

Structural and geomorphic constraints on active normal faulting and landscape evolution in Calabria, Italy

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ABSTRACT

Calabria is one of the fastest-uplifting and most seismically active regions in the Mediterranean, yet the time-averaged ($\sim 10^6$ yrs) rates of normal faulting remain poorly constrained. Here, we use DEM analysis, geologic cross-sections, and a compilation of published data to quantify systematically along strike, the fault throws and time-averaged throw rates of the Serre, Cittanova, Armo, East Crati and West Crati faults. We show that regional uplift has uplifted both their hangingwall and footwall blocks by ~ 200 - 400 m, and the Aspromonte massif by up to ~ 1150 - 1300 m. We find that these faults have throws between ~ 640 - 1430 m, and throw rates between ~ 0.7 - 1.5 mm/yr. Their footwall ranges have variable proportions of inherited relief, up to ~ 300 - 800 m. The channels draining these ranges reflect the active normal faulting and relief in their steepness indices, becoming ~ 5 - 8 m^{0.9} steeper for each in 0.1 mm/yr throw rate increment and each 100 m relief increase. Finally, the presence of knickpoints suggests that these channels are transiently responding to changes in relative base level, which could be due to fault linkage or regional strain rate increases for the southern Calabrian faults; and to regional uplift acceleration in the case of the Crati faults.

Supplementary material: 76 topographic profiles of the marine terraces, 146 river long profiles.

Calabria is one of the fastest uplifting regions in the Mediterranean (e.g. Ferranti *et al.*, 2006; Antonioli *et al.*, 2006). Here, high relief is generated by the superposition of back-arc normal faulting and long wavelength regional uplift. However, the origin, timing and relative contributions of these two mechanisms are still highly debated (e.g. Ghisetti, 1981; Molin *et al.*, 2004; Cucci & Tertulliani, 2010; Faccenna *et al.*, 2011; Spampinato *et al.*, 2014). The elevation of Pleistocene marine terraces has been widely used to quantify regional uplift rates (e.g. Miyauchi *et al.*, 1994; Antonioli *et al.*, 2006; Ferranti *et al.*, 2006), but some terraces are also affected by normal faults, which can distort their elevations by up to 700 m depending on if they are situated at the footwall

or hangingwall and their position along fault strike (e.g. Valensise & Pantosti, 1992; Cucci & Cinti, 1998; Cucci & Tertuliani, 2010; Roberts et al., 2013). Consequently, the spatial distribution and rates of the background regional uplift can only be unravelled once the distribution of fault-related uplift and subsidence is subtracted. Detailed along-strike quantification of fault activity and constraints on fault array evolution are therefore needed. Moreover, these constraints are essential because Calabria is one of the most seismically active regions in the Mediterranean, with records of ca. 20 $M_w > 6$ earthquakes in the last two millennia, but its seismogenic framework remains insufficiently characterized (e.g. Jacques et al., 2001; Jenny et al., 2006; Galli et al., 2007; Catalano et al., 2008; Galli & Peronace, 2015). Studies to-date have provided only discrete minimum estimates on normal fault throw rates, because they only consider the footwall or hangingwall components of fault throw (e.g. Tortorici et al., 1995; Monaco & Tortorici, 2000; Jacques et al., 2001; Catalano et al., 2008; Spina et al., 2011) or potentially, single fault splays (e.g. Galli & Bosi, 2002; Galli et al., 2007; Galli & Peronace, 2015).

In addition, Calabria's stream network and its relationship to active faulting has received little attention. Molin et al. (2004) and Olivetti et al. (2012) studied channels draining the Sila massif (Fig. 1), and suggested that they are transiently responding to both regional uplift and normal faulting. Recently, Pirrotta et al. (2016) analysed two rivers near the Piani d'Aspromonte, and found that their morphology is controlled by the active normal faulting. However, these studies do not systematically characterize channel response to fault segments evolution explicitly. The aim of this paper is to fill these gaps and provide new along-strike, long-term, tectonic constraints on Calabria's normal faulting and its associated landscape response, by combining structural data and tectonic geomorphology.

Along normal faults, positive stress feedback dictates that the central portions of faults have greater slip rates and accumulate more displacement over time, which typically leads to an approximately elliptical displacement profile with scale-invariant displacement/length ratios (γ) (Anders & Schilische, 1994; Dawers & Anders, 1995; Gupta & Scholz, 2000; Cowie & Roberts, 2001; Walsh et al., 2003). Displacement/length ratios for individual faults and arrays are typically between $\gamma = 0.001 - 0.1$, with greater γ values possibly associated with more mature faults, and lower γ values with unlinked fault arrays (Schlishe et al., 1996; Walsh et al., 2002; Kim & Sanderson, 2005). Cumulative displacement is partitioned between footwall uplift and hangingwall subsidence, with ratios of footwall:hangingwall throw that are $\sim 1:1$ at a minimum and can be up to $1:10$ (e.g. Jackson & McKenzie, 1983; King et al., 1988; Anders et al., 1993; Gupta & Scholz, 1998). Footwall relief grows as fault displacement accumulates, as long as slip rates are greater than erosion rates, so it can reflect along-strike variations in fault activity and the displacement histories of fault segments (e.g. Anders & Schlishe, 1994; Mirabella et al., 2004; Cowie et al., 2006; Roda-Boluda & Whittaker, 2016). However, if pre-faulting relief is significant, it will dominate footwall topography until the magnitude of fault-induced relief exceeds the inherited component.

Because erosion rates increase non-linearly with increasing slope or relief, driven by the onset of landsliding beyond a certain threshold (e.g. Ouimet *et al.*, 2009; DiBiase *et al.*, 2010), footwall relief can also become decoupled from the fault displacement in later fault evolution stages (e.g. Densmore *et al.*, 2004).

Rivers crossing normal faults are sensitive to tectonics and can record normal fault growth and linkage (e.g. Commins *et al.*, 2005; Whittaker *et al.*, 2008; Whittaker & Walker, 2015; Hopkins & Dawers, 2015; Roda-Boluda & Whittaker, 2016). Their geometry can be described by a stream power erosion “law” (e.g. Whipple & Tucker, 1999, 2002; Kirby & Whipple, 2012; D’Arcy & Whittaker, 2014). In this case, channel slope, S , is related to drainage area, A , by a power law, which implies that channels in topographic steady-state exhibit a concave up profile that reflects the erosional balance between downstream increase in discharge and decrease in gradient. For a simple stream power model in a steady-state system:

$$S = \left(\frac{U}{K}\right)^{\frac{1}{n}} A^{\frac{-m}{n}} \quad (1)$$

Where U is an uplift rate, K is a coefficient that includes bedrock erodibility and other factors, and m and n are positive exponents related to erosional dynamics and hydraulic geometry (e.g. Whipple & Tucker, 1999, 2002). The term $\left(\frac{U}{K}\right)^{\frac{1}{n}}$ can be represented by the channel steepness index, k_s , and the ratio of m/n by the channel concavity, θ . A reference value of θ is often used to estimate a normalized channel steepness index, k_{sn} , allowing comparisons between channels with different concavities (e.g. Snyder *et al.*, 2000; Wobus *et al.*, 2006a). Equation (1) makes an explicit relationship between k_{sn} and uplift rate; which has been observed empirically (Wobus *et al.*, 2006a; Cyr *et al.*, 2010; Kirby & Whipple, 2012). Consequently, channels are expected to present different values of k_{sn} along fault strike (Densmore *et al.*, 2007; Miller *et al.*, 2012; Roda-Boluda & Whittaker, 2016), although adjustments of channel geometry and sediment cover in response to tectonic forcing may add scatter to this relationship (e.g. Sklar & Dietrich, 2001; Whittaker *et al.*, 2007; Attal *et al.* 2008).

As faults accumulate strain and grow along their tip-line, neighbouring faults might reach a critical distance from each other and eventually link, which typically leads to an enhancement of their slip rates (e.g. Peacock & Sanderson, 1991; McLeod *et al.*, 2000; Gupta & Scholz, 2000; Cowie & Roberts, 2001). This enhancement is more acute in the centres of the newly-linked faults and in the old segment boundaries, because these areas need to accumulate more throw in order for the new linked structure to attain an adjusted, elliptical throw profile similar to that of single faults and pre-linkage γ values (e.g. Dawers & Anders, 1995; Gupta & Scholz, 2000; Cowie & Roberts, 2001). After linkage, the centres of the pre-linkage segments and their segment boundaries can often be recognized for some time, by the positions of maximum and minimum cumulative displacement zones, respectively (Peacock & Sanderson, 1991; Anders & Schlische, 1994; Dawers & Anders, 1995; McLeod *et al.*, 2000).

These interactions affect the channels crossing the faults, which may experience relative base-level changes due to the slip rate enhancements (Cowie *et al.*, 2006; Whittaker *et al.*, 2007; Attal *et al.*, 2008). Channels respond by incising and steepening to adjust to the new fault slip rates over timescales of *ca.* 10^6 years, so while they are transiently responding to tectonics, their long profiles are typically divided between an incised, adjusted, lower reach, and an unincised, unadjusted upper reach (e.g. Snyder *et al.*, 2000; Whittaker *et al.*, 2008; Attal *et al.*, 2011). The limit between both sectors is marked by a convexity in the long profile, often referred as knickpoint (e.g. Crosby & Whipple, 2006; Kirby & Whipple, 2012). As incision progresses, knickpoints migrate upstream with a vertical velocity that is a function of the magnitude of the perturbation experienced (Whittaker *et al.*, 2008; Attal *et al.*, 2008, 2011; Whittaker & Boulton, 2012; Roda-Boluda & Whittaker, 2016). Because following fault linkage, the old segment boundaries and centres of newly linked faults experience greater throw rate changes, linkage-generated knickpoints should migrate faster and be higher in these areas (e.g. Commins *et al.*, 2005; Boulton & Whittaker, 2009). In contrast, following spatially uniform changes in base level lowering rates, knickpoints formed by the same event should appear at similar elevations (e.g. Whipple & Tucker, 1999; Niemann *et al.*, 2001; Crosby & Whipple, 2006; Harkins *et al.*, 2007). In both cases, ratios of steepness index upstream and downstream of knickpoints inform about the magnitude of the relative base-level fall that generated the transient response (Wobus *et al.*, 2006b; Whittaker & Walker, 2015).

Here, we present a systematic along-strike quantification of fault activity that accounts for the footwall and hangingwall components of fault slip, for five major Calabrian faults: the West Crati, East Crati, Serre, Cittanova and Armo faults. We compile measures of relief and marine terrace elevations along the strike of these faults, and synthesize published data on hangingwall subsidence and terrace ages to derive new constraints on fault total throw and time-averaged throw rates. We analyse systematically the long profiles of 146 rivers draining the footwalls of these faults; and compare their steepness indices and knickpoint distributions, which we use to extract information about landscape response and fault evolution. With this data, we examine for the first time Calabrian normal faults in the context of inherited relief, fault evolution, and coupled landscape response.

GEOLOGICAL SETTING

Geodynamic evolution

The Calabrian arc is the emerged forearc of a Neogene subduction zone related to the African-Eurasian collision (Malinverno & Ryan, 1986; Patacca *et al.*, 1990). The NW-dipping Ionian lithosphere subducting beneath Eurasia has been identified by seismic tomography and by a Wadatti-Benioff zone dipping at 70-80° (Wortel & Spakman, 2000; Chiarabba *et al.*, 2008). The subducting slab is heterogenous, facilitating the formation of slab tears, which have enabled fast roll back towards the SE (Wortel & Spakman, 2000; Chiarabba *et al.*, 2008; Faccenna *et al.*, 2011; Magni *et al.*, 2014).

Back-arc extension started in the Tyrrhenian Sea in the Serravallian-Tortonian (e.g. Malinverno & Ryan, 1986; Patacca *et al.*, 1990; Magni *et al.*, 2014). Since at least the Early Pleistocene, the extensional locus has been situated along the western side of the Calabrian arc and has created a network of high-angle normal faults that extends on- and offshore for about 350 km to NE Sicily, defining the “Siculo-Calabrian Rift Zone” (Fig. 1a; e.g. Monaco *et al.*, 1996; Monaco & Tortorici, 2000), accommodating 1-4 mm/yr of extension (D’Agostino & Selvaggi, 2004; D’Agostino *et al.*, 2011; Catalano *et al.*, 2008).

Around the Early-Middle Pleistocene, a major geodynamic reconfiguration of the subduction system has been recognized (Westaway, 1993; Hippolyte *et al.*, 1994; Goes *et al.*, 2004). This resulted in the onset of rapid regional uplift ~0.6-1 Ma (e.g. Dumas *et al.*, 1981, 2005; Ghisetti, 1984; Westaway, 1993; Miyauchi *et al.*, 1994; Ferranti *et al.*, 2006). One of the most popular hypotheses is that regional uplift is the isostatic response to slab break-off, supported by an imaged slab window at 150-250 km depth (e.g. Westaway, 1993; Wortel & Spakman, 2000). However Faccenna *et al.* (2011) pointed out that uplift affects a much wider area than the imaged slab window, and that its timescale exceeds the 10^4 years expected for an isostatic response. They proposed instead that uplift is driven by mantle upwelling around the teared slab edges (e.g. Chiarabba *et al.*, 2008; Magni *et al.*, 2014), a model that explains the spatial distribution of uplift and volcanism and their timing, operating as long as subduction does.

Regional uplift and marine terraces

Regional uplift is evidenced by the 11-13 orders of uplifted marine terraces recognized along the Calabrian coast, whose spatial distribution reveals long wavelength (>50-100 km), dome-shaped positive topography (e.g. Dumas *et al.*, 1981, 2005; Miyauchi *et al.*, 1994; Ghisetti, 1981; Westaway, 1993; Bordoni & Valensise, 1999; Ferranti *et al.*, 2006; Antonioli *et al.*, 2006; Faccenna *et al.*, 2011). Estimates of time-averaged uplift rates derived from these terraces vary between ~0.2-2 mm/yr, due to the intrinsic spatial variability of regional uplift and the normal faulting (e.g. Ghisetti, 1981; Dumas *et al.*, 1981; Westaway, 1993; Miyauchi *et al.*, 1994; Bordoni & Valensise, 1999; Cucci, 2004; Ferranti *et al.*, 2006; Antonioli *et al.*, 2006; Roberts *et al.*, 2013). Absolute dates on these terraces are restricted to the youngest sets, while the oldest terraces have often been attributed an age assuming that each successively higher one corresponds to the immediately older marine highstand (e.g. Westaway, 1993; Miyauchi *et al.*, 1994; Dumas *et al.*, 2005; Spampinato *et al.*, 2014), .

