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Usage Guidelines: Please refer to usage guidelines at https://eprints.bbk.ac.uk/policies.html or alternatively contact lib-eprints@bbk.ac.uk. The relationships between regional Quaternary uplift, deformation across active normal
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 D'Orlando Fault, NE Sicily.

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10 Abstract

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In order to investigate deformation within the upper plate of the Calabrian subduction zone 12 we have mapped and modelled a sequence of Late Quaternary palaeoshorelines tectonically-deformed 13 by the Capo D'Orlando normal fault, NE Sicily, which forms part of the actively deforming Calabrian 14 Arc. In addition to the 1908 Messina Strait earthquake (Mw 7.1), this region has experienced 15 16 damaging earthquakes, possibly on the Capo D'Orlando Fault, however, it is not considered by some 17 to be a potential seismogenic source. Uplifted Quaternary palaeoshorelines are preserved on the 18 hanging wall of the Capo D'Orlando Fault, indicating that hanging wall subsidence is counteracted by regional uplift, likely because of deformation associated with subduction/collision. We attempt to 19 20 constrain the relationship between regional uplift, crustal extensional processes and historical 21 seismicity, and we quantify both the normal and regional deformation signals. We report uplift 22 variations along the strike of the fault and use a synchronous correlation technique to assign ages to palaeoshorelines, facilitating calculation of uplift rates and the fault throw-rate. Uplift rates in the 23 24 hanging wall increase from 0.4 mm/yr in the centre of the fault to 0.89 mm/yr beyond its SW fault tip, 25 suggesting 0.5 mm/yr of fault related subsidence, which implies a throw-rate of  $0.63 \pm 0.02$  mm/yr, and significant seismic hazard. Overall, we emphasise that upper plate extension and related vertical 26 motions complicate the process of deriving information on the subduction/collision process, such as 27

coupling and slip distribution on the subduction interface, parameters that are commonly inferred forother subduction zones without considering upper plate deformation.

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Keywords: Quaternary; Palaeoshorelines; Marine terraces; Sea level changes; Synchronous
correlation method; Uplift rate; Normal faulting, Fault slip-rate; DISS; Crustal deformation
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Data on coastal uplift in the upper plate of subduction zone are commonly used to infer the slip 39 40 distributions and gain insight into the processes of coupling along the subduction interface and mantle 41 upwelling [McCloskev et al., 2005; Meltzner et al., 2006; Nalbant et al., 2013; Nic Bhloscaidh et al., 2015; D'Agostino et al., 2001; Faure Walker et al., 2012; Faccenna et al., 2014]. This paper 42 emphasises that there is a growing body of evidence that the upper plates of subduction zones can also 43 be deformed by active normal faults. This evidence is widespread for example from central Greece 44 45 and Crete [Armijo et al., 1992; Papanikolaou et al., 2006; Gallen et al., 2014], south America [Saillard et al., 2011; Binnie et al., 2016], New Zealand [Nicol and Beavan, 2003], Japan [Hasegawa 46 et al., 2000] and southern Italy [Monaco and Tortorici, 2000; Jacques et al., 2001; Spampinato et al., 47 2012; Roberts et al., 2013]. Deformation related to normal faulting must be removed if the observed 48 49 coastal uplift is to be used to constrain both the slip-distribution on the subduction interface and 50 mantle dynamics-related topography.

Long-term crustal extension processes occurring in Calabria and NE Sicily have been accommodated by active normal faults that have been deforming palaeoshorelines through the Late Quaternary [*Monaco and Tortorici*, 2000; *Jacques et al.*, 2001; *Catalano and De Guidi*, 2003; *Giunta et al.*, 2012; *Roberts et al.*, 2013]. The locations of historical damaging earthquakes from Italian 55 catalogues [Guidoboni et al., 2007; Stucchi et al., 2013] lie close to these mapped normal faults 56 [Monaco and Tortorici, 2000; Galli et al., 2008; Roberts et al., 2013]. Potential seismogenic sources 57 have been collated within the Database of Individual Seismogenic Source (DISS) [Basili et al., 2008], 58 providing a base from which to define the geography of seismic hazard in Italy. However, we ask 59 whether the locations of all active normal faults that can be considered to be candidate seismogenic 60 sources are known. For example, even though two well-documented medium-magnitude historical 61 seismic events have been reported [Guidoboni et al., 2007] around the Capo D'Orlando area, in NE 62 Sicily, only a few studies [Scicchitano et al., 2011; Giunta et al., 2012] have attempted to identify 63 plausible potential seismogenic sources, such as the Capo D'Orlando Fault. These authors recognised that Quaternary palaeoshorelines are tilted and hence deformed by the Capo D'Orlando Fault, 64 suggesting the fault is active. However, the results are considered equivocal by some, for example 65 because no active faults are reported in this location within the DISS [Basili et al., 2008]. In this 66 67 study, we investigate whether the Capo D'Orlando Fault reported by Scicchitano et al. [2011] and Giunta et al., [2012] should be added to the DISS. 68

A quantitative understanding of Late Quaternary upper-crustal vertical movements such as 69 tectonic uplift and/or subsidence and their associated slip-rates on active normal faults within a plate 70 71 boundary region is fundamental to long-term seismic hazard assessment [Roberts et al., 2013]. We take into account the notion that any evidence of fault movement since the Middle/Late Pleistocene 72 has been accepted by some as the definition of an "active fault" [Yeats, 2012; Chapman et al., 2014]. 73 74 Therefore, we study the long-term deformation since the Middle Pleistocene by investigating 75 sequences of deformed palaeoshorelines, which can be used to (i) help differentiate between transitory 76 strain-rates associated with temporal earthquake clustering, and (ii) judge how long-term strain-rates 77 measured over many seismic cycles relate to those measured over shorter timescales [Yeats and 78 Prentice, 1996; Ward, 1998; Friedrich et al., 2003; Papanikolaou et al., 2005; Faure Walker et al., 79 2010; Roberts et al., 2013].

The approach that we have taken is to examine differential uplift across the candidate active fault in question [*Massonnet et al.*, 1993; *Massonnet and Feigl*, 1995; *Armijo et al.*, 1996; *Roberts et al.*, 2009, 2013; *Walters et al.*, 2009; *Papanikolaou et al.*, 2010]. In particular, we focus our attention

83 on the 15 km onshore section of the NE-SW oriented Capo D'Orlando Fault [Scicchitano et al., 2011; Giunta et al., 2012]. We conduct new mapping alongside a review of ages for previously-mapped 84 85 palaeoshorelines outcropping on the hangingwall of the Capo D'Orlando Fault. The age review is 86 conducted by attempting to correlate palaeoshorelines that are unevenly spaced in elevation with 87 glacio-eustatic sea-level highstands that are unevenly spaced in time through iteration of the uplift rate 88 history [Roberts et al., 2009, 2013]. This work (i) quantifies uplift rates values, (ii) investigates along-89 strike variation in uplift rate, which if correlated with the fault offset and fault-tip locations, will 90 confirm Quaternary activity on the fault, (iii) investigates rates of tilting for palaeoshorelines along the strike of the fault to define displacement gradients, and (iv) estimates the associated slip-rate 91 92 through correlation between offset palaeoshorelines preserved in the hangingwall and footwall, which 93 has fundamental tectonic and seismic hazard implications [Cowie et al., 2012]. We investigate the 94 above by mapping the inner edges of marine terraces (palaeoshorelines) both through detailed 95 topographic surveying using a 10-m resolution Digital Elevation Model (DEM) [Tarquini et al., 2007, 2012] and fieldwork, seeking to confirm the reliability of the mapping by Giunta et al. [2012]. We 96 97 then correlate our mapped inner edge elevations with glacio-eustatic sea-level highstands since the Middle Pleistocene, by iterating the uplift-rate. We assess the robustness of our correlations between 98 99 multiple mapped palaeoshorelines and multiple sea-level highstands through linear regression analysis. Finally, we discuss our results in terms of local and regional tectonic implications and 100 seismic hazard assessment within the Ionian subduction zone and the associated Plio-Pleistocene 101 regional extensional processes, which are accommodated by several upper crustal active normal faults 102 potentially producing damaging earthquakes. 103

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#### 105 **2. Background**

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#### 107 *2.1. Geological background*

The study area lies in the southernmost part of the Calabrian Arc, which forms the link
between the NW–SE oriented southern Apennines thrust belt in mainland Italy and the E-W oriented

110 Maghrebide chain in northern Sicily [Tortorici et al., 1995] (Figure 1). As a response to Neogene-111 Quaternary Africa-Eurasia continental collision and the ongoing southeastwardly subduction of the 112 Ionian plate beneath Calabria, probably associated with the opening of Tyrrhenian Extensional Basin 113 [Rehault et al., 1984; Malinverno and Ryan, 1986; Dewey et al., 1989; Selvaggi and Chiarabba, 1995; 114 Gutscher et al., 2017], the Calabrian Arc represents one of the most tectonically active regions in the 115 Mediterranean. Since the Pliocene, structural features produced by Neogene shortening have been 116 fragmented by extensional faults producing geomorphological landscapes characterised by structural 117 highs and sedimentary basins [Barone et al., 1982; Ghisetti and Vezzani, 1982; Trincardi and 118 Zitellini, 1987; Kastens et al., 1988; Pepe et al., 2000, 2003].

