Out of phase uplift-rate changes during the Quaternary reveal normal fault interaction, implied by deformed marine palaeoshorelines, in southern Italy

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Abstract

We have mapped and constrained the timing of tectonically deformed uplifted Late Quaternary palaeoshorelines in the Messina Strait, southern Italy, an area above a subduction zone containing active normal faults. The palaeoshorelines are

preserved from up to thirteen Late Quaternary sea-level highstands, providing a record of the deformation over this timescale (~500 ka) for the Messina-Taormina Fault, the Reggio Calabria Fault and the Armo Fault. The palaeoshorelines reveal spatial patterns of uplift through time along the strike of these normal faults, and, given the across strike arrangement of the faults, also reveal how the contribution of each fault to the regional strain-rate progressed through time. The results reveal that the uplift rates mapped within the hangingwalls and footwalls of these were not constant through time with a marked change in the location of strain accumulation at ~50 ka. The uplift rates, once converted into throw-rates, imply that three faults has similar throw-rates prior to ~50 ka (in the range 0.77-0.96 mm/yr), with the Armo and Reggio Calabria faults then switching to lower rates (0.32 mm/yr and 0.33 mm/yr respectively), whilst the Messina-Taormina Fault accelerated to 2.34 mm/yr; the regional extension rate gained by summing the implied heave rates across the three faults was maintained through time despite this re-organisation of local strain accumulation at ~50 ka. We interpret these out-of-phase throw-rate changes during the constant-rate regional extension as due to interaction between these upper plate normal faults. We discuss implications for seismic hazard implied by spatial and temporal changes in fault-controlled uplift are mapped within active normal fault systems.

Keywords: Palaeoshorelines, active faults, Messina Strait, Quaternary, Synchronous correlation approach

1. Introduction

Knowledge of tectonic uplift rates that extend over multiple seismic cycles has been derived by investigating preserved palaeoshorelines from seismically deforming upper plates above subduction zones such as Western Burma, South America, Japan, southern Italy and Greece (e.g. González-Alfaro et al., 2018; Ott et al., 2019; Roberts et al., 2009; Roberts et al., 2013; Robertson et al., 2019; Saillard et al., 2009; Shikakura, 2014; Shyu et al., 2018). Such studies can provide continuous along-strike profiles of deformation rate of faults responsible for the uplift over different timescales, and across multiple faults. However, such information has rarely been used to constrain how neighbouring faults share the task of accommodating the regional strain-rate over tens to hundreds of thousands of years, providing information on the dynamics of crustal deformation. For northern and central Calabria, Italy, an area located in the upper plate of the Ionian Subduction Zone, observations of knickpoints in rivers crossing faults have been used to suggest that some faults change their slip-rates over the last 300 ka (Quye-sawyer et al., 2021; Roda-Boluda and Whittaker, 2017). This information provides important new insights that hint at the larger scale dynamic processes that occur in such extensional settings above subduction zones. However, these studies did not concentrate on whether fault slip-rate changes were associated with changes in regional extensional rates, and the timing of changes was relatively imprecise as results came from an inversion of river profile data and not absolute dating of deformed horizons. Hence it is unclear how the slip-rate changes over the Middle to Late Pleistocene can be interpreted in terms of regional dynamics associated with the subduction processes. Such information would be useful, because elsewhere interaction between multiple across-strike active normal faults has been shown to be an important process during intraplate crustal extension located within zones of convergence between colliding tectonic plates, and other tectonic settings; the details of the interaction, revealed by data on how the faults experience changes in slip-rate through time, are essential to understand the dynamics governing the overall deformation (Anders and Schlische, 1989; Contreras et al., 2000; Cowie and Roberts, 2001; Cowie and Shipton, 1998; Gupta et al., 1998; Mcleod et al., 2000; Nicol et al., 2006; Roberts et al., 2002). The Messina Strait is located on the extending upper plate of the Ionian Subduction Zone (ISZ; southern Italy), within an area of active convergence between the African and Eurasian plates, and is considered one of the most tectonically-active regions of the entire

Mediterranean (Monaco and Tortorici, 2000; Serpelloni et al., 2010) (Figure 1). The geodetically constrained crustal extension rate of ~ 3 mm/yr is accommodated within the Messina Strait by synthetic and antithetic normal faults (Doglioni et al., 2012; Monaco and Tortorici, 2000; Serpelloni et al., 2010) (Figure 1), which hosted the most powerful recorded earthquake during the 20th and the 21st centuries in Europe to date (1908 Messina Earthquake – M 7.1; e.g. Aloisi et al., 2013; De Natale and Pingue, 1991; Meschis et al., 2019; Mulargia and Boschi, 1983; Valensise and Pantosti, 1992). However, Late Quaternary crustal deformation rates associated with these seismically active normal faults are poorly constrained and so the processes that control the dynamics of the deformation are poorly understood. Uplifted Late Quaternary palaeoshorelines suggest Middle to Late Pleistocene deformation (Catalano and De Guidi, 2003; Stewart et al., 1997; Valensise and Pantosti, 1992), but rates of activity through time, and the likely effects of interaction on the closely-spaced normal faults are still unclear. Indeed, some have even questioned if these faults are still active (Argnani et al., 2009). Previous studies have shown deformed uplifted Late Quaternary palaeoshorelines mapped along the strike of the offshore Messina-Taormina Fault on its onshore footwall, between Messina town and Taormina town (Catalano and De Guidi, 2003; Pavano et al., 2016; Stewart et al., 1997). Likewise, major capable onshore normal faults, such as the Reggio Calabria Fault and the Armo Fault, and their variable activity throughout the Quaternary on the Calabrian side, have been previously investigated by studying sequences of uplifted Late Quaternary palaeoshorelines both on their footwalls and hangingwalls (Catalano et al., 2003; Miyauchi et al., 1994; Monaco and Tortorici, 2000; Valensise and Pantosti, 1992). Yet, for one of the most seismically active regions in the Mediterranean realm like the fault-bounded Messina Strait, details are poorly constrained on how slip-rates on these crustal-scale faults compare between neighbouring structures, whether the faults interact and hence what controls the changes in the deformation through time in response to the tectonic forcing.

This paper provides new mapping and age controls and suggests changing uplift-rates through time over the Middle to Late Pleistocene from southern Calabria and Sicily bordering the Messina Strait, Italy (Figure 1). The uplift rate changes are constrained by the deformation of Late Quaternary marine palaeoshorelines, and we demonstrate synchronous, out-of-phase changes in uplift rate and show how these relate to slip-rate changes and regional extension rate and hence the regional processes of the subduction system. We firstly use observations of uplifted and tectonically deformed palaeoshorelines to refine the chronology and spatial extent of the uplift (Figure 2-8). We undertook new detailed topographic analysis, taking advantage of a 10 m high resolution Digital Elevation Model (DEM; Tarquini et al., 2012), combined with new field mapping to collect palaeoshoreline elevations and check those previously mapped by others (Catalano and De Guidi, 2003; De Guidi et al., 2003; Figures 2, 3 and SM 1-10). We support this with a review of existing age controls (Aloisi et al., 2013; Antonioli et al., 2006; Balescu et al., 1997; Dumas et al., 2005, 1993; Table 1), and an attempt to gain new absolute ages from U/Th determinations on corals (Table 2). These ages are used to drive a “synchronous correlation” approach, previously proposed by some to overcome the overprinting problem on relatively low uplifting regions (Meschis et al., 2018; Meschis et al., 2020; Pedoja et al., 2018; Roberts et al., 2009; Roberts et al., 2013; Robertson et al., 2019), which provides a regional chronology for the palaeoshorelines that is consistent with proposed uplift rates and known palaeo sea-level elevations (Rohling et al., 2014; Siddall et al., 2003). We then use our results to define fault throw-rates derived from uplift rates (Figures 3-9), and how these combine to produce the regional extension, to discuss local and regional tectonic implications and the associated long-term seismic hazard assessment within the upper plate above the Ionian Subduction zone (Figure 10).

2. The geological background of the Messina Strait region

The Messina Strait, separating Calabria from Sicily, southern Italy, is a down-faulted graben between inward-dipping Quaternary normal faults, deforming a pre-existing fold and thrust belt made of Palaeozoic, Mesozoic and Cenozoic rock formations interposed during Alpine thrusting (Malinverno and Ryan, 1986; Figure 1). This strait is bounded by active normal faults onshore (Catalano et al., 2003; Monaco and Tortorici, 2000; Stewart et al., 1997) and offshore (De Guidi et al., 2003; Doglioni et al., 2012; Meschis et al., 2019). In particular, the offshore and E-dipping Messina-Taormina Fault offsets pre-Quaternary basement and has propagated upwards to produce a fault-related anticline on its footwall, from Messina town to Taormina town (Catalano et al., 2003; Meschis et al., 2019; Pavano et al., 2016; Stewart et al., 1997; Figure 1). This fault has deformed the Late Quaternary-Holocene palaeoshorelines outcropping onshore on the Sicilian side of the Messina Strait (Catalano et al., 2003; De Guidi et al., 2003; Pavano et al., 2016; Stewart et al., 1997). Likewise, W-dipping antithetic normal faults such as the Armo Fault and the Reggio Calabria Fault control the coastline topography and the Plio-Pleistocene sedimentary basins. These normal faults deform the Palaeozoic crystalline basement and its clastic Cenozoic cover, with the Middle-Late Pleistocene shallow marine deposits, progressively onlapping on fault planes and suggesting persistent faulting (Ghisetti, 1984; Monaco and Tortorici, 2000).