The oldest marine terraces are the most relevant for our study, because they are the only ones present in some of the footwalls of the studied normal faults, and are offset by the faults in some locations (in the Piani d’Aspromonte, by the Cittanova fault; and along the Armo fault; Fig.1c), so there is a general consensus that the onset of normal faulting post-dates their formation (e.g. Tortorici *et al.*, 1995; Jacques *et al.*, 2001; Catalano *et al.*, 2008). These terraces are wide and laterally continuous, and formed as wave-cut

platforms during marine highstands, abrading the crystalline basement (e.g. Ghisetti, 1981; Dumas *et al.*, 1981; Westaway, 1993; Miyauchi *et al.*, 1994; Monaco *et al.*, 1996; Catalano *et al.*, 2008). Although it is widely acknowledged that they formed in the Early-Middle Pleistocene, their exact age is debated. Catalano *et al.* (2008) considered them as young as 580 ka, and Tortorici *et al.* (1995), 1.8 Myr old. In contrast, Westaway (1993) suggests they formed between 900-700 ka, and Valensise and Pantosti (1992) propose an age of 700-780 ka based on extrapolating coastal uplift rates. Ibbeken & Schleyer (1991) and Miyauchi *et al.* (1994) estimate that they are 1 and 1-1.2 Myr old, respectively. Reported fossils on the terraces include *Globorotalia truncatulinoides excelsa*, a foraminera whose first appearance is placed around 1-1.2 Ma and abundant during MIS 25 936 ka (Barrier *et al.*, 1986; Rio *et al.*, 1991; Miyauchi *et al.*, 1994; Berggren *et al.*, 1995; Cita *et al.*, 2008); and *Arctica Islandica*, a cold water mollusc associated with Pleistocene glacial periods (Bandy & Wilcoxon, 1970; Raffi 1986; Barrier *et al.*, 1986; Miyauchi *et al.*, 1994), which Rio *et al.* (1996) found to be distinctively abundant in northern Calabria during MIS 22 866 ka.

Therefore, based on these range of terrace age estimates, the maximum onset age of normal faulting is around 0.99 ± 0.21 Ma (excluding the youngest and oldest age estimate from Catalano *et al.*, 2008; and Tortorici *et al.*, 1995; because they are not supported by palaeontological data). In the Armo fault area, these terraces are underlain by the Early Pleistocene Vinco calcarenites unit, which is also offset by the fault and outcrops in its hangingwall and footwall (Ghisetti, 1992; Atzori *et al.*, 1983; Fig.1c). The minimum possible fault initiation ages would be given by the age of the syn-tectonic coarse alluvial and deltaic sediments deposited in the hangingwall basins and onlapping into the fault planes, suggested to be Middle Pleistocene in the Gioia Tauro and Crati basins (Fig. 1; e.g. Ghisetti, 1984, Colella, 1988; Tortorici *et al.*, 1995; Jacques *et al.*, 2001; Galli & Bosi, 2002; Catalano *et al.*, 2008; Galli & Peronace, 2015).

Published constraints on the evolution and activity of the studied normal faults

We selected the five normal faults in Calabria that bound the main mountain ranges (Fig. 1): The Serre, Cittanova and Armo faults (SF, CNF and AF, respectively), which form a more or less continuous normal fault array in southern Calabria; and the West and East Crati normal faults, in northern Calabria (WCF and ECF, respectively). These are high-angle normal faults with predominantly dip-slip movement, steep cumulative escarpments of hundreds of meters, and wide cataclastic zones (Westaway, 1993; Tortorici *et al.*, 1995; Jacques *et al.*, 2001; Catalano *et al.*, 2008; Spina *et al.*, 2011; Galli & Peronace, 2015). They all exhume the crystalline basement composed of Paleozoic metamorphic rocks (gneisses, schists and phyllites) intruded by Hercynian granitoids (e.g. Atzori *et al.*, 1983; Fazio *et al.*, 2015).

The SF, CNF and AF are NNE-SSE striking, NW-dipping normal faults, and bound the Serre range and the Aspromonte massif (Fig. 1; Monaco & Tortorici, 2000). The oldest marine terraces, described above, are continuously present along their footwalls (Fig.

1c). The Mesima and Gioia Tauro basins are the connected hangingwall basins of the SF and CNF respectively (Fig. 1; e.g. Westaway, 1993; ISMES report, 1999; Jacques *et al.*, 2001; Galli & Bosi, 2002). These are half-grabens infilled by mainly Plio-Pleistocene marine to fluvial shallowing sequences, lying unconformably on top of the basement (Ghisetti, 1981; Miyauchi *et al.*, 1994; Tortorici *et al.*, 1995; Jacques *et al.*, 2001; Catalano *et al.*, 2008; De Rosa *et al.*, 2008; Galli & Peronace, 2015). The Mesima basin has a sedimentary infill of minimum ~425 m thick, (De Rosa *et al.* 2001); while the Gioia Tauro basin infill has been estimated to be 600-1000 m thick (Westaway, 1993; Tortorici *et al.*, 1995; Catalano *et al.*, 2008; ISMES, 1999; Jacques *et al.*, 2001; Galli & Peronace, 2015). Around the Armo fault, regional uplift has been rapid enough to counterbalance hangingwall subsidence, so the whole fault throw is exposed (Atzori *et al.*, 1983; Ghisetti, 1992).

The WCF and ECF bound the Crati basin (Fig. 1b), an asymmetric graben that deepens to the east (Spina *et al.*, 2011). The WCF is an E-dipping, N-S trending fault, formed by four main en échelon segments bounding the Coastal range (Monaco & Tortorici, 2000; Spina *et al.*, 2009). The ECF dips west, formed by three main N-S to NNE-SSW striking segments (e.g. Tansi *et al.*, 2005; Spina *et al.*, 2009) that bounds the W side of the Sila massif, a ~40 km wide plateau with elevations of 1000-1200 m a.s.l. (e.g. Molin *et al.*, 2004; Faccenna *et al.*, 2011). Normal faulting in the Crati basin likely started in the Early-Middle Pleistocene (Spina *et al.*, 2011), as elsewhere in Calabria (i.e. 0.99 ± 0.21 Ma), but the basin opened around the Middle-Late Miocene as a pull-apart basin, due to strike slip faulting to its north and south (Van Dijk *et al.*, 2000; Cifelli *et al.*, 2007; Tansi *et al.*, 2007). This is evidenced by the Tortonian to Holocene ca. 2200 m sedimentary succession that infills the Crati basin, ranging from marine to deltaic and fluvial (e.g. Spina *et al.*, 2009, 2011). There are no marine terraces preserved at the footwalls of the WCF and ECF. Based on the offset of a base-Pleistocene seismic horizon, Spina *et al.* (2011) calculated that approximately 600 m of basin subsidence corresponds to hangingwall subsidence of the ECF. On the WCF side, the base-Pleistocene horizon is offset by ~300 m, based on the same seismic line presented by Spina *et al.* (2011) and their suggested depth-velocity conversion for the basin.

There is evidence that some relief existed in the studied footwall ranges before the onset of high-angle normal faulting; with some authors suggesting that from Late Miocene, the cores of these massifs were exhumed and constituted islands separated by palaeo-straits (e.g. Ghisetti, 1981; Colella & d'Alessandro, 1988; Westaway, 1993; Thomson, 1994a, b). This is based on Late Miocene-Pliocene sediments with provenance from the Serre, Sila and Aspromonte massifs crystalline basements (Ghisetti 1981; Ghisetti & Vezzani, 1981; Colella, 1988; De Rosa *et al.*, 2001, 2008; Spina *et al.*, 2011), thermochronological data (Thomson, 1994a, b), and the deep weathering profile of the Sila plateau, up to tens of meters thick (e.g. Le Pera & Sorriso-Valvo, 2000; Scarciglia *et al.*, 2016).

Displacement rates for the faults have been previously estimated from terrace elevations, cumulative fault scarps and triangular facets (Westaway, 1993; Miyauchi *et al.*, 1994; Tortorici *et al.*, 1995; Monaco & Tortorici, 2000; Jacques *et al.*, 2001; Catalano *et al.*, 2008); offsets of Late Pleistocene sediments exposed by trenching (Galli & Bosi, 2002; Galli *et al.*, 2007; Galli & Peronace, 2015); and seismic profile data (Spina *et al.*, 2011). These are summarized in Table 1. However, they generally provide minimum constraints, because throw rates have often been derived only for the footwall or the hangingwall component of throw, rather than the total cumulative throw (Table 1). Trenching data has provided insights into late Pleistocene slip rates at discrete locations, but may underestimate rates because trenches characterize displacement in one of perhaps several parallel fault splays (e.g. Jacques *et al.*, 2001; Spina *et al.*, 2011), and because coseismic displacement is likely to be attenuated in the trenched, incompetent sedimentary layers (e.g. Walsh & Watterson, 1989; Ghisetti, 1992).

METHODS

Our methods involve (1) analysis of topographic and structural constraints on active faulting, using GIS in combination with hangingwall subsidence and fault onset age data derived from the literature (see Geologic Setting). This is used to obtain new insights into fault throw and throw rates, regional uplift and inherited relief for the studied normal faults; and (2) a systematic examination of the channel network draining the fault footwalls, to examine landscape response to faulting and regional uplift.

Topographic and structural data

Topographic data was acquired from the ASTER digital elevation model (DEM), with a resolution of 27.3 x 27.3 m and an overall mean elevation error of < 1 m (ASTER GDEM2 validation report, 2011), projected in WGS 1984 UTM Zone 33N. Faults were digitally mapped based on: (a) the positions of the lithologic contact between the crystalline basement and the Quaternary deposits, (b) the presence of laterally continuous breaks in topographic slope, and (c) published maps (Tortorici *et al.*, 1995; Monaco *et al.*, 1996; Monaco & Tortorici, 2000; Jacques *et al.*, 2001; Galli & Bosi, 2002, 2003; Cifelli *et al.*, 2007; Catalano *et al.*, 2008; Galli *et al.*, 2008; Spina *et al.*, 2009; 2011). Lithologies were mapped based on the digital Italian Geological Survey (ISPRA) lithological map. The distribution of the Vinco calcarenites was extracted from a higher resolution 1:50000 geological map (Atzori *et al.*, 1983). The oldest marine terraces, at the footwalls of the Serre, Cittanova and Armo faults, have been named differently by different authors; for simplicity, we call them the “Serre-Cittanova-Armo (SCA) terraces”. We have outlined these terraces based on published maps (Ghisetti, 1981; Dumas *et al.*, 1981; Tortorici *et al.*, 1995; Monaco *et al.*, 1996; Galli & Peronace, 2015) and further identification in the DEM of low slope surfaces at similar elevations to the mapped terraces (i.e. slopes < 10°, which correlates with the terraces mapped in detail by other authors).

Swath profiles of the mean, minimum, maximum and range of footwall elevations were constructed along the footwall blocks using a sampling window ~27 m wide (1 pixel).

Polygons for the fault footwalls blocks were defined as the area between the fault traces and the footwall range drainage divide. The minimum elevation swaths represent the elevation of the fault traces, and the maximum elevation swaths the elevation of the drainage divide, so the range of elevation swath depicts the footwall relief profile. Estimates of footwall throw and hangingwall subsidence are both referenced from the fault trace elevation a.s.l., so their summed cumulative throw should be insensitive to the effects of regional uplift. Throw and throw rates are used because they are measured independently of fault dip. The heights of SCA terraces above the fault traces provide a good indication of the footwall component of fault throw, because they formed as a continuous, relatively flat surface before faulting onset. A total of 76 topographic cross-sections of the SCA terraces have been extracted perpendicular to the SF, CNF and AF fault traces (in the supplementary material). From these, we measured the heights of the outer terrace edges from the fault trace, and plotted the values at the position along strike where they have been measured. On the southern CNF, and along the AF, the full fault throw can be measured from the offset of the SCA terraces on the Piani d'Apronte and the Vinco Calcarenes, respectively.

The hangingwall component of fault throw is estimated from the depth of the crystalline basement and/or basin sediment thickness. However, this information is only available at specific localities; and none of the published values have been explicitly derived from the central areas of the hangingwall basins (e.g. De Rosa *et al.*, 2001; Spina *et al.* 2011), where subsidence is expected to be greatest (e.g. Anders & Schilische, 1994). Accordingly, we consider these published values as minimum estimates and plot them at the centres of the fault to build simplified elliptical minimum subsidence profiles, using 2nd order polynomials pinned at the fault tips, which resemble the idealized subsidence profiles in normal faults (e.g. Anders & Schilische, 1994; Gupta & Scholz, 2000). This is supported by findings showing that normal faults or fault segments in the Apennines, and hangingwall subsidence, tend to have elliptical profiles (e.g. Roberts & Michetti, 2004; Amicucci *et al.*, 2008; Villani & Pierdominici, 2011; Roda-Boluda & Whittaker, 2016). We built minimum cumulative throw profiles by summing the SCA terrace heights above the fault trace to the minimum hangingwall subsidence values along strike, derived from the idealized elliptical profiles at the positions where each terrace height has been measured.

For the ECF and WCF, where there are no terraces preserved, we estimated the cumulative throw based on a seismic profile (Spina *et al.*, 2011), which allows the hangingwall component of throw to be constrained. From these values, we extrapolate the footwall throw component based on plausible footwall:hangingwall throw ratios. We consider that the maximum possible value of footwall throw is that given by a 1:1 ratio, according to published theoretical and field data (e.g. King *et al.*, 1988; Anders *et al.*, 1993; Gupta & Scholz, 1998), which has also been found in faults in the Southern Apennines (Roda-Boluda & Whittaker, 2016). We estimate a lower possible footwall throw by using the footwall:hangingwall ratio that we find in the SF and CNF, of 1:1.6 (see Results), which is the same value that Bianca *et al.* (1999) found in faults of the same rift system and of similar age in Eastern Sicily. Catalano *et al.* (2008) also used

this approach and a 1:1.6 ratio to estimate throw rates in the Taormina and Capo Vaticano faults. Because there are no markers of the distribution of throw along these footwalls, we use the footwall mean relief swath profiles as a possible indicator of throw distribution along the footwalls, but we lower these profiles until their maximum relief reaches the values that correspond to the footwall throw values expected by the 1:1 and 1:1.6 ratios of throw partitioning. To reflect the associated uncertainty on throw distribution, we also show in the figures the footwall throw distribution that could be expected from idealized normal fault elliptical profiles (e.g. Anders & Schlische, 1994; Gupta & Scholz, 2000). To obtain the range of likely cumulative throw profiles, we sum the modelled hangingwall subsidence profiles to the possible footwall throw profiles given by the above end-members (1:1 and 1:6). We use as “mean total throw” the throw profile that falls between the two solutions, and use the range between them as the uncertainty range.

The resulting cumulative throw profiles are converted into throw rate profiles by dividing the total throw by the range of possible ages of faulting onset of 0.99 ± 0.21 Ma (Geological Setting). For the SF and CNF, uncertainties result mostly from the hangingwall subsidence estimates. The range of published estimates for the Gioia Tauro basin depth differ by ± 200 m, which implies an uncertainty of $\pm 25\%$. There is one published estimate for the depth of the Mesima Basin, ~ 425 m (De Rosa *et al.*, 2001), so we apply a $\pm 25\%$ uncertainty analogous to the Gioia Tauro basin, obtaining an error range of ± 105 m. In the AF, total throws are well-constrained by the offset of the Vinco calcarenites, but we apply a $\pm 15\%$ error due to the uncertainties in the original geometry of this formation. For the ECF and WCF, the uncertainty derived from the differences in predicting footwall throw using 1:1.6 or 1:1 partitioning are ca. 10%, but we also apply conservative errors of $\pm 25\%$. Throw rate estimates also include the systematic errors derived from the ± 0.21 Myr uncertainty on the onset of normal faulting, which translates into uncertainties up to +58% and -38% for the ECF and WCF, and up to +45% and -30% for the SF, CNF and AF.