Since the Pliocene-Early Pleistocene, Calabria and NE Sicily have been affected by active 119 120 normal faulting mostly on the Tyrrhenian side and within the Messina Strait between Sicily and Calabria, uplifting and deforming Quaternary marine deposits in response to NW-SE regional 121 122 extension [Monaco and Tortorici, 2000], including near Capo D'Orlando town [Giunta et al., 2012]. Some geoscientists have proposed a cessation or slowing of the roll-back process and associated 123 124 extension within the Tyrrhenian Basin due to the de-coupling of the Ionian slab from the Calabrian Arc since 700 ky [Gvirtzman and Nur, 1999; Wortel and Spakman, 2000; Goes et al., 2004; 125 126 Serpelloni et al., 2005, 2007; Palano et al., 2012]. This suggested slab detachment process is thought to have produced both the sinking of the slab itself, with related isostatic rebound and lithospheric 127 tearing-related faulting near the SW and NE tips of the NW-dipping Ionian slab, producing flow of 128 129 mantle material through slab windows just beneath the crust of the Calabrian Arc. These processes 130 have produced significant uplift and crustal extension within the upper plate of the Ionian subduction zone through the Middle Pleistocene [Gvirtzman and Nur, 1999; Faccenna et al., 2011]. 131

Ongoing extension and uplift is confirmed by (i) GPS investigations, which demonstrate an extension rate of 2 mm/yr with local uplift rates as high as 0.5-1.0 mm/yr [*Serpelloni et al.*, 2005; *Mastrolembo Ventura et al.*, 2014; *Scarfi et al.*, 2016a; *Chiarabba and Palano*, 2017], and (ii) historical seismicity in the overriding plate [*Monaco and Tortorici*, 2000]. Historical damaging earthquakes have been reported in and around the study area [*Guidoboni et al.*, 2007; *Stucchi et al.*, 2013]. In particular, two medium historical seismic events have been located within the investigated

138 area close the Capo D'Orlando Fault. It remains unclear whether or not the 1613 A.D. Naso 139 earthquake (Mw 5.6, Figure 1) ruptured the Capo D'Orlando Fault or other smaller active faults in its 140 surrounding area (epicentres have been located within five km from the investigated area). Towns 141 such as Naso, Capo D'Orlando and Santa Agata di Militello were shaken by a maximum intensity of 142 IX [Guidoboni et al., 2007], indicating a source fault within a few tens of kilometres or less. A second 143 seismic event, the 1739 A.D. Naso earthquake (Mw 5.1), may also have ruptured Capo d'Orlando 144 Fault or other active faults nearby, because maximum intensities of VIII-IX were recorded 145 [Guidoboni et al., 2007]. Empirically-derived structural parameters such as fault length and expected 146 earthquake magnitude [Wells and Coppersmith, 1994; Galli et al., 2008] can be used to suggest that the  $\sim$ 15 km mapped length of the Capo D'Orlando Fault could be capable of producing earthquakes as 147 large as Mw 6, but because the fault length is poorly constrained where it goes offshore in the east, 148 larger magnitudes are not excluded. However, this potential seismogenic structure has not been 149 150 mapped within the DISS [Basili et al., 2008; INGV - DISS Working Group, 2015] although it shows very similar geological/structural parameters to other mapped "debated seismogenic sources" such as 151 the Vibo Valentia Fault and the Taormina Fault which have themselves been mapped through study of 152 Quaternary deformed palaeoshorelines [Catalano and De Guidi, 2003; De Guidi et al., 2003; 153 Tortorici et al., 2003; Bianca et al., 2011; Roberts et al., 2013]. We note that the Capo D'Orlando 154 Fault may be capable of hosting surface ruptures to earthquakes, because Giunta et al. [2012] report 155 kinematic measurements from a striated fault scarp at outcrop, showing dip slip normal movement 156 157 (see their inset in their Figure 2), implying slip at the surface rather than activity on a blind fault.

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2.2. Late Quaternary palaeoshorelines and existing age controls in the Capo D'Orlando area

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The Calabrian Arc has been experiencing uplift above the Ionian subduction zone suggested
by the presence of uplifted Quaternary palaeoshorelines and Holocene coastal notches [*Dumas et al.*,
1988, 1993, 2005; *Patacca et al.*, 1990; *Westaway*, 1993; *Miyauchi et al.*, 1994; *Balescu et al.*, 1997; *Stewart et al.*, 1997; *Gvirtzman and Nur*, 1999; *Bonardi et al.*, 2001; *Doglioni et al.*, 2001; *Faccenna et al.*, 2004; *Lucente et al.*, 2006; *Cucci et al.*, 2006; *Ferranti et al.*, 2007; *Bianca et al.*, 2011; *Roberts*

166 et al., 2013] (Figure 1). Furthermore, as already observed by several geoscientists [Dumas et al., 167 1981, 1988, Ghisetti, 1981, 1984; Valensise and Pantosti, 1992; Westaway, 1993; Miyauchi et al., 168 1994; Bianca et al., 1999, 2011; Catalano and De Guidi, 2003; Tortorici et al., 2003] the Calabrian 169 Arc provides excellent geological signatures of the interaction between tectonic uplift process and 170 sea-level changes over the Quaternary identified by the presence of dramatic sequences of marine 171 terraces. Here we focus on the fact that tectonically-deformed flights of palaeoshorelines have 172 recorded the effects of Late Quaternary normal faulting activity within the Calabrian Arc [Jacques et 173 al., 2001; Roberts et al., 2013]. In agreement with previous authors [e.g. Armijo et al., 1996; Bianca 174 et al., 2011; Giunta et al., 2012; Roberts et al., 2013] we interpret mapped seaward-sloping marine surfaces as palaeoshoreface surfaces cut by wave-action, with palaeoshorelines at their up-dip, inner 175 edges, which can be traced parallel to the present-day coastline between the towns of Capo D'Orlando 176 and Acquedolci (Figure 2a and 2b). These palaeoshoreface surfaces have been carved into the "Ghiaie 177 178 di Messina" Formation and, in places, the Mesozoic limestones and/or the Palaeozoic basement (Figure 3). Furthermore, field observations show that in places these palaeosurfaces have been 179 covered by palaeoshoreface deposits such as sandstones and marine conglomerates (Figure 4). In 180 places, we found rounded, marine beach cobbles made of Mesozoic limestone or Palaeozoic 181 182 crystalline basement as well as borings made by lithophagids affecting the Mesozoic limestones confirming the geological observations of previous authors [Scicchitano et al., 2011; Giunta et al., 183 2012]. It has been suggested that the Capo D'Orlando Fault has been deforming a partially-dated Late 184 185 Quaternary sequence of marine terraces in part accommodating the regional extension [Serpelloni et al., 2005; Mastrolembo Ventura et al., 2014; Scarfi et al., 2016b; Chiarabba and Palano, 2017], and 186 187 we investigate this further herein.

Age control on the marine terrace sequence is limited (Table 1), and here we review existing constraints. *Giunta et al.* [2012] used Optically Stimulated Luminescence (OSL) dating of two samples of marine sands associated with two different palaeoshorelines (their II and IV). The more robust of these is sample 23 on palaeoshoreline II, at an elevation of c. 50 m, near the SW fault tip area between Torrenova and Sant'Agata di Militello town (Figure 2a and 2b). This sample shows robust luminescence behaviour, using a widely-applied protocol, and gives an age of  $118 \pm 7$  ka

194 [Giunta et al., 2012], probably indicating the presence of the  $\sim 125$  ka palaeoshoreline. An *in-situ* shell 195 of Spondylus sp. from sediments just above the marine deposit overlying palaeoshoreline II in the 196 Rocca Scodoni' area was dated by U/Th to c. 125 ka [Scicchitano et al., 2011; Sulli et al., 2013], 197 consistent with the OSL determination. This sequence is located in the hangingwall, close to the 198 centre of the fault if it continues offshore. A further OSL age of  $283 \pm 22$  ka is available from 199 palaeoshoreline IV at 208 m beyond the mapped fault tip close to Fiorita-Sprazzi town (sample 21 in 200 Giunta et al. [2012], Figure 2a and 2b). The luminescence characteristics of this sample are not 201 described, but large error bars suggest that the analysis may be close to saturation. Further information 202 would be required to assess the robustness of this age. Other studies have examined a mammal 203 assemblage from deposits at a similar altitude (135 m) to palaeoshoreline III thought to be c. 200 ka 204 old based on isoleucine epimerization dating of bones [Bada et al., 1991]. In this study, we do not use this data point because the stratigraphic link to the marine terrace sequence is tenuous and the method 205 206 is considered to give relative ages only, despite the attempted quantification.