Existing ages of marine terraces mapped in the Messina Strait are briefly summarized here and in Table 1. In particular, along the mapped palaeoshorelines on the footwall of the Messina-Taormina Fault, shallow marine shells have been dated close to Taormina town, identifying the 125 ka palaeoshoreline (Antonioli et al., 2006). By using the Electron Spin Resonance technique on marine mollusc shells such as *Patella* and *Venerupid,* shallow marine deposits have been dated (Table 1). Moreover, aeolian non-fossiliferous sediments have been dated north of Reggio Calabria (Figure 1) by applying a thermoluminescence dating technique, identifying the 50 ka palaeoshoreline (Balescu et al., 1997; Dumas et al., 1993). Thermoluminescence has also been used to date shallow marine deposits from marine terraces, south of Reggio Calabria, identifying the 125 ka palaeoshoreline (Balescu et al., 1997). South of Reggio Calabria and within the hangingwall of the Armo Fault, *Strombus Bubonius* a fossil that is commonly used to date marine oxygen isotope stage 5 deposits, have been collected *in situ* from within shallow sea deposits and used to identify the 125 ka palaeoshoreline (Aloisi et al., 2013; Antonioli et al., 2006; Dumas et al., 2005; Ferranti et al., 2006; Miyauchi et al., 1994).

3. Methods

In this section, we present approaches and methodologies used in this paper to refine fault-related deformation rates within the crustal extending Messina Strait.

3.1 Topographic analysis: DEMs and fieldwork to map palaeoshorelines.

Detailed topographic analysis has been carried out using 10 m high resolution DEMs (Tarquini et al., 2012) to create serial topographic profiles along the strikes of the Messina-Taormina Fault, the Armo Fault and the Reggio Calabria Fault (Figure 1 and SM 1-3). These topographic profiles were chosen where the geomorphology of palaeoshorelines is appropriate due to their preservation from erosion (e.g. Figure 2) and also to run close to locations revealed in previous maps, that have been used as a guide (Aloisi et al., 2013; Antonioli et al., 2006; Balescu et al., 1997; Catalano et al., 2003; Catalano and De Guidi, 2003; De Guidi et al., 2003). The serial topographic profiles cover the lengths of the faults, from their centres towards their lateral tips, but complete coverage along strike has not been achieved as the Reggio-Calabria Fault goes offshore in the SW and palaeoshorelines are unclear in the high topography at the NE-end of the Armo Fault. For the Messina-Taormina Fault along strike coverage has been achieved, and palaeoshoreline elevations have been constrained along the entire fault length (Figure 1). The key feature that must be identified is the palaeoshoreline itself, characterised either by palaeo-beach deposits or a palaeo-rocky shoreline. The key features that allow identification of palaeo-beach deposits are shallow marine deposits, such as symmetrical ripples, bar-forms, truncation surfaces, beach pebbles/cobbles and marine conglomerates that suggest deposition and re-working in a shoreface environment, unconformably overlying the Palaeozoic crystalline basement and/or Mesozoic/Neogene limestones (Figure 2). Palaeo-rocky shorelines can be identified from (i) flat-surfaces cut into bedrock by erosion of wave action (Anderson et al., 1999; Armijo et al., 1996; Ferranti et al., 2007; Jara-Muñoz and Melnick, 2015; Meschis et al., 2018; Ott et al., 2019; Roberts et al., 2009; Roberts et al., 2013; Robertson et al., 2019), (ii) caves, lithophagid borings and notches (Ferranti et al., 2006; Meschis et al., 2018; Roberts et al., 2013; Robertson et al., 2019), and (iii) millholes (or marine erosion pan) which are quasi-circular depressions lying on the wave-cut platform formed by the scouring action of pebbles onto the terrace-forming surface as a result of wave action (Miller and Mason, 1994) (Figure 2). It is important to highlight that all these features form within the subtidal/intertidal zone a few decimetres to metres down-dip of the inner edge of the marine terrace. For example, gently-sloping surfaces have been interpreted as palaeoshoreface surfaces cut by wave-action and bounded up-dip by fault scarp-like resembling palaeo-sea-cliffs, following previous marine terrace investigations (Armijo et al., 1996; Roberts et al., 2009; Roberts et al., 2013; Robertson et al., 2020, 2019).

Once palaeoshorelines and their associated palaeoshoreface deposits and wave-cut platforms were identified in the field (Figure 2), their UTM coordinates and elevation were recorded using a hand-held GPS with barometric altimeters with a precision of ± 3m), with the barometer calibrated to sea-level every few hours. Field-based palaeoshoreline elevations were georeferenced onto DEMs to confirm their reliability, following approaches from recent studies (Meschis et al., 2018; Meschis et al., 2020; Roberts et al., 2013; Robertson et al., 2019).

3.2 $^{234}U/^{230}Th$ coral dating

New age controls have been obtained through dating of corals with the ^{234}U/^{230}Th dating technique. In particular, dated corals allow us to place some constraints on the age for a prominent marine terrace on the footwall of the Reggio Calabria Fault (Table 2). The corals we collected were from a calcarenite boulder within shallow marine deposits, from the same footwall terrace mapped by other authors (Catalano et al., 2003). We then carried out $^{234}U/^{230}Th$ dating at the Geochronology and Tracers Facility of the British Geological Survey, Keyworth, UK. Here we use total dissolution methods as outlined by Crémière et al., (2016), with ratios of the isotopes measured on a Neptune Plus MC-ICP-MS (Multi-Collector Inductively Coupled Plasma Mass Spectrometer). We undertook coral preparation and cleaning, a critical phase before $^{234}U/^{230}Th$ analysis, at Birkbeck College. In particular, we isolated millimetre-scale fragments of corallite, carefully selected and systematically cleaned. We removed as much as possible of any material showing evidence of alteration and/or detrital matrix on the outside of the corallite wall. We did this, following approaches from previous studies (e.g. Meschis et al., 2020; Roberts et al., 2009; Robertson et al., 2020), mechanically using a scalpel under a microscope and/or chemically by washing the wall with HCl (10%) for 5-10 seconds, followed by thorough rinsing with ultrapure water. Moreover, we separated and removed coral septa from the corallite wall because they are thinner and more prone to diagenetic alteration (Roberts et al., 2009; Robertson et al., 2020). Following other studies (e.g. Meschis et al., 2020), we also examined both bulk corallite wall fragments (2 – 10 mg) and powdered subsamples obtained using a computer-controlled drill equipped with a 200 μm drill bit in order to avoid any portion of the coral that showed discolouration or other evidence of alteration.

3.3 Synchronous correlation approach to map multiple palaeoshorelines and multiple sea-level highstands.

This technique has been used within the Mediterranean realm and elsewhere (Meschis et al., 2018; Meschis et al., 2020; Pedoja et al., 2018; Roberts et al., 2009; Roberts et al., 2013; Robertson et al., 2019; De Santis et al., 2021). This technique is built on the concept that sea-level highstands, which are thought to produce palaeoshorelines

(Lajoie, 1986), are unequally-spaced in time, implying that for a constant uplift rate through time, palaeoshorelines will be unequally-spaced in elevation (Houghton et al., 2003; Roberts et al., 2009). To use this approach, it is important to obtain at least one age for a palaeoshoreline across the investigated area. The age control drives the iteration of uplift rate to replicate the elevation of the dated palaeoshoreline, but also predicts the elevations of palaeoshorelines from other Quaternary sea-level highstands, for comparison with the elevations of mapped yet un-dated palaeoshorelines. The modelling can involve either a single constant uplift rate or can include multiple changes in uplift rate at times that can be specified by the user. For example, Roberts et al. (2009), studying central Greece, found that a single change in uplift rate through time was necessary to replicate measured palaeoshoreline elevations, whereas Roberts et al. (2013), studying central Calabria (southern Italy), found that no change in uplift rate was needed and a constant uplift rate throughout the Late Quaternary could explain the measured palaeoshorelines. In summary, this approach tests if un-dated palaeoshorelines can be modelled by iterated uplift rates implied by the dated palaeoshorelines. This iteration is enabled by a "Terrace Calculator" built in Excel, available in the literature where data from sea-level highstands are input (Roberts et al., 2013). The "Terrace Calculator" uses an input uplift rate (UR), which is iterated to calculate the predicted elevations (PE) of all sea-level highstands using the age of the highstands (T) and the sea level elevations of each highstand (SLE) using this formula: PE = (UR x T) + SLE (e.g. Meschis et al., 2020). More particularly, the uplift for the whole profile is iterated based on the palaeoshoreline with the age control such that the measured elevation matches that predicted by the "Terrace Calculator". Then the measured elevations are matched to the predicted elevations (within a range +/- 10 m) which allows undated palaeoshorelines to be allocated to sea-level highstands. This approach forces the user to maximise the coefficient of determination (R^2 value) for linear regression analysis through data including the "measured" (or mapped) elevations of all palaeoshoreline elevations on a topographic profile (GIS analysis and field) and the "predicted" (or expected) elevations which identify sea-level highstand elevations implied by iterating uplift rate values driven by age constrains and by means of available sea-level curves for the last ~0.9 - 1 My (SM 11 - Table SM 1) (Rohling et al., 2014; Siddall et al., 2003).

We discuss how uplift-rates can be used to constrain slip-rates on the faults in the discussion section. However, note that the topographic profiles we study exist in the footwall of the Messina-Taormina Fault and the hangingwalls of the Reggio Calabria and Armo faults; this must be factored into interpretations of the throw-rates and (and slip-rates if the fault dip is known) because an increase in footwall uplift rate implies an increase in slip-rate whereas an increase in hangingwall uplift rate may imply a decrease in slip-rate given a constant background regional uplift rate.

4. Results

Table 3 shows all mapped palaeoshoreline elevations defined in this study with ages constrained by the synchronous correlation carried out in this paper; data cover the regions associated with all 3 faults we have studied across. These elevation data support the plots in Figure 3, which are shown as examples (and Figures SM 4-10 for our synchronous correlations applied to all topographic profiles across the 3 investigated faults), with detailed analysis of topographic profiles across the footwall of the Messina-Taormina Fault and the hangingwalls of the Armo and Reggio Calabria faults. The following sections describe the procedures we performed to gather the data in Table 3 and justify their robustness.

