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Uplifted Late Holocene shorelines along the coasts of the Calabrian Arc: geodynamic and seismotectonic implications

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ABSTRACT

Late Holocene (~6.5 ka) shorelines represented by tidal notches, beach deposits, wave-cut terraces and intertidal organic rims are raised from few decimetres up to 5.5 m above the present sea level in the southern part of the Calabrian Arc, southern Italy. At five localities (Capo Vaticano and Scilla in southern Calabria and Taormina, Schisò, Capo Milazzo in north-eastern Sicily), the uplifted paleo-shorelines form a distinct vertical sequence where the older shorelines rest invariably above the younger ones. Such arrangement documents the occurrence of abrupt uplift events that, within the limits imposed by existing age controls, we attribute to ancient earthquakes. A comprehensive appraisal of published studies has allowed to draw an inventory with a total of possibly sixteen earthquakes which, based on the amount of shoreline displacement (~0.5-2 m) and the length of coastal section involved in uplift, were likely to be of strong size. It appears that the amount of uplift decreased with time during the Late Holocene at all sites but Capo Vaticano, where it remained almost stationary. The co-seismic events appear grouped within four temporal clusters, during which uplift occurred at most of the five coastal sectors investigated here. These clusters spanned time intervals whose duration, although difficult to bracket with precision, is of few hundred years, and are separated by longer (~0.5-1.5 ka) periods of apparent tectonic quiescence. The sources of co-seismic uplifts are still undefined, and should be searched between normal faults in the stretched Calabrian upper crust, or lower crustal thrust faults related to the Ionian subduction.

Keywords*: raised paleoshorelines, co-seismic uplift, earthquake clusters, Late Holocene, southern Calabrian Arc.*

INTRODUCTION

Coastal deformation at subduction margins is commonly characterized by significant co-seismic uplifts that result from faulting related to subduction (Keller & Pinter, 2002). The pattern of uplift at the coast depends, in addition to complexities of the rupture processes, on the distance of the coast from the seismogenic source (e. g. Natawidjaja *et alii*, 2004; Subarya *et alii*, 2006 for the 2004 Sumatra Mw 9.1 thrust earthquake).

In the Mediterranean setting, subduction of the African plate beneath Europe occurs underneath Greece (Shaw *et alii*, 2008) and possibly Calabria (Faccenna *et alii*, 2011). Recent and historical meter scale uplifts (up to 9 m) of marine notches are documented at Crete (Shaw *et alii*, 2008), and elsewhere in Greece (Pirazzoli *et alii*, 1994) during thrust earthquakes in the overriding plate ~100 km inboard of the subduction interface.

In the Calabrian Arc (Fig. 1), coastal uplifts were not reported during historical earthquakes, but raised Holocene shorelines have been documented, indeed (Pirazzoli *et alii*, 1997; Rust & Kershaw, 2000: Antonioli *et alii*, 2006; Stewart *et alii*, 1997; De Guidi *et alii*, 2003; Ferranti *et alii*, 2007; 2008; Scicchitano *et alii*, 2011; Spampinato *et alii*, 2012; 2014). Fault-related displacement represents a component of the overall uplift that affects the Calabrian Arc since the Early-Middle Pleistocene, as documented by widespread flights of raised marine terraces (Westaway, 1993; Miyauchi *et alii*, 1994; Roberts *et alii*, 2013). Whereas Pleistocene co-seismic uplifts are difficult to study, because terraces do not offer high spatial resolution so that individual events were obliterated during time, raised Holocene shorelines provide valuable clues for geodynamic and seismotectonic analysis. Specifically, the finding of distinct and datable paleoshorelines over a significant part of the Calabrian Arc offers three appealing promises: 1) to discriminate between a local (related to shallow-crustal structures) and a regional (ensuing from deeper processes in the lower crust or in the upper mantle) component of vertical deformation (e. g. Ferranti *et alii*, 2007; Faccenna *et alii*, 2011); 2) to document that the local component ensues from a seismogenic fault, and thus provide information on the timing and amount of vertical displacement during past earthquakes; and 3) to test geodynamic models for the region.

This contribution reviews the existing knowledge on uplifted Late Holocene shorelines in southern Calabria and northeastern Sicily, and it is specifically focused on the local component of vertical displacement. Our aim is twofold. The basic purpose is to provide a comprehensive database of sudden uplift events at the coasts, which can be then related to past earthquakes. Building on this, we are interested to look, within this record, for broad temporal and spatial patterns of earthquake occurrence, and to test alternative geodynamic scenarios for uplift.

Inconveniences affecting our effort reside in correctly estimating the size of these events (in terms of equivalent earthquake magnitude), and in attributing them to specific sources. Because uplifts described here typically range

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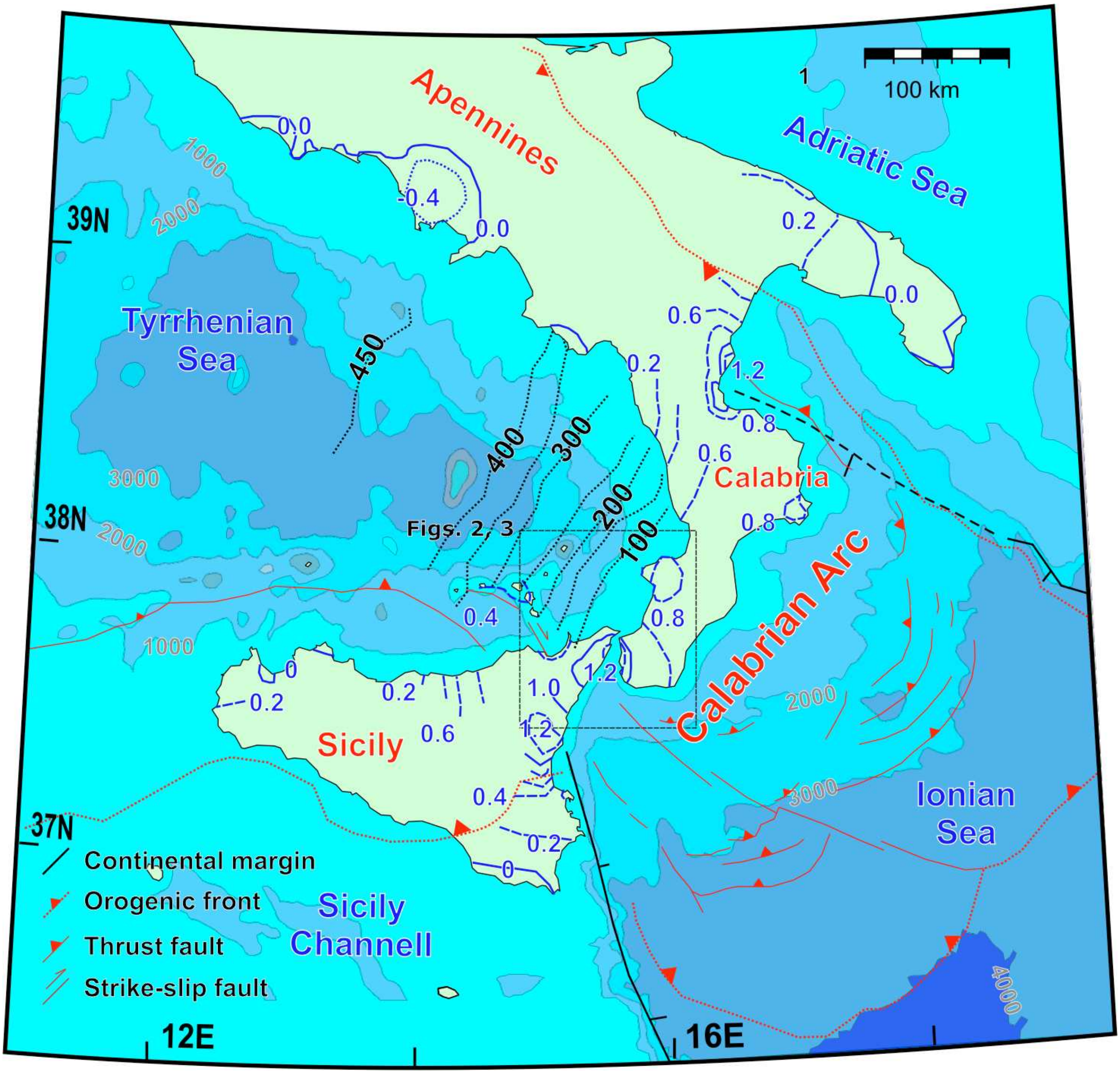