We extract displacement(i.e. throw)/length ratios (γ) for the Calabrian faults, and compare them with values directly calculated from published fault throw and length data for the Apennines normal faults and normal fault arrays (Roberts & Michetti, 2004; Papanikolaou & Roberts, 2007; Roda-Boluda & Whittaker, 2016). We calculate γ for the whole Calabrian array based on a 200 km length (from the northern tip of the WCF to the southern tip of the AF, Fig. 1a), and considering the sector across-strike of the Cittanova fault as the most probable area of highest distributed throw, because there are two other documented faults in this sector (Fig. 1a and c): the Scilla (~ 30 km long and 900 m minimum throw, Ferranti *et al.*, 2008) and Santa Eufemia faults (~ 18 km long and 300 m minimum throw, Monaco and Tortorici, 2000; Catalano *et al.*, 2008). We apply a 25% uncertainty to the γ array values.

Drainage Analysis and Landscape Response

A drainage network was obtained using a flow accumulation threshold of 0.37 Km² (500 pixels), confirmed against mapped streams. Ninety-five footwall catchments were extracted upstream of the studied faults, with a mean drainage area of 14 km² and a maximum of 288 km² (Fig. 1). Catchment outlets were picked along the mapped fault trace, but if a channel confluence was present within 1.5 km² downstream from the fault, the catchment was extended to include it, to account for the uncertainty on the fault mapping and allow for bigger catchments (this only affected 8% of the catchments). Catchments smaller than 2.5 km² were excluded. Stream long profiles were extracted using the Stream Profiler toolbar (Wobus *et al.*, 2006a), and can be found in the supplementary material. For catchments with several channels that share at least 2/3 of their length, only the channel with greater drainage area was extracted. If channels shared less than 2/3 of their length, a long profile was extracted for each. A reference concavity of 0.45 was used to calculate k_{sn} values, to compare our k_{sn} values with those published in Calabria and the Southern Apennines using this value (Cyr *et al.*, 2010; Olivetti *et al.*, 2012; Roda-Boluda & Whittaker, 2016). Because we are interested in knickpoints related to potential throw rate increases, only slope-break knickpoints (c.f. Kirby & Whipple, 2012) bounding a lower section of the channel which registers $\geq 10\%$ increase in k_{sn} were marked on the long profiles. None of the identified knickpoints were observably coincident with mapped lithologic boundaries. The vertical heights of knickpoints were measured from the basin-bounding fault (e.g. Whittaker & Walker, 2015; Roda-Boluda & Whittaker, 2016). Both k_{sn} values and knickpoint heights are presented as catchment-averaged values, plotted at the along-strike position that corresponds to their catchment outlet, with the scatter within each catchment represented by error bars. Each catchment has been assigned a throw rate value, determined from the mean throw rate profiles for the position of catchment outlet, as tectonic signals are propagated upstream from this point (e.g. Whittaker *et al.*, 2007).

RESULTS

Fault traces and relief

The Serre (SF), Cittanova (CNF) and Armo (AF) faults constitute an approximately continuous, ~100 km long fault system, in a right-and-left-stepping en échelon arrangement (Fig. 1c). The East (ECF) and West Crati faults (WCF) are formed by 3 and 4 main segments respectively, separated by relay ramps (Fig. 1b). Along-strike swath profiles of the mean, maximum and minimum elevations of the SF, CNF and AF footwall blocks show greatest relief at about 80 km along strike, for which mean and maximum elevations reach ~1600 m and ~1900 m respectively (Fig. 2a). This peak corresponds to the Aspromonte massif, bounded by the southern half of the CNF and by the AF (Fig. 1). Along the Serre range, bounded by the SF and the northern half of the CNF, mean elevation is approximately uniform, with values around 700 m. The ECF swath profiles show that mean elevation in the Sila massif increases progressively, from

~400 m at its northern tip to a mean value of ~1000 the south (Fig. 2b). The WCF swath profiles show a mean elevation of ~1900 m to its northern tip, which to the south decays rapidly to values of ~800 m in just 8 km (Fig. 2c).

The minimum elevation swaths represent the elevations of the projected mapped fault traces that vary along strike due to fluvial incision. In the central areas of the Aspromonte massif (where there is no sedimentation because regional uplift has counter-balanced hangingwall subsidence; e.g. Pucci et al., 2014), the traces of the CNF and AF are uplifted up to ~1300-1400 m a.s.l. (Fig. 2a). At the northern and southern edges of the Aspromonte and along the Serre range, fault traces of the AF, CNF, and SF (Fig. 2a), as well as Pleistocene marine sediments on the Mesima and Gioia Tauro basins (Fig.1), appear now at elevations of ~300-500 m a.s.l. In the Crati basin, the ECF and WCF fault traces (Fig. 2b, c) and Pleistocene marine sediments (Fig. 1) are generally at elevations of ~350-500 m a.s.l. Maximum sea-level fluctuations in this area during the Pleistocene are thought to have been of the order of ± 100 -150 m (Ghisetti, 1981; Westaway, 1993; Cucci & Cinti, 1998; Dumas *et al.*, 2005). Therefore, subtracting these fluctuations, a minimum of ~200-400 m of relief has probably been generated by regional uplift along the studied ranges since at least ~1 Ma, a value that could increase up to ~1150-1300 m in the centre of the Aspromonte massif. These estimates would yield regional uplift rates of the order of 0.2-1.3 mm/yr, similar to those estimated from younger terrace levels (see Geological setting).

We propose that the current elevations of the fault traces are markedly influenced by the effects of regional uplift. The reason is that normal faulting likely started soon after the formation of the SCA terraces, which formed at sea level ~ 1 Ma: Indeed, given the Middle Pleistocene age of the syn-extensional hangingwall sediments, there is a short period of time between the SCA terrace formation and the initiation of faulting (see Geological Setting). As the faults uplift and/or dissect these terraces, they clearly did not simply cut through areas of pre-existing relief. Consequently, we deduce that the current elevations of the fault traces are influenced by coeval regional uplift since ~ 1 Ma. Alternative explanations imply that after the formation of the SCA terraces, there was substantial regional uplift before the faults formed and dissected the already uplifted SCA terraces. However, for the SCA terraces to be substantially and differentially uplifted before the faulting started would require, for this short time period, regional uplift rates orders of magnitude greater than previous estimates, for which we have no evidence.

Footwall relief along the SF, CNF and AF decays to values close to zero at their tips, with maximum values potentially corresponding to the centres of fault segments, and/or to areas of inherited relief (Fig. 3a). The SF displays two flat-topped footwall relief maxima, a northern one between 3-13 km along strike, and a southern one at 30-34 km along strike. The boundary between the SF and CNF is marked by a minimum in footwall relief, of ~440 m, at about 37 km along strike. Along the CNF, footwall relief displays two maxima, at about 42 km and 72 km along strike. The CNF and AF are separated by a relief minimum of ~200 m, at about 84 km along strike. The AF presents

a single footwall relief maximum. Footwall relief along the ECF has a similar distribution to the classic elliptical profiles of normal faults (Fig. 3b), but the range-of-relief swath profile is slightly asymmetric, with a single maximum at around 30 km along strike. The WCF has four footwall relief maxima at the centres of the mapped fault segments, at ca. 7 km, 38 km, 51 km, and 63 km along strike; and the segment boundaries can be identified from the relief minima. However, the much higher footwall relief at the north of the fault may be due to inherited relief from the NE part of the Coastal range (Fig. 1).

New constraints on long-term normal fault activity

SCA terraces and total throw on the Serre, Cittanova and Armo faults

Along the AF and CNF, the SCA terraces lie at similar elevations and have a similar distribution to the derived footwall relief (Fig. 3a), which suggests that current footwall relief is almost entirely fault-generated. The geologic throw derived from the offset of the Vinco calcarenites along the AF also has similar values and distribution to the terrace heights and footwall relief, showing that its entire throw is exposed and is well-represented by the topography (Fig. 3a). At the boundary between the CNF and AF, in the Piani d'Aspromonte, the remnants of the SCA terrace are preserved on both the footwall and hangingwall, so their offset of ~60-100 m represents fault total throw in this area. However, footwall relief is greater than the terrace offsets, suggesting inherited topography from the Aspromonte massif before the terraces formed. At the boundary between the CNF and SF, the SCA terrace is found at heights of only ~100 m; and along the SF, terraces have a relatively constant height of ~ 320 m. However footwall relief above and to the east of the SCA terraces, is consistently ~300-550 m greater than the terrace elevations (Figs. 1 and 3a), suggesting again the existence of some relief prior to the formation of the SCA terraces and subsequent onset of normal faulting.

In the resulting cumulative throw profiles (Fig. 4a), estimated mean throws reach values of $\sim 780 \pm 105$ m on the SF, $\sim 1430 \pm 200$ m on the CNF, and $\sim 700 \pm 105$ m on the AF; with the CNF having approximately twice as much throw as the SF and AF. Because the tips of the SF and CNF overlap in an en échelon arrangement, the two modelled subsidence profiles overlap at their boundary, which would imply the existence of an intra-basin high through which the Gioia Tauro and Mesima basin are connected, as supported by basin maps (Fig. 1). Importantly, throw does not decay to zero at any point along strike, suggesting that these three faults are linked, as we discuss later. The boundary between the SF and CNF has a total throw of ~415 m, while the boundary between the CNF and AF registers a total throw of ~100 m, which may indicate that these two sectors have accumulated throw for different amounts of time.

Total throw on the East and West Crati faults

The footwall component of throw on the ECF and WCF is harder to constrain, because marine terraces are not present on their footwalls and there is evidence of significant

pre-existing relief before the onset faulting. However, hangingwall subsidence constraints exist from a seismic reflection profile across the Crati basin (Spina *et al.*, 2011). Using the rationale outlined in the Methods, we obtain footwall throw estimates between 600-360 m for the ECF, and between 300-180 m for the WCF. The resulting cumulative throw profiles, considering a 25% uncertainty, have maximum throw values of $\sim 1260 \pm 315$ m at the fault centre of the ECF; while for the WCF the maximum total throw values, of $\sim 640 \pm 160$ m, are found at the fault centre and at the northernmost segment.

Throw rate profiles

Based on our synthesis of the literature, these normal faults likely initiated their activity at 0.99 ± 0.21 Ma (Geological setting). Using this range of fault initiation times, and the fault throws, above, we obtain mean time-averaged throw rates of up to $0.80^{+0.33}_{-0.22}$ mm/yr for the Serre fault, $1.45^{+0.65}_{-0.45}$ mm/yr on the Cittanova fault, and $0.72^{+0.33}_{-0.22}$ mm/yr on the Armo fault (Fig. 4a); and up to $1.3^{+0.73}_{-0.51}$ mm/yr on the East Crati fault and $0.65^{+0.35}_{-0.25}$ mm/yr on the West Crati fault (Fig. 4b).

Throw/length ratios

Figure 5 shows that the throw/length ratios (γ) for the studied faults are between 0.01-0.047, to first order, similar to γ values reported for normal faults on the Southern Apennines (0.025-0.058, Papanikolaou & Roberts, 2007; Roda-Boluda & Whittaker, 2016) and Central Apennines (0.035-0.083, Roberts & Michetti, 2004). However, in detail, γ values for the Calabrian faults γ values are generally on the lower end of the range for faults in Italy. Notable is the West Crati fault, which appears considerably underdisplaced. Summing the throws of the Cittanova, Scilla and Santa Eufemia faults (~ 2600 m of minimum distributed throw), we estimate that the Calabrian fault array has $\gamma = 0.013$, similar to those found in the Southern Apennines (0.014-0.022; Papanikolaou & Roberts, 2007) and Central Apennines fault arrays (0.014, Roberts and Michetti, 2004).

Stream long profiles

Channel steepness indices

Using these tectonic constraints, we evaluate how the landscape records the active faulting, inherited relief and regional uplift. Figure 6 shows the catchment-averaged normalized steepness index, k_{sn} ($m^{0.9}$), of the channels draining the fault footwalls, plotted at the along-strike distance where they cross the fault (i.e. the footwall catchment outlets; Fig. 1). For all faults, k_{sn} varies between $\sim 50 m^{0.9}$ and $\sim 150 m^{0.9}$ (Table 2, Fig. 6), channels are generally steeper where throw rates and relief are higher, and become progressively less steep towards the fault tips; indicating that they are recording variation in fault slip rates. In the Serre fault (Fig. 6a), k_{sn} values display two peaks that are coincident with those found in the footwall relief and that do not

correspond to throw rates. In the northern sector of the Cittanova fault, k_{sn} values are about half of those in the southern sector; this could be due to differences in or lithology, as the southern part of the CNF fault is dominated by metamorphic rocks and the northern one by granites (Fig. 1c). On the Armo fault, the along-strike distribution of k_{sn} values is a good reflect of footwall relief and throw. We note that k_{sn} values decay to $\sim 50 \text{ m}^{0.9}$ at the SF-CNF and CNF-AF boundaries. On the East Crati fault, the spatial distribution of k_{sn} reflects to first order footwall relief. Along the West Crati fault, k_{sn} values are higher at the centres of the identified fault segments, and decay to values up to $\sim 70 \text{ m}^{0.9}$ at the segment boundaries.

In Fig. 7, we compare catchment-averaged k_{sn} directly with catchment relief and estimated throw rate. We use the mean throw rate values, but since the errors are systematic, the trends would remain the same for any of the plausible throw rate profiles presented in Fig. 4. For all faults, k_{sn} values increase and are more variable with increasing relief (Fig. 7a), as observed in Fig. 6. However, the correlation has slightly different scalings when each fault is considered separately; particularly the WCF channels seem to steepen about twice as fast as the other faults with each relief increment (Table 3). There is also a reasonable scaling of k_{sn} with throw rate (Fig. 7b), with channels of all faults steepening at similar rates of $\sim 5\text{-}7 \text{ m}^{0.9}$ for each 0.1 mm/yr increment; except the WCF channels which steepen at about twice that rate (Table 3). However, depending on the fault, the absolute k_{sn} magnitude is different for similar throw rates. In two cases (SF and ECF), k_{sn} correlates significantly better with relief than with throw rates (see Table 2), which could relate to the fact that the footwalls of these faults have a greater proportion of pre-existing relief that is unrelated to normal faulting. On the CNF and AF, the degree of correlation of k_{sn} with relief and throw rates is similar, which supports the finding that footwall relief is mostly fault-related (Table 2). We explore the implications of this in the discussion.