This paucity of absolute age control for mapped palaeoshorelines near Capo D'Orlando is a 207 typical problem for areas affected by low-uplift rates. Thus, a common problem is how to extrapolate 208 the knowledge of known palaeoshoreline ages to help identify the ages of other un-dated 209 210 palaeoshorelines. Several authors [e.g. Bianca et al., 1999; Catalano et al., 2003; Tortorici et al., 2003; Giunta et al., 2012; Gallen et al., 2014] have derived uplift rates by applying a sequential 211 correlation approach. This method is based on the idea that, given a dated palaeoshoreline/horizon, the 212 next higher and older palaeoshoreline is likely to belong to the next older sea-level highstand [e.g. 213 Tortorici et al., 2003; Giunta et al., 2012; Gallen et al., 2014]. However, this method can be prone to 214 error if it does not take into account the well-known "overprinting or re-occupation problem" where 215 216 palaeo-sea-level highstands that have maximum elevations beneath that of subsequent highstands can 217 be overwhelmed by a subsequent, higher palaeo-sea-level highstand; palaeoshoreline indicators from 218 the former can be eroded and not preserved [Westaway, 1993; Roberts et al., 2013]. If not considered, 219 the overprinting problem can lead to an erroneous assignment of age. Overprinting is particularly problematic in areas with relatively low uplift rates such as southern Italy [Westaway, 1993; Tortorici 220 221 et al., 2003; Bianca et al., 2011; Giunta et al., 2012; Roberts et al., 2013]. However, Houghton et al.

222 [2003] and *Roberts et al.* [2009, 2013] have suggested an alternative approach, whereby an iterative 223 method is used to calculate all expected palaeoshoreline elevations for a given uplift rate, with all 224 measured palaeoshoreline elevations correlated with all predicted palaeoshoreline elevations 225 synchronously rather than sequentially. An example of this approach was demonstrated using the 226 Vibo Fault, Calabria [Roberts et al., 2013]. Here the 125ka-dated palaeoshoreline was used by 227 previous authors [Tortorici et al., 2003; Bianca et al., 2011] to suggest that the next higher 228 palaeoshoreline belonged to the next older major highstand on the sea-level curve (200 ka), thus 229 deriving a temporally-varying uplift rate. However, Roberts et al. [2013] verified the age of the 125ka-dated palaeoshoreline using <sup>238</sup>U/<sup>230</sup>Th of corals that formed part of the terrace, and with this 230 231 age constraint and application of the synchronous correlation method, they showed that the next 232 higher palaeoshoreline was, instead, the 240 ka marine highstand, resulting in a constant uplift rate throughout the Late Quaternary of 0.75 mm/yr (for detailed reference, see Profile 8 in Figure 2a and 233 234 table 3 in Roberts et al. 2013). This approach takes into account the overprinting problem and is considered here to provide more robust estimates of the uplift history than the sequential approach. 235

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#### 237 **3. Approach and Methods**

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239 The study area offers a set of special circumstances that allows investigation of the 240 relationship between regional uplift process and counteracting local tectonics. For example, (i) the 241 Capo D'Orlando normal fault is quasi-parallel to the present-day shoreline, oriented NE-SW, with its 242 displacement decreasing towards the south-west where its tip lies onshore, (ii) hangingwall tectonic subsidence due to normal faulting appears to be slower than the regional uplift process allowing a 243 244 sequence of marine terraces to be preserved in the hangingwall of the fault, and (iii) the inner edges of the uplifted marine deposits (the palaeoshorelines) can be mapped quasi-parallel to the present-day 245 246 shoreline. These special circumstances led us to map palaeoshorelines through a detailed DEM-based 247 topographic survey and fieldwork, using existing detailed mapping by Giunta et al. [2012] as a guide. We then used a synchronous correlation approach to assign ages to multiple palaeoshorelines, using 248

dating constraints from previous papers [*Scicchitano et al.*, 2011; *Giunta et al.*, 2012]. We also
present previous authors dating for the investigated area (Table 1).

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#### 252 *3.1 Palaeoshoreline elevation data: DEM-based topographic analysis and fieldwork*

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254 To ensure that we mapped inner edges of marine terraces (palaeoshorelines) which represent 255 the palaeo-sea level related to a highstand, we rely on (i) the presence of key evidence such as 256 lithophagid borings, backshore/foreshore marine deposits containing shallower marine fossils (corals, 257 molluses, vermetid shells, etc.) as suggested by previous geoscientists [Ferranti et al., 2006; Roberts et al., 2009, 2013; Giunta et al., 2012], and (ii) geomorphic features such as coastal notches [Boulton 258 and Stewart, 2015]. In places, the inner edges of marine terraces can be covered by a few meters of 259 younger terrigenous deposits that produce uncertainty regarding the exact palaeoshoreline elevation. 260 261 However, our mapping shows these are small in vertical extent (a few metres) and hence the uncertainty is likely to have a minimal impact when calculating the implied uplift rates. Inner-edge 262 elevations defining palaeoshorelines for the Capo D'Orlando area were mapped onto a 10-m 263 resolution Digital Elevation Model (DEM) [Tarquini et al., 2007, 2012] and combined, following 264 265 ground-truthing during fieldwork, with those published by Giunta et al. [2012] (Figure 2a). Fifteen topographic profiles, each capturing a sequence of palaeoshorelines, were produced perpendicular to 266 the strike of the fault covering the 15-km extent of the onshore fault (Figure 2b). The topography and 267 presence of preserved palaeoshoreline indicators was used to decide the location of each 268 palaeoshoreline profile; areas of incision caused by rivers were avoided to ensure that the geomorphic 269 270 features investigated were marine and not fluvial. The presence of palaeoshorelines was confirmed by 271 extensive geological fieldwork during 2015, with elevations determined using a barometric altimeter 272 that we calibrated to elevation benchmarks such as sea-level every few hours. Note that in places we 273 were unable access the palaeoshorelines locations because of thick vegetation and limited access onto 274 private land. However, analysis of DEMs allowed us to map along strike from our field observations and identify palaeoshoreface surface from slightly seaward-sloping surfaces, bounded up-dip by 275 abrupt palaeocliff-like features marking the palaeoshorelines. 276

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#### 278 *3.2 Synchronous correlation approach*

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280 The synchronous correlation approach is based on the concept that sea-level highstands, 281 which are thought to produce palaeoshorelines, are unevenly spaced in time, and so for a constant 282 uplift rate, one would expect the palaeoshorelines to be unevenly spaced in elevation. For 283 synchronous correlation, given that at least one palaeoshoreline has age control, the first step is to 284 assume a constant uplift rate and examine whether the implied elevations of palaeoshorelines of 285 different ages match the elevations of measured palaeoshorelines. If they do not, then the uplift-rate can be varied through time and iterated to find the best match with measured palaeoshoreline 286 elevations. This approach was described in detail in Houghton et al. [2003] and Roberts et al. [2009, 287 2013]. 288

289 To implement the synchronous correlation approach, the method is that topographic profiles are constructed across the strike of the palaeoshorelines from DEM data (Figure 5). Then, using 290 fieldwork to ground-truth the profile, interpretations are made of the inner-edge elevations of 291 palaeoshorelines. These elevations are then input into a spreadsheet that is referred to as the Terrace 292 293 Calculator [Roberts et al., 2009, 2013]. The initial uplift rate for each profile is constrained using one or more dated palaeoshorelines, which is then used to predict the expected elevations for 294 palaeoshoreline of different ages for comparison with measured elevations. R<sup>2</sup> linear regression 295 analysis quantifies the relationship between the predicted and measured inner-edge elevations. The 296 uplift value is iterated to maximise the  $R^2$  value, with values commonly achieved of > 0.99. Where 297 there is no dated surface within a profile, the uplift rates of profiles on either side of the one in 298 299 question are used to determine the initial uplift value and this was then iterated as described above. 300 Once ages are allocated to all of the palaeoshorelines within the sequence of profiles, a comparison of 301 palaeoshoreline elevations versus age parallel to the strike of the fault is used to determine the extent 302 of the along-strike deformation caused by the fault.

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#### 305 Capo D'Orlando Fault

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307 Palaeoshorelines have been mapped both on the hangingwall and partially on the footwall of 308 the Capo D'Orlando Fault (see Topographic profile 7, Fig. 6). In particular, a wave cut platform 309 (WCP) cut into limestone associated with Late Quaternary palaeoshoreline deposits has been mapped 310 on its footwall close to the supposed centre of the onshore fault segment at 345 m above sea level 311 (a.s.l) (Figure 2b). Evidence of an upper shoreface marine environment have been recognized such as 312 rounded marine beach cobbles, possible mill-holes and poorly-preserved and hence equivocal lithophagid borings, all of which probably indicate a palaeo-rocky beach. We use the elevations of 313 these footwall wave cut platforms, and their hanging wall equivalents identified mapping around the 314 SW fault tip, to estimate long-term fault displacement by applying a long-term uplift/subsidence ratio 315 316 proposed by several authors [King et al., 1988; Armijo et al., 1996; McNeill and Collier, 2004]. A value of 1/3.5 (uplift/subsidence) ratio has been applied, and we use the elevation of the 340 ka 317 palaeoshoreline mapped close the centre of fault on the hangingwall at 129 m and within the fault "tip 318 zone" at 291 m as being the correlative surface with the lowest WCP on the footwall. 319

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#### **321 4. Results**

First, we show that the approach advocated above can re-produce measured palaeoshoreline elevations by matching them with predicted elevations. We then correlate palaeoshoreline elevations along-strike for the Capo D'Orlando Fault. Finally, we use the derived spatial and temporal constraints on the palaeoshoreline geometries to derive uplift rates and how these relate to displacements on the active normal fault.