Fig. 1 - Tectonic setting of the Calabrian Arc. Dotted red lines: Front of the collisional orogen in the Apennines, in southern Sicily, and in the Sicily Channell, and of the accretionary prism in the Ionian Sea; solid red lines: thrust faults in the Ionian accretionary prism (after Polonia *et alii*, 2011) and offshore northern Sicily (solid teeth toward the overthrust block). Thick solid (dashed where buried) black lines: ancient continental margins rimming the Ionian Sea. Thin dotted black lines: depth (km) to the Benioff-Wadati zone of the Ionian slab (after D'Agostino & Selvaggi, 2004). Thin, solid, dashed (uplift) and dotted (subsidence) blue lines: contour lines of vertical deformation rates (mm/yr) during the Late Pleistocene (after Ferranti *et alii*, 2006).

between 0.5-2 m during individual earthquakes, and affect coastal sectors of southern Calabria and northern Sicily having up to and probably more than ~20 km length, we are however dealing with significant-sized earthquakes. In addition, limited information exist on seismogenic sources that may be responsible for these uplifts. Because the Calabrian Arc is the narrower and longer stretch of mainland Italy (Fig. 1), and taking into account its strong seismicity record (Fig. 2), it is predicted that several seismogenic sources must reside across the coastline and in the offshore (DISS Working Group, 2015).

Notwithstanding these limitations, we found that co-seismic uplifts recurrently affected five distinct coastal sectors during relatively limited time intervals of few hundred yrs. This occurrence repeated four times in the last ~6 kyr with an apparent 0.5-1.5 kyr periodicity. This space-time pattern of co-seismic deformation supports the contention that clustering of large earthquakes may be a

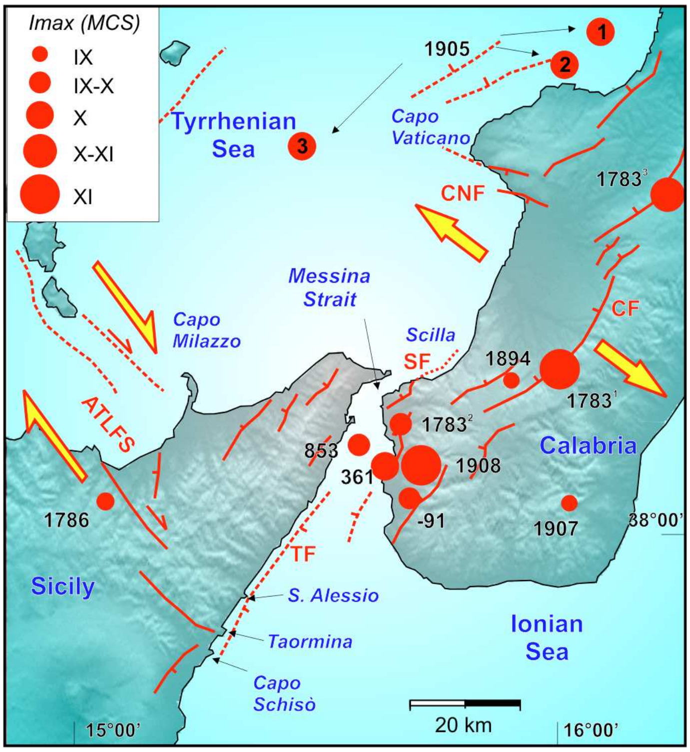

Fig. 2 - Active faults and historical seismicity in the southern Calabrian Arc. Faults (red lines, solid on-land and dashed offshore) are extensional (barbed on the downthrown side) or strike-slip modified (arrowed): ATLFS, Aeolian-Tindari-Letojanni fault system; CF, Cittanova Fault; MEF, CNF, Coccorino-Nicotera fault; SF, Scilla Fault; TF, Taormina Fault. Large arrows show the dominant extensional and strike slip current deformation in Calabria and in northeast Sicily, respectively. Red dots are macroseismic epicenters of historical earthquakes, with date indicated, scaled according to magnitude (after CFTI4Med catalogue, Guidoboni *et alii*, 2007). Dots with numbers 1, 2, 3 for the 1905 earthquake are the different locations proposed by 1) Postpischl (1985); 2) Camassi & Stucchi (1997); 3) Michelini *et alii* (2005) and reported in Cucci & Tertulliani (2010). The apex notations (1, 2, 3) for the 1783 earthquake refers to the 5, 6 and 7 February shocks, respectively. Focal mechanism of the 1908 earthquake after Gasparini *et alii* (1982).

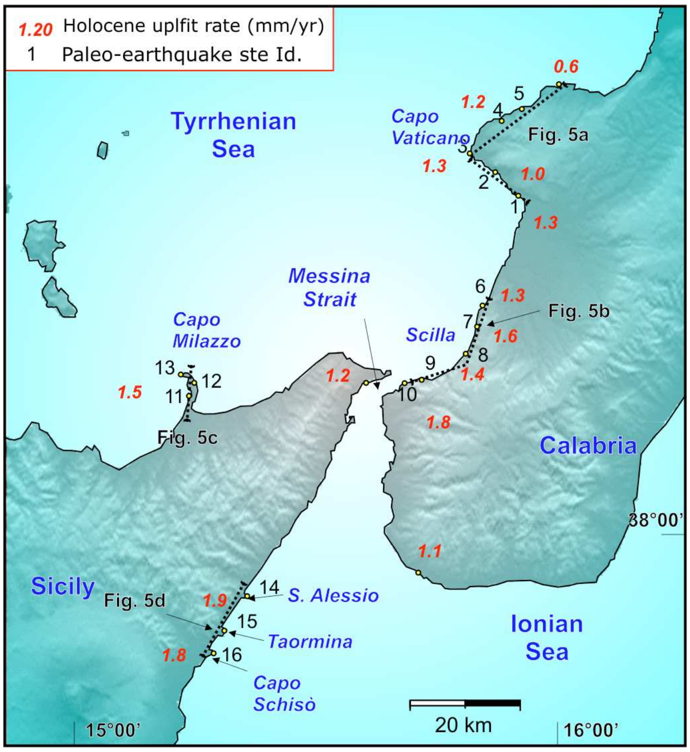

Fig. 3 - Late Holocene uplift rates (adapted from Ferranti *et alii*, 2010), and sites of late Holocene paleoearthquakes (numbers refers to Table 2) in the southern Calabrian Arc.

viable mechanism for temporally punctuated seismic energy release in the Calabrian Arc.