4.1 Check of the reproducibility of topographic measurements

We conducted a check of the consistency of elevations of palaeoshorelines between different datasets using (i) a handheld GPS with barometric altimeter in the field (Figure

2), (ii) digital mapping from the DEM (Figure 3), and (iii) maps published in the literature. Elevation data from our DEM-based analysis were compared with elevations from our field-based palaeoshoreline mapping, where we visited palaeoshorelines locations from the literature and new sites that we identified. Comparison of the elevations shows a robust correlation with R^2 values >0.99 (Figure 4). This suggests that: (i) elevations measured elsewhere in DEMs are likely to be reliable and (ii) that our mapping is consistent with mapping data published by other authors (Antonioli et al., 2006; Catalano et al., 2003; Catalano and De Guidi, 2003; De Guidi et al., 2003; Miyauchi et al., 1994), but ages of un-dated marine terraces may need to be reviewed.

4.2 Comparison of the elevations of measured palaeoshorelines and the elevations of palaeoshorelines predicted by iterated uplift rate scenarios

We use age controls (Table 1 and 2) combined with the Terrace Calculator to iterate uplift rates to obtain a correlation between mapped palaeoshoreline elevations and predicted sea level highstand elevations for undated yet mapped palaeoshorelines. This allows us to investigate palaeoshoreline elevations and uplift rates along the strike of the 3 investigated faults. In particular, uplift rates were iterated (see SM 4 -10) and linear regression was used to assess the robustness of correlations between the predicted elevations iteratively calculated given (i) an uplift rate value driven by either new age controls from this study and from literature (Aloisi et al., 2013; Antonioli et al., 2006; Balescu et al., 1997; Ferranti et al., 2006; Miyauchi et al., 1994; Table 1 and 2) and (ii) fixed values for sea-level relative to present-day sea-level for several well-known highstands (SM 11 - Table SM 1; Rohling et al., 2014; Siddall et al., 2003) and those mapped in DEMs (Figures 3 and SM 4-10).

Figure 5 shows correlations between measured and predicted palaeoshorelines elevations using both constant (Figure 5a, b, c and SM 12-19) and fluctuating uplift rates through time (Figure 5d, e, f and SM 12-19). Initially, we assumed constant uplift rates through time. Correlations between measured and predicted palaeoshorelines elevations produced reasonably good correlations (R^2 values in the range of 0.9677-0.9954; y = 0.9665x to y = 0.903x; Figure 5a, b and c). However, after a number of iterations, we found that correlations improved if we included changing uplift-rates through time, specifically a change in uplift-rate on all 3 faults at 50 ka (R^2 values >0.9985; y =0.9697x to y = 1.0167x – Figure 5d, e and f), with a very robust correlation for all topographic profiles (R^2 > 0.99 - Figure 5g, h and i). Coefficient of determination, R^2, for each topographic profile (1-22) for the fluctuating uplift rate scenario is higher compared to the constant uplift rate scenario (SM 12-19). We did not enforce this value of 50 ka onto the calculations. Instead, this value arose as it produced the best fit for each of the 3 faults, even though they were analysed separately. The fact that the 50 ka value produces the best fits on 3 separate faults in 3 separate calculations suggests to us that it may well signify a major re-organisation of strain distribution in the rift. The result of our analyses tested this hypothesis by exploring the implications of this possibility. The results of assuming changing rates at 50 ka are shown in detail in Figures 5 and 6.

Figures 6a, b and c show spatial variations of uplift along the strikes of the investigated normal faults recorded by the geometry of the palaeoshorelines. The fact that the palaeoshorelines are tilted and/or folded along strike suggests faulting activity spanning the Middle-Late Pleistocene. Furthermore, Figures 6d, e and f imply that uplift rates vary along the strike of the faults and through time. Note that our interpretation of the uplift rates for the footwall of the Messina-Taormina Fault differs from that of Pavano et al. (2016) who utilise elevation data and uplift rates from Catalano et al. (2003), Catalano and De Guidi, (2003) and De Guidi et al. (2002). Similar to our interpretation, Pavano et al. (2016) show uplift changing along the coast with minima in the NE and SW near Capo Peloro and Taormina respectively, and a maximum near to Nizza di Sicilia (located in Figure 1), however they suggest the MIS 5e terrace (~125 ka) is at ~220 m near Nizza di Sicilia whereas we suggest this palaeoshoreline is at ~170 m elevation (topographic profiles 8 and 9 show the palaeoshoreline elevation between 160 m and 173 m), defining an amplitude of uplift-variation along strike that is smaller than in our interpretation. Moreover, we show that in most cases prominent palaeoshorelines on the sea level curve, mapped elsewhere in the Mediterranean realm such as the 125 ka (MIS 5e), 240 (MIS 7e) and the 340 ka (MIS 9e) (e.g. Meschis et al., 2020; Roberts et al., 2013; Robertson et al., 2019), identify clear geomorphic inner edges of marine terraces on topographic profiles. More subtle sea level highstands such as the 76.5 (MIS 5a), the second peak of the MIS 5e (119 ka) already recognized in SE Sicily (Meschis et al., 2020) and Apulia region (De Santis et al., 2021) within the Italian territory, and the 410 ka (MIS 11c) are also identified in places across all the 3 faults (in total, we identify palaeoshorelines from 50, 76, 100, 125, 200, 240, 310, 340, 410, 478 ka).

In our interpretation, values of uplift rates in the footwall of the Messina-Taormina Fault vary from ~ 0.5 mm/yr close to the NNE tip zone to ~ 0.8 mm/yr in the centre of the fault pre- 50 ka; post- 50 ka uplift rates accelerated from ~ 1.2 mm/yr close to the NNE tip zone to ~ 1.9 mm/yr in the centre of the fault (Figure 6d); this implies an uplift rate increase through time by a factor in the range of 2.375-2.400 (Table 4a). For the hangingwall of the Reggio-Calabria fault, values for uplift rates for pre-50 ka are 0.9 mm/yr beyond the NNE tip zone and 0.55 mm/yr close to the centre of the fault, with accelerated uplift-rate values after 50 ka of 2 mm/yr beyond the tip zone and 1.33 mm/yr close to the centre of the fault (Figure 6e); this indicates an uplift-rate increase by a factor in the range of 2.222-2.418 (Table 4a). It is important to note that for this region, close to Scilla region, our uplift rates from Profile 14 for the post-50 ka (2 mm/yr) are in agreement with Late Holocene uplift rates (~2 mm/yr) proposed by others (Antonioli et al., 2021, 2006a; Ferranti et al., 2007). For the hangingwall of the Armo Fault, uplift-rates vary between 0.85 mm/yr close to the southern tip and 0.56 mm/yr close to the centre of the fault prior to ~50 ka, with accelerated uplift rate values after 50 ka of 2.2 mm/yr close to the southern tip and 1.45 mm/yr close to the centre of the fault (Figure 6f); this indicates an uplift-rate increase by a factor in the range of 2.588-2.589 (Table 4a). In summary, the range of uplift-rate increase factors from these 6 different locations (3 fault centres and close to 3 fault tips) is small (2.222-2.589), with an average value of 2.43. This small range, and the fact that all 6 values were derived in independent calculations, suggests this is unlikely due to chance, but rather reflects a real change in the distribution of strain that affects all 3 faults in a similar manner. We discuss this further below, but for now note that change in fault-controlled uplift rates over the Late Quaternary are not unprecedented; for instance, within the Gulf of Corinth in Greece, tectonically deformed palaeoshorelines mapped within the footwall of the South Alkyonides Fault indicate that uplift rates have varied through time, with an uplift-rate change factor of ~3.20 at ~175 ka, suggesting an acceleration of slip-rate for this normal fault (Roberts et al., 2009).

We calculate how much the mapped palaeoshorelines have been tilted along-strike due to displacement gradients along the fault. This tests the hypothesis that the faults have been active throughout the Late Quaternary, because if this is the case older palaeoshorelines will have experienced a longer history of deformation and hence should exhibit higher tilt angles (e.g. Armijo et al., 1996; Meschis et al., 2018; Roberts et al., 2013; Robertson et al., 2019). Results confirm that the topographically higher and older palaeoshorelines present higher tilt angle values, demonstrating that they have experienced a longer faulting history, with progressive active faulting throughout the Middle-Late Pleistocene (Figure 7). It is important to note that similar along-strike variations of Late Holocene uplift, associated rates and tilting over 10 km along the strike of the Messina-Taormina Fault, close to its southern tip, had been reported by previous studies, suggesting faulting activity (Antonioli et al., 2006a; De Guidi et al., 2003; Spampinato et al., 2012), so our result is consistent with theirs.

To gain information on fault slip-rates from uplift-rates it is important to note that the acceleration in uplift at ~50 ka, measured on (i) hangingwalls of Reggio Calabria Fault and Armo Fault and (ii) footwall of the Messina-Taormina Fault, must reflect the interplay between fault-related vertical motions and vertical motions that are more “regional” in nature related to the underlying subduction system (Catalano and De Guidi, 2003; Catalano and Di Stefano, 1997; Westaway, 1993). It is widely accepted that there is an important regional uplift in this region, but debate surrounds the precise value, and how it can be separated from more regional uplift variations produced by normal faulting (e.g. Meschis et al., 2018; Roberts et al., 2013). However, if the regional uplift stayed constant through time, and affects both the hangingwall and footwalls of the active normal faults, then the following is implied: (i) the footwall uplift on the Messina-Taormina Fault has accelerated at ~ 50 ka, suggesting that the throw-rate on the fault increased at ~ 50 ka; (ii) the component of hangingwall subsidence produced by slip on the Reggio Calabria Fault and Armo Fault has decelerated at ~50 ka implying that the throw-rates on these faults decreased at ~50 ka. If our assumption is correct, and regional uplift-rates have remained constant through time, this out-of-phase behaviour, where the slip-rates on some faults accelerate accompanied by a synchronous deceleration of slip on others, implies that some sort of fault interaction may be acting.

4.3 Field observations that help to convert uplift-rates into throw-rates on the faults

We have collected a number of field observations that allow us to convert uplift-rate histories into throw-rate histories on the faults.