We show our synchronous correlation between mapped palaeoshorelines and palaeoshore elevations predicted through iteration of the uplift rate (Figure 6). We iterated the uplift rates to find the best fit between mapped and predicted palaeoshorelines using the dual criteria of (i) making sure that the clearest mapped palaeoshorelines were matched by the most prominent sea-level highstands at 125, 240 and 340 ka, and (ii) maximising the  $R^2$  value that shows how well other less prominent 332 mapped palaeoshorelines match the predicted palaeoshoreline elevations. Through our synchronous 333 correlation we are able to reassess ages for all mapped but un-dated palaeoshorelines (Table 2). It is 334 important to note that our interpreted palaeo-sea-cliffs defining palaeoshorelines are clear on the 335 DEM. However, in places some of the palaeoshorelines are too small in geographic extent to see at 336 the resolution of the DEM, yet were clear during the fieldwork (Figure 4 for the Profile 6 with 337 the125ka-dated palaeoshoreline clear in the field). Nonetheless, we have indicated these subtle 338 mapped palaeoshorelines and included them in the synchronous correlation (Figure 6). In order to 339 check (a) the correlation between elevations determined from the DEM and those measured with a 340 hand-held barometric altimeter in the field, and (b) how well the measured elevations match the predicted elevations from synchronous correlation (Figure 7). We find that (a) elevations measured on 341 342 the DEM match those measured in the field within measurement error, suggesting our measured elevations are robust (Figure 7a), and (b) our predicted elevations match the measured ones within 343 344 error, suggesting we have gained a robust correlation, and reliable uplift-rate estimates (Figure 7b).

The linear regression analysis described above implies a robust, synchronous correlation 345 346 between multiple sea-level highstands and multiple palaeoshoreline elevations. This key observation also suggests that uplift rates have not fluctuated through time. Another implication is that we have 347 348 identified palaeoshorelines associated with the sea-level highstands from 76 ka, 100 ka, 125 ka, 175 ka, 200 ka, 217 ka, 240 ka, 285 ka, 310 ka, 340 ka and 410 ka (not all mapped within a single profile) 349 (Table 3); these synchronously-derived ages of palaeoshorelines have been recognised elsewhere in 350 the Mediterranean area [e.g. Roberts et al., 2009, 2013]. Our results also confirm that mapping by 351 Giunta et al. [2012] is reliable and robust, but we assign amended ages to his mapped 352 353 palaeoshorelines.

We use our interpretations between multiple mapped palaeoshorelines and multiple iteratively-predicted highstand elevations to produce a correlation of palaeoshorelines along the strike of the Capo D'Orlando Fault (Figure 8). In particular, our synchronous correlation shows that uplift rates are constant over the Late Quaternary yet vary spatially, with an uplift rate of 0.35 mm/yr in the centre of the hangingwall of the fault, increasing towards the fault tip and beyond where the uplift rate is 0.89 mm/yr (Figure 8a). Because the uplifted palaeoshorelines are in the hangingwall of the Capo 360 D'Orlando Fault, this suggests that finite uplift is a combination of a "regional" uplift signal and local361 fault-controlled subsidence.

362 The observation that uplift varies along the strike of the fault, with folded and tilted 363 palaeoshorelines (Figure 8b), suggests that there is a displacement gradient along the fault. We have 364 investigated whether folding and tilting have occurred through time or after formation of all the 365 palaeoshorelines by examining values of tilt along strike and how these vary for different 366 palaeoshoreline ages. If faulting has occurred progressively through time we would expect older 367 palaeoshorelines to be more tilted than younger ones along the strike of the fault. Note that tilt angle values for each investigated palaeoshoreline have been calculated, as a tan<sup>-1</sup> of a gradient "m" of 368 straight line equation (y=mx). We then show that older and higher mapped palaeoshorelines present 369 higher tilt angle values, implying that they have experienced a longer history of faulting activity 370 (Figure 8c). We interpret this evidence to indicate that faulting has occurred progressively through 371 372 time, during the progressive formation of successive palaeoshorelines. Our interpretations also reveal another stratigraphic feature consistent with along-strike variation in fault activity rate. The implied 373 increase in uplift rate in the hangingwall of the fault towards the fault tip has allowed more 374 palaeoshorelines to be preserved where the uplift rate is higher (Figure 8b). This fact is to be expected 375 376 because the overprinting problem mentioned above will destroy some palaeoshorelines if the uplift rate is low. Thus, the increase in the number of palaeoshorelines with uplift rate and increase in tilt 377 angle with age are both diagnostic of incremental fault-controlled deformation, and similar features 378 have been reported for other areas deformed by active normal faults in the Gulf of Corinth [Armijo et 379 al., 1996; Roberts et al., 2009] and the Calabrian Arc [Roberts et al., 2013]. 380

We recognize a "tip zone" defined by (i) higher number of preserved marine terraces, (ii) a shallowing of the long-term tilt angle value recorded by palaeoshorelines from NE to SW and (iii) field-based evidence showing that the fault scarp mapped by Giunta et al. [2012] dies out along strike towards the tip zone (Figure 8b). This "zone" in figure 2b coincides with the red-coloured dashed line in the SW fault tip. This observation provides the opportunity to attempt to correlate hangingwall palaeoshorelines with those on the footwall by mapping them around the fault tip. It, in turn, allows us to calculate the throw-rate on the fault. Our field mapping suggests a correlation between the 388 hangingwall palaeoshoreline that (i) we have assigned to the 340 ka sea-level highstand, and (ii) we have mapped at 291 m in the tip zone, with a footwall palaeoshoreline that we have mapped to the NE 389 390 in the footwall at an elevation of 345 m near the middle of the footwall of the fault. In other words, we 391 have been able to correlate a palaeoshoreline across the fault from the hangingwall to the footwall. To 392 gain the rate of vertical offset we have (i) applied a long-term uplift/subsidence ration of 1/3.5 along 393 Profile 7 at the centre of fault, intercepting the WCP mapped in the footwall to predict the footwall 394 elevation of the 340 ka palaeoshoreline, and (ii) taken into account the implied "minimum 395 displacement" (or the hangingwall subsidence) for the 340 ka palaeoshoreline calculated between the 396 hangingwall elevation and the elevation within the fault tip zone (Profile 13). We obtained a "predicted" footwall palaeoshoreline elevation of 335 m which we suggest could be associated with 397 the 345 m high palaeoshoreline that we have mapped in the footwall. The offset between the footwall 398 and the hanging wall implies a constant long-term fault throw-rate of  $0.63 \pm 0.02$  mm/yr derived by a 399 400 fault throw of 216 m for the last 340 kyrs (Figure 8b). Note that the uncertainty has been estimated by applying a formula to calculate error propagation as follows:  $dTR = |TR| * sqrt[(dD/D)^2 + (dt/T)^2]$ 401 where dTR is the calculated uncertainty, TR (0.63 mm/yr) is the throw rate, D (216 m = 216000 mm) 402 is the measured displacement and T (340 kyr = 340000 yr) is the time over the displacement occurred. 403 404 Furthermore, error value associated with the displacement (dD) is 5000 mm which is derived by barometric altimeter error resolution; error value associated with the age of highstand (dT) is 4000 yr 405 406 [Siddall et al., 2003; Rohling et al., 2014].

These results confirm that the Capo D'Orlando Fault has been offsetting the investigated palaeoshorelines at the surface throughout the Late Quaternary, proving that this fault is not blind. Our interpretations described above suggest that the regional uplift can be defined within and beyond the tip-zone of the Capo D'Orlando Fault; it is implied that this value is  $\sim 0.9$  mm/yr. However, note that further detailed studies are needed to define whether this candidate value for the regional uplift is in fact influenced by possible active faults offshore.

- 413
- 414 5. Discussion
- 415

In this study, we have investigated the relationship between multiple Late Quaternary 416 417 palaeoshorelines, active normal faulting and regional uplift. Our results indicate a long-term constant 418 fault throw-rate and related fault-modified regional uplift rate, rather than an uplift rate that fluctuates 419 through time (Figure 9). Recognition that the Capo D'Orlando Fault has modified the "regional" uplift 420 signal with a constant rate has implications for the geography of the seismic hazard of NE Sicily and 421 within the wider area of the geological domain of the Calabrian Arc (Figure 10). In particular, it 422 implies that slip distributions calculated for subduction interfaces based on uplift data need to 423 consider ongoing crustal deformation within the upper plate. We discuss this in more detail with 424 regard to local and regional processes.