REGIONAL SEISMOTECTONIC SETTING

Calabria and north-eastern Sicily together form the Calabrian Arc that represents the emerging part of a forearc terrane emplaced above the subducted Ionian slab, which dips steeply to the NW underneath the Tyrrhenian back-arc basin (Fig. 1; Chiarabba *et alii*, 2005). The forearc high has been stretched by Pliocene-Quaternary extension, and today a belt of active extensional faults run along the Tyrrhenian Sea margin and the chain axis (Fig. 2). The extension direction, determined by fault slip analysis (Tortorici *et alii,* 1995; Faccenna *et alii*, 2011), focal mechanisms of crustal earthquakes and global positioning system (GPS) geodetic velocities (D'Agostino & Selvaggi, 2004; Palano *et alii*, 2012), is NW-SE (Fig. 2). Residual geodetic velocities across the normal fault belt point to extension rates of up to ~3 mm/yr (Serpelloni *et alii*, 2010; Devoti *et alii,* 2011).

Several large (M≥6) earthquakes ruptured the whole length of the Calabrian Arc in the last ~2 ka (CPTI15, 2016) and are mostly associated to the extensional belt (see the review of Tiberti *et alii,* this volume). Most of the events are clustered during a short time period of ~3 centuries between the 17th and 20th, with the strongest of them being located in southern Calabria (Fig. 2; Jacques *et alii*, 2001). With the exception of the 1908 event, placed on the Tyrrhenian margin, the macroseismic epicenter of major earthquakes is located close to the axis of the mountain ridge running through Calabria.

The extensional fault belt wanes in north-eastern Sicily where deformation is transferred to an ~E-W oriented belt of contractional earthquakes that identifies an active thrust system offshore northern Sicily (Fig. 1; Neri *et alii*, 2005; Billi *et alii*, 2007). The transition zone between these two belts occurs along a NNW-SSE striking dextral transcurrent array, the Aeolian-Tindari-Letojanni (ATL) fault system (Fig. 2). Geological, seismological and marine geophysical data point that the ATLFS is characterized by active right-lateral motion in the Tyrrhenian offshore and on the Tyrrhenian margin of Sicily (Billi *et alii*, 2006; Cultrera *et alii*, this volume), and GPS velocities indicate dextral shear occurs till the Ionian coast of Sicily is reached (Palano *et alii*, 2012).

The nature and location of active faults offshore the Calabrian Arc are not well constrained. Underneath the Tyrrhenian Sea shelf and slope, and in the wider Messina Strait between Calabria and Sicily, active faults are thought to be extensional (Loreto *et alii*, 2013; Tiberti *et alii,* this volume). Beneath the Ionian Sea, conversely, active structures are related to the Ionian accretionary complex (Fig. 1; Polonia *et alii*, 2011; 2012). Active contraction at the front