We test explicitly the role of lithology in modulating channel steepness in Fig. 7c. We find that channels underlain by metamorphic rocks and granites steepen at a similar rate as throw rates increase (Table 3), but those draining metamorphic rocks are generally about $\sim 30 \text{ m}^{0.9}$ steeper than those draining granites, for all the range of throw rates. This is likely due to the different erodibilities of these lithologies: Schmidt hammer rebound values for gneisses and schists in the area are about twice as much as those reported for the granites, with average values of ~ 27 and ~ 16 respectively (Roda-Boluda, 2016). This probably explains why k_{sn} values are lower along the SF and northern CNF than on the southern CNF and AF (Fig. 6a).

Knickpoints

The presence, distribution and heights of knickpoints upstream of the faults can provide information about past changes in base level lowering rates, often related to the faults evolution. Along the AF, we only find one set of knickpoints, at heights between $\sim 200\text{-}800 \text{ m}$, which are related with a downstream k_{sn} increase of a factor of ~ 3 (Fig. 8a, b, Table 2). Along the SF and CNF, there is at least one set of knickpoints on all channels, and most of them have two sets, with their upper knickpoints at heights of $\sim 200\text{-}750 \text{ m}$,

and registering downstream k_{sn} increases of three to four times (Fig. 8a, b, Table 2). The upper (for the SF and CNF) or single (for the AF) knickpoints are found at similar, or slightly higher elevations, to the SCA terraces, and vary along strike with a similar pattern to our estimated footwall throw and footwall relief (Fig. 8a), so we suggest that they formed as a result of the onset of normal faulting, or early in faulting history (e.g. Whittaker & Walker, 2015). The lowest knickpoints on the SF and CNF are found at heights between ~100-600 m, associated with average k_{sn} increases of a factor of two for both faults, and are evidently younger. Their height also varies systematically along strike reflecting footwall throw and relief, indicating that these knickpoints relate to normal fault activity. The change in relative base-level that created them, not recorded along the AF, could have been associated with changes in fault throw rates, driven by fault interaction or a regionally-driven acceleration of the studied faults. We explore these hypotheses in the discussion.

Channels crossing the ECF and WCF have one to two knickpoints. On the ECF channels, the single or lowest set of knickpoints is found at ~150-600 m above the fault, recording overall a two-fold k_{sn} increase, and an upper knickpoint is only found in three channels (Fig. 8d). On the WCF, most channels have one knickpoint, at elevations between 150 m and 770 m with downstream k_{sn} increasing approximately 1.4 times; and two channels have upper knickpoints at ~550 m associated with a three-fold k_{sn} change (Fig. 8e). Along the ECF and WCF, the upper knickpoints plot very close to the top of the footwall relief, so they could have formed as normal faulting initiated. The single or lowest knickpoints do not vary significantly or consistently along strike, so we hypothesize that they represent a change in base level lowering rates unrelated to the normal faulting.

DISCUSSION

Fault throw rates: comparison with previous estimates

The data presented here is the first comprehensive and methodologically consistent along-strike evaluation of long-term fault throw and throw rates on the studied faults in Calabria. Because the estimates of basin subsidence or sediment thickness that we use do not necessarily document the point of maximum subsidence, our total throw and throw rates should be considered minimum estimates. Our approach also takes into account the hangingwall and footwall components of fault throw. For this reason, and due to the diversity of methodologies used by different authors to estimate fault activity, previously published estimates (Table 1) differ from ours in some cases.

For the Cittanova fault, previous estimates of throw rates are highly variable (Table 1). Westaway (1993) estimated a total throw rate of 0.4 mm/yr, after subtracting ~700 m of regional uplift to his footwall uplift estimate. This approach likely results in an underestimation of fault throw rates, because regional uplift affects the elevation of the fault trace and hangingwall basins as well. Tortorici *et al.* (1995) considered that given

their estimate of 1200 m of total throw and attributing a 1.8 Myr age to the SCA terraces, the minimum uplift rate of the CNF is 0.6-0.7 mm/yr. They also estimated throw rates using two sets of “triangular facets” developed at the fault scarp. Assuming that the breaks between the sets of “facets” correspond to warmer, wetter periods of enhanced erosion linked to the last interglacials, they obtain throw rates of 0.7 mm/yr for the last 120 kyrs, and 0.8-1 mm/yr for the last 240 kyrs. Catalano *et al.* (2008) suggested throw rates of about 1.2 mm/yr by dividing the ~700 m SCA terrace height by the 580 ka age that they assign them. We note that the estimates of Catalano *et al.* (2008) and Tortorici *et al.* (1995) rely on ages for the same SCA terraces that differ by a factor of 3. Constraints have also been derived from paleoseismic trenching: Galli & Bosi (2002) estimated a throw rate of 0.44 mm/yr for the past 25 kyrs, and Galli & Peronace (2015) of 0.6 ± 0.1 mm/yr for the past 28 ka. However, these are minimum estimates because they are derived from one of potentially several fault splays, and are only representative of recent fault activity. Our long-term throw rate estimate is $1.45^{+0.65}_{-0.45}$ mm/yr, twice the values estimated by Tortorici *et al.* (1995) and Galli & Peronace (2015). The throw rate suggested by Catalano *et al.* (2008), 1.2 mm/yr, is closer to our estimated value, although it was derived using different assumptions.

For the Serre fault, Catalano *et al.* (2008) reported throw rates of 0.6-0.7 mm/yr, based on the footwall scarp which they identify as being ~380 m in elevation, and attributing the footwall terraces to 580 ka. Monaco & Tortorici (2000) report throw rates of 0.6-1 mm/yr, but they do not specify their methodology. Our results suggest throw rates of $0.80^{+0.33}_{-0.22}$ mm/yr, similar to these values, although using a revised methodology.

For the Armo fault, Ghisetti (1992), based on the displacement of Pleistocene beds, estimated that fault throw had a minimum value of 0.28 mm/yr for the last 0.7 Myrs. Miyauchi (1994) estimated that faulting started 0.8-1.2 Ma, with a time-averaged throw rate of 1 mm/yr, based on terrace offsets. Our estimated time-averaged throw rate is $0.72^{+0.33}_{-0.22}$ mm/yr, which lies between previous estimates. The combination of faster regional uplift in the Aspromonte area, and the lower slip rates of this faults, explain why accommodation space has not been created on the AF hangingwall (e.g. Pucci *et al.*, 2014).

On the East Crati fault, Spina *et al.* (2011) estimated a minimum throw rate of 0.9 mm/yr for the last 0.7 Ma, based on the offset of the seismic horizon identified as the top Middle Pleistocene. However, this considers only the hangingwall component of total throw, and is derived from the northern part of the basin, where rates are likely lower than in the fault centres. Our total throw profiles are derived from their data in the northern part of the basin, but we have also inferred the footwall component of throw, from which we obtained greater minimum time-averaged throw rates of $1.3^{+0.73}_{-0.51}$ mm/yr.

On the West Crati fault, Tortorici *et al.* (1995) derived a throw rate estimate of 0.8-1 mm/yr by dividing the footwall relief by their estimated age of faulting onset, 0.7 Ma. Their approach neglects that pre-existing relief is reported in the area and only includes the footwall throw. They also estimate throw rates from triangular facets, following the

same approach described above, and report values of 0.6-0.9 mm/yr for the last 120
kyrs, and 1 mm/yr for the last 240 kyr. However, Spina *et al.* (2009, 2011), who also
recognize triangular facets on the East Crati fault, suggest that these actually represent
long-term fault activity. Therefore, throw rates deduced from triangular facets, which do
not have exposure ages that could confirm their age of development, may be
misleading. Finally, Monaco & Tortorici (2000), based on the 150 m offset of Middle
Pleistocene Gilbert type deltas, suggest a slip rate of 1.2 mm/yr for the last 125 kyrs.
Our results suggest throw rates of $0.65^{+0.35}_{-0.25}$ mm/yr, on the lower end of published
estimates, because we do not consider that all relief in the footwall is necessarily fault-
related.

Overall, the disagreements on the estimated fault throw rates arise from how different
authors have dealt with the main sources of uncertainty: (1) isolating the effects of
superimposed regional uplift; (2) deciphering the footwall and hangingwall components
of fault slip, and differentiating them from potential pre-existing relief; (3) lack of an
absolute dating framework on the SCA terraces, fault scarps or facets, and oldest basin
sediments; (4) the ages that different authors have used as reference age for the
“Middle” Pleistocene. We believe that problem (1) is minimized by characterizing the
footwall and hangingwall components of throw independently, using as reference the
elevation of the fault traces a.s.l. We have dealt with problem (2) by using the along-
strike heights from the fault of the SCA terraces as indicators of minimum footwall
throw instead of footwall relief, and by taking into account published estimates of
hangingwall basin depth where available. Where there are no markers to estimate
footwall throw (ECF and WCF), it has been estimated by considering the possible range
of footwall:hangingwall throw ratios, based on published estimates of other faults in the
area and the ones derived here for the SF and CNF. We overcome problems (3) and (4)
by reconciling the range of published ages for the SCA terraces, basin sediments depth
and ages, and faulting onset; and by expressing our results (Fig. 4) as a range of
possible throw rate values that account for the propagated uncertainties. Our throw rate
estimates are in some cases different from previous published estimates, and similar in
others, but are derived using a consistent methodological framework to address this
problem. For the CNF and ECF, our throw rate estimates are > 0.2 mm/yr greater than
any previous published value for those faults, so a revision of their seismic potential
should be addressed in future work.

The slightly lower γ values for these faults, in comparison with those in the Central and
Southern Apennines (Fig. 5), potentially relate to the fact that the Calabrian normal fault
array is ca. 1-2 Myr younger than those elsewhere in the Apennines (e.g. Roberts and
Michetti, 2004; Papanikolaou & Roberts, 2007; Roda-Boluda & Whittaker, 2016), and
therefore these faults have not accumulated yet enough displacement to achieve a
“mature” γ value in accordance with their fault lengths (e.g. Walsh *et al.*, 2002; Kim &
Sanderson, 2005). The considerable underdisplacement of the WCF suggests that either
we have severely underestimated fault throw (by a minimum of ~ 1000 m, which is

unlikely), or that as we explore below, the West Crati fault segments are not fully linked yet.

Comparison of fault activity with regional uplift and inherited relief

The question of how much of the present-day footwall relief is due to normal faulting, regional uplift, and/or pre-existing relief, has to-date never been fully addressed. Our results suggest spatially variable regional uplift rates of between ~0.2-1.3 mm/yr, which agree well with published estimates of ~0.2-2 mm/yr (see Geological Setting). Besides the potential heterogeneity of regional uplift, the overlap of normal faulting and the different methodologies used also explain the wide range of published values.

The relative magnitudes of regional uplift and normal fault-related uplift are debated. Westaway (1993) considered that regional uplift rates are 10 times higher than fault throw rates, which he estimated as being ~0.1 mm/yr. Ghisetti (1992) suggested that fault slip rates are one order of magnitude lower than regional uplift rates, there quantified as 2-3 mm/yr. The very low fault throw rates suggested by these authors are on the threshold of observation; and if true, given the larger erosion rates measured in Calabria using cosmogenic nuclides (Cyr *et al.*, 2010; Olivetti *et al.*, 2012; Roda-Boluda, 2016) footwall ranges might be expected to have very subdued relief, which is not the case (e.g. Fig. 3). Roberts *et al.* (2013) evaluated how the activity of the Vibo fault, at ~1 mm/yr, affects the elevations of marine terraces and impose an apparent gradient of regional uplift from 0.4 to 1.75 mm/yr over a few tens of km. Our newly derived fault throw rates, together with previous fault throw rate estimates (e.g. Catalano *et al.*, 2008; Tortorici *et al.*, 1995), also suggest that faults in Calabria have throw rates of similar magnitude to regional uplift rates. Absolute dating of the oldest sets of marine terraces or low temperature thermochronology would further help to elucidate the interplay of regional and fault-related uplift; but some regional uplift constraints should be revisited in the light of new along-strike distributions of fault-related uplift (e.g. Roberts *et al.*, 2013, this work).

On the AF, fault throw is fully exposed and it is up to ~700 m, which superimposed to the Aspromonte's regional uplift, creates the current relief of up to ~1900 m, without the need to invoke pre-existing relief (Fig. 2). Along its footwall, the height of the SCA terraces and the offset of the Vinco calcarenites have similar values to the footwall relief (Fig. 3a), implying that current footwall relief is entirely fault-generated. At the boundary between the AF and the CNF, terraces are ~550 m lower than footwall relief (Fig. 3a), so this sector of the Aspromonte was likely an area of considerable relief, part of which is still preserved, before the SCA terraces formed and normal faulting started, as suggested by Ghisetti (1981). Along most of the CNF, the footwall component of throw is ~400-750 m, which superimposed into the ~200-400 m of regional uplift, can explain the maximum relief of ~1000-1100 m that is found on its footwall (Fig. 2a). On the SF footwall, the SCA terraces are ~250-400 m above the fault trace (i.e. Fig. 3a), which summed to the ~200-400 m of regional uplift in this area, do not account for the maximum elevations of ~950-1300 m a.s.l. along the Serre range (Fig. 2). The SCA

terraces are also ~300-550 m lower than the footwall relief along the entire SF length (Fig. 3). Therefore, relief must have existed in the Serre range before the SCA terraces formed, and is now still expressed in the ~300-550 m “excess” relief of the SF footwall. For the Sila massif, based on our throw estimates along the ECF (Fig. 3b), pre-normal faulting relief could have been between ~300-800 m a.s.l., in agreement with some published estimates that suggest significant relief prior to the onset of normal faulting (e.g. Molin *et al.*, 2004; Olivetti *et al.*, 2012, Thomson *et al.*, 1994a, b; Tansi *et al.*, 2007; Spina *et al.*, 2011). Similarly, pre-normal faulting relief along the Coastal Range, bounded by the WCF, could have been ~350-700 m, based on the whole range of plausible fault throw values, and it is probably particularly significant on the northern end of the fault (Fig. 4).

These values should be considered minimum estimates, because we are not considering the effects of erosion. However, they confirm that a minimum pre-existing relief of ~300 m a.s.l. existed along the Serre and Coastal ranges, and the Sila massif. Although this does not allow us to clarify the mechanism that created this pre-SCA relief; it is unlikely that it was due to the studied normal faults being active before the SCA terraces formed, because their activity would have prevented the formation of a such a continuous level of terraces, and they are offset by the faults in some localities (i.e. Piani d’Aspromonte, Fig. 1c).