The long-term throw-rate on the Reggio Calabria Fault can be constrained due to what we interpret to be observations of a mapped faulted-offset of the 125 ka marine terrace along the fault-crossing Profile 16. For the hangingwall of the fault, age constraints in the literature (Table 1) driving our synchronous correlation technique suggest that a prominent terrace composed of marine conglomerates dates to the 5e highstand at ~125 ka whose associated terrace surface exists at ~ 123 m elevation (Figure 8). On the footwall a marine conglomerate deposit exists at ~ 190 m (Figure 8), which can be mapped up-dip to a prominent terrace surface. Although we have not achieved a direct age determination of the footwall deposits, we have derived ages for material that is contained within, and hence pre-dates this conglomerate. We achieved

^{234}U/^{230}Th age determinations for a death assemblage of detrital corals contained within a boulder of cemented shallow marine sands in this conglomerate of 449 ± 17 ka, 384 ± 11 ka and 480 ± 25 ka (Table 2). These ages suggest a minimum age of formation of this boulder of 384 ± 11.5 ka (implying the 448 ±17 ka and 480 ±25 ka corals are detrital ages for corals inherited from a previous highstand at 384 ±11 ka). However, the boulder itself is detrital, and its age could be older than the terrace deposits within which it is found. Thus, 384 ±11 ka is the maximum age of the marine terrace deposit containing the boulder, and the actual age must be younger. It is suggested its age is 125 ka because a very lithologically similar layer of marine conglomerate that caps the marine terrace related to the 125 ka highstand (Balescu et al., 1997; Catalano et al., 2003), has been mapped on the hangingwall of the same fault with a base at ~ 123 m. If the terraces are one and the same, this implies a vertical offset across the fault of ~77 m over 125 ka (Figure 8). This would suggest a long-term fault throw-rate averaged over 125 kyrs of 0.62 ± 0.04 mm/yr, in agreement with previous studies (0.6 mm/yr - Monaco and Tortorici, 2000). However, the interpreted increase in uplift-rate in the hangingwall at ~50 ka means that the 125 kyrs average throw-rate should not be used over shorter time intervals. If the uplift-rate change factor is applied (2.43) for the ~77 m of mapped vertical offset (Figure 8), the throw-rate was 0.80 mm/yr from 125 ka to 50 ka and 0.33 mm/yr from 50 ka to the present day, implying that the throw-rate decreased by a factor 0.41 at ~50 ka (Figure 8 and SM 20 for throw calculations).

For the Armo Fault, its long-term throw rate can be constrained due to the mapped offset of a marine terrace associated to the 478 ka sea level highstand, a refined age derived by applying a synchronous correlation approach along the fault-crossing Profile 20 (Figure 9 and Figure 1 for profile location). In particular, we show that the topographically highest and oldest terrace mapped on the hanging wall of the Armo Fault at 355 m dates from 478 ka, according to our synchronous correlations. This terrace, as well as all the lower terraces mapped along the Profile 20 (Figure 9), is cut into Plio-Pleistocene bioclastic and siliciclastic marine sandy deposits (Chiarella et al., 2021). A flat terraced surface at the footwall cut-off of the Armo Fault is mapped at ~700 m cut into the Palaeozoic basement. If this footwall terrace is assumed to be coeval and with the same age of the hangingwall cut-off terrace mapped at 355 m with a synchronously-derived age of 478 ka, this implies a vertical displacement of 345 m, suggesting a throw-rate of 0.72 ± 0.012 mm/yr averaged over 478 kyrs in agreement with other geoscientists that have studied this fault (e.g. 0.7 mm/yr - Roda-Boluda and Whittaker, 2017). However, the interpreted decrease in throw-rate at ~50 ka from uplift rates suggests that the 478 kyrs average throw-rate should not be used over shorter temporal windows. If the uplift-rate change factor is applied (2.43) then from 478 ka to 50 ka the throw-rate was 0.77 mm/yr and from 50 ka to present day 0.32 mm/yr for 345 m of offset, implying that the throw-rate decreased by a factor 0.41 at ~50 ka in the hangingwall (Figure 9 and SM 20 for throw calculations).

For the Messina-Taormina Fault, we do not have direct measurements of faulted offsets of Late Quaternary deposits. However, we derive a throw-rate by subtracting the rate of regional uplift and utilising a value for the ratio of footwall uplift and hangingwall subsidence. In particular, we map the highest uplift rates of 1.9 mm/yr (50 ka to present) in centre of the fault along Profiles 8 and 9 (Figure 6d). Previous studies have suggested that a "regional" component of uplift, with a rate of ~1 mm/yr for this region (Ferranti et al., 2007; Spampinato et al., 2014; Westaway, 1993), and our observations close to the fault tip, where the effect of faulting would be minimised, approach this value, supporting the ~1 mm/yr "regional" uplift rate. Some authors suggest a change in the rate of regional uplift through time from 1 Ma to present, with a marked increase at ~200 ka and then relatively constant through time until the present day (Quye-sawyer et al., 2021). For these reasons, we subtract 1 mm/yr from the "total" mapped post-50 ka uplift rate in the centre of the fault of 1.9 mm/yr (1.9–1 mm/yr = 0.9 mm/yr of footwall uplift) and we then apply a uplift/subsidence ratio of 1:1.6, a value proposed for the Calabrian Arc by previous studies (Quye-sawyer et al., 2021). This implies a hangingwall subsidence of 1.44 mm/yr that, if summed with 0.9 mm/yr of footwall uplift, implies a throw-rate of 2.34

mm/yr for the last 50 kyrs (0.9 mm/yr footwall uplift plus 1.44 mm/yr hangingwall subsidence). If the uplift rate change factor is applied (2.43), then a throw-rate of 0.96 mm/yr before 50 ka is suggested.

Overall, our results produce a pattern of uplift through time that differs from previous authors (e.g. Catalano et al., 2003; Catalano and De Guidi, 2003; De Guidi et al., 2002; Pavano et al., 2016). In particular, our interpretations suggest a major re-organisation of the activity rates on the three main faults in the region at ~50 ka that has not been noted by previous authors. Changes in activity rate have been reported from further north on the Cittanova, Serre and East Crati faults (Quye-Sawyer et al., 2021; Roda-Boluda and Whittaker, 2017). Finally, it is important to note that recently authors have claimed a possible different seismogenic source from the Messina-Taormina Fault for the 1908 Messina Earthquake (Barreca et al., 2021). In particular, they propose an offshore NNE-oriented fault, named "W-Fault", with its onshore prolongation bending towards southern Calabria, for a total length of ~34 km (Figure 15 from Barreca et al., 2021), close to our Profiles 14 and 15 on the hangingwall of the Reggio Calabria Fault. However, note that this geometry and orientation would not explain the geomorphology of well-mapped and tectonically deformed marine terraces in this paper and by others on the footwall of the Messina-Taormina Fault. Indeed, where lower uplift rates are mapped close to Messina town in this paper and already proposed in other studies (e.g. Catalano and De Guidi, 2003; Pavano et al., 2016) coincides with the centre of the "W-Fault" proposed by Barreca et al. 2021, and thus where a maximum long-term footwall-related uplift rate should be expected. Furthermore, on its onshore prolongation there is no co-seismic evidence or mapped fault scarp likely produced by successive earthquakes; instead, the Reggio Calabria Fault is well-known and previously mapped by several studies (Aloisi et al., 2013; Basili et al., 2008; INGV - DISS Working Group, 2018; Monaco and Tortorici, 2000; Tortorici et al., 1995), deforming the marine terraces outcropping along the Calabrian coastline of the Strait.

5. Discussion

As observed herein and worldwide within zones of convergence such as active subduction zones, uplifted palaeoshorelines can be used to derive rates of crustal deformation through time, from seismically deforming upper plates (e.g. Catalano et al., 2003; Catalano and De Guidi, 2003; De Guidi et al., 2002; González-Alfaro et al., 2018; Ott et al., 2019; Roberts et al., 2009; Roberts et al., 2013; Robertson et al., 2019; Saillard et al., 2009; Shikakura, 2014; Shyu et al., 2018).

For Calabria, Quye-Sawyer et al. (2021) and Roda-Boluda and Whittaker (2017) suggest an increase in throw-rate on the Serre, East Crati and Cittanova faults (Figure 1) between ~100-300 ka, using observations of knickpoints along rivers crossing these faults and incising into marine terraces, attributing these changes to the interaction of these faults during fault growth and linkage. The questions that arise are (a) whether these slip-rate changes are related to a change in rate across the whole subduction system or due to a change in the internal organisation of strain of the upper plate of the subduction system, and (b) how the changes in rate influence seismic hazard. We discuss a comparison between the rates we have measured, and regional extension rates measured with GPS and then discuss seismic hazard (Figure 10).

5.1 The relationship between fluctuating slip-rates on individual faults and the regional extension rate

Constraints on the regional extension rate are available from GPS observations and modelling based on those observations. Serpelloni et al. (2010) observed a maximum extensional strain-rate of ~65 nanostrains/yr and an extension rate of 3 mm/yr across the Messina Strait (Figure 10). Their inversion of these observations, in an attempt to resolve slip-rate on faults, and the bootstrap analysis of model uncertainties, that for a modelled fault that "dips gently SE-ward" located in the Messina Strait with dimensions and location similar to the Messina-Taormina fault considered herein, finds optimal values of 3.5+2.0/−1.3 and 1.6+0.3/−0.2 mm/yr for the dip–slip and strike–slip components, respectively, locked above 7.6+4.6/−2.9 km depth; we show the implied heave-rate through time for these inversion results as an inset in Figure 10d.