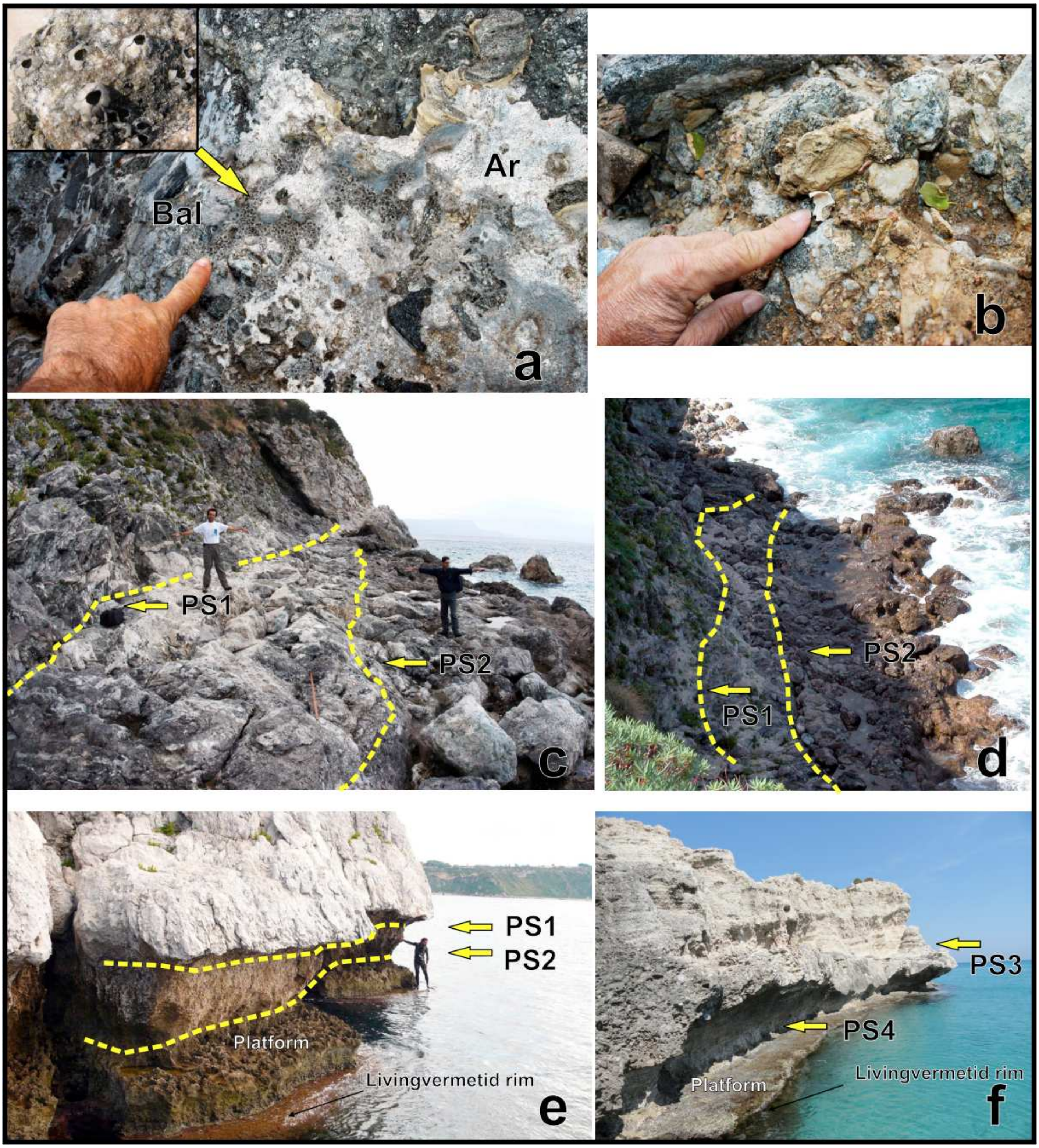

Fig. 4 - Examples of markers used for positioning the current elevation of uplifted paleo-shorelines: a) close-up of a barnacle band (Bal) defining the inner margin of paleoshoreline PS2 at Scilla (see Figures 5c, 5d); AR is an algal rim underlying the barnacle band, and associated to the paleoshoreline; b) marine deposit of paleoshoreline PS1 from Scilla. Finger points to a bivalve shell; c) upper and lower terraces and related inner margins (dashed lined) related to paleoshorelines PS1 and PS2 at Scilla, respectively; d) same as Fig. 4c, from above: e) upper and lower notches at Punta Gamba di Donna (Capo Milazzo) attributed to PS1 and PS2, respectively; f) Well-developed lowermost notch and platform, and overlying poorly preserved notch attributed to PS4 and PS3, respectively, observed at S. Domenica (Capo Vaticano).

and along thrusts splaying within the accretionary wedge from the basal detachment is suggested by seismic reflection profiles (Polonia *et alii*, 2011). In addition, the wedge is segmented across strike by crustal transfer tectonic systems, which represent the shallow expression of shears in the subducted plate (Fig. 1; Polonia *et alii*, 2016). GPS velocities and dynamic modeling suggest up to ~5 mm/yr contraction across the Calabria forearc (D'Agostino & Selvaggi, 2004; D'Agostino *et alii*, 2011; Carafa *et alii,* 2015), which could stem from current subduction (Devoti *et alii,* 2008).

During Quaternary, the Calabrian Arc experienced vigorous uplift (Westaway, 1993; Miyauchi *et alii*, 1994; Antonioli *et alii*, 2006). Uplift estimates cumulate the effects of both regional and local processes, the latter related to faulting (Westaway, 1993; Ferranti *et alii*, 2007; 2010; Roberts *et alii*, 2013). Much of the regional uplift is associated with the Ionian subduction (Faccenna *et alii*, 2011; Roberts *et alii*, 2013), as suggested by the spatial coincidence between the locus of largest surface uplift and the extent of the slab (Fig. 1). Uplift is interpreted as the response to asthenospheric wedging into the gap resulting from slab detachment (e.g. Westaway, 1993; Wortel & Spakman, 2000) or from crustal delamination (Gvirtzman & Nur, 2001), or as due to underplating beneath the accretionary wedge (Minelli & Faccenna, 2010), or finally as the viscoelastic response to enhanced erosional flux from land to sea following the onset of glacial-interglacial cycles (Westaway & Bridgland, 2007).

A smaller fraction of Quaternary uplift has been related to footwall uplift along extensional faults (e. g. Westaway, 1993; Tortorici *et alii*, 2003). This occurrence concerns large planar normal faults that rotate about a horizontal axis while they move, causing a tilt that is observable in the geological record (Jackson *et alii,* 1988), and locally during extensional earthquakes in the Mediterranean area (Jackson *et alii,* 1982). According to this scenario, extension in southern Calabria would be characterized by the so-called domino-style faulting. Conversely, hanging-wall subsidence counteracts the effects of regional uplift, which in the long-term prevails (Valensise & Pantosti, 1992; Roberts *et alii*, 2013).

Integrated (regional and local) Holocene uplifts, peaking at ~2 mm/yr (Fig. 3), have been documented in Calabria at several places where raised shorelines were analyzed in detail. These localities include: Capo Milazzo in northern Sicily (Scicchitano *et alii*, 2011); Taormina-S. Alessio (Stewart *et alii*, 1997; Antonioli *et alii*, 2003; De Guidi *et alii*, 2003) and Capo Schisò (Spampinato *et alii*, 2012) in eastern Sicily; the Scilla (Ferranti *et alii*, 2007; 2008) and Capo Vaticano (Spampinato *et alii*, 2014) coasts in southern Calabria. At the studied sectors, Late Holocene (~6.5 ka or younger) shorelines are represented by different geomorphologic or depositional markers (Fig. 4), including notches and wave-cut terraces, and organic rims and shore deposits, respectively (for a detailed description of characteristics and position of markers the reader is referred to the papers quoted above). Currently, these ancient shorelines are raised up to ~5.5 m above the present sea level (Tab. 1).

Regional synthesis on Late Holocene shorelines in Calabria have been presented before (Pirazzoli *et alii*, 1997; Antonioli *et alii*, 2006; 2009; Ferranti *et alii*, 2010). Although Antonioli *et alii* (2006) and Ferranti *et alii* (2010) attempted to single out the regional pattern of coastal deformation, pointing out the differences between long-term (100 to 1000 ka) and short-term (10 ka) uplift occurrence, no comprehensive analysis exists regarding possible spatial and temporal links among the uplifting sectors, as well as of the tectonic context that caused displacements.

LATE HOLOCENE COASTAL UPLIFTS

In this section, we review and homogenise evidence of past uplifts documented along the coastline of the southern Calabrian Arc by a number of studies. Table 1 reports the mapped paleoshorelines (PS) numbered progressively within each sector, along with their age and the type of marker(s) used for their identification. The elevation of each paleoshoreline is drawn from published papers and already incorporates paleo-bathymetric and tidal corrections to marker measurements.

Table 2 lists, for each coastal sector, the actual sites of uplifted shorelines (see Fig. 3 for location of individual outcrops) with the displacement measured therein (Fig. 5). The timing and amount of displacement (Tabs. 1, 2) is derived from the age and elevation difference between sequentially uplifted shorelines. For sake of simplicity, data provided in published papers and listed in Tables 1 and 2 have been rounded to one decimal, including their nominal uncertainties. The uncertainty on the age of uplift events mostly derives from the uncertainty in age control on the shorelines duration.

Figure 6 shows the pattern of uplift during time obtained by combining data from local sites within individual coastal sectors. Note that the uncertainty bar on the vertical displacement estimate for single events in Figure 6 does not represent a computational uncertainty. Rather, it shows the spread of uplift measurements at different sites (Tab. 2).

The number of uplift events noted in Roman numbers in Tables 1 and 2 and Figures 6 and 7 is the sequence established at each site. The age difference between sequential events defines the event recurrence at individual sectors (Tab. 1).

To avoid inconsistency among different datasets caused by contrasting carbon-14 calibrations applied in the original studies, published conventional radiocarbon ages were calibrated here with the CALIB software (Stuiver & Reimer, 1993) version 6.0. On the same line, all published uplifts were recalculated using the sea-level curves of Lambeck *et alii* (2011). Thus, age and elevation of some shorelines and of related uplift events reported here may slightly differ from those presented in previous studies (specifically results from Scilla and Capo Milazzo: Ferranti *et alii*, 2007; Scicchitano *et alii*, 2011).