Fluvial response to normal faulting and constraints on normal fault evolution

The fluvial network draining the normal fault footwalls is responding to fault displacement, with steeper channels in sectors where fault throw and relief are greater (Fig. 6 and 7). The scaling of k_{sn} with relief is between $k_{sn}=0.05R$ and $k_{sn}=0.08R$ (except for the WCF, $k_{sn}=0.13R$), similar to the global trend found by D’Arcy & Whittaker (2014). We find a similar scaling with throw rate, of k_{sn} increments of ~5-7 $m^{0.9}$ for each 0.1 mm/yr increase, despite the fact that for three of the faults, throw rates have been constrained independently of relief. The steepness indices of channels draining those faults with none or minor pre-existing relief (i.e. the AF and CNF) correlate better with catchment throw rates than with catchment relief, indicating that the stream network characteristics are largely dominated by active normal faulting (Fig. 7; Table 3). On the contrary, the k_{sn} of channels draining along the faults with more pre-existing relief (the ECF and SF), correlate better with catchment relief than with catchment time-averaged throw rates (Fig. 7; Table 3). We suggest this is because their channels are draining topography which is not fully related to normal faulting. Overall, the steepness of the footwall channels is reflecting a combination of normal fault activity and the proportion of inherited relief (Fig. 6, 7a, b), with lithology being a secondary modulating factor (Fig. 7c)

Most of the studied footwalls, except the AF, have two sets of knickpoints in some catchments, implying that they have experienced two changes in their relative base level lowering rates. We suggest that the most plausible explanation for the upper knickpoints, which appear close to the top of the footwall relief and footwall throw, is that they formed at the onset of normal faulting (e.g. Whittaker & Walker, 2015). We

hypothesize that these set of knickpoints probably formed in all channels, but have migrated all the way upstream in some of them, so the upper knickpoint can no longer be recognized along some channels. This is supported by the fact on those channels with only one set of knickpoints, incision seems to have progressed all the way upstream (see long profiles on the supplementary material). In contrast, for the channels crossing the AF, it can be appreciated on their long profiles that the sectors above their only knickpoints are completely unincised. These knickpoints appear at the top of the relief, at similar elevations to the SCA terraces (Fig. 8b), so we suggest that they are the 1st generation knickpoints, formed as a result of the onset of normal faulting.

Along the SF and CNF, the distribution of the lower set of knickpoints is similar to the distribution of throw along strike (i.e. SCA terraces), so we hypothesize that these were caused by a later change in fault slip rate. If throw rate enhancements were caused by fault interaction, knickpoints would be expected to be higher around the old fault boundaries (e.g. Commins *et al.*, 2005; Roda-Boluda & Whittaker, in review), because they migrate vertically at a rate that is proportional to the magnitude of the perturbation experienced, and these are the areas that experience greater changes in throw rates following linkage (see Introduction). However, we find that knickpoints are lower around the fault boundaries, and that their distribution mirrors the relief and throw distribution. This pattern would be compatible with a general acceleration in base level lowering rates which is not directly related to fault interaction (e.g. Harkins *et al.*, 2007; Miller *et al.*, 2012, Olivetti *et al.*, 2012), for example due to an overall acceleration of strain rates in Calabria.

In contrast, the throw profiles of SF and CNF reveal that the throw minima between these two faults has accumulated ~415 m of throw, and the hangingwall basins of the SF and CNF are connected (Fig. 1), which would imply that they are physically linked. Similarly, between the CNF and AF, there is a throw minima of non-zero (~125 m), suggesting that these faults are linked; but we do not find a second set of knickpoints that could be associated with acceleration following this linkage. Therefore, from the distribution of throw, it appears that the three faults are now physically linked, and that the SF-CNF linked earlier than the CNF-AF. However, the distribution of knickpoints along the SF and CNF is more consistent with a regional acceleration of fault throw rates than with a fault interaction scenario, and the channels do not reflect, at least yet, the CNF-AF linkage. Two possible explanations for this apparent disagreement could be: (a) that the fault boundaries have not completely breached (Fig. 1), and hence because these faults are only partially linked, throw rates have not significantly accelerated and created a 2nd set of knickpoints in the CNF-AF boundary, or fast knickpoint migration rates on the SF-CNF boundary; (b) that if the CNF-AF linkage is very recent, the knickpoints related to this event are still very close to the fault and cannot be differentiated from its scarp. Incipient or recent segment interaction would also be consistent with the slightly lower γ values on the studied faults, in comparison with the Central and Southern Apennines ones (Fig. 5), which have experienced linkage episodes ~ 0.7-1 Ma (Roberts & Michetti, 2004; Roda-Boluda & Whittaker, 2016). In any case, it is clear that the SF and CNF faults have experienced throughout their

faulting history a change in throw rates; which k_{sn} ratios suggest could have been of the order of two (Table 2). This acceleration would imply the fault throw rates acting on these faults are greater than the time-averaged throw rates.

Along the ECF and WCF, the single or lowest knickpoints appear at relatively uniform elevations along strike, which are similar for both faults (Fig. 8). Because the Crati basin was connected with the sea until the Middle-Late Pleistocene (e.g. Spina *et al.*, 2011), they could have formed after a change in base level lowering rates related to regional uplift (e.g. Niemann *et al.*, 2001; Wobus *et al.*, 2006b; Crosby and Whipple, 2006). Based on the ratios of k_{sn} above and below these knickpoints, the change in lowering rate could have been of the order of ~ 1.4 -2 times (Table 2). Olivetti *et al.* (2012) also found that channels draining the Sila massif had two sets of knickpoints, which they attributed to the onset of doming uplift and a later (~ 400 ka or ~ 700 ka) episode of uplift acceleration. It is difficult to assess the role of normal fault interaction on these perturbations; although the ECF and WCF fault segments could be linked at depth, the distribution of knickpoints is not consistent with acceleration following segment linkage. For the WCF, the very low γ value also suggests that segments have not fully interacted yet (Fig. 5). Our findings extend those of Olivetti *et al.* (2012), suggesting that the change in base level lowering rates that they identified on the Sila massif probably also affected the entire Crati basin.

CONCLUSIONS

Swath profiles along the footwall blocks of the Armo (AF), Serre (SF), Cittanova (CNF), East (ECF) and West Crati (WCF) faults reveal that a minimum of ~ 200 -400 m of Calabria's present relief, and up to ~ 1150 -1300 m of the Aspromonte massif relief, has probably been generated by regional uplift since the Middle Pleistocene, at rates between ~ 0.2 -1.3 mm/yr.

From a compilation of hangingwall subsidence data and new footwall throw constraints, we have estimated cumulative throws of 780 ± 105 m on the SF, 1430 ± 200 m on the CNF, and 700 ± 105 m on the AF; 1260 ± 315 m on the ECF, and 640 ± 160 m on the WCF. Using our best estimates of the range of fault initiation time (0.99 ± 0.21 Ma) we derive time-averaged throw rates of $0.80^{+0.33}_{-0.22}$ mm/yr for the SF, $1.45^{+0.65}_{-0.45}$ mm/yr for the CNF, $0.72^{+0.33}_{-0.22}$ mm/yr for the AF, $1.3^{+0.73}_{-0.51}$ mm/yr for the ECF, and $0.65^{+0.35}_{-0.25}$ mm/yr for the WCF. These data suggest that the Cittanova fault is the fastest slipping normal fault in Calabria.

Comparison of footwall relief and footwall throw reveals that pre-faulting relief, if it existed, has been eroded along the CNF and AF footwalls. In contrast, there is still ~ 300 -550 m of pre-faulting relief on the Aspromonte, and along the SF footwall, which was present before the SCA marine terraces formed and normal fault activity started. On the Coastal Range, bounded by the WCF, and the Sila massif, bounded by the ECF, the amount of relief pre-dating the normal fault onset could be of ~ 300 -800 m.

For rivers crossing these faults, channel steepness index (k_{sn}) varies between $\sim 50 \text{ m}^{0.9}$ and $\sim 150 \text{ m}^{0.9}$, with k_{sn} reflecting the active normal faulting and relief. Channels become $\sim 5\text{-}8 \text{ m}^{0.9}$ steeper for each increment of 0.1 mm/yr in throw rates and 100 m increase in relief. In those channels draining footwalls with greater proportion of estimated pre-existing relief (ECF and SF), k_{sn} scales more poorly with fault throw rates, highlighting the influence of inherited relief.

Finally, one to two sets of knickpoints are found on the channels draining the footwalls of the studied faults, generally associated with k_{sn} increases of $\sim 2\text{-}3\times$, implying that these channels are transiently responding to perturbations to their base level lowering rates. For the CNF and SF, we suggest that these are associated with throw rate acceleration caused by fault interaction or a regional increase in strain rates. For the ECF and WCF, the distribution of knickpoints is more consistent with a change in base level lowering rates caused by regional uplift. As some of our time-averaged throw rate estimates are higher than previously reported, and because our analysis of the drainage network indicates that current fault throw rates are likely greater than time-averaged estimates, we strongly suggest that the seismic potential of these faults should be revisited.

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FIGURE CAPTIONS

Table 1. Compilation of published throw rate constraints for the studied faults.

Table 2. Catchment-averaged whole channel k_{sn} ; catchment-averaged k_{sn} of the sections above and below knickpoints (k_{sn}^1 lowest section, k_{sn}^3 highest section); k_{sn} ratios; and knickpoint heights from fault, for all studied catchments (catchment numbers are shown in Fig. 8). The $\pm$ errors represent the scatter of values for the different tributaries in the catchments, if any. Stream long profiles of all the studied 146 channels can be found in the supplementary material.

Table 3. Parameters and correlation coefficients of the linear fits of k_{sn} against relief (Fig. 7a) and against mean throw rates (Fig. 7b), for each individual fault, all faults, and for the main lithologies (Fig. 7c).

Figure 1. (a) DEM of the study area, showing the main ranges and massifs of Calabria, and a simplified map of the active normal faults of the “Siculo-Calabrian Rift Zone”. The inset shows the study area in the context of the subduction zone and associated back-arc extension. (b) Simplified geological and faults map of the northern Calabria study area, with the West and East Crati faults bounding the Crati basin. (c) Simplified geological and faults map of the southern Calabria study area. The Serre and Cittanova normal faults bound the Mesima and Gioia-Tauro basins, respectively. The SCA terraces (in pink) are found continuously along the strike of these faults, at different elevations on their footwalls depending on their position along strike. They are offset by the Cittanova fault at the Piani d’Aspromonte area. On the Armo fault, these terraces are found in the footwall and hangingwall, directly above the Vinco calcarenites unit, also offset by the fault.

Figure 2. Swath profiles of the minimum, mean, and maximum elevations of the footwall blocks of the Serre, Cittanova and Armo faults (a), East Crati fault (b) and West Crati fault (c), extracted along the fault strikes.

Figure 3. Constraints and estimates of cumulative fault throw along the strike of the studied faults. **(a)** Footwall relief along the Serre, Cittanova and Armo faults. The heights of the SCA terraces from the fault trace are plotted at the distance along strike where they have been measured (red squares). The 76 topographic cross sections can be found in the supplementary material. The offset (i.e. geologic throw) of the top of the Vinco calcarenites is shown in blue circles. The estimated simplified profiles of hangingwall subsidence are shown as black lines, with their uncertainty range in grey, measured as depth from the fault trace. **(b)** and **(c)** show, for the East and West Crati faults respectively, the footwall relief, simplified profiles of the minimum hangingwall subsidence, and estimates of the magnitudes of the footwall throw according to the likely footwall:hangingwall throw partitioning ratios.

Figure 4. Total throw and time-averaged throw rates, along the strike of the Serre, Cittanova and Armo **(a)**, East Crati **(b)** and West Crati **(c)** faults. For comparison and to reflect the uncertainty on the distribution of throw and throw rates along the East and West Crati faults, we also show a simplified elliptical profile with similar values to the estimated mean throw rates.

Figure 5. Fault throw vs. length for the studied normal faults (in gray), and the Scilla and Santa Eufemia faults (stars), plotted together with published data for faults on the Central (Roberts & Michetti, 2004) and Southern Apennines (Papanikolaou & Roberts, 2007; Roda-Boluda & Whittaker, 2016) normal faults and fault arrays. The range of typical γ values is shown for comparison.

Figure 6. Along-strike distribution of the catchment-averaged whole channel k_{sn} values (Table 2) of the channels draining the footwalls of the Serre, Cittanova and Armo **(b)**, East Crati **(d)** and West Crati **(e)** faults. **(a)** and **(b)** show the plain-view maps with channels colour-coded by their k_{sn} value. Profiles of the smoothed footwall relief, throw rates, and SCA terrace heights are shown for comparison. The error bars represent the scatter of k_{sn} values for different channels within one catchment.

Figure 7. Catchment-averaged whole channel k_{sn} values (Table 2, Fig. 6) plotted directly against each catchment range of relief **(a)**, and estimated throw rate at catchment outlet **(b)**, colour-coded by fault. **(c)** k_{sn} against throw rates, colour-coded by each catchment dominant lithology. The parameters and correlation coefficients of linear fits for this graphs can be found in Table 3.

Figure 8. Knickpoint heights, measured from the fault traces, plotted along strike for the Serre, Cittanova and Armo **(b)**, East Crati **(d)** and West Crati **(e)** faults. The heights are shown as catchment-averaged values, and the difference in heights in different tributaries is reflected in the error bars. Knickpoints are coloured according to if they are the only knickpoint on the studied catchment, or the lower or upper one. Smoothed footwall relief, total throws and throw rates, and heights of the SCA terraces along strike, are shown for comparison. The plan view with the knickpoint positions, and the sections above and below them coloured by their k_{sn} value, are shown in **(a)** and **(c)**. The long profiles of all studied channels can be found in the supplementary material.