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5.1. Local tectonic implications: estimating fault throw-rate and Earthquake Recurrence Interval for the Capo D'Orlando Fault 427

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At the local scale, the investigated area shows clear evidence that the uplift rate field varies 429 along strike of the Capo D'Orlando Fault (Figure 8a), indicating that this normal fault is active. This 430 fact is not surprising considering that NE Sicily has been affected by historical damaging earthquakes 431 432 (Figure 1). Therefore, we suggest that the Capo D'Orlando Fault should be added within DISS at least as "Debated Seismogenic Source" to improve the seismic hazard assessment for the NE Sicily. 433

For the Capo D'Orlando Fault, we suggest a constant throw-rate of  $0.63 \pm 0.02$  mm/yr on the 434 as the most likely scenario by investigating fault-deformed Late Quaternary palaeoshorelines 435 outcropping in the hangingwall and footwall of this fault (Figure 9). The throw-rate value is not 436 unusual considering that slip-rate values measured for other active normal faults which have been 437 438 accommodating the Plio-Pleistocene crustal extension along the Italian Apennines and the Calabrian 439 Arc are within the range 0.3 mm/yr to 2.0 mm/yr [Jacques et al., 2001; Galli and Bosi, 2002; Roberts 440 and Michetti, 2004]. Also, well-known empirical correlations between fault length, maximum expected magnitude and maximum expected displacement [Wells and Coppersmith, 1994; Galli et al., 441 2008] allow us to calculate, for the first time, an estimated earthquake recurrence interval or  $T_{mean}$  for 442 the Capo D'Orlando Fault which, considering the length of the fault mapped onshore, could be 443

capable of earthquakes with maximum magnitude (M) of 6.2. To produce a fault throw-rate of  $0.63 \pm$ 444 0.02 mm/yr given 50 cm maximum vertical slip events in Mw 6.2 earthquakes implies an earthquake 445 446 recurrence interval of 820 years; this value is comparable to those that characterize active normal 447 faults along the Italian peninsula [Jacques et al., 2001; Galli et al., 2008; Roberts et al., 2013]. 448 However, the NE tip of the fault has not identified because hangingwall uplift (that is hangingwall 449 subsidence plus regional uplift) is still low relative to the tip zone that has been identified at the SW 450 end of the fault (Figure 8). We suggest that the NE fault tip is likely to be offshore, implying a longer 451 fault length. If the Capo D'Orlando Fault is longer than 15 km, this increases the possible maximum 452 earthquake magnitude to > Mw 6.2; in turn, it implies larger slip events and hence longer earthquake recurrence intervals, suggesting that further study of the offshore are needed. We point out that we 453 have explored a scenario using a possible maximum magnitude earthquake, assuming that earthquakes 454 rupture along the entire length of the Capo D'Orlando Fault; shorter recurrence intervals are implied if 455 456 only part of the fault length ruptures.

457

458 5.2. Crustal deformation within the upper plate of the Ionian subduction zone: regional
459 tectonic implications, slip distribution calculations, mantle-related uplift and the associated seismic
460 hazard on subduction zones

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462 Our study shows that the "regional" uplift signal, within the upper plate of the Ionian 463 subduction zone since the Late Quaternary, has been spatially perturbed by "local" crustal 464 deformation that needs to be considered to attempt long-term seismic hazard assessment.

Generally, it is common to infer slip distributions on the subduction interface and mantle upwelling processes from observations of uplift in the upper plate of the subduction zone *[e.g. Gvirtzman and Nur, 1999; Wortel and Spakman 2000; D'Agostino et al., 2001; McCloskey et al., 2005; Meltzner et al., 2006; Faure Walker et al., 2012; Nalbant et al., 2013; Nic Bhloscaidh et al., 2015].* The Ionian subduction associated with roll-back of the Ionian slab [*Goes et al., 2004*], and asthenospheric upwelling beneath the continental crust of the Calabrian Arc [*Gvirtzman and Nur,*  471 1999; Wortel and Spakman, 2000] has occurred synchronously with uplift of the Calabrian forearc 472 over the Late Quaternary. However, we emphasise that the Calabrian Arc shows prominent intra-473 crustal deformation mostly in the form of active normal faulting controlling the topography of the area 474 (Figure 10). In particular, topographic highs exist due to tectonic uplift in the footwalls of active 475 normal faults such as the Maratea Fault [e.g. Papanikolaou and Roberts, 2007], the Pollino Fault [e.g. 476 Michetti et al., 1997], the Vibo Fault [e.g. Roberts et al., 2013], the Cittanova Fault [e.g. Jacques et 477 al., 2001; Galli and Bosi, 2002; Roda-Boluda and Whittaker, 2017], the Taormina Fault [e.g. 478 Catalano and De Guidi, 2003; De Guidi et al., 2003; Spampinato et al., 2012] and the Capo 479 D'Orlando Fault itself [e.g. Scicchitano et al., 2011; Giunta et al., 2012 and this study] (Figure 1). These faults have been seismically deforming the upper plate of the Ionian subduction zone producing 480 481 damaging earthquakes. Spatial variation in uplift rates measured over (i) the Late Quaternary [Antonioli et al., 2006, 2009; Ferranti et al., 2006; Roberts et al., 2013 and this study] and (ii) the last 482 483 decades shown by using GPS analysis [Serpelloni et al., 2013] along the strike of these faults (Figure 10a and 10b) imply that uplift is not simply controlled either by slip on the subduction interfaces or 484 mantle upwelling-related dynamic topography; the upper plate seismogenic sources will strongly 485 affect the "regional" uplift over wavelengths of a few tens of kilometres within the Calabrian Arc, 486 487 implying that these normal faults need to be well-defined. We suggest that differential uplift due to the "local effect" of normal faulting has been occurring through time along the Calabrian forearc 488 (Figure 8 and 9). Therefore, if the variation in uplift rates due to these normal faults is not recognised 489 and removed from calculations, this could lead to (i) overly complicated and misleading subduction 490 interface slip distributions and (ii) erroneous conclusions about the dynamic topography, due to the 491 492 mantle upwelling [D'Agostino et al., 2001; Faure Walker et al., 2012]. We emphasise that such upper 493 plate normal faulting is widespread with clear examples in central Greece and Crete, Japan and south 494 America [Armijo et al., 1996; Hasegawa et al., 2000; Saillard et al., 2011; Vacchi et al., 2012; Gallen 495 et al., 2014; Binnie et al., 2016]. One finding that is now emerging is that for at least some upper plate 496 normal faults, the throw-rate on the fault through the Late Quaternary is constant through time (e.g.  $0.63 \pm 0.02$  mm/yr from this study), rather than fluctuating through time [e.g. *Giunta et al.*, 2012] 497 (Figure 9). For example, a constant throw-rate through the late Quaternary has also been reported for 498

499 the Vibo Fault, within the Calabrian Arc [*Roberts et al.* 2013]. If this is common it is implied that 500 constant values of uplift through time need to be subtracted from regional uplift-rate signals if 501 subduction zone slip distributions and mantle dynamics are to be inferred.

Turning to the regional contribution of the Capo D'Orlando Fault to the regional extension, 502 we suggest that in order to accommodate geodetically-derived regional extension rates of  $\sim 2 \text{ mm/yr}$ 503 [Serpelloni et al., 2005] or ~3 mm/yr [Mastrolembo Ventura et al., 2014] a well-constrained long-504 term constant throw-rate through time on the Capo D'Orlando Fault of  $0.63 \pm 0.02$  mm/yr implies that 505 additional crustal deformation has to be accommodated by other active faults across strike. It also 506 507 perhaps implies that faults across strike will also need to remain active through time to maintain constant throw-rates and hence slip-rates [e.g. Roberts et al., 2002]. Seismic profiles quasi-508 perpendicular to the coastline of Capo D'Orlando area have already shown offshore crustal 509 extensional processes due to normal faulting [Nigro and Sulli, 1995]. It would be interesting to see 510 511 whether these faults also have constant slip-rates.

512 However, note that in other locations, active fault systems have been shown to be accommodating crustal deformation with associated rates varying through time. For instance, 513 tectonically-deformed uplifted marine terraces have been investigated within the Gulf of Corinth in 514 Greece [Roberts et al., 2009] who suggest varying long-term fault slip-rates, implying a synchronous 515 516 change in faulting activity on active faults across strike. In particular, the investigated South Alkyonides active fault in the Gulf of Corinth, Greece, has accelerated its slip-rate synchronous with a 517 deceleration on other faults located across strike over the Late Quaternary [Roberts et al., 2009]. This 518 519 evidence suggests that when active faults are arranged across strike and interacting, activity can swap 520 back and forth through time on a multi-millenium timescale to accommodate the regional deformation 521 [Roberts et al., 2002; Bennett et al., 2004; Cowie et al., 2005; Dolan et al., 2007; Nixon et al., 2016]. 522 We stress that more studies are needed to better identify the locations long-term crustal deformation, 523 and how they change through time, by studying (i) sequences of tectonically-deformed Late 524 Quaternary marine terraces onshore and (ii) seismic profiles to define faulting activity offshore the 525 investigated area.