Capo Vaticano

The Capo Vaticano peninsula is a structural high bounded by SW-NE and NW-SE trending normal faults (Fig. 2). This area was hit by a large [Mw 6.95 (macroseismic) and 7.4 (instrumental)] earthquake in 1905, whose source is debated (Loreto *et alii,* 2013, Tiberti *et alii,* this volume). The headland experienced Quaternary uplift that is recorded by raised coastal terraces, whose number and distribution vary according to different investigators (Miyauchi *et alii*, 1994; Tortorici *et alii*, 2003; Cucci & Tertulliani, 2006; Bianca *et alii*, 2011). Notwithstanding, consensus exists on a north-eastern tilt of the promontory as reflected by the decreasing elevation of Pleistocene marine terraces towards the northeast. The tilt evidenced by the uplifted Pleistocene terraces is mirrored by the differential displacement pattern of lowstand prograding wedges formed during the Last Glacial Maximum (LGM) at the shelf-break around Capo Vaticano (Pepe *et alii*, 2014).

TABLE 1

Distribution and characteristics of Late Holocene paleo-shorelines and earthquakes in different sectors of the southern Calabrian Arc.

Sector	Region	Displaced marker	Paleo-shoreline		Paleoshoeline age constraint (yr BP)		Paleo-shoreline minimum duration (ka BP)	Uplift event id.	Bracketed event age (kyr BP)	Preferred event age (ka BP)	Recurrence (ka)	Base reference
			No.	Elevation (m asl)	onset	end						
Capo Vaticano	SW Calabria	beach deposit-notch-algal-barnacle rim	PS1	2.3	5756±114	5701±112	N/A	I	5.7-5.5	5.6	N/A	Spampinato et al., 2014
		barnacle-vermetid rim	PS2	1.8	5455±124	3903±151	1.6	II	3.9-3.5	3.7	1.9	
		beach deposit-notch-algal-barnacle rim	PS3	1.4	3486±99	1856±83	1.6	III	1.9	1.9	1.8	
		notch	PS4	0.8	<1856±83	N/A	N/A	IV	<1.9	1.0	0.9	
Scilla		terrace	PS0	>3.8	N/A	> 5350±40	N/A	I	>5.3	5.5	N/A	Ferranti et al 2007, 2008
		beach deposit	PS1	2.3-3.8	5350±40	3708±130	1.6	II	3.7	3.7	1.8	
		barnacle rim	PS2	1.2-1.8	3667±120	1883±338	1.8	III	2.2-1.7	1.9	1.8	
Capo Milazzo	N Sicily	beach deposit-notch-barnacle rim	PS1	2.3	6363±71	1914±40	4.5	I	1.9-1.6	1.8	N/A	Scicchitano et al., 2011
		notch-barnacle rim	PS2	0.8	1613±92	?	N/A	II	<1.6	1.0	0.75	
Taormina-Capo S. Alessio	E Sicily	notch	PS1	5.5	5954±320	>5057±200	N/A	I	6-5.1	5.6	N/A	de Guidi et al., 2003; Stewart et al., 1997; Antonioli et al., 2003
		notch-borings	PS2	4.5	5057±200	4437±340	0.6	II	4.4-3.3	3.9	1.7	
		notch-borings	PS3	1.8-2.4	3334±521	2164±139	1.1	III	2.1-1.8	2.0	1.9	
		notch	PS4	0.8	1791±160	N/A	N/A	IV	<1.8	0.9	1.0	
Capo Schisò		beach deposit	PS1	4.7±0.3	6431±144	>3907±357	N/A	I	6-3.9	4.2	N/A	Spampinato et al., 2012
		algal-barnacle-vermetid rim	PS2	2.9±0.5	3907±357	>977±63	N/A	II	3.9-1.0	2.5	1.7	
		algal-barnacle-vermetid rim	PS3	1.2±0.6	977±63	N/A	N/A	III	<1.0	0.9	1.3	

Detailed mapping of geomorphological and biological sea-level markers around the promontory has documented the occurrence of four Holocene paleo-shorelines, represented by fossiliferous deposits and intertidal bands of organisms such as balanids and vermetids, raised at different elevations (Tab. 1; Spampinato *et alii*, 2014). The highest

TABLE 2

Vertical displacement caused by each paleo-earthquake recorded at individual sites in different sectors of the southern Calabrian Arc. Site numbers refer to Fig. 3. The site inter-distance is computed, along the reported azimuth, between adjacent sites in each domain.

Site	Site Id.	Site inter-distance		Clusters, events, events age & site event displacement (m)			
		(km)	Azimuth	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Capo Vaticano				**I**	**II**	**III**	**IV**
Event age (ka)				**5.7-5.5**	**3.9-3.5**	**1.9**	**<1.9**
Joppolo	*1*	0	-	0.4	N/A	N/A	N/A
Coccorino-Ricadi	*2*	6	NW	0.4	0.4	0.6	0.8
Capo Vaticano	*3*	1	NW	N/A	0.3	0.7	0.8
S. Domenica	*4*	7	NE	0.5	0.6	0.5	0.7
Tropea	*5*	3	NE	0.9		0.6	0.6
Scilla				**I**	**II**	**III**	
Event age (ka)				**5.5?**	**3.7**	**2.2-1.7**	
Palmi Marina	*6*	0	-	N/A	1.3	1.0	
Pietra Galera	*7*	2	SW	N/A	1.8±1.0	1.4±0.8	
Bagnara Calabra	*8*	4	SW	N/A	1.8±0.3	1.2±0.3	
Punta Paci	*9*	12	SW	N/A	1.7±0.8	1.2±0.6	
S. Gregorio Marina	*10*	1	SW	N/A	2.0±0.3	1.8±0.2	
Capo Milazzo						**I**	**II**
Event age (ka)						**1.9-1.6**	**<1.6**
Punta del Tono	*11*	0	-			2.3±0.4	
Punta Cirucco	*12*	2	NNE			1.3±0.3	0.8±0.3
Punta Gamba di donna	*13*	2	NW			1.3±0.3	0.8±0.3
Taormina-S. Alessio				**I**	**II**	**III**	**IV**
Event age (ka)				**6.0-5.1**	**4.4-3.3**	**2.1-1.8**	**<1.8**
Capo S. Alessio	*14*	0	-	1.0	2.7	1.0	0.8
C. S. Andrea-C.Taormina	*15*	8	SW	0.8	2.6±0.5	0.9±0.1	0.6
Capo Schisò					**I**	**II**	**III**
Event age					**4.2?**	**2.5?**	**<1.0**
Capo Schisò	*16*	4	SW		1.8±0.1	1.1±0.1	0.6±0.5

shoreline (PS1) is found at a rather constant elevation of ~2.3 m along both the SW and NW coastal cliffs limiting the promontory, for a ~20 km total length (Fig. 5a). Similarly, subjacent PS2 is mapped for ~15 km at an elevation of ~1.8 m along both coasts. Younger PS3 and PS4, which are represented by poorly developed notches and by raised platforms (Fig. 4f), are mapped for ~12 km at elevations of ~1.4 and ~0.8 m, respectively (Fig. 5a). Figure 5a shows that PS3 and PS4 start losing elevation north of S. Domenica and Tropea, so that the lowermost shoreline PS4 is found at present sea-level at Briatico, ~10 km north of Tropea.