Fault	Authors	Method	Estimated component of the fault throw	Distance along fault strike (km, from our mapped northeast fault tip)	Throw rate estimate (mm/yr)	Approximate time of throw rate averaging
Armo	Ghisetti (1992)	offsets of Pleistocene strata	total throw	~ 10 km	0.28	0.7 Ma
	Miyauchi et al. (1994)	offsets of marine terraces	total throw	unspecified	1	0.8-1.2 Ma
Cittanova	Westaway (1993)	elevations of ~ 900 m a.s.l. marine terraces minus regional uplift estimates (~700 m), divided by his estimate of terrace ages (~0.9 Ma)	total throw (he multiplies his estimates of the footwall component by 2)	unspecified	0.4	0.9 Ma
	Tortorici et al. (1995)	estimated total throw (~ 1200 m) divided by estimated fault onset age (~ 1.8 Ma)	total throw	unspecified	0.6-0.7	1.8 Ma
		heights of two sets of triangular facets at the fault scarp, assumed by them to be 120 ka and 240 ka	footwall component	various locations (~12 km, ~18 km, ~25 km, ~29 km, ~36 km, etc.)	0.7 0.8-1	120 ka 240 ka
	Monaco and Tortorici (2000)	unspecified	unspecified	~ 22-26 km	0.7	unspecified
	Galli and Bosi (2002)	trenching of Pleistocene deposits close to the fault scarp	total throw	~16 km, ~20 km and ~23 km	0.44	25 ka
	Catalano et al. (2008)	footwall relief (~700 m) divided by their estimated terrace ages (~ 580 ka)	footwall component	unspecified	1.2	0.58 Ma
	Galli and Peronace (2015)	trenching of Pleistocene deposits close to the fault scarp	total throw	various locations between ~6 and ~25 km	0.6 ± 0.1	28 ka
	Monaco and Tortorici (2000)	unspecified	unspecified	unspecified	0.6 - 1	unspecified
Serre	Catalano et al. (2008)	footwall "scarp" (~380 m) divided by their estimated terrace ages (~ 580 ka)	footwall component	unspecified	0.6 -0.7	0.58 Ma
East Crati	Spina et al. (2011)	offset of the seismic horizon identified in the Crati basin as Middle Pleistocene (~ 600 m)	hanginwall component	~ 6 km	0.9	0.7 Ma
West Crati	Tortorici et al. (1995)	footwall relief (~600-700 m) divided by their estimated fault onset age (~0.7 Ma)	footwall component	unspecified	0.8 - 1	0.7 Ma
		heights of two sets of triangular facets at the fault scarp, assumed by them to be 120 ka and 240 ka	footwall component	various locations (~13 km, ~17 km, ~23 km, ~25 km, ~33 km, ~44 km, etc.)	0.6 - 0.9 1	120 ka 240 ka
	Monaco and Tortorici (2000)	footwall relief (~600-700 m) divided by their estimated fault onset age (~0.7 Ma)	total throw	~ 30-40 km	0.8-1	0.7 Ma

Table 2. Channels steepness indices and knickpoint heights

Fault	Catchment	Whole channel k_{sn} (m ^{0.45}), $\theta=0.45$	k_{sn}^1	k_{sn}^2	k_{sn}^3	k_{sn}^1 / k_{sn}^2	average	k_{sn}^2 / k_{sn}^3	average	Lower or single knickpoint height from fault (m)	Upper knickpoint height from fault (m)
Serre	1	47 ± 6	84 ± 10	35 ± 5		2.4				118 ± 19	
	2	72 ± 6	120	28		4.3				272	
	3	89	101	66		1.5				270	
	4	95 ± 7	146	66 ± 8		2.2				277 ± 23	
	5	77	130	67	59	1.9		1.1		299	501
	6	111 ± 2	127 ± 17	89 ± 8		1.4				359 ± 20	
	7	80	126	30		4.1				298	
	8	91	230	68	44	3.4		1.5		285	519
	9	80	161	86	34	1.9		2.6		265	412
	10	69	204	83	21	2.5		3.9		228	416
	11	73	137	55	11	2.5		4.8		286	398
	12	84 ± 6	180	104 ± 16	27 ± 3	1.7	2.4	3.8	2.6	160	330 ± 8
	13	74 ± 4	214	134	26 ± 3	1.6		5.1		179	341
	14	72	184	51	43	3.6		1.2		251	429
	15	94	174	64	40	2.7		1.6		279	564
	16	83 ± 10	172 ± 8	63 ± 10	39 ± 8	2.7		1.6		282 ± 8	541 ± 38
	17	61	99	50		2.0				298	
	18	101 ± 1	172 ± 3	94 ± 5	74	1.8		1.3		326 ± 4	634 ± 7
	19	87 ± 6	185	70	48	2.6		1.5		254	632
	20	80	149	126	48	1.2		2.6		223	371
	21	71 ± 1	163	148	54	1.1		2.8		167	299
	22	64	223	68	22	3.3		3.1		168	310
	23	51	148	54	26	2.8		2.0		134	204
	24	53	128	70	24	1.8		3.0		129	265
Citranova	25	75 ± 10	144 ± 14	90 ± 32	44 ± 4	1.6		2.0		335 ± 123	628 ± 69
	26	70 ± 3	141	68 ± 1	43 ± 1	2.1		1.6		277 ± 5	643 ± 143
	27	73 ± 19	83.2 ± 8	35 ± 6		2.4				407 ± 174	
	28	69	101	77		1.3				352	
	29	75	72	27		2.7				408	
	30	74 ± 1	88 ± 8	57	53	1.5		1.1		261 ± 20	470
	31	78 ± 2	78 ± 2	16		5.0				363	
	32	87	88								
	33	101 ± 2	104 ± 5	68 ± 8		1.5				467 ± 43	
	34	130	202	113	25	1.8		4.6		471	651
	35	152 ± 30	297 ± 18	233 ± 23	126 ± 34	1.3		1.9		473 ± 55	607 ± 40
	36	101 ± 3	428	174	92 ± 4	2.5	2.0	1.9	2.6	344	505 ± 27
	37	139 ± 6	244 ± 5	177 ± 1		1.4		6.8		576 ± 13	
	38	131	215	202		1.1				609	
	39	136 ± 6	297	192 ± 33		1.6				648 ± 33	
	40	153 ± 7	205 ± 17	159 ± 33	59 ± 19	1.3		2.7		430 ± 35	674 ± 85
	41	118	188	119	37	1.6		3.2		597	684
	42	131 ± 3	172	118	74	1.5		1.6		426	753
	43	110 ± 15	159 ± 24	83 ± 4	52	1.9		1.6		398 ± 37	536
	44	95 ± 1	195 ± 5	81 ± 1		2.4				239	
	45	56	120	55		2.2				109	
	46	84	120	91		1.3				165	
	47	77	118	38		3.1				115	
Arno	48	105	111	21		5.2				303	
	49	109	124	73		1.7				368	
	50	123 ± 13	132 ± 12	38 ± 22		3.5				806 ± 45	
	51	93	151	35		4.3	3.2			567	
	52	97 ± 5	121 ± 1	23 ± 6		5.2				635 ± 41	
	53	59	97	41		2.4				198	
	54	62	67	40		1.7				258	
	55	67	94	49		1.9				216	
East Crati	56	50 ± 4	58 ± 7	34 ± 1		1.7				218 ± 11	
	57	56	93	53	31	1.7		1.7		361	506
	58	60	60								
	59	58	60	26		2.4				211	
	60	81 ± 25	191 ± 21	94 ± 18	32 ± 18	2.0		2.9		548 ± 176	940
	61	75	92	61		1.5				197	
	62	113 ± 3	139	103		1.3				128	
	63	91	91								
	64	120 ± 8	170 ± 19	100 ± 9	35	1.7	1.9	2.9	2.5	377 ± 10	905
	65	92	134	66		2.0				406	
	66	59	59								
	67	91 ± 15	109 ± 3	56		1.9				282	
	68	129. ± 24	163 ± 18	78 ± 20		2.1				620 ± 286	
	69	94	94								
	70	123 ± 9	161 ± 9	73 ± 45		2.2				588 ± 298	
	71	83	83								
	72	43	43								
West Crati	73	151 ± 30	188 ± 48	92 ± 19		2.0				775 ± 302	
	74	177	176								
	75	79 ± 12	66 ± 8	47		1.4				300	
	76	100	121	104		1.2				535	
	77	96	109	86		1.3				279	
	78	99	101	93		1.1				260	
	79	104	104								
	80	69 ± 4	92	67 ± 3	24	1.4		2.8		153	567
	81	105	106								
	82	119	127	88		1.4				268	
	83	119	119								
	84	137	180	120		1.5	1.4		2.7	216	
	85	104	112								
	86	105	110								
	87	100	100								
	88	95	177	103	41	1.7		2.5		239	524
	89	99	103	67		1.5				178	
	90	110 ± 16	121 ± 17	112		1.1				467	
	91	85 ± 6	94 ± 7	66 ± 14		1.4				325 ± 68	
	92	101	90 ± 11								
	93	87 ± 18	87 ± 18								
	94	71 ± 2	71 ± 2								
	95	51 ± 5	52 ± 4								

	$K_{sn} \text{ (m}^{0.9}\text{)} = a + b \times \text{Catchment range of relief (m)}$			$K_{sn} \text{ (m}^{0.9}\text{)} = a + b \times \text{Catchment mean throw rate (m)}$		
	Intercept, a	Slope, b	Correlation coefficient, R ²	Intercept, a	Slope, b	Correlation coefficient, R ²
Serre	23.5 ± 9.9	0.07 ± 0.01	0.54	34.7 ± 10.5	69.6 ± 17.2	0.38
Cittanova	34.8 ± 20.9	0.08 ± 0.03	0.26	47.6 ± 14.9	46.2 ± 13.0	0.33
Armo	39.7 ± 13.0	0.06 ± 0.02	0.61	59.3 ± 9.7	71.9 ± 21.7	0.53
East Crati	36.8 ± 12.5	0.05 ± 0.01	0.47	43.3 ± 18.7	47.7 ± 21.1	0.2
West Crati	5.6 ± 34.5	0.13 ± 0.04	0.29	28.1 ± 17.1	149.7 ± 33.3	0.47
All	39.6 ± 8.2	0.06 ± 0.09	0.31	67.6 ± 5.8	31.9 ± 7.1	0.17
Gneiss and Schist	39.4 ± 9.5	0.07 ± 0.01	0.39	69.3 ± 6.1	37.6 ± 7.7	0.28
Granites	64.5 ± 13.8	0.02 ± 0.02	0.02	42.5 ± 11.6	43.5 ± 12.4	0.31

Figure 1

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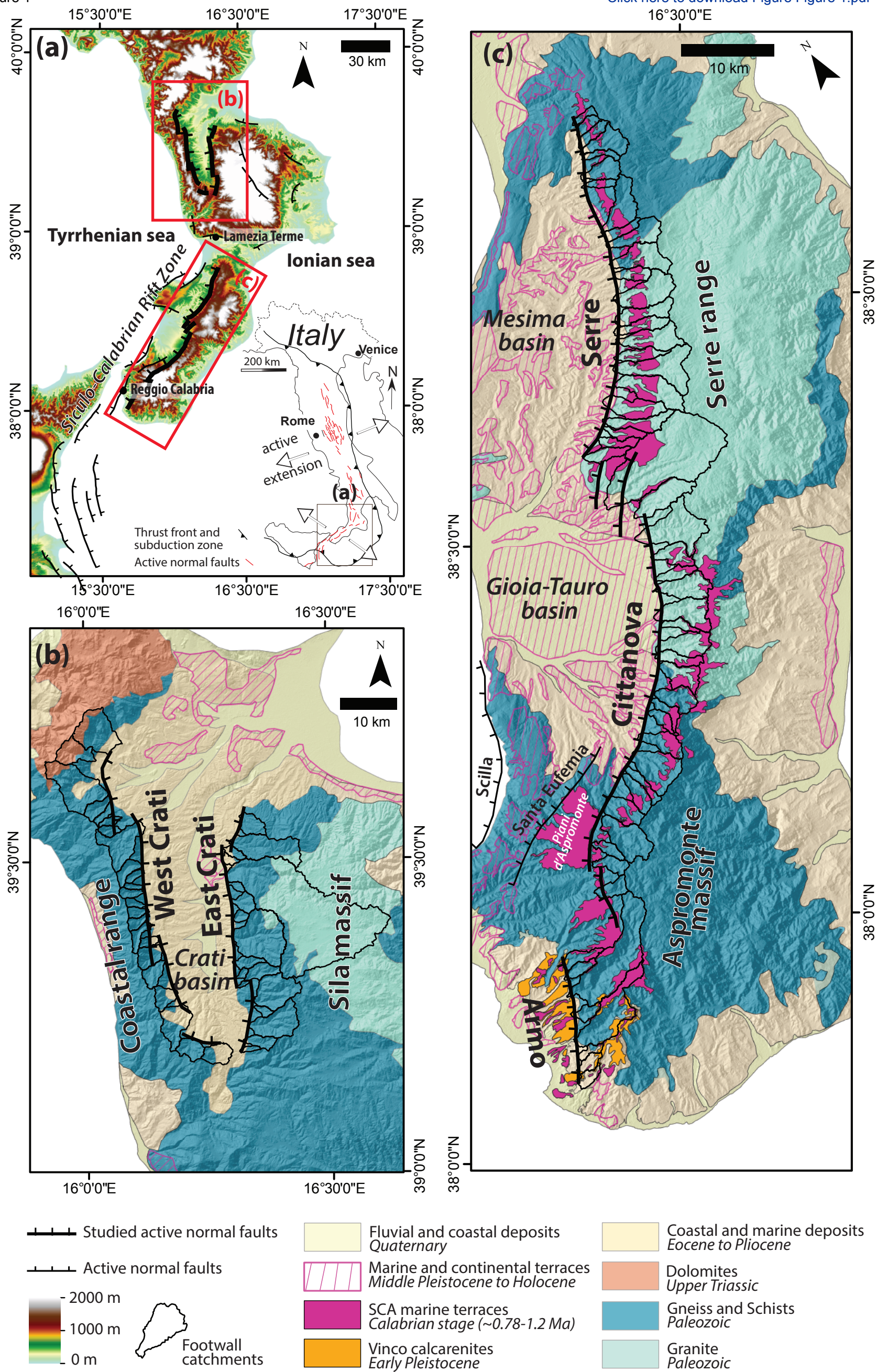