In order to compare our results with those from Serpelloni et al. (2010), we have summed the implied throw-rates on the faults through time and converted these into heave-rates (extension rates) by assuming fault dips ranging from 40-70^{o} (Figure 10d and SM 21 for calculations). Although the throw-rates on the faults decrease at 50 ka by a factor of 0.41 on the Reggio Calabria Fault and on the Armo Fault, alongside an increase by a factor of 2.43 at 50 ka on Messina-Taormina Fault, the combined effect of these out-of-phase throw-rate histories is to maintain a relatively constant heave-rate (see before and after the red dashed line in Figure 10d); these results are not inconsistent with those from Serpelloni et al. (2010), although we prefer higher values for fault dip constrained with field measurement from outcropping fault planes for the Armo and Reggio-Calbaria faults, and modelling of coseismic effects from the 1908 earthquake (Meschis et al. 2019). This suggests that these slip-rate changes are not related to a change in rate across the whole subduction system, but rather due to a change in the internal organisation of strain of the upper plate of the subduction system. It is worth noting that these faults are closely-spaced across-strike, with a distance less than 10-15 km at the base of the seismogenic layer, where large earthquakes likely nucleate. This distance is much less than half a fault length (~29 km for the Messina-Taormina Fault which is 58 km in length), a distance within fault interaction is expected. This is consistent with the conclusions from Quye-Sawyer et al. (2021) and Roda-Boluda and Whittaker (2017) who suggest that slip-rate changes in Calabria in the Late Quaternary are due to interactions between faults. Where one fault increases its slip-rate other faults across strike decrease their slip-rates to maintain constant regional strain-rates, and this has been reported in a number of other locations (the North Sea, central Italy, central Greece, Baja California, New Zealand; (Cowie et al., 2005, 2017;

Cowie and Roberts, 2001; Gupta et al., 1998; Nicol et al., 2006; Roberts et al., 2002; Roberts and Michetti, 2004), and in models of activity rates on faults (Cowie et al., 2012; Cowie, 1998; Cowie and Roberts, 2001; Mildon et al., 2019; Sgambato et al., 2020).

Our observations suggest summed heave-rates in the range of 0.92-3.56 mm/yr across faults that are assumed to dip in the range of 40-70°, but note that in detail it is challenging to reconcile this with the heave rates of 0.75-4.76 mm/yr derived through inversion of GPS data by Serpelloni et al. (2010) because they suggest a 30+1.1/−0.7° SE-ward dipping normal fault. It is challenging because Meschis et al. (2019) show that a dip of ~70° for the Messina-Taormina Fault is required to explain levelling data of the coastline that was deformed by the 1908 Mw 7.1 Messina earthquake, not 30+1.1/−0.7° implied by the results of Serpelloni et al. (2010). Possible explanations of this disparity are unclear, but may include factors such as (a) that Serpelloni et al. (2010) only included a single fault in their inversion, whilst the palaeoshoreline data we present shows that at least 3 faults have been active during the Late Quaternary, (b) that rates measured over interseismic timescales where elastic processes dominate (e.g. decadal timescales from GPS), may differ from rates measured over multiple seismic cycles (10^4-10^5 year timescales from deformed Quaternary palaeoshorelines) and (c) that the nearby Mt. Etna volcano has undergone changes in its chemistry due to re-organisation of the volcanic plumbing system in the Late Quaternary (plume–arc transition recorded by Etnean primitive melt inclusions from 125 ka – to present; Schiano et al., 2001), or even at ~60 ka (Barreca et al., 2018), and these changes may be associated with changes in the spatial distribution of strain within the overall subduction system. More work is needed to reconcile rates measured over different timescales. Serpelloni et al. (2010) do show that changes in slip-rate of several millimetres per year can be produced by changes in the locking depths of faults in the overall subduction system, and hence how faults interact, and this may be a way forward towards reconciling slip-rates measured over different timescales. However, for now we conclude that the changes in slip-rates we have constrained are broadly consistent with those in Serpelloni et al. (2010), but our results suggest that rates of late Quaternary slip appear to have been out-of-phase on faults located across strike from each other, and the summed heave rate is relatively constant through time, suggesting that the slip-rate changes are not related to a change in rate across the whole subduction system, but instead due to a change in the internal organisation of strain of the upper plate of the subduction system.

5.2 Fault interaction and its impact on seismic hazard assessment within the Messina Strait

Turning this to a broader point of view related to the seismic hazard affecting the Messina Strait, the newly-refined long-term fault throw-rates in this paper, and the associated T_{mean} values (or also known as Earthquake Recurrence Interval), play a crucial role for seismic hazard calculations. For example, Earthquake Recurrence Intervals (or T_{mean}) for a given earthquake magnitude are shorter for higher fault slip-rates (e.g. Cowie and Roberts, 2001). We are aware that in some cases rates of deformation are averaged over longer and different timescales (e.g. Martín-Banda et al., 2021; Roberts et al., 2013; Robertson et al., 2019) compared to this study because it is simply difficult to obtain more detailed faulting activity through time. However, herein, using a throw-rate on the Reggio Calabria Fault for instance over 125 kyr would provide a misleadingly short value for T_{mean}, because the throw-rate decreased by a factor of 0.41 at 50 ka (throw-rate over 125 ka = 0.62 mm/yr; assuming 1 m slip per event implies a T_{mean} of 1612 years; throw-rate over 50 ka = 0.33 mm/yr; assuming 1 m slip per event implies a T_{mean} of 3030 years). Similarly, for the Armo Fault, whose throw-rate has decreased by a factor of 0.41 at 50 ka (throw-rate of 0.32 mm/yr), this would imply a T_{mean} of 3125 years assuming a 1 m slip per event, rather than a T_{mean} of 1388 years for throw-rate of 0.72 mm/yr over the last 478 kyrs. For the Messina-Taormina Fault, we estimate a T_{mean} of 427 years assuming 1 m slip per event or 855 years assuming 2 mm slip per event for a throw-rate of 2.34 mm/yr over the last 50 ka. These values are summarized in Table 5. Thus, in this paper, we emphasise that it is vital to assess not just the throw-rate, but also the variability in throw-rates through time on a fault so that an appropriate throw-rate can be used in seismic hazard calculations. However, to do this, one must identify the correct ages of geological markers used in defining slip-rates.

6. Conclusion

A new uplift rate scenario has been presented within the tectonically extending Messina Strait, southern Italy, on the upper plate of the Ionian Subduction zone by refining ages of tectonically deformed Late Quaternary marine terraces. Palaeoshorelines investigated on the Sicilian coast, lying on the footwall of the offshore Messina-Taormina Fault, show along-strike deformed geometry, implying faulting activity over the Late Quaternary. Similarly, long-term faulting activity is implied for the Reggio Calabria Fault and the Armo Fault by showing along-strike deformed geometries of palaeoshorelines. Changes of uplift rates along-strike of the investigated faults confirm: (i) tectonic subsidence of the hangingwalls, which is presumably counteracting the “regional” uplift signal possibly associated either with the Ionian subduction process (Malinverno and Ryan, 1986; Roberts et al., 2013) or with mantle upwelling (Gvirtzman and Nur, 1999), and (ii) the footwall tectonic uplift. The changes in uplift rates are determined to be correlated with some faults speeding up and others slowing down at around 50 ka. We stress that this new scenario of temporally changing fault throw-rates has critical tectonic implications and effect the long-term seismic hazard approach either for the Messina Strait region and worldwide.

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Data Availability Statement

All data for this paper are properly cited and referred to in the reference list and available in Figure 3 and SM 4-10, as topographic data where paleoshoreline elevations have been mapped, and in Table 3 (all mapped paleoshoreline elevations and assigned ages). These data can be used to reproduce all results shown in Figure 6. SM 20 and 21 are used to produce results in Figure 10. The data will be stored online within Mendeley data (Reserved DOI: 10.17632/s3ygs5pdk2.1).

References

Aloisi, M., Bruno, V., Cannavò, F., Ferranti, L., Mattia, M., Monaco, C., Palano, M., 2013. Are the source models of the M 7.1 1908 Messina Straits earthquake reliable? Insights from a novel inversion and a sensitivity analysis of levelling data. Geophysical Journal International 192, 1025–1041. doi:10.1093/gji/ggs062

Anders, M.H., Schlische, R.W., 1989. Overlapping Faults, Intrabasin Highs, and the Growth of Normal Faults. Journal of Geology 102.

Anderson, Densmore, Ellis, 1999. The generation and degradation of marine terraces. Basin Research 11, 7–19. doi:10.1046/j.1365-2117.1999.00085.x

Antonioli, F., Calcagnile, L., Ferranti, L., Mastronuzzi, G., Monaco, C., Montagna, P., Orru, P.E., Quarta, G., Pepe, F., Scardino, G., Scicchitano, G., Stocchi, P., Taviani, M., 2021. Relative sea level change during MIS 3: a black hole in the world. New observations from Calabria, central Mediterranean sea EGU21-4048. doi:https://doi.org/10.5194/egusphere-egu21-4048

Antonioli, F., Ferranti, L., Lambeck, K., Kershaw, S., Verrubbi, V., Dai Pra, G., 2006a. Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and northeastern Sicily (southern Italy, Central Mediterranean Sea).

Tectonophysics 422, 23–40. doi:10.1016/j.tecto.2006.05.003

Antonioli, F., Kershaw, S., Renda, P., Rust, D., Belluomini, G., Cerasoli, M., Radtke, U., Silenzi, S., 2006b. Elevation of the last interglacial highstand in Sicily (Italy): A benchmark of coastal tectonics. Quaternary International 145–146, 3–18. doi:10.1016/j.quaint.2005.07.002

Argnani, A., Brancolini, G., Bonazzi, C., Rovere, M., Accaino, F., Zgur, F., Lodolo, E., 2009. The results of the Taormina 2006 seismic survey: Possible implications for active tectonics in the Messina Straits. Tectonophysics 476, 159–169. doi:10.1016/j.tecto.2008.10.029

Argnani, A., Brancolini, G., Rovere, M., Accaino, F., Zgur, F., Grossi, M., Fanzutti, F., Visnovic, P., Sorgo, D., Lodolo, E., Bonazzi, C., Mitchell, N., 2008. Hints on active tectonics in the southern Messina Straits: Preliminary results from the TAORMINA-2006 seismic cruise. Bollettino di Geofisica Teorica ed Applicata 49, 163–176.