Based on the separation between paleoshorelines, four abrupt uplift events at 5.7–5.5 ka, 3.9–3.5 ka, ~1.9 ka and <1.9 ka ago are recognized (Tab. 1). The vertical uplift occurred during the four events is quite similar with a small, steady growth during time (Fig. 6). The comparable amount of uplift per event suggests that the causative source may be the same for all of them. The recurrence time between events is at a regular interval of ~1.8 ka (Tab. 1).

Corrections for sea-level changes point to a cumulative uplift rate in the last ~6 ka that decreases from ~1.3 to 0.6 mm/yr moving from south to north along the headland coastline (Fig. 3). The asymmetric Holocene uplift, with a greater magnitude in the southwest sector of the promontory, is akin to the long- and intermediate-term deformation attested by Pleistocene terraces and submerged LGM lowstands (Pepe *et alii*, 2014). Spampinato *et alii* (2014) suggested that the larger uplift in the south-western sector reflects the additional contribution, onto the large-wave-

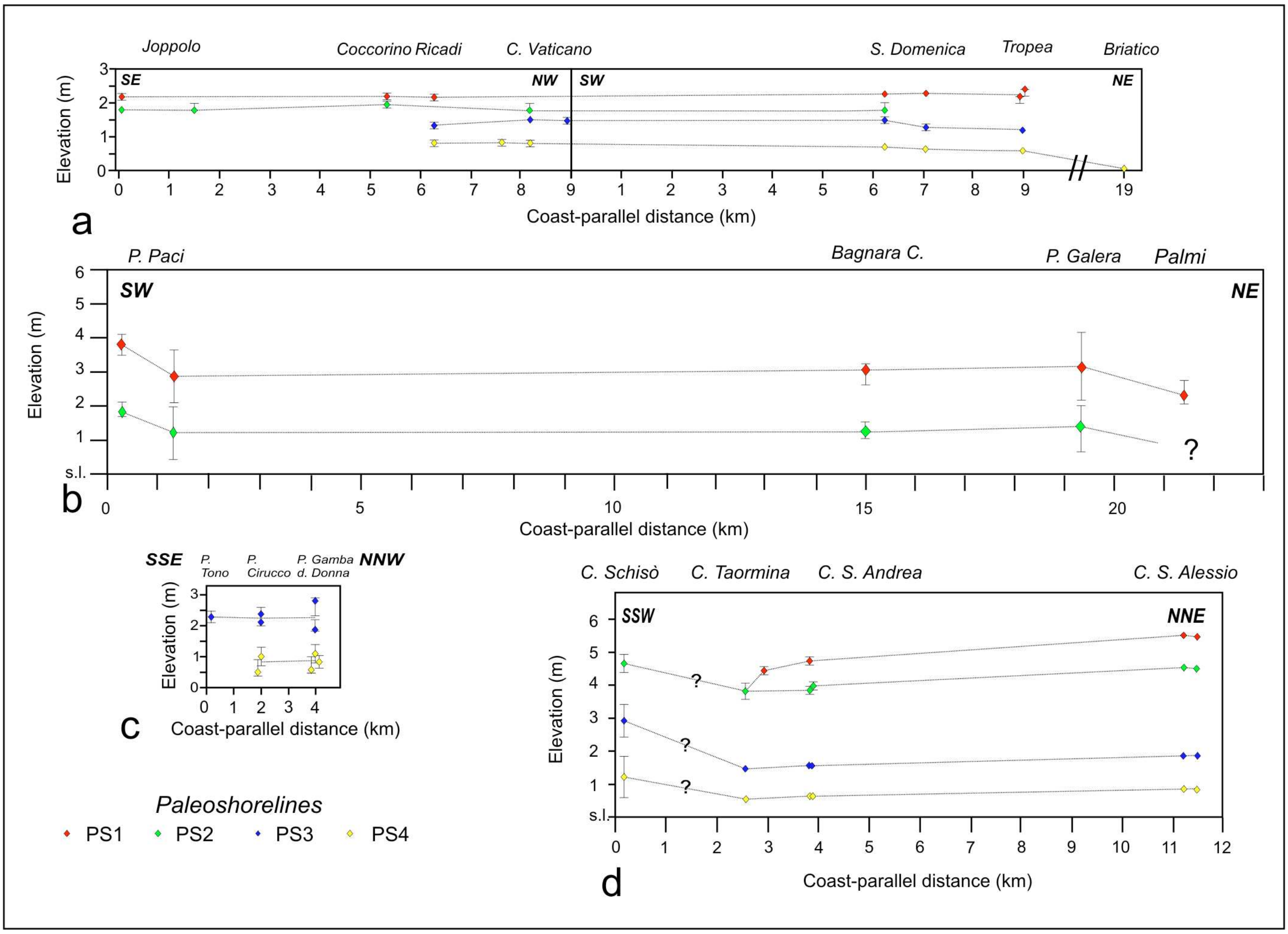

Fig. 5 - Projection, on a profile parallel to the coastline, of the elevation of Late Holocene shorelines PS1 to PS4 at Capo Vaticano (a), Scilla (b), Capo Milazzo (c), and Capo Schisò-Taormina (d). Dots and related bars indicate the estimate and assigned uncertainty for shoreline position, respectively.

length regional signal, of earthquake displacements, which are not registered in the north-east. In fact, PS4 at Briatico has been uplifted only by regional processes and not by co-seismic deformation (ANZIDEI *et alii*, 2013). It is not established whether older shorelines thus far north experienced co-seismic uplift or were similarly raised only by the steady regional process.

SCILLA-PALMI

The cliff-limited coastline east of the Messina Strait runs ~20 km between the villages of Scilla and Palmi (Figs. 2, 3). ANTONIOLI *et alii* (2004) firstly provided age of fossils found up to ~3 m above the present sea level at two outcrops along this coast (9 and 10, Fig., 3). Later on, FERRANTI *et alii* (2007) mapped, at these two and at three additional outcrops, two distinct paleoshorelines.

The shorelines, PS1 and PS2, are dominantly represented by a fossiliferous marine deposit (Fig. 4b) lying in patches above an upper wave-cut terrace (Figs. 4c, 4d), and by a barnacle band (Fig. 4a) located at the inner margin of a lower terrace (Figs. 4c, 4d), respectively. These markers have been uplifted at a rate decreasing from 1.8 to 1.3 mm/yr moving from south to north (Fig. 3).

PS1 is found at an elevation of between 2.3-3.8 m (Fig.. 5b), and it has been dated between 5.4-3.7 ka (Tab. 1). The subjacent PS2 stands at between 1.2-1.8 m, it formed between 3.7-2.1 ka, and it was superposed by a fresh-water flowstone aged at 1.7 ka. Based on shoreline ages, rapid displacements of up to 2 m for both events are tightly constrained at 2.2-1.7 and 3.7 ka, with a ~1.8 ka recurrence time (Tab. 1).