Figure 1

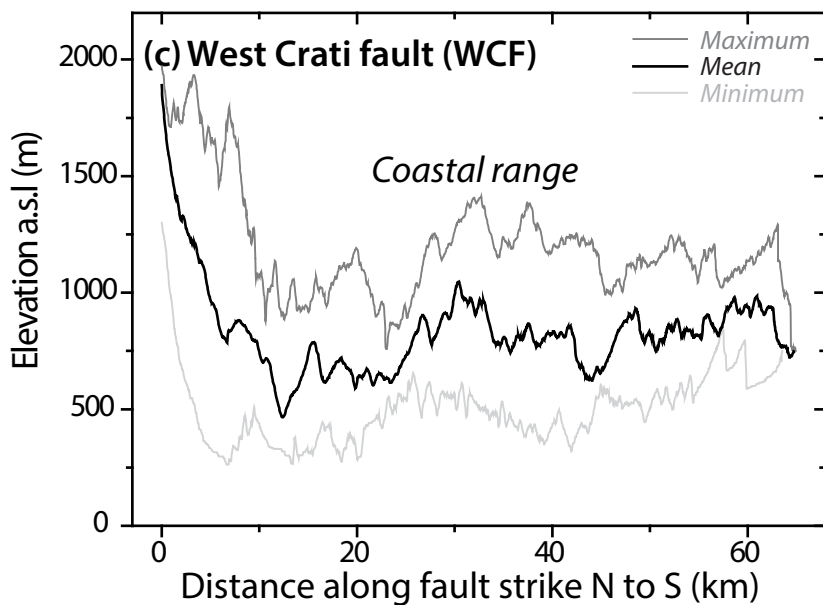
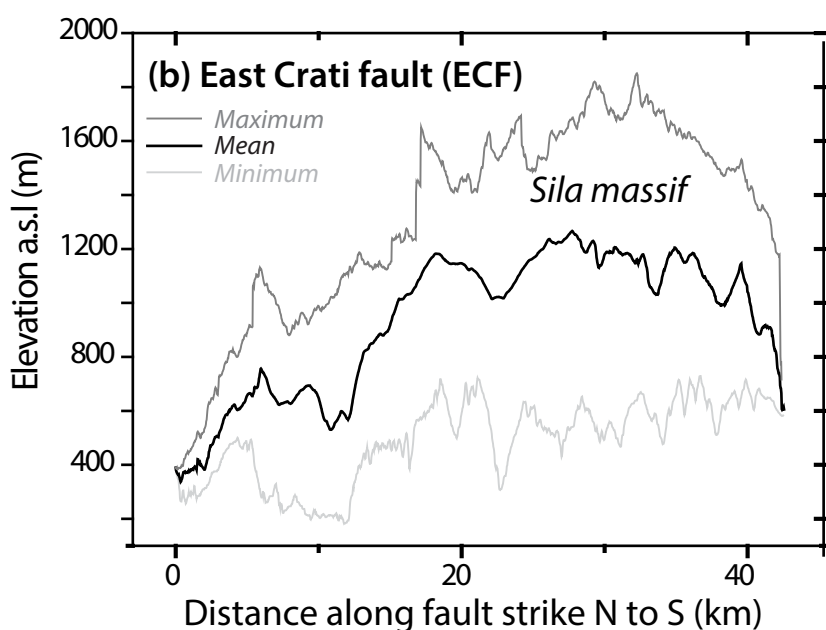
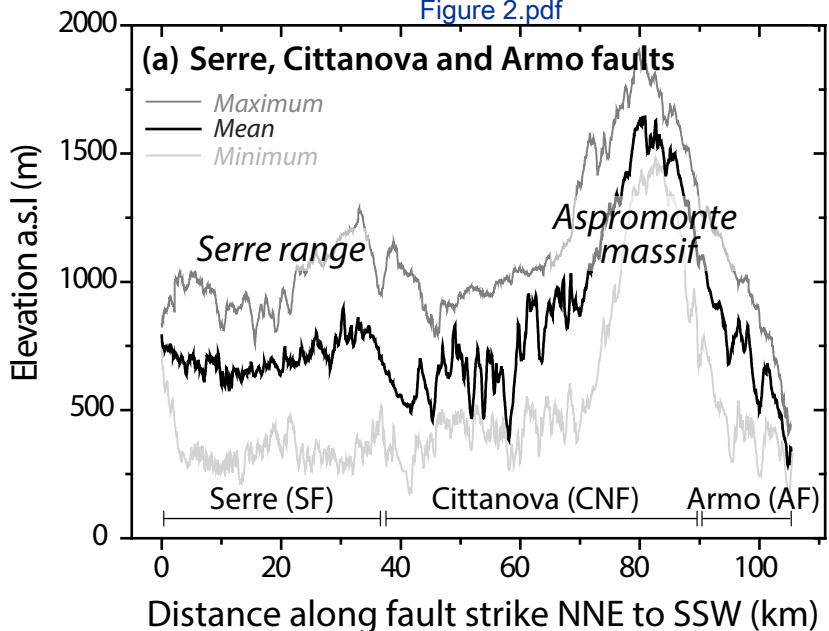


Figure 2

Figure 3 [Click here to download Figure Figure 3.pdf](#)

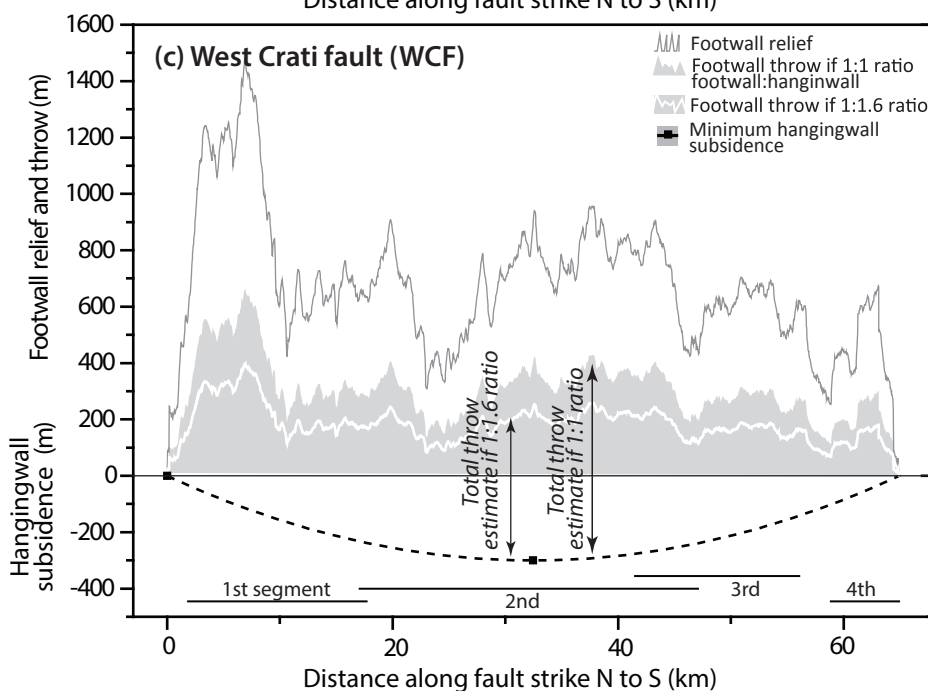
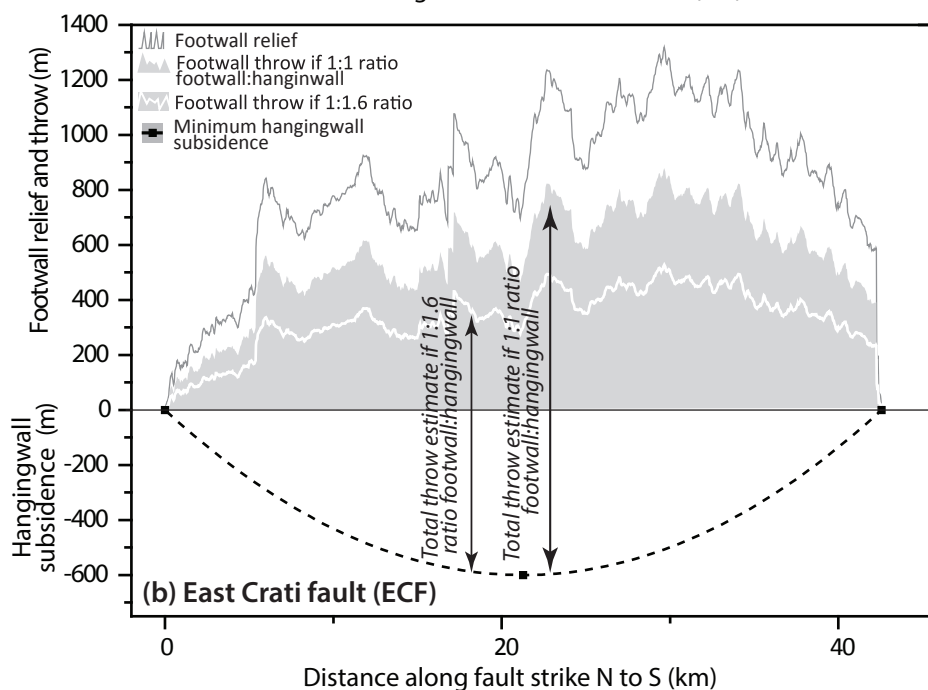
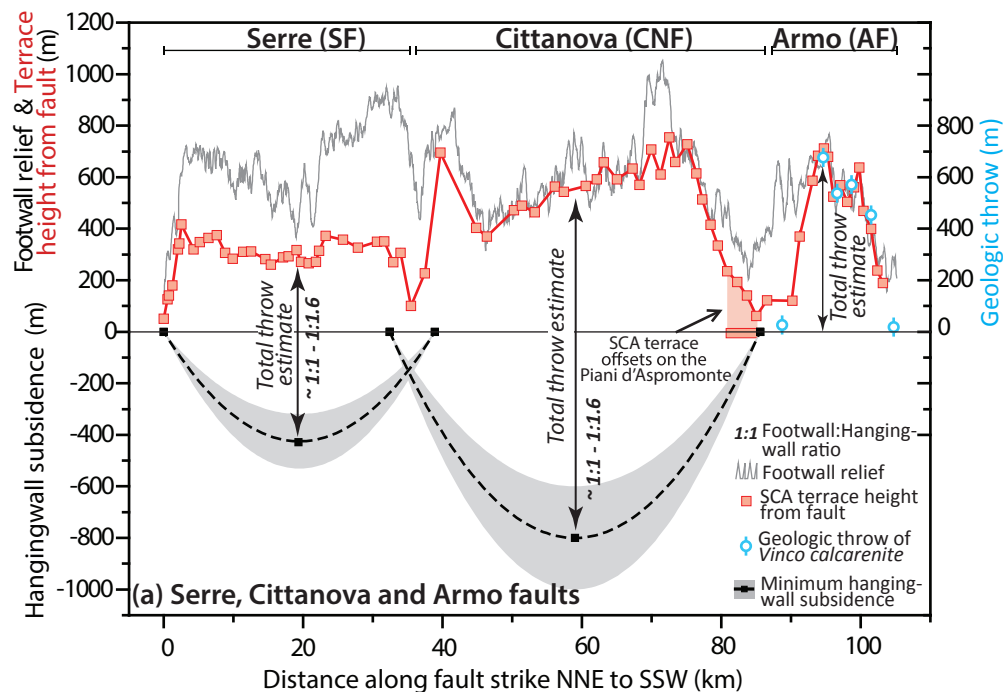


Figure 3

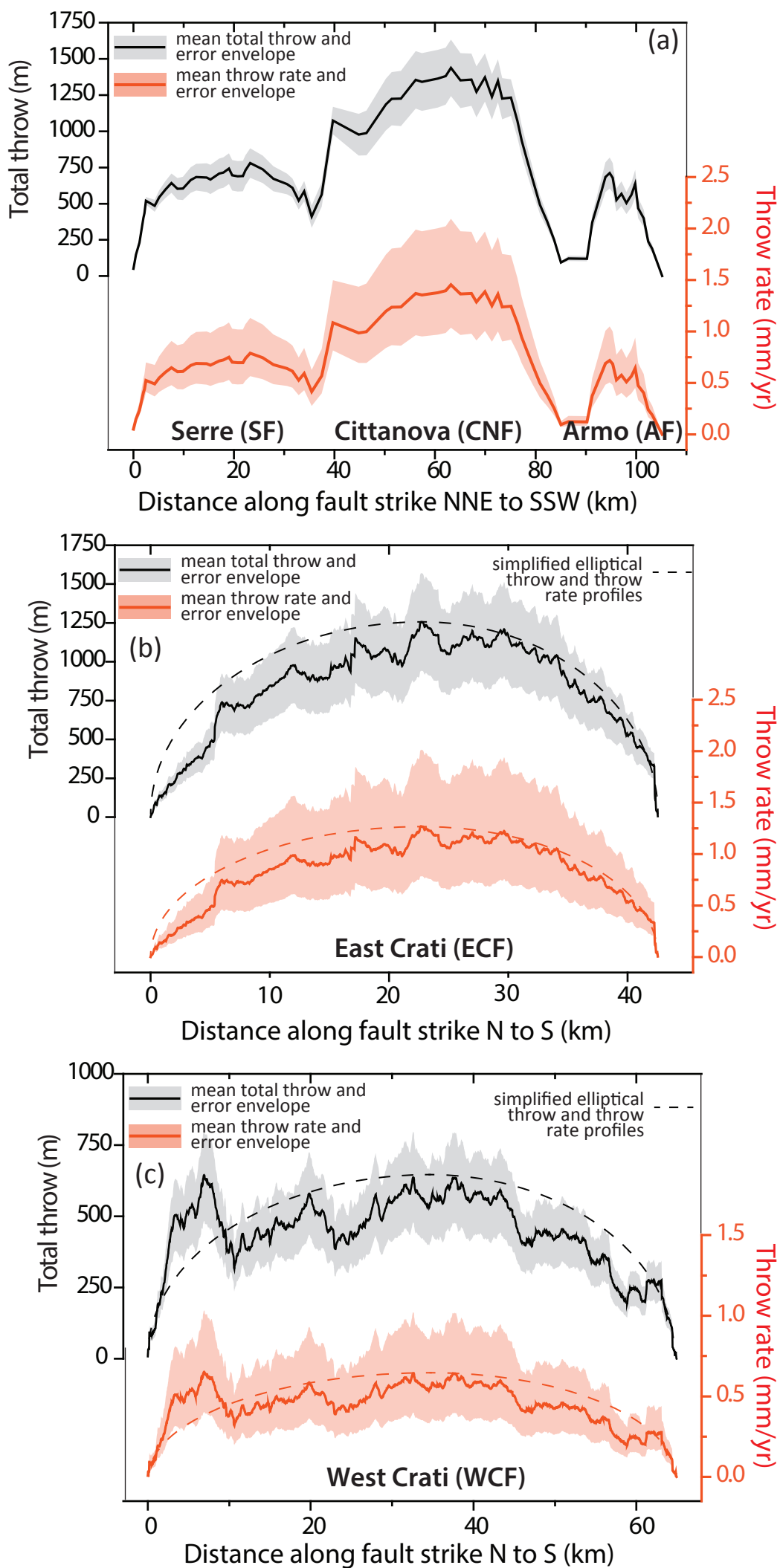


Figure 4

Figure 5

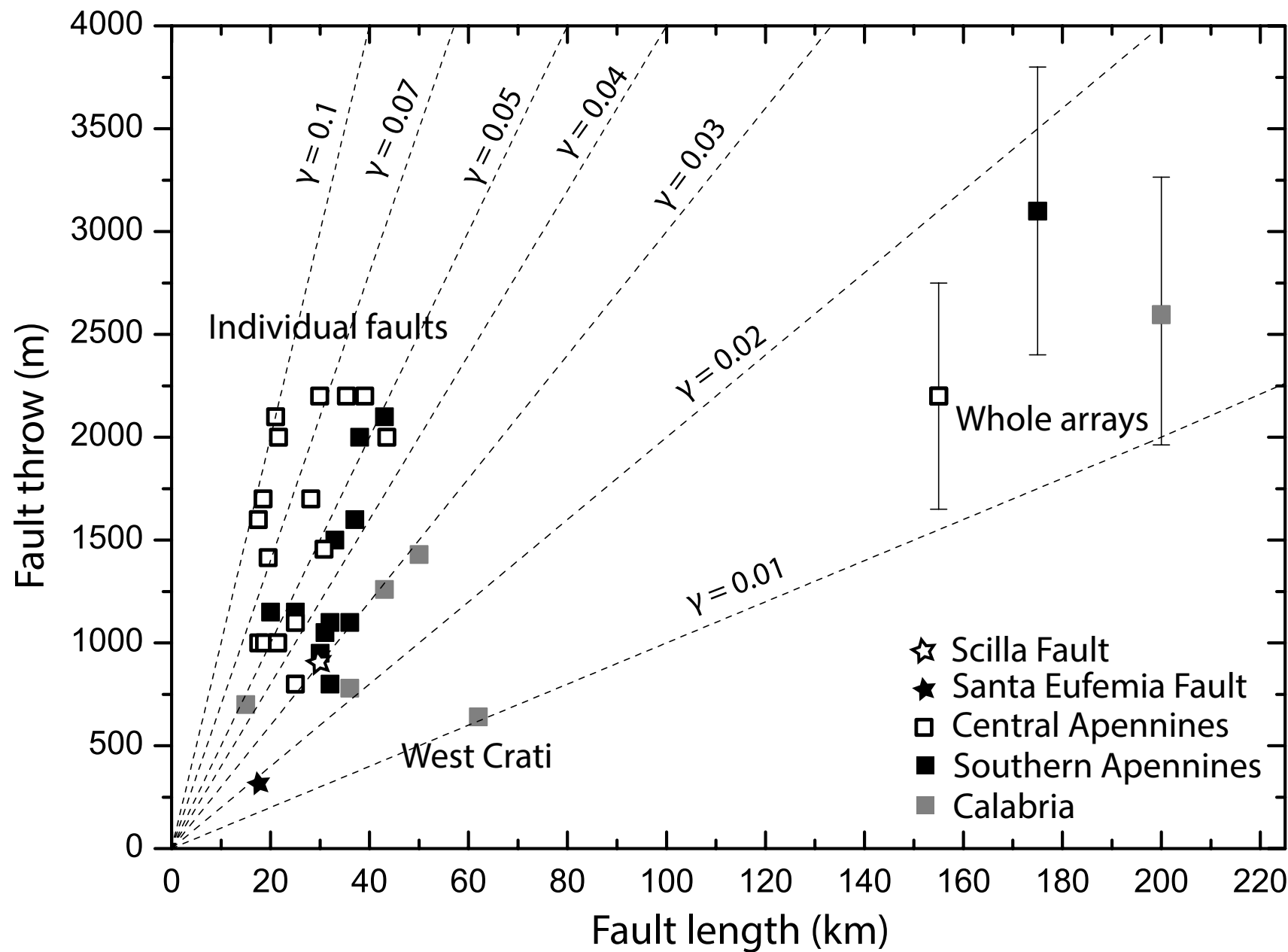
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FIGURE 5