Armijo, R., Meyer, B., King, G.C.P., Rigo, A., Papanastassiou, D., 1996. Quaternary evolution of the Corinth Rift and its implications for the Late Cenozoic evolution of the Aegean. Geophysical Journal International 126, 11–53. doi:10.1111/j.1365-246X.1996.tb05264.x

Balescu, S., Dumas, B., Guérémy, P., Lamothe, M., Lhénaff, R., Raffy, J., 1997. Thermoluminescence dating tests of Pleistocene sediments from uplifted marine shorelines along the southwest coastline of the Calabrian Peninsula (southern Italy). Palaeogeography, Palaeoclimatology, Palaeoecology 130, 25–41. doi:10.1016/S0031-0182(96)00119-8

Barreca, G., Branca, S., Monaco, C., 2018. Three-Dimensional Modeling of Mount Etna Volcano: Volume Assessment, Trend of Eruption Rates, and Geodynamic Significance. Tectonics 37, 842–857. doi:10.1002/2017TC004851

Barreca, G., Gross, F., Scarfì, L., Aloisi, M., Monaco, C., Krastel, S., 2021. The Strait of Messina: Seismotectonics and the source of the 1908 earthquake. Earth-

Science Reviews 218, 103685. doi:10.1016/j.earscirev.2021.103685

Basili, R., Valensise, G., Vannoli, P., Burrato, P., Fracassi, U., Mariano, S., Tiberti, M.M., Boschi, E., 2008. The Database of Individual Seismogenic Sources (DISS), version 3: Summarizing 20 years of research on Italy's earthquake geology. Tectonophysics 453, 20–43. doi:10.1016/j.tecto.2007.04.014

Catalano, S., De Guidi, G., 2003. Late Quaternary uplift of northeastern Sicily: Relation with the active normal faulting deformation. Journal of Geodynamics 36, 445–467. doi:10.1016/S0264-3707(02)00035-2

Catalano, S., De Guidi, G., Monaco, C., Tortorici, G., Tortorici, L., 2003. Long-term behaviour of the late Quaternary normal faults in the Straits of Messina area (Calabrian arc): Structural and morphological constraints. Quaternary International 101–102, 81–91. doi:10.1016/S1040-6182(02)00091-5

Catalano, S., Di Stefano, A., 1997. Sollevamenti e tettogenesi pleistocenica lungo il margine tirrenico dei Monti Peloritani: integrazione dei dati geomorfologici, strutturali e biostratigrafici. Il Quaternario 10, 337–342.

Chiarella, D., Capella, W., Longhitano, S.G., Muto, F., 2021. Fault-controlled base-of-scarp deposits. Basin Research 33, 1056–1075. doi:10.1111/bre.12505

Contreras, J., Anders, M.H., Scholz, C.H., 2000. Growth of a normal fault system : observations from the Lake Malawi basin of the east African rift. Journal of Structural Geology 22, 159–168. doi:10.1016/S0191-8141(99)00157-1

Cowie, P. A., Roberts, G.P., Bull, J.M., Visini, F., 2012. Relationships between fault geometry, slip rate variability and earthquake recurrence in extensional settings. Geophysical Journal International 189, 143–160. doi:10.1111/j.1365-246X.2012.05378.x

Cowie, P.A., Underhill, J., Behn, M., Lin, J., Gill, C., 2005. Spatio-temporal evolution of strain accumulation derived from multi-scale observations of Late Jurassic rifting in the northern North Sea: A critical test of models for lithospheric extension. Earth and Planetary Science Letters 234, 401–419. doi:10.1016/j.epsl.2005.01.039

Cowie, P.A., 1998. A healing–reloading feedback control on the growth rate of seismogenic faults. Journal of Structural Geology 20. doi:https://doi.org/10.1016/S0191-8141(98)00034-0

Cowie, P.A., Phillips, R.J., Roberts, G.P., McCaffrey, K.J.W., Zijerveld, L.J.J., Gregory, L.C., Faure Walker, J.P., Wedmore, L.N.J., Dunai, T.J., Binnie, S.A., Freeman, S.P.H.T., Wilcken, K., Shanks, R.P., Huismans, R.S., Papanikolaou, I., Michetti, A.M., Wilkinson, M., 2017. Orogen-scale uplift in the central Italian Apennines drives episodic behaviour of earthquake faults. Scientific Reports 7, 44858. doi:10.1038/srep44858

Cowie, P.A., Roberts, G.P., 2001. Constraining slip rates and spacings for active normal faults. Journal of Structural Geology 23, 1901–1915. doi:10.1016/S0191-8141(01)00036-0

Cowie, P.A., Shipton, Z.K., 1998. Fault tip displacement gradients and process zone dimensions. Journal of Structural Geology 20, 983–997. doi:10.1016/S0191-8141(98)00029-7

Crémière, A., Lepland, A., Chand, S., Sahy, D., Condon, D.J., Noble, S.R., Martma, T., Thorsnes, T., Sauer, S., Brunstad, H., 2016. Timescales of methane seepage on the Norwegian margin following collapse of the Scandinavian Ice Sheet. Nature Communications 7, 11509. doi:10.1038/ncomms11509

D'Agostino, N., Selvaggi, G., 2004. Crustal motion along the Eurasia-Nubia plate boundary in the Calabrian Arc and Sicily and active extension in the Messina Straits from GPS measurements. Journal of Geophysical Research: Solid Earth 109, n/a-n/a. doi:10.1029/2004JB002998

De Guidi, G., Catalano, S., Monaco, C., Tortorici, L., 2003. Morphological evidence of Holocene coseismic deformation in the Taormina region (NE Sicily). Journal of Geodynamics 36, 193–211. doi:10.1016/S0264-3707(03)00047-4

De Guidi, G., Catalano, S., Monaco, C., Tortorici, L., Di Stefano, A., 2002. Long-term effects of late Quaternary normal faulting in southern Calabria and eastern Sicily.

Studi Geologici Camerti 1, 79–93.

De Natale, G., Pingue, F., 1991. A Variable Slip Fault Model For the 1908 Messina Straits (Italy) Earthquake, By Inversion of Levelling Data. Geophysical Journal International 104, 73–84. doi:10.1111/j.1365-246X.1991.tb02494.x

De Santis, V., Scardino, G., Meschis, M., Ortiz, J.E., Sánchez-Palencia, Y., Caldara, M., 2021. Refining the middle-late Pleistocene chronology of marine terraces and uplift history in a sector of the Apulian foreland (southern Italy) by applying a synchronous correlation technique and amino acid racemization to Patella spp. and Thetystrombus latus. Italian Journal of Geosciences 140. doi:https://doi.org/10.3301/IJG.2021.05

Doglioni, C., Ligi, M., Scrocca, D., Bigi, S., Bortoluzzi, G., Carminati, E., Cuffaro, M., D’Oriano, F., Forleo, V., Muccini, F., Riguzzi, F., 2012. The tectonic puzzle of the Messina area (Southern Italy): Insights from new seismic reflection data. Scientific Reports 2, 970. doi:10.1038/srep00970

Dumas, B., Gueremy, P., Lhenaff, R., Raffy, J., 1993. Rapid uplift, stepped marine terraces and raised shorelines on the Calabrian coast of Messina Strait, Italy. Earth Surface Processes and Landforms 18, 241–256. doi:10.1002/esp.3290180306

Dumas, B., Guérémy, P., Raffy, J., 2005. Evidence for sea-level oscillations by the “characteristic thickness” of marine deposits from raised terraces of Southern Calabria (Italy). Quaternary Science Reviews 24, 2120–2136. doi:10.1016/j.quascirev.2004.12.011

Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P., Verrubbi, V., 2006. Markers of the last interglacial sea-level high stand along the coast of Italy: Tectonic implications. Quaternary International 145–146, 30–54. doi:10.1016/j.quaint.2005.07.009

Ferranti, L., Monaco, C., Antonioli, F., Maschio, L., Kershaw, S., Verrubbi, V., 2007.

The contribution of regional uplift and coseismic slip to the vertical crustal motion in the Messina Straits, southern Italy: Evidence from raised Late Holocene shorelines. Journal of Geophysical Research 112, B06401. doi:10.1029/2006JB004473

Firth, C., Stewart, I., 1996. Coastal elevation changes in eastern Sicily: implications for volcano instability at Mount Etna. Geological Society, … 153–167. doi:10.1144/GSL.SP.1996.110.01.12

Ghisetti, F., 1984. Recent deformations and the seismogenic source in the Messina Strait (southern Italy) 109, 191–208. doi:https://doi.org/10.1016/0040-1951(84)90140-9

Ghisetti, F., Vezzani, L., 1982. Different styles of deformation in the calabrian arc (Southern Italy): Implications for a seismotectonic zoning. Tectonophysics 85, 149–165. doi:10.1016/0040-1951(82)90101-9

González-Alfaro, J., Vargas, G., Ortlieb, L., González, G., Ruiz, S., Báez, J.C., Mandeng-yogo, M., Caquineau, S., Álvarez, G., 2018. Abrupt increase in the coastal uplift and earthquake rate since ~40 ka at the northern Chile seismic gap in the Central Andes. Earth and Planetary Science Letters 502, 32–45. doi:10.1016/j.epsl.2018.08.043

Gupta, S., Cowie, P.A., Dawers, N.H., Underhill, J.R., 1998. A mechanism to explain rift-basin subsidence and stratigraphic patterns through fault-array evolution. Geology 26, 595–598. doi:10.1130/0091-7613(1998)026<0595:AMTERB>2.3.CO;2

Gvirtzman, Z., Nur, A., 1999. The formation of Mount Etna as the consequence of slab rollback. Nature 401, 782–785. doi:10.1038/44555

Houghton, S.L., Roberts, G.P., Papanikolaou, I.D., McArthur, J.M., 2003. New 234 U-230 Th coral dates from the western Gulf of Corinth: Implications for extensional tectonics. Geophysical Research Letters 30, 2013. doi:10.1029/2003GL018112

INGV - DISS Working Group, 2018. Database of Individual Seismogenic Sources

(DISS), Version 3.2.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. doi:10.6092/INGV.IT-DISS3.2.1.