The amount of uplift during these events appears to be consistent, so that the deformation profile parallel to the coast is similar for both shorelines (Fig. 5b). Uplift decreases to the NE and it could reach a termination at ~25-30 km. On the other hand, uplift increases at the SW limit of the mapped outcrop, suggesting that it could continue further to the SW (Fig. 5b).

Because no shell older than 5.3 ka has been dated from the base of the beach deposit which represents PS1, it was suggested that the underlying and rather wide (~5 m) terrace found at site 9 (Figs. 4c, 4d), which is cut into metamorphic rocks and Miocene carbonate dykes, is polycyclic (FERRANTI *et alii*, 2007). Therefore, the terrace could have

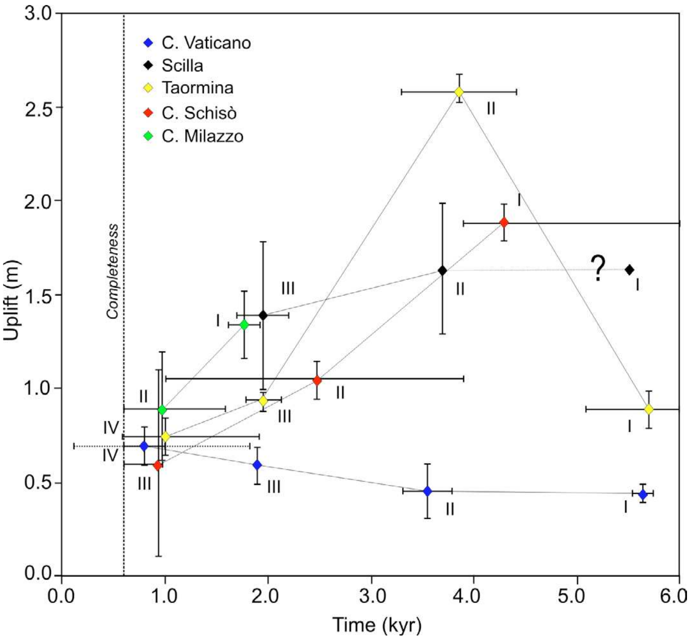

Fig. 6 - Pattern of uplift against time for individual Late Holocene earthquakes at the studied localities in the southern Calabrian Arc. Roman numerals designate the sequence of individual events at each locality (see Table 1).

been partly raised during a previous event, and any deposit eventually resting on it (PS0 in Table 1) would have been stripped off. The age of this previous event was inferred to be only slightly older than 5.3 ka using backward extrapolation of displacement curves and recurrence established for this site. The amount of uplift is unconstrained (question mark in Fig. 6).

Capo Milazzo

Capo Milazzo forms an ~N-S striking, ~2 km wide and ~6 km long peninsula located along the Tyrrhenian coast of north-eastern Sicily (Fig. 3). The headland is located within the broad transcurrent deformation belt associated to the ATLFS (Fig. 2). Rust & Kershaw (2000) described the existence of two uplifted paleoshorelines. Later on, Scicchitano *et alii* (2011) mapped the shorelines at few additional sites and provided ages for these uplift events. Because of the limited extent of the promontory, these two shorelines appear uplifted at a constant elevation in a profile elongated parallel to the promontory (Fig. 5c).

The upper shoreline (PS1) is represented by notches, marine sediments, and barnacle rims. The notch is found at an average elevation of 2.3 m (Figs. 4e, 5c), is filled by a marine deposit containing shells dated between 6.4 and 4.1 ka BP, and by pottery of Roman age (~2 ka), and is rimmed by a balanid band aged between 4.1 and 1.9 ka. Because the notch and the balanid rim lie at similar elevation, they are part of a single shoreline. The lower shoreline (PS2) involves a notch at ~0.8 m (Fig. 4e), and a balanid rim dated at ~1.6 ka.

Large (1.5 m) vertical displacement of PS1occurred between 1.9 and 1.6 ka, the bracketed ages of cessation and inception of the upper and lower shorelines, respectively (Tabs. 1, 2). A younger and lesser (~0.8 m) uplift occurred probably shortly after 1.6 ka. These abrupt displacements superimposed on the regional uplift that operated steadily during the last ~6 ka, yielding a cumulative uplift rate of ~1.5 mm/y (Fig. 3).

Taormina-S. Alessio

The Taormina-S, Alessio (hereinafter Taormina for sake of simplicity) sector is located along the Ionian coast of north-eastern Sicily (Fig. 3). Several workers (Stewart *et alii*, 1997; De Guidi *et alii*, 2003; Antonioli *et alii*, 2003; 2006a) studied a vertical sequence of notches, lithophaga boring bands and fossil organisms (algal rims, shells) along the steep carbonate cliff between Capo S. Alessio to the north and Capo Taormina to the south. These sea-level markers have been uplifted at this coast at a total rate of ~2 mm/yr (Fig. 3).

Based on leveling measurements, De Guidi *et alii* (2003) distinguished four notches separated by lithophaga bands. Elevation of the notches increases from south to north along a ~10 km coastal stretch (Fig. 5d), and the two highest of them (maximum elevation ~5.5 and ~4.5 m, respectively) are tilted landwards, suggesting a local source of deformation. The highest total elevation reached in the north at Capo S. Alessio suggests that uplift could continue further north. Due to the lack of carbonate outcrops northwards Capo S. Alessio, notches were not mapped.

At Capo Taormina in the south, the two highest notches, which elsewhere are spaced ~1 m apart, converge into a single form (Fig. 5d). Separation between the upper (PS1) and the lower (PS2) notch was attributed by De Guidi *et alii* (2003) to an earthquake occurred >5.1 ka, the upper age constraint for PS2 as documented by lithophaga bivalves boring the notch (Stewart *et alii*, 1997).

In turn, PS2, which lasted until 4.4 ka (the age of *Cladocora* corals found in its biogenic rim; Stewart *et alii*, 1997), was raised of ~2.5 m (Tab. 2; Fig. 4d) along the whole coast by a second, more severe event. The age of this uplift is constrained between 4.4 ka and the ~3.3 ka age of bivalves from a lower lithophaga band associated with a subjacent notch found at ~1.4 in the south and 1.8 m in the north. Both the lower lithophaga band and the notch are attributed to paleoshoreline PS3, that lasted at least until the 2.1 ka age of a mollusk shell found within the notch (Antonioli *et alii*, 2003).

In turn, PS3 was raised of ~1 m (Tab. 2) after 1.8 ka, when a lowermost notch (PS4) was formed as constrained by the age of a vermetid crust associated to it. Finally, notch PS4 was uplifted to the present 0.5-0.8 m elevation during a last event (Tab. 2).

Overall, it appears that uplift events at this coast were broadly of similar size with the notable exception of the second one, which produced the highest recorded vertical displacement in the southern Calabrian Arc (Fig. 6).