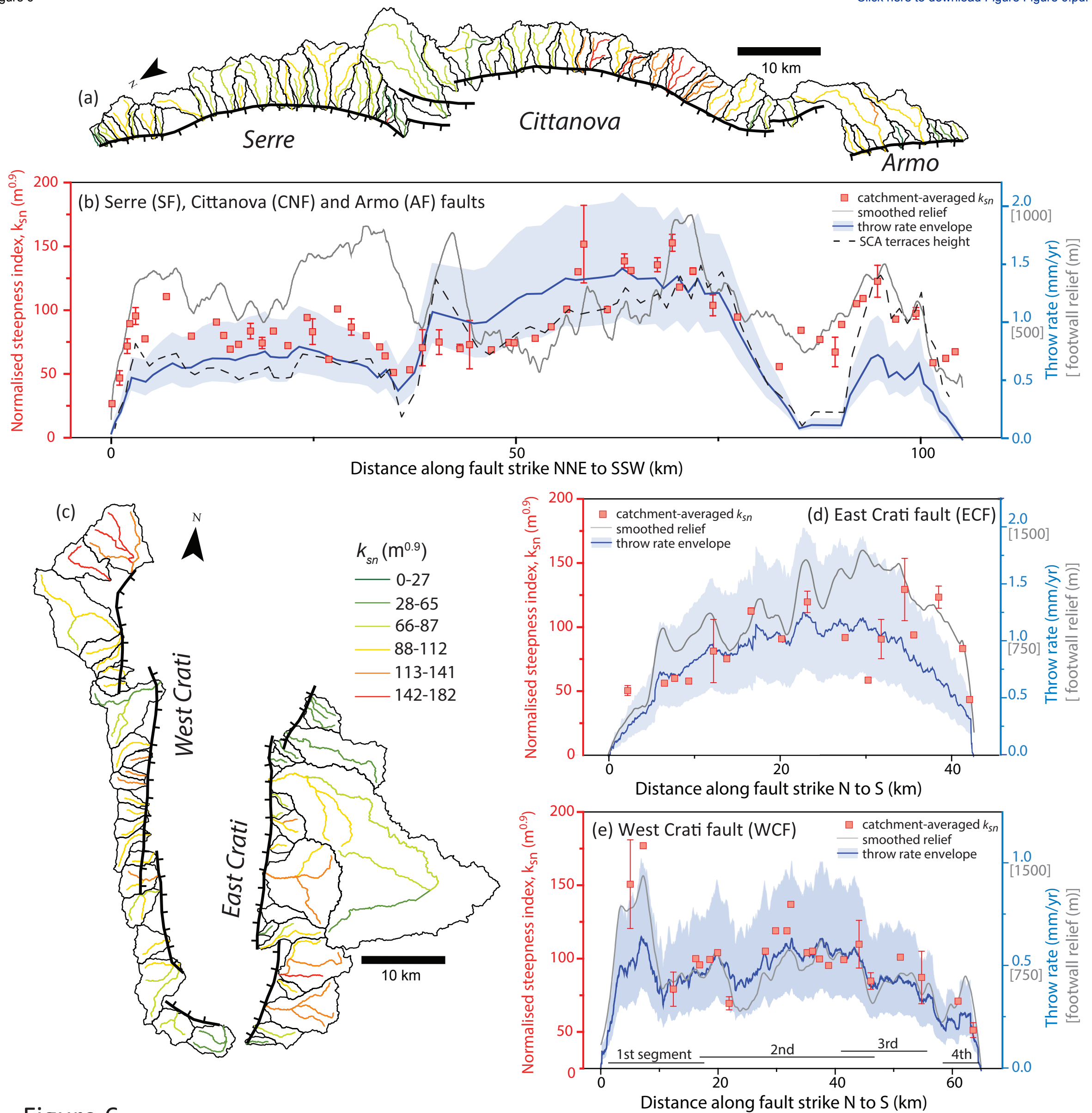


Figure 6

Figure 7

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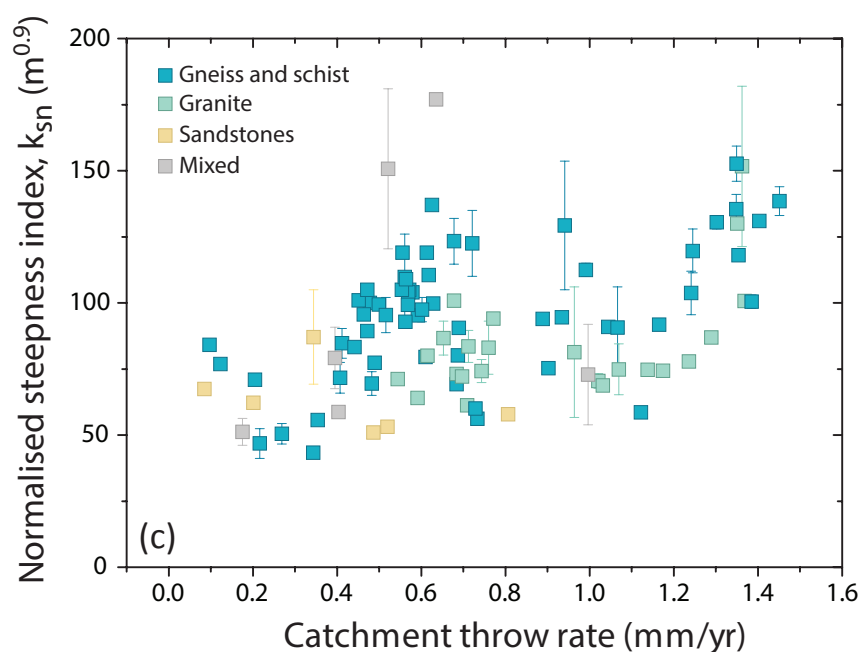
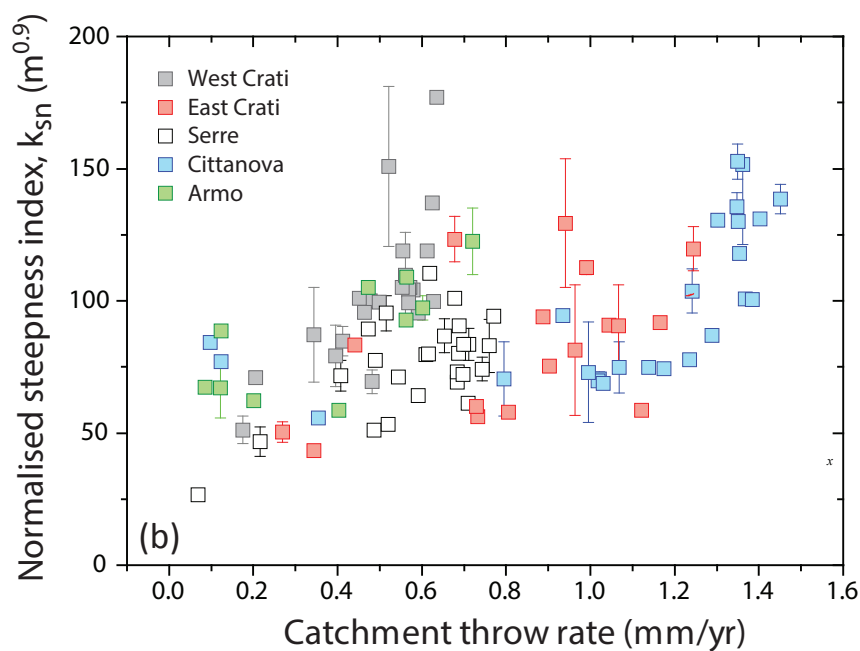
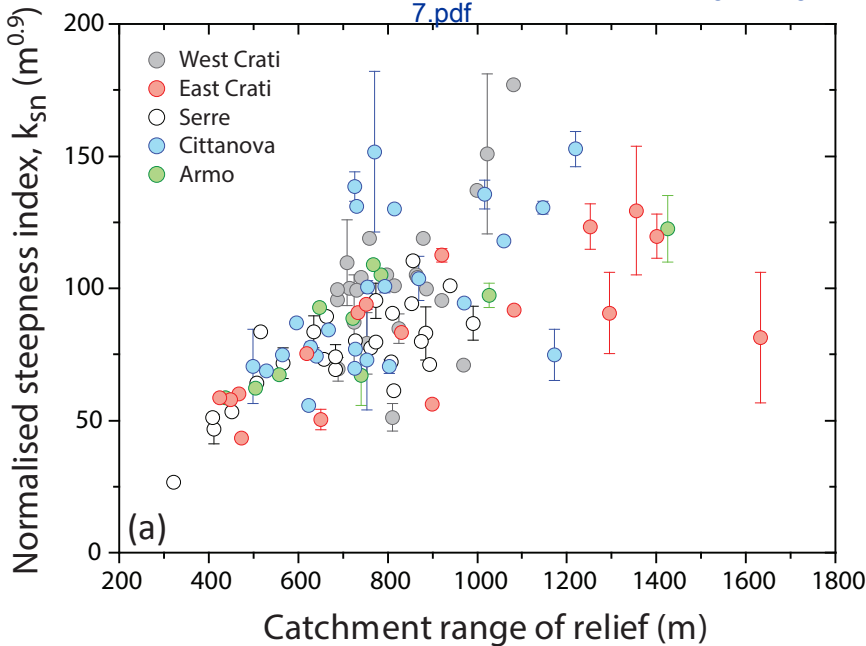


Figure 7

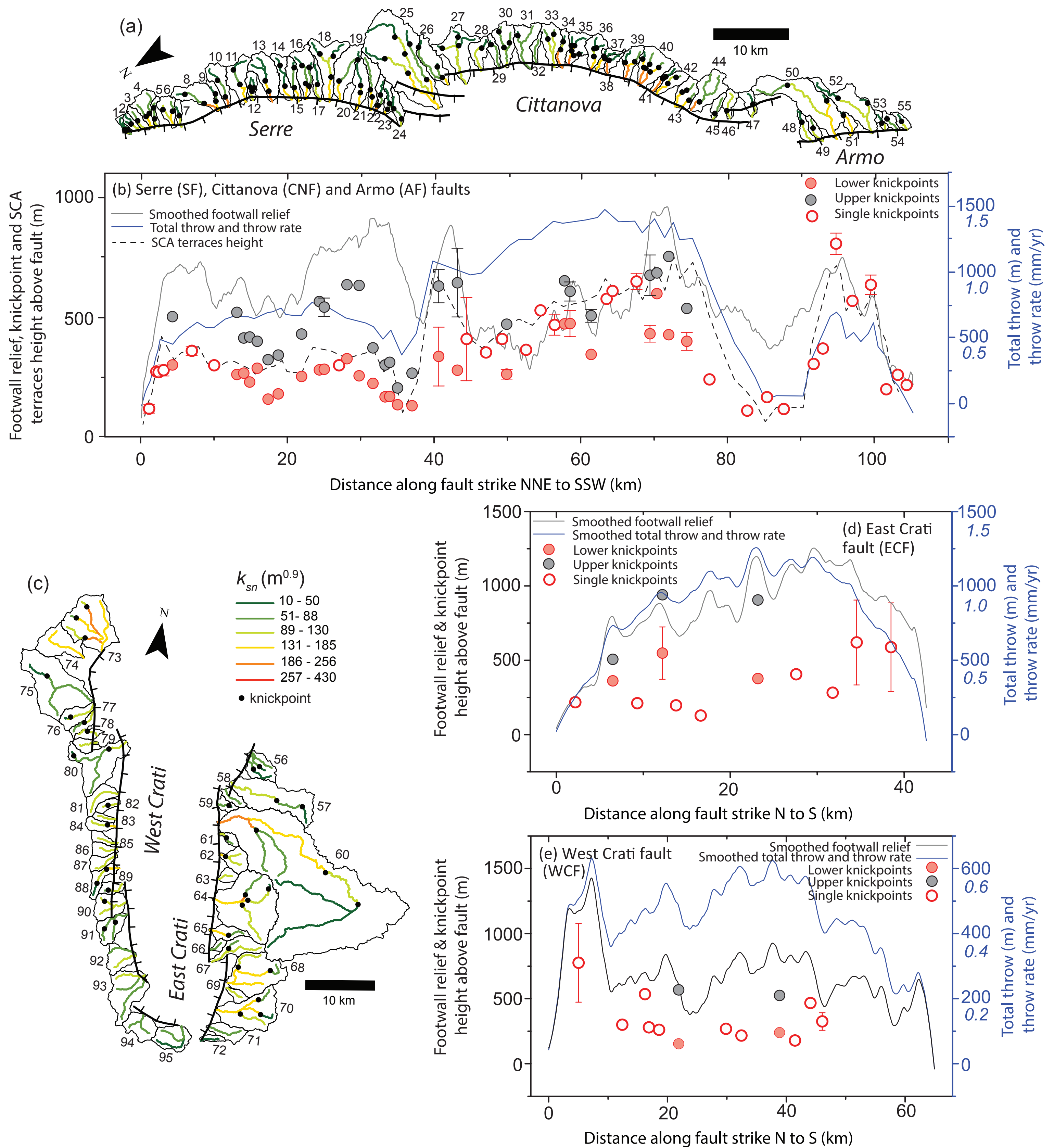


Figure 8