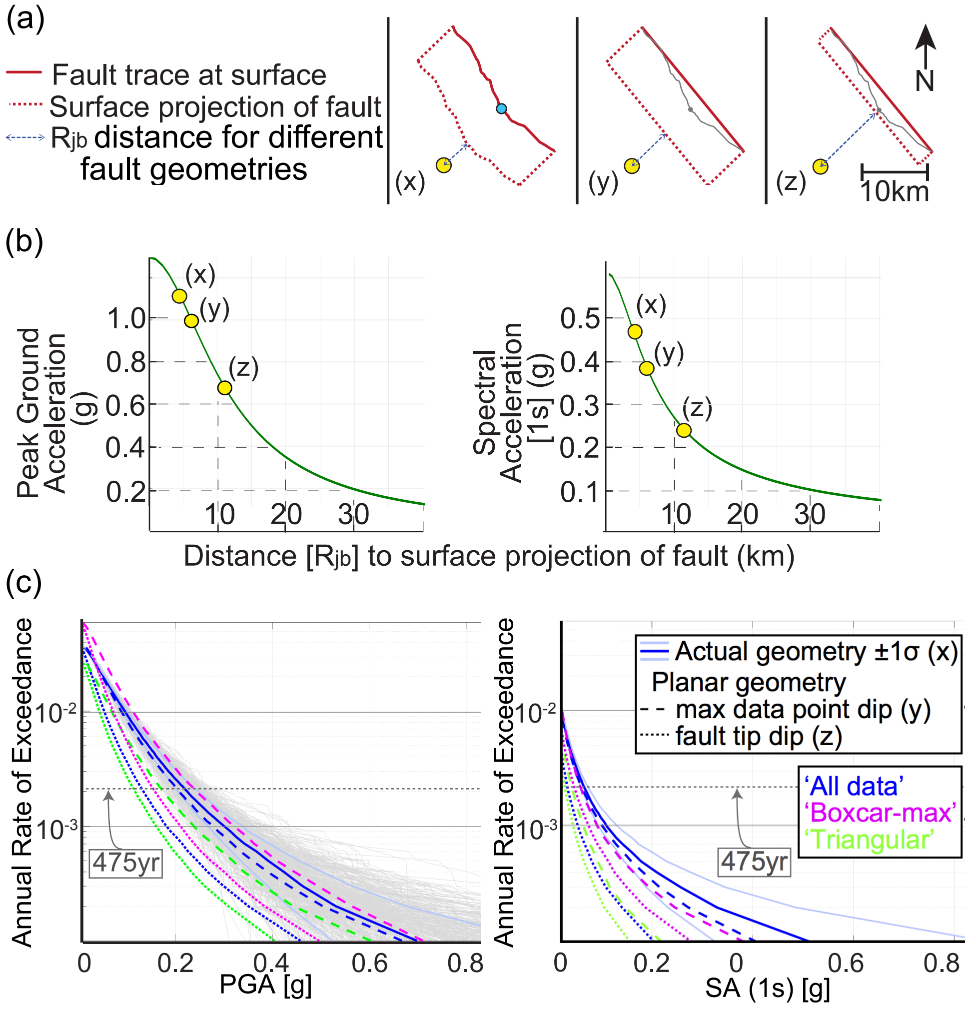

Figure 7: Effect of using simplified geometry and displacement-rate profiles on annual rates of exceeding specified ground shaking intensities. The figure shows that ignoring fault bends and measured dips changes calculated shaking beyond 1σ uncertainty. (a) Maps show actual fault geometry (x) and surface projection of fault assuming the depth of the seismogenic layer is 15km and non-listric geometry with depth. The example site, Valle Massima, is shown as a yellow circle. The R_{jb} distance to the example site is 4.6km (x) (apparent dip of fault at (x) is 55°), but this distance is increased to 6.4km and 11.3km if the fault is simplified to having planar geometry between the tips with the dip projected from the maximum throw-rate site (y) (55° apparent dip) and tip (z) (81° apparent dip) respectively. (b) The graphs show how the R_{jb}

distance affects peak ground acceleration and spectral acceleration with distances (x), (y) and (z) shown, using GMPEs from Bindi et el. (2011). (c) Annual rates of exceedance against peak ground acceleration (PGA) and spectral acceleration (SA) from earthquakes on the Pescasseroli fault at the given example site, Valle Massima. PGA and SA are calculated for the 'all data' throw profile for fault-to-site distances (R_{jb}) based on detailed fault geometry ((x), blue solid line, ±1σ uncertainty shown with paler blue solid lines). Grey lines show each of the 500 simulation lines run for the PGA calculations. Ground shaking is further calculated using simplified planar fault geometries using a straight fault trace from tip-to-tip and fault dip projected from the maximum throw data site ((y), dashed line) and dip at the fault tip ((z), dotted line). The simplified fault geometry source-to-site distances are also combined with recurrence rates calculated for the 'boxcar-max' (pink lines) and 'triangular' (green lines) throw-profiles to show the combined effect of simplifying throw profiles and using simplified geometries. In this example, using a simplified throw-rate profile and planar fault geometry gives lower values of calculated ground shaking intensities than using the actual values and therefore may underestimate the seismic hazard to a region or town.