526 Overall, we suggest that local deformation rates measured over the Late Quaternary on upper 527 plate normal faults provide important insights into the subduction process. The deformation within the 528 upper plate must be subtracted to derive a better understanding of subduction and mantle upwelling, 529 and allow calculation of more robust slip distributions for subduction interface events to feed into 530 seismic hazard analysis associated with subduction-related earthquakes. This knowledge help to 531 understand the seismic hazard related to the upper plate of the Ionian subduction zone in southern 532 Italy.

533

- 534 6. Conclusion
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536 In this paper, we report constant crustal deformation rates through time on a normal fault within the upper plate of the Ionian subduction zone. Late Quaternary palaeoshorelines deformed by 537 538 the Capo D'Orlando Fault have been investigated by applying a synchronous correlations method. The study shows that the Capo D'Orlando Fault is an active and potential seismic source with a 539 throw-rate of  $0.63 \pm 0.02$  mm/yr that has been constant through the late Quaternary. In particular, we 540 show that fault displacements have folded and tilted the investigated palaeoshorelines along the strike 541 542 of the fault, and that higher and older palaeoshorelines have experienced a longer faulting history. The deformed palaeoshorelines demonstrate that the Capo D'Orlando fault is active and should be 543 included in seismic hazard assessments of NE Sicily. The throw-rate of  $0.63 \pm 0.02$  mm/yr has been 544 constant through time showing that other unidentified active faults are needed to explain the observed 545 2-3 mm/yr of regional extension measured with GPS. The results suggest that care is needed to 546 include or exclude upper plate deformation, using surface uplift data, when inferring (i) mantle 547 upwelling-related dynamic topography and (ii) slip distributions on subduction interfaces. 548

549

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All data for this paper are properly cited and referred to in the reference list and available on Figure 6 as topographic data where palaeoshoreline elevations have been mapped and in Table 2. These data can be used to re-produce Results shown in Figure 7, 8 and 9. They are also available by contacting

the corresponding author (<u>marco.meschis.14@ucl.ac.uk</u> or marco.meschis@gmail.com).

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902

#### 903 **Table 1**

Reference	Dating	Dated sample	Profile	Reported	Assigned	Palaeo-
	Method	description	numbe	Age (ky)	Highstand	shoreline
			r		(ka)	Elevation
						(m a.s.l)
Scicchitano	U/Th	"A shell of	6	100 - 125	125	53
et al., 2011	dating	Spondylus sp				
and Sulli et	_	collected within				
al., 2013		thick marine				
-		deposit constituted				
		by				
		coarse polygenic				
		conglomerates,				
		micro-				
		conglomerates and				
		crossed				
		lamination sands."				
Giunta et al.,	OSL	"Yellow shore	10	$118 \pm 7$	125	61
2012	dating	sands from				
	_	unconsolidated				
		marine sands."				
Giunta et al.,	OSL	"Sandy levels from	14/15	$283 \pm 22$	285	208
2012	dating	unconsolidated				
	5	marine sands."				



 Table 1 – Previous dating of palaeoshorelines lying within the investigated area by Scicchitano et al.

905 [2011], Giunta et al. [2012] and Sulli et al. [2013]. Note that different dating methods have confirmed

- the age (125 ky) of a prominent marine terrace along the strike of fault and over its tip. Details about
- 907 their location are shown in Figure 2a and b.

908

### 909 **Table 2**

Palaeoshoreline (Profile	DEMs Elevations	Expected Elevations	Field Elevations	Giunta's Elevations	Our proposed	Age proposed	UTM Coordinate
number)	(m)	(m)	(m)	(m)	Age (kyrs)	by Giunta et al., 2012 (kyrs)	
3 (1)	57	59	-	57	125	125	33 S 0475871 4219672
7 (1)	99	99	-	99	240	200	33 S 0476308 4219436
3 (2)	57	59	-	57	125	125	33 S 0474722 4217578
7 (2)	98	98	-	98	240	200	33 S 0475083 4217269
3 (3)	54	54	-	54	125	125	33 S 0474353 4217219
7 (3)	87	89	-	87	240	200	33 S 0474511 4216876
3 (4)	49	50	-	49	125	125	33 S 0473994 4216902
7 (4)	80	79	-	-	240	-	33 S 0474049 4216761
10 (4)	124	124	-	124	340	200	33 S 0474265 4216425
3 (5)	51	51	50	51	125	125	33 S 0473639 4216783
7 (5)	81	84	85	-	240	-	33 S 0473912 4216612
9 (5)	98	93	-	98	310	200	33 S 0473868 4216424
10 (5)	125	131	120	-	340	-	33 S 0473996 4216277
3 (6)	53	53	50	53	125	125	33 S 0472871 4216042
7 (6)	83	86	85	-	240	-	33 S 0473005 4215984
9 (6)	100	96	110	100	310	200	33 S 0473260 4215861
3 (7)	54	51	-	54	125	125	33 S 0472915 4215755
10 (7)	129	131	-	129	340	200	33 S 0473105 4215415