Jara-Muñoz, J., Melnick, D., 2015. Unraveling sea-level variations and tectonic uplift in wave-built marine terraces, Santa María Island, Chile. Quaternary Research 83, 216–228. doi:10.1016/j.yqres.2014.10.002

Lajoie, K.R., 1986. Coastal Tectonics, in: Active Tectonics: Impact on Society. pp. 95–124.

Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. Tectonics 5, 227–245. doi:10.1029/TC005i002p00227

Martín-Banda, R., Insua-Arévalo, J.M., García-Mayordomo, J., 2021. Slip Rate Variation During the Last ~210 ka on a Slow Fault in a Transpressive Regime: The Carrascoy Fault (Eastern Betic Shear Zone, SE Spain). Frontiers in Earth Science 8, 1–21. doi:10.3389/feart.2020.599608

Mcleod, A.E., Dawers, N.H., Underhill, J.R., 2000. The propagation and linkage of normal faults : insights from the Strathspey – Brent – Statfjord fault array , northern North Sea. Basin Research 12, 263–284.

Meschis, M., Roberts, G.P., Mildon, Z.K., Robertson, J., Michetti, A.M., Faure Walker, J.P., 2019. Slip on a mapped normal fault for the 28 th December 1908 Messina earthquake (Mw 7.1) in Italy. Scientific Reports 1–8. doi:10.1038/s41598-019-42915-2

Meschis, M., Roberts, G.P., Robertson, J., Briant, R.M., 2018. The Relationships Between Regional Quaternary Uplift, Deformation Across Active Normal Faults, and Historical Seismicity in the Upper Plate of Subduction Zones: The Capo D'Orlando Fault, NE Sicily. Tectonics 37, 1231–1255. doi:10.1029/2017TC004705

Meschis, M., Scicchitano, G., Roberts, G.P., Robertson, J., Barreca, G., Monaco, C., Spampinato, C., Sahy, D., Antonioli, F., Mildon, Z.K., Scardino, G., 2020. Regional deformation and offshore crustal local faulting as combined processes to explain uplift through time constrained by investigating differentially-uplifted Late Quaternary palaeoshorelines: the foreland Hyblean Plateau, SE Sicily. Tectonics. doi:10.1029/2020TC006187

Mildon, Z.K., Roberts, G.P., Faure Walker, J.P., Beck, J.W., Papanikolaou, I.D., Michetti, A.M., Toda, S., Campbell, L., McCaffrey, K.J.W., 2019. Earthquake clustering controlled by shear zone interaction. doi:https://doi.org/10.31223/osf.io/qkx2v

Miller, W.R., Mason, T.R., 1994. Erosional Features of Coastal Beachrock and Aeolianite Outcrops in Natal and Zululand, South Africa. Journal of Coastal Research 10, 374–394. doi:10.2307/4298223

Miyauchi, T., Dai Pra, G., Sylos Labini, S., 1994. Geochronology of Pleistocene marine terraces and regional tectonics in the Tyrrhenian coast of South Calabria, Italy. Il Quaternario 7, 17–34.

Monaco, C., Tortorici, L., 2000. Active faulting in the Calabrian arc and eastern Sicily. Journal of Geodynamics 29, 407–424. doi:10.1016/S0264-3707(99)00052-6

Mulargia, F., Boschi, E., 1983. "The 1908 Messina earthquake and related seismicity. Earthquakes: observation, theory and interpretation 493–518.

Nicol, A., Walsh, J.J., Berryman, K., Villamor, P., 2006. Interdependence of fault displacement rates and paleoearthquakes in an active rift. Geology 34, 865–868. doi:https://doi.org/10.1130/G22335.1

Ott, R.F., Gallen, S.F., Wegmann, K.W., Biswas, R.H., Herman, F., Willett, S.D., 2019. Pleistocene terrace formation, Quaternary rock uplift rates and geodynamics of the Hellenic Subduction Zone revealed from dating of paleoshorelines on Crete, Greece. Earth and Planetary Science Letters 525, 115757. doi:10.1016/j.epsl.2019.115757

Pavano, F., Pazzaglia, F.J., Catalano, S., 2016. Knickpoints as geomorphic markers of active tectonics: A case study from northeastern Sicily (southern Italy). Lithosphere 8, 633–648. doi:10.1130/L577.1

Pedoja, K., Jara-Muñoz, J., De Gelder, G., Robertson, J., Meschis, M., Fernandez-Blanco, D., Nexer, M., Poprawski, Y., Dugué, O., Delcaillau, B., Bessin, P., Benabdelouahed, M., Authemayou, C., Husson, L., Regard, V., Menier, D., Pinel, B., 2018. Neogene-Quaternary slow coastal uplift of Western Europe through the perspective of sequences of strandlines from the Cotentin Peninsula (Normandy, France). Geomorphology 303, 338–356. doi:10.1016/j.geomorph.2017.11.021

Quye-sawyer, J., Whittaker, A.C., Roberts, G., Rood, D., 2021. Fault Throw and Regional Uplift Histories From Drainage Analysis : Evolution of Southern Italy. Tectonics 40. doi:https://doi.org/10.1029/2020TC006076

Ridente, D., Martorelli, E., Bosman, A., Chiocci, F.L., 2014. High-resolution morpho-bathymetric imaging of the Messina Strait (Southern Italy). New insights on the 1908 earthquake and tsunami. Geomorphology 208, 149–159. doi:10.1016/j.geomorph.2013.11.021

Roberts, G. P., Houghton, S.L., Underwood, C., Papanikolaou, I., Cowie, P.A., Van Calsteren, P., Wigley, T., Cooper, F.J., McArthur, J.M., 2009. Localization of quaternary slip rates in an active rift in 105 years: An example from central Greece constrained by 234U- 230Th coral dates from uplifted paleoshorelines. Journal of Geophysical Research: Solid Earth 114, 1–26. doi:10.1029/2008JB005818

Roberts, G.P., Meschis, M., Houghton, S., Underwood, C., Briant, R.M., 2013. The implications of revised Quaternary palaeoshoreline chronologies for the rates of active extension and uplift in the upper plate of subduction zones. Quaternary Science Reviews 78, 169–187. doi:10.1016/j.quascirev.2013.08.006

Roberts, G.P., Michetti, A.M., 2004. Spatial and temporal variations in growth rates along active normal fault systems: an example from The Lazio–Abruzzo Apennines, central Italy. Journal of Structural Geology 26, 339–376. doi:10.1016/S0191-8141(03)00103-2

Roberts, G.P., Michetti, A.M., Cowie, P., Morewood, N.C., Papanikolaou, I., 2002.

Fault slip-rate variations during crustal-scale strain localisation, central Italy. Geophysical Research Letters 29, 9-1-9–4. doi:10.1029/2001GL013529

Robertson, J., Meschis, M., Roberts, G.P., Ganas, A., Gheorghiu, D.M., 2019. Temporally Constant Quaternary Uplift Rates and Their Relationship With Extensional Upper-Plate Faults in South Crete (Greece), Constrained With ^{36}Cl Cosmogenic Exposure Dating. Tectonics 38. doi:10.1029/2018TC005410

Robertson, J., Roberts, G.P., Iezzi, F., Meschis, M., Gheorghiu, D.M., Sahy, D., Bristow, C., Sgambato, C., 2020. Distributed normal faulting in the tip zone of the South Alkyonides Fault System, Gulf of Corinth, constrained using 36Cl exposure dating of late-Quaternary wave-cut platforms. Journal of Structural Geology 136, 104063. doi:10.1016/j.jsg.2020.104063

Roda-Boluda, D.C., Whittaker, A.C., 2017. Structural and geomorphological constraints on active normal faulting and landscape evolution in Calabria, Italy. Journal of the Geological Society jgs2016-097. doi:10.1144/jgs2016-097

Rohling, E.J., Foster, G.L., Grant, K.M., Marino, G., Roberts, A.P., Tamisiea, M.E., Williams, F., 2014. Sea-level and deep-sea-temperature variability over the past 5.3 million years. Nature 508, 477–482. doi:10.1038/nature13230

Saillard, M., Hall, S.R., Audin, L., Farber, D.L., Hérail, G., Martinod, J., Regard, V., Finkel, R., Bondoux, F., 2009. Non-steady long-term uplift rates and Pleistocene marine terrace development along the Andean margin of Chile (31° S) inferred from 10 Be dating. Earth and Planetary Science Letters 277, 50–63. doi:https://doi.org/10.1016/j.epsl.2008.09.039

Schiano, P., Clocchiatti, R., Ottolini, L., Busà, T., 2001. Transition of Mount Etna lavas from a mantle-plume to an island-arc magmatic source. Nature 412, 900–904. doi:10.1038/35091056

Serpelloni, E., Bürgmann, R., Anzidei, M., Baldi, P., Mastrolembo Ventura, B., Boschi, E., 2010. Strain accumulation across the Messina Straits and kinematics of Sicily and Calabria from GPS data and dislocation modeling. Earth and Planetary

Science Letters 298, 347–360. doi:10.1016/j.epsl.2010.08.005

Sgambato, C., Faure Walker, J.P., Mildon, Z.K., Roberts, G.P., 2020. Stress loading history of earthquake faults influenced by fault/shear zone geometry and Coulomb pre-stress. Scientific Reports 10, 12724. doi:10.1038/s41598-020-69681-w

Shikakura, Y., 2014. Marine terraces caused by fast steady uplift and small coseismic uplift and the time-predictable model: Case of Kikai Island, Ryukyu Islands, Japan. Earth and Planetary Science Letters 404, 232–237. doi:10.1016/j.epsl.2014.08.003

Shyu, J.B.H., Wang, C., Wang, Y., Shen, C., Chiang, H., Liu, S., Min, S., Thu, L., Than, O., Thura, S., 2018. Upper-plate splay fault earthquakes along the Arakan subduction belt recorded by uplifted coral microatolls on northern Ramree Island , western Myanmar (Burma). Earth and Planetary Science Letters 484, 241–252. doi:https://doi.org/10.1016/j.epsl.2017.12.033

Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. Nature 423, 853–858. doi:10.1038/nature01690

Spampinato, C.R., Ferranti, L., Monaco, C., Scicchitano, G., Antonioli, F., 2014. Raised Holocene paleo-shorelines along the Capo Vaticano coast (western Calabria, Italy): Evidence of co-seismic and steady-state deformation. Journal of Geodynamics 82, 178–193. doi:10.1016/j.jog.2014.03.003

Spampinato, C.R., Scicchitano, G., Ferranti, L., Monaco, C., 2012. Raised Holocene paleo-shorelines along the Capo Schisò coast, Taormina: New evidence of recent co-seismic deformation in northeastern Sicily (Italy). Journal of Geodynamics 55, 18–31. doi:10.1016/j.jog.2011.11.007

Stewart, I.S., Cundy, A., Kershaw, S., Firth, C., 1997. Holocene coastal uplift in the taormina area, northeastern sicily: Implications for the southern prolongation of the calabrian seismogenic belt. Journal of Geodynamics 24, 37–50. doi:10.1016/S0264-3707(97)00012-4

Tarquini, S., Vinci, S., Favalli, M., Doumaz, F., Fornaciai, A., Nannipieri, L., 2012. Release of a 10-m-resolution DEM for the Italian territory: Comparison with global-coverage DEMs and anaglyph-mode exploration via the web. Computers & Geosciences 38, 168–170. doi:10.1016/j.cageo.2011.04.018

Tortorici, G., Bianca, M., De Guidi, G., Monaco, C., Tortorici, L., 2003. Fault activity and marine terracing in the Capo Vaticano area (southern Calabria) during the Middle-Late Quaternary. Quaternary International 101–102, 269–278. doi:10.1016/S1040-6182(02)00107-6

Tortorici, L., Monaco, C., Tansi, C., Cocina, O., 1995. Recent and active tectonics in the Calabrian arc (Southern Italy). Tectonophysics 243, 37–55. doi:10.1016/0040-1951(94)00190-K

Valensise, G., Pantosti, D., 1992. A 125 Kyr-long geological record of seismic source repeatability: the Messina Straits (southern Italy) and the 1908 earthquake (M s 7/ 2). Terra Nova 4, 472–483. doi:10.1111/j.1365-3121.1992.tb00583.x

Westaway, R., 1993. Quaternary uplift of southern Italy. Journal of Geophysical Research 98, 741–772. doi:10.1029/93JB01566

Figure and table captions

Figure 1: Map of the investigated area. Sketched fault map of the Messina Strait is shown. Locations of several topographic profiles across the Messina-Taormina Fault, the Reggio Calabria Fault and the Armo Fault. Locations of age controls are shown from new ^{234}U/^{230}Th coral ages and from literature (Table 1 and 2). Inner edges are shown with different coloured dots indicating refined ages (Table 3). Inset A, modified from Ghisetti et al. (1984), shows a sketched structural scheme of the Messina Strait, accommodating ongoing crustal extension of ~ 3 mm/yr (Serpelloni et al., 2010). Inset B shows Quaternary active normal faults within the Calabrian Arc.

Zoom in on these locations (dotted black squares) are shown in supplementary materials (Figure SM 1, SM 2 and SM 3).

Figure 2: (a) A sequence of uplifted marine terraces is shown on the Sicilian coast, in particular on the footwall of the offshore Messina-Taormina Fault. Inner edges of marine terraces have been mapped in the field (coloured dots) and on DEMs (see topographic profile), and refined ages are assigned using a synchronous correlation approach. Field evidence of palaeoshorelines such as lithophagid borings (b) and a Mesozoic limestone-made wave-cut platform overlies by shallow marine conglomerate identifying an unconformity (c) are shown. Location of this profile is also shown in Figure 1.

Figure 3: Topographic profiles for each investigated active fault derived by using 10-m high resolution DEMs (Tarquini et al., 2012), showing modelled palaeoshoreline elevations. Sea-level highstands, identifying predicting palaeoshoreline elevations, are represented by coloured lines that are calculated by iterating values of uplift rate to find the best match with the mapped (numbered arrows) palaeoshorelines. All topographic profiles (13 profiles for the Messina-Taormina Fault, 4 profiles for the Reggio Calabria Fault and 5 profiles for the Armo Fault) are shown on Figures SM 4-10). Inner edge elevations with refined ages are also shown in Table 3.

Figure 4: Linear regression analysis showing the relationship between field-based and DEM-based inner edge elevation measurements for the Messina-Taormina Fault (a), Reggio Calabria Fault (b) and Armo Fault (c). The R^2 value > 0.99 confirms a strong correlation suggesting that elevations measured from the DEM are likely to be accurate.

Figure 5: Linear regression analysis for all 3 investigated faults showing that a better and higher R^2 value is obtained if a changing uplift rate through time is claimed to model multiple mapped palaeoshoreline elevations and multiple synchronously-predicted sea-level highstand elevations. Indeed, constant scenario (a, b and c) vs fluctuating scenario (d, e and f) for one topographic profile for each fault is shown. Linear regression for all

topographic profiles (1-22) for the fluctuating scenario are shown in g, h and i. Linear regression analysis between our measured and predicted palaeoshoreline elevations for the Messina-Taormina Fault, Armo Fault and Reggio Calabria Fault for each topographic profile (1-22) is shown in Figure SM 12-19. The predicted elevations, representing the synchronously calculated sea-level highstand elevations, indicate a fluctuating uplift rate through time, that has been derived by iterating uplift rates to find the best match to the measured and mapped palaeoshorelines. Note that “measured” elevations represent palaeoshoreline elevations mapped in the 10 m high resolution DEMs. Coefficient of determination, R^2 value, has been used between these two datasets to quantify the best fit for all topographic profiles presented in this paper, with a value > 0.99.

Figure 6: Crustal uplift and uplift rates over the Quaternary. Topographic profiles from Figure 1 are labelled. Palaeoshoreline elevations change along the strikes of the Messina-Taormina Fault (a), Reggio Calabria Fault (b) and Armo Fault (c), suggesting Late Quaternary faulting activity. Spatial variations of rates of uplift measured along the strikes of the investigated faults and on the footwall of the Messina-Taormina Fault (d) and on hangingwalls of the Reggio Calabria Fault (e) and the Armo Fault (f). Changes in uplift rates through time (“Pre-50ka” and “post-50ka”) are shown, derived by applying a synchronous correlation approach on the investigated palaeoshorelines deformed by normal faulting activity.

Figure 7: Tilt angle values calculated for each mapped palaeoshoreline shown in Figure 6a-c, showing that older palaeoshorelines have higher tilt angles, suggesting that they have experienced a longer history of differential uplift, and that differential uplift has been ongoing progressively during the Late Quaternary. Note that for the Messina-Taormina Fault, a flex point is not recorded because we were not able to map palaeoshorelines belonging to the 50 ka sea level highstand. Inset A shows a no-scaled cartoon sketch of the tilt angle of a palaeoshoreline along the strike of a fault.

Note that values of tilt angle for each investigated palaeoshoreline have been calculated as a $\tan^{-1}$ of a gradient "m" of a straight-line equation (y=mx), as proposed by previous studies (Meschis et al., 2018; Meschis et al., 2020; Robertson et al., 2019).

Figure 8: Cartoon field sketch showing the Reggio Calabria Fault offsetting terraced shallow marine deposits over 125 ka. On the footwall terrace a boulder made of cemented bioclastic sands containing corals with ages given in Table 2 (Samples 15, 16 and 17) and the significance of the ages described in the text.

Figure 9: Topographic profile and field sketch showing mapped uplifted palaeoshorelines on the hangingwall of the Armo Fault cut into Plio-Pleistocene marine deposits. It is also shown the Armo Fault offsetting the synchronously-derived 478-aged marine terrace, suggesting faulting activity over the Late Quaternary. Bottom photo shows some of the palaeoshorelines mapped on the hangingwall of the Armo Fault along the Profile 20. Note that bottom photo is made by 3 puzzled photos to re-create a panoramic view. Profile location is shown in Figure 1.

Figure 10: (a) Throw-rates through time are shown for the Messina-Taormina Fault, Reggio Calabria Fault and Armo Fault. Changing throw rates through time have been calculated from faulted coeval marine terraces for the Reggio Calabria Fault and Armo Fault. In (b) and (c) a tectonic sketch with refined throw-rate through time, pre and post 50 ka, with horizonal extension rates from Serpelloni et al. (2010). Note that photos are from Google EarthTM. In (d), values of throw-rates-converted heave rates are shown, iterating different fault dip-angles for all 3 investigated faults, compared to those proposed by Serpelloni et al. (2010) using geodetic measurements. In (d), we assume that fault dip angles for all 3 investigated faults are the same because we have no information for those values.

The contrast of changing throw-rates of individual faults with constant heave-rates when summed all the faults suggests that faults are interacting to maintain the regional extension rate.

Table 1: Age controls from literature used to drive our synchronous correlation approach for each investigated fault.

Table 2: Measurements of $^{234}U/^{230}Th$ Isotope ratios of coral samples collected on the footwall of the Reggio Calabria Fault (see Figure 1 for location).

Table 3: Mapped inner edge elevations of marine terraces from fieldwork and DEM analysis with refined ages assigned using a synchronous correlation approach are shown. Note that age controls from literature (*) are stated throughout the table.

Table 4: Uplift-rate change factors (a) and uplift-rate-derived throw-rate change factor (b) are shown. Note that acceleration of uplift rates is mapped on both coastlines of the Messina Strait.

Table 5: Values of Earthquake Recurrence Interval (T_{mean}) are summarized showing the variability if pre-50 ka rates and/or long-term rates are used instead of post-50 ka rates. Note that throw-rates for the Messina-Taormina Fault are for the first time estimated in this paper, implying that no long-term rates are available from literature.