2 (9)					1	1	
3 (0)	56	56	-	56	125	125	33 S 0472539
							4215404
7 (8)	96	93	_	96	240	200	33.8
7 (0)	20	75		70	240	200	0472701
							4215060
2 (0)		5.4	5.4		105	105	4213000
3 (9)	55	54	54	55	125	125	33 8
							0471586
							4215093
7 (9)	88	89	75	88	240	200	33 S
							0471462
							4214794
0 (0)	102	00	100	1	310		33 8
9(9)	102	,,,	100	-	510	-	0471767
							04/1/0/
							4214611
3 (10)	61	63	-	61	125	125	33 S
							0470269
							4213855
7 (10)	105	105	115	105	240	200	33 S
			-		-		0470442
							4213664
0 (10)	102	101			210		22.5
9(10)	123	121	-	-	510	-	33 8
							04/0528
							4213527
10 (10)	152	161	145	-	340	-	33 S
							0470823
							4213768
1 (11)	26	21	_	_	76	_	33.5
1 (11)	20	21			70		0469214
							4212802
2 (11)	50	12		50	100	7(	4213692
2 (11)	50	42	-	50	100	76	33 S
							0469289
							4213580
3 (11)	87	89	-	87	125	125	33 S
. ,							0469370
							4213279
5 (11)	125	120		125	200	200	22.8
5(11)	123	129	-	125	200	200	33 3
							4212057
							4213057
7 (11)	150	156	-	-	240	-	4213057 33 S
7 (11)	150	156	-	-	240	-	4213057 33 S 0469528
7 (11)	150	156	-	-	240	-	4213057 33 S 0469528 4212622
7 (11)	150	156	-	-	240	-	4213057 33 S 0469528 4212622 33 S
7 (11) 9 (11)	150	156	-	-	240	-	0409433 4213057 33 S 0469528 4212622 33 S 0469673
7 (11) 9 (11)	150	156	-	-	240	-	0469433 4213057 33 S 0469528 4212622 33 S 0469673 4212322
7 (11) 9 (11)	150 190	156	-	-	240	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322
7 (11) 9 (11) 10 (11)	150 190 230	156 186 233	-	-	240 310 340	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S
7 (11) 9 (11) 10 (11)	150 190 230	156 186 233	-	-	240 310 340	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 0469861
7 (11) 9 (11) 10 (11)	150 190 230	156 186 233	-	-	240 310 340	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020
7 (11) 9 (11) 10 (11) 11 (11)	150 190 230 274	156 186 233 270	-	-	240 310 340 410?	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S
7 (11) 9 (11) 10 (11) 11 (11)	150 190 230 274	156 186 233 270	-	-	240 310 340 410?	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0470076
7 (11) 9 (11) 10 (11) 11 (11)	150 190 230 274	156 186 233 270	-	-	240 310 340 410?	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0470076 4211665
7 (11) 9 (11) 10 (11) 11 (11)	150 190 230 274 25	156 186 233 270 28	-	-	240 310 340 410?	-	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0470076 4211665 33 S
7 (11) 9 (11) 10 (11) 11 (11) 1 (12)	150 190 230 274 25	156 186 233 270 28	-		240 310 340 410? 76	- - - 76 (?)	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440
7 (11) 9 (11) 10 (11) 11 (11) 1 (12)	150         190         230         274         25	156         186         233         270         28	-		240 310 340 410? 76	- - - 76 (?)	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543
7 (11) 9 (11) 10 (11) 11 (11) 1 (12)	150 190 230 274 25	156 186 233 270 28	-		240 310 340 410? 76	- - - 76 (?)	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543
7 (11) 9 (11) 10 (11) 11 (11) 1 (12) 2 (12)	150 190 230 274 25 50	156       186       233       270       28       51	-	- - - 25 50	240 310 340 410? 76 100	- - - 76 (?)	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543 33 S
7 (11) 9 (11) 10 (11) 11 (11) 1 (12) 2 (12)	150           190           230           274           25           50	156         186         233         270         28         51	- - - -	- - - 25 50	240 310 340 410? 76 100	- - - 76 (?) 76 (?)	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543 33 S 0468458 421357
7 (11) 9 (11) 10 (11) 11 (11) 1 (12) 2 (12)	150         190         230         274         25         50	156         186         233         270         28         51	- - - -	- - - 25 50	240 310 340 410? 76 100	- - - 76 (?) 76 (?)	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543 33 S 0468458 4213177
7 (11) 9 (11) 10 (11) 11 (11) 1 (12) 2 (12) 3 (12)	150 190 230 274 25 50 100	156           186           233           270           28           51           100	- - - -	- - - 25 50 100	240 310 340 410? 76 100 125	- - - 76 (?) 125	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4211665 33 S 0468440 4213543 33 S 0468440 4213543 33 S
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)	150         190         230         274         25         50         100	156         186         233         270         28         51         100	- - - - -	- - - 25 50 100	240 310 340 410? 76 100 125	- - - 76 (?) 76 (?) 125	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543 33 S 0468458 4213177 33 S 0468478
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)	150         190         230         274         25         50         100	156         186         233         270         28         51         100	- - - - -	- - - 25 50 100	240 310 340 410? 76 100 125	- - - 76 (?) 76 (?) 125	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468458 4213543 33 S 0468458 4213177 33 S 0468478 4212907
7 (11) 9 (11) 10 (11) 11 (11) 1 (12) 2 (12) 3 (12) 6 (12)	150         190         230         274         25         50         100         143	156           186           233           270           28           51           100           147	- - - - -	- - - 25 50 100	240 310 340 410? 76 100 125 200	- - - 76 (?) 125	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468465 4213177 33 S 0468478 4212907 33 S
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)	150         190         230         274         25         50         100         143	156         186         233         270         28         51         100         147	- - - - -	- - - 25 50 100	240 310 340 410? 76 100 125 200	- - - 76 (?) 125	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468440 4213543 33 S 0468458 4213177 33 S 0468478 4212907 33 S 04684880
7 (11) 9 (11) 10 (11) 11 (11) 1 (12) 2 (12) 3 (12) 6 (12)	150         190         230         274         25         50         100         143	156         186         233         270         28         51         100         147	- - - - -	- - - 25 50 - - - - - - - - - - - - - - - - - -	240 310 340 410? 76 100 125 200	- - - 76 (?) 125 -	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468461 4213543 33 S 0468458 4213177 33 S 0468478 4212907 33 S 0468480 4212536
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)	150         190         230         274         25         50         100         143	156         186         233         270         28         51         100         147	- - - - -	- - - 25 50 100	240 310 340 410? 76 100 125 200 240	- - 76 (?) 76 (?) 125	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543 33 S 0468458 4213177 33 S 0468478 4212907 33 S 0468480 4212536
7 (11)         9 (11)         10 (11)         11 (11)         2 (12)         3 (12)         6 (12)         7 (12)	150         190         230         274         25         50         100         143         180	156         186         233         270         28         51         100         147         177	- - - - - - -	- - - 25 50 100 - 180	240 310 340 410? 76 100 125 200 240	- - - 76 (?) 76 (?) 125 - 200	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468461 4213543 33 S 0468458 4213543 33 S 0468458 4213543 33 S 0468458 4212907 33 S 0468458 4212536 33 S 0468458 4212556 33 S 0468458 4212556 33 S 0468458 4212556 33 S 0468458 4212556 33 S 0468458 4212556 33 S 0468458 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 4212556 421556 421556 421556 421556 421556 421556 421556 421556 4215566 421556756 42155675756 421556756756 421556756757
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)	150         190         230         274         25         50         100         143         180	156         186         233         270         28         51         100         147         177	- - - - - - -	- - - 25 50 100 - 180	240 310 340 410? 76 100 125 200 240	- - - 76 (?) 76 (?) 125 - 200	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 04696673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468461 4213543 33 S 0468458 4213177 33 S 0468478 4212907 33 S 0468478 4212907 33 S 0468478 4212536 33 S 0468453 0468455 0468455 0468455 0468455 0468455 0468455 0468455 046855 046855 046855 046855 046
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)	150         190         230         274         25         50         100         143         180	156         186         233         270         28         51         100         147         177	- - - - - - -	- - - 25 50 100 - 180	240 310 340 410? 76 100 125 200 240	- - - 76 (?) 76 (?) 125 - 200	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469661 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468465 4213177 33 S 0468478 4212907 33 S 0468478 4212907 33 S 0468478 4212536 33 S 0468453 4212205
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)         10 (12)	150         190         230         274         25         50         100         143         180         264	156         186         233         270         28         51         100         147         177         263	- - - - - - - -	- - - 25 50 100 - - 180 264	240 310 340 410? 76 100 125 200 240 340	- - - - - - - - - - - - - - - - - - -	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468440 4213543 33 S 0468458 4212907 33 S 0468478 4212536 33 S 0468453 4212205 33 S
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)         10 (12)	150         190         230         274         25         50         100         143         180         264	156         186         233         270         28         51         100         147         177         263	- - - - - - - -	- - - 25 50 100 - 180 264	240 310 340 410? 76 100 125 200 240 340	- - - 76 (?) 125 - 200 340	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468440 4213543 33 S 0468440 4213543 33 S 0468440 4212536 33 S 0468453 4212205 33 S 0468453 4212205 33 S 0468453 4212205 33 S 0468424
7 (11)         9 (11)         10 (11)         11 (11)         11 (12)         2 (12)         3 (12)         6 (12)         7 (12)         10 (12)	150         190         230         274         25         50         100         143         180         264	156         186         233         270         28         51         100         147         177         263	- - - - - - -	- - - 25 50 100 - 180 264	240 310 340 410? 76 100 125 200 240 340	- - - 76 (?) 76 (?) 125 - 200 340	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0470076 4211665 33 S 0468440 4213543 33 S 0468458 4213177 33 S 0468458 4212907 33 S 0468458 4212907 33 S 0468458 4212205 33 S 0468453 4212205 33 S 0468424 4211752
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)         10 (12)         2 (13)	150         190         230         274         25         50         100         143         180         264         52	156         186         233         270         28         51         100         147         177         263         57	- - - - - - - - -	- - - - 25 50 - - - - - - - - - - - - - - - - - -	240       310       340       410?       76       100       2200       240       340	- - - 76 (?) 76 (?) 125 - 200 340 - 76	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468458 4213543 33 S 0468458 4213543 33 S 0468458 4212907 33 S 0468458 4212907 33 S 0468458 4212536 33 S 0468453 4212205 33 S 0468453 4212205 33 S
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)         10 (12)         2 (13)	150         190         230         274         25         50         100         143         180         264         52	156         186         233         270         28         51         100         147         177         263         57	- - - - - - - - - -	- - - 25 50 100 - 180 264 52	240 310 340 410? 76 100 125 200 240 340 100	- - - 76 (?) 76 (?) 125 - 200 340 76	4213057 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468461 4213543 33 S 0468458 4213543 33 S 0468458 4212907 33 S 0468458 4212907 33 S 0468458 4212907 33 S 0468458 4212536 33 S 0468453 421205 33 S 0468453 421205 33 S 0468453 421205 33 S 0468453 421205 33 S 0468453 4212536 33 S 0468453 4212536 33 S 0468453 4212536 33 S 0468453 4212536 33 S 0468453 4212536 33 S 0468453 4212536 33 S 0468453 421205 33 S 0468453 4212536 33 S 0468453 4212555 33 S 0468453 4212755 33 S 04678357 35 04678575 35 046785757 35 046785757 35 046785757 35 046785757 35 046785757 35 046787577 35 046787577 35 046787577 35 046787577 35 046787577 35 046787777 35 046787777 35 046787777 35 046787777 35 04678777776 35 04678777776 35 0467877777677777777777777777777777777777
7 (11)         9 (11)         10 (11)         11 (11)         1 (12)         2 (12)         3 (12)         6 (12)         7 (12)         10 (12)         2 (13)	150         190         230         274         25         50         100         143         180         264         52	156         186         233         270         28         51         100         147         177         263         57	- - - - - - - - - -	- - - 25 50 100 - 180 264 52	240 310 340 410? 76 100 125 200 240 340 100	- - - 76 (?) 76 (?) 125 - 200 340 76	4213057 33 S 0469528 4212622 33 S 0469528 4212622 33 S 0469673 4212322 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0469861 4212020 33 S 0468458 4213177 33 S 0468478 4212907 33 S 0468478 4212020 33 S 046878 4212020 33 S 0468782 4213028 33 S 0467832 4213028 33 S

3 (13)	105	108	-	105	125	125	33 S 0467886	
6 (13)	149	159	-	140 (?)	200	200 (?)	4212584 33 S 0467996	-
7 (13)	200	192	-	-	240	-	4212239 33 S 0468052	-
9 (13)	228	232	-	-	310	-	4211966 33 S	_
							0468046 4211866	
10 (13)	291	284	278	300	340	340	33 S 0467955 4211523	
1 (14)	27	33	-	40	76	76 (?)	33 S 0467030 4213264	
2 (14)	64	57	-	64	100	76 (?)	33 S 0467078 4212875	-
3 (14)	109	108	-	109	125	125	33 S 0467227 4212394	
6 (14)	155	159	-	146 (?)	200	200 (?)	33 S 0467206 4212147	
7 (14)	187	192	-	-	240	-	33 S 0467153 4211987	
8 (14)	208	204	-	208	285	285	33 S 0467140 4211866	
10 (14)	288	284	-	288	340	340	33 S 0467020 4211313	
1 (15)	40	38	-	40	76	76 (?)	33 S 0466553 4213014	
2 (15)	61	64	-	61	100	76 (?)	33 S 0466577 4212733	
3 (15)	112	116	-	112	125	125	33 S 0466629 4212216	
5 (15)	174	173	-	174	200	200	33 S 0466644 4211888	1
8 (15)	225	224	-	225	285	285	33 S 0466664 4211696	1
9 (15)	253	254	-	253	310	340	33 S 0466677 4211574	
able 2 - W	Ve show al	l mapped	inner edge	s from D	EM and	fieldwork	with age a	assigned vi

911 synchronous correlation. This table also shows different ages sequentially-assigned by *Giunta et al.*912 [2012] leading them to derive fluctuating uplift rate values through time. Note that we were unable to
913 check all locations of inner edges mapped through DEM analysis in the field because the investigated
914 area is thickly-vegetated and densely-populated with private properties.

**Table 3** 

Age (ka)	Elevation of highstands (mm)
0	0
30	-80000
50	-60000
76	-30000
100	-25000
125	5000
175	-30000
200	-5000
217	-30000
240	-5000
285	-30000
310	-22000
340	5000
410	-5000

917 Table 3 - Values of sea-level highstands derived from *Siddall et al.* [2003] used to calculate predicted
918 palaeoshoreline elevations given a value for uplift rate.

919

920 Figure captions

Figure. 1. Location map showing the tectonic setting of Calabria and NE Sicily. Pink dots represent 921 922 locations for historical earthquakes with the associated earthquake magnitude from Guidoboni et al. 923 [2007]. Yellow dots show Holocene uplift rate values by Antonioli et al., [2006, 2009]. White-924 coloured dashed square shows the investigated area. Reported active normal faults are from Michetti 925 et al., [1997], Monaco and Tortorici, [2000], Bianca et al. [2011], Giunta et al. [2012] and Roberts et al., [2013]: MrF: Maratea Fault, PoF: Pollino Fault, CrF: Crati Fault, RoF: Rossano Fault VF: Vibo 926 927 Fault, TrF: Tropea Fault, CoF: Coccorino Fault, MF: Mileto Fault, SeF: Serre Fault, CF: Cittanova 928 Fault, SeF: Sant'Eufemia Fault, ScF: Scilla Fault, AF: Armo Fault, RCF: Reggio Calabria Fault, TF: 929 Taormina Fault, AcF: Acireale Fault, CDOF: Capo D'Orlando Fault, SBT: Sicilian Basal Thrust. Note that the CDF (Capo D'Orlando Fault) has not been reported within DISS as shown in inset b. In inset 930 c amended tomographic cross-section from the Gulf of Lion to the Calabrian Arc by [Lucente et al., 931 932 2006] is shown. Section trace A-B shows the Ionian slab beneath the Calabrian Arc characterized by 933 intermediate and deep earthquakes (white dots).

934

Figure 2. Location maps for palaeoshorelines within the hangingwall of the Capo d'Orlando activenormal fault. A 10-m resolution DEMs with the associated coloured Slope to highlight breaking-

937 slopes is used as base-map. In (a) is shown amended map from *Giunta et al.* [2012] showing the 938 investigated area from Capo d'Orlando town to Santa Agata di Militello town. Location and ages of 939 marine terraces from *Giunta et al.* [2012] are shown as well as locations of U/Th dating and OSL 940 dating by *Scicchitano et al.* [2011] and *Giunta et al.* [2012]. In (b) inner edges of marine terraces with 941 our reviewed ages (see numbered dots and the associated age within Legends panel), the "tip zone" 942 area marked in the SW with red-coloured dashed line and 15-topographic profile locations are shown 943 from this study.

944

945 Figure 3. View of interpreted marine terraces in the field (shaded polygons) within the Profile 8 with 946 the associated inner edge elevations and the synchronously-assigned ages. The synchronous 947 correlation approach allowed us to reassign the age of 240 ky to the palaeoshoreline at 96 m 948 previously [*Giunta et al.*, 2012] sequentially-assigned to the 200 ka sea-level highstand.

949

**Figure 4.** Field evidence, lying along Profile 6, of inner edge showing upper palaeoshoreface depositional environment. The picture shows a marine abrasion platform made of Mesozoic limestone unconformably overlain by marine conglomeratic deposits already well-described by *Scicchitano et al.* [2011] and *Giunta et al.* [2012]. In places lithophagid borings into Mesozoic limestone and scattered evidence of beach cobbles have been mapped close this area, suggesting the presence of the 125ka-dated palaeoshoreline. This inner edge could have not been mapped in the DEMs due to the resolution.

957

**Figure 5.** Example of a modelled topographic profile (profile 8 herein) showing a synchronouslymodelled sequence of marine terraces on the hangingwall of the Capo D'Orlando Fault by iterating uplift rates values to find the best match between mapped palaeoshorelines (using GIS analysis and/or fieldwork) and the predicted sea-level highstands (coloured lines). RMS devation vs Uplift rates (mm/yr) is shown, suggesting that our preferred uplift rate is very robust. Note that our "best fit" is based on the fact that the iteration of uplift rate values is driven by a dated horizon/palaeoshoreline 964 (125 ka). RMS deviation calculations for each topographic profile are shown in the Supplementary965 material.

966

**Figure 6.** Topographic profiles derived by using 10-m high-resolution Digital Elevation Models [*Tarquini et al.*, 2007, 2012] showing modelled and mapped palaeoshoreline elevations. The coloured lines represent the sea-level highstands (or predicted palaeoshoreline elevations) calculated by iterating uplift rate values to find the best match with the mapped (numbered arrows) palaeoshorelines. More detailed profiles locations on Figure 2b. Inner edge elevations with refined ages are also shown in Table 2

973

**Figure 7.** In (a) the graph is showing the relationship between field-based and DEM-based inner edge elevations. The  $R^2$  value > 0.99 confirms a very robust relationship suggesting that elevations measured elsewhere in the DEM are likely to be accurate. In (b) the graph is showing linear regression analysis between our measured and predicted elevations. The predicted elevations, representing the synchronously-calculated sea-level highstand elevations, have been derived by defining a constant uplift rate through time, and iterating this value to find the best match to the measured and mapped palaeoshorelines.

981

Figure 8. Diagrams showing evidence of Quaternary Capo D'Orlando Fault activity. In (a) uplift rates 982 is spatially varying along strike the Capo D'Orlando Fault. In (b) palaeoshoreline elevations are 983 changing along the strike of the Capo D'Orlando Fault. Solid lines represent our mapped and 984 measured palaeoshoreline elevations mapped by using DEMs and checked in the field; closely-dashed 985 coloured lines represent modelled iteratively-calculated sea-level highstand elevations (or the 986 expected elevations) mostly matching with the solid lines. Uplift/Subsidence ratio (U:S) value of 1/3.5 987 988 has been applied to the oldest (340 ka) palaeoshoreline mapped within the hangingwall to estimate the expected elevation on the footwall and derive long-term fault slip-rate. A black dashed arrowed line 989 shows the displacement between terraces mapped in the hangingwall and footwall cut-offs. In (c) the 990 991 faulting activity of Capo D'Orlando Fault over the Late Quaternary has tilted the investigated marine terraces; in fact, older and higher palaeoshorelines show higher tilt angle values because they havebeen experiencing a longer history of faulting activity.

994

**Figure 9.** In (a) uplift gradients are shown derived from [*Giunta et al.*, 2012] (orange-coloured dashline) and this study (blue line). The orange-coloured dash line shows an exponential growth of the uplift gradient through time driven by an absolutely-dated palaeoshoreline (125 ka). Instead, the blue-coloured line shows a constant growth of the uplift gradient through time also driven by an absolutely-dated palaeshoreline (125 ka). Note that changing uplift rates through time is also shown in Figure 7 (section 2) in *Giunta et al.*, [2012].

1001

Figure 10. Regional extension accommodated by normal faults within the upper plate of the Ionian Subduction Zone, along the geological domain of Calabrian Arc, is shown. In (a) prominent changing uplift rates from GPS analysis (light blue values) [*Serpelloni et al.*, 2013] are shown along the Calabrian Arc. Similarly, in (b) Late Quaternary uplift rates change by up to a factor of 4 across the Calabrian Arc, with large variations between the footwalls and hangingwall of faults, and along the strike of faults towards fault tips, suggesting prominent heterogeneity for slip on subduction interface through time.

Light blue values in b are reported by *Catalano and De Guidi*, [2003] and *Ferranti et al.* [2006], and
black values are reported from this study (black square) and *Roberts et al.* [2013].



100km

Debated

Source

Seismogenic









0.5 m

## Marine conglomerate

U-11-

Ν

### Unconformity

# **Mesozoic limestone**









**Topographic Profile 7 with modelled shoreline elevations** 







Measured vs Predicted Elevations

b



Measured Elevations (m)

350



Inner edges Elevations Vs Distance along the strike of the Capo D'Orlando Fault





Time (kyr)