Capo Schisò

This site is located immediately south of Taormina (Fig. 3) and forms a volcanic headland ensuing from the Mt. Etna lava flows. Spampinato *et alii* (2012) documented the occurrence of three Holocene paleo-shorelines raised at different elevations, and, by integrating their data with those coming from nearby Taormina, suggested ages for ancient earthquakes that displaced the shorelines along the whole coastal sector.

The uppermost shoreline (PS1) at Schisò is represented by a fossiliferous beach deposit at elevations of ~5 m above the present sea level (Tab. 1). A gastropod shell sampled from the deposit yielded an age of ~6.4 ka, possibly coeval with PS1 at Taormina, which lies at a similar elevation (Fig. 5d). However, the bracketed age of PS1 (6.4-3.9 ka) at Schisò indicates that the shoreline here incorporates both PS1 and PS2 found to the north, and there is no information on event n. I that caused separation between the two highest notches at Taormina. Note that because of the broad age constraints, PS1 at Schisò is shown in Figure 5d as correlative with PS2 at Taormina. Notwithstanding, PS1 at Schisò was uplifted of ~1.8 m possibly during the same large event n. II found at Taormina. It is not established whether previous event I at Taormina did not extend south to Schisò, or, more likely, its effects are not resolved in the shoreline record at the latter place.

The intermediate shoreline (PS2) outcrops at a maximum elevation of ~3 m and is represented by algal rims, remnants of barnacle bands and vermetid concretions, and by a fossiliferous beach deposit. The algal rim has a 3.9 ka age, thus providing a lower bound for uplift of the superjacent PS1.

The lowermost shoreline (PS3) includes remnants of algal rims, vermetid concretions, fossil barnacle bands and a beachrock, and reaches an elevation of ~1.2 m (Fig. 5d). A serpulid rim was dated at 1.0 ka. Thus, ~1 m of displacement (event II) of PS2 (Tab. 2) occurred between 3.9 (age of cessation of PS2) and 1.0 ka Finally, PS3 was abruptly displaced during a <1.0 ka event III (Tab. 2). The amount of uplift during this last event is not well constrained and ranges between 0.5-2.0 m (Tab. 2).

Spampinato *et alii* (2012) suggested that the deformation events at Taormina and the adjacent Capo Schisò were synchronous, based on the overlap on their age uncertainties. However, the uneven uplift magnitude between the two sectors may indicate that co-seismic uplifts were temporally separated (question marks in Table 1 and Figure 5d).

ORIGIN AND CHARACTERISTICS OF THE UPLIFT EVENTS

At five sectors in the southern part of the Calabrian Arc (Fig. 3) the occurrence of raised Holocene shorelines has been documented. Since the global sea level never stood higher than the present day during the Late Holocene in southern Italy (Lambeck *et alii*, 2011), the existing elevation of past shorelines must be attributed to coastal uplift. This uplift includes a steady, regional-scale component, which in the region is thought to occur at a rate of ~1 mm/yr (Ferranti *et alii*, 2007; Spampinato *et alii*, 2014), and a stick-slip component that abruptly raised the shorelines above the coeval sea-level. This last occurrence is documented by the relative position of the ancient shorelines indicators, with older markers lying invariably above, and distinctly separated from younger ones. Because of such clear vertical separation, uplift must have been rapid enough that coastal erosion was not able to modify or destroy the uplifted markers. Given the location of the sites above an active forearc region, and the lack of different sources for uplifts (e. g. volcanic vents, which can be invoked only in part for Taormina-Capo Schisò), the abrupt uplifts are interpreted to result from earthquake displacement.

Our age bracket on the uplift events has a typical uncertainty of some 10 to 100 years (Tab. 1), which is intrinsic in dating techniques. This result is well comparable to those coming from paleoseismological trenching (Galli *et alii*, 2008), and similarly suggest the occurrence of ancient earthquakes. Thus, although uncertainty does not allow to tightly pinpointing the age of individual uplift events, nevertheless morphostratigraphic relations and available age controls of shorelines imply co-seismic uplifts.

Summing up the uplifts amongst the different sectors, a possible total of sixteen co-seismic uplifts that occurred during the Late Holocene are recorded in the region (Tab. 1). The exact number depends whether co-seismic uplifts within adjacent domains during a limited temporal lag were separate or occurred simultaneously, and thus are duplicate events.

Our inventory has a lower age limit placed at around 6 ka and certainly after 6.8 ka, the timing of a major inflection point of the relative sea-level (RSL) curve (Lambeck *et alii*, 2011; Antonioli *et alii*, 2015). Before this age span, no distinct paleoshoreline could have reasonably formed or preserved because sea-level rise outpaced the tectonic rate. This time of change in the RSL curve has been widely recognized in the Mediterranean Sea, and is independent of location. On the contrary, the rate of change in RSL does depend on location because of a different isostatic response to deglaciation. The southern Calabrian Arc is predicted to have had a RSL rise at 7.4 mm/yr between 8-6.8 ka, at 3.1 mm/yr between 6.8-6 ka, and at 1.4 mm/yr between 6-2 ka; overall these rates are close to the maximum estimation for the central Mediterranean (Lambeck *et alii*, 2011). With the Holocene cumulative uplift rate in the region (Fig. 3; Tab. 2) being by far lower than the rate of RSL rise before 6 ka, we consider a 6.5 ka age as the lower bound for shoreline formation. This estimate is calibrated against the oldest documented paleoshoreline age (Tab. 1), and is consistent with the regional notch database published by Boulton & Stewart (2015), where, apart for few outliers, the oldest uplifted notches in the Mediterranean Sea are younger than 6.5 ka.

On this basis, we allow an arbitrary 0.5 ka minimum time for shoreline development, and hence assign a 6 ka lower age limit for our paleo-earthquakes record. This estimation is corroborated by published rates regarding notches formation based on their erosion rates (see review in Antonioli *et alii,* 2015). These rates in the Mediterranean setting vary from 0.3 mm/yr (Furlani & Cucchi, 2013) up to 0.6 mm/yr (Evelpidou & Pirazzoli, 2016), so overall a 0.5mm/yr seems to be a reasonable assumption. We are aware that a correlation of published erosion rates with the time duration of ancient shorelines studied here can be attempted when the latter are represented by notches, which in our case are well developed at Taormina and Milazzo only, and locally at Capo Vaticano. The oldest and highest notches at Taormina (PS1) have an average depth of ~0.3 m, and, assuming a mean development rate of ~0.5 mm/yr, ~500 yr are needed for their formation. This estimate is consistent with our minimum estimate for development of the oldest shoreline in the region, and for the inception of our earthquake inventory.

We have also computed a minimum paleoshoreline duration where upper and lower age constraints existed

(Tab. 1), in order to compare this value with an estimate of shoreline development. We note that in SW Calabria (Scilla and Capo Vaticano) this duration is strikingly similar (1.6-1.8 ka), but paleoshorelines here are represented by terraced deposits and platforms, and by balanid rims. In northeastern Sicily, shorelines PS2 and PS3 at Taormina lasted 0.6 and 1.1 ka, suggesting earthquakes displaced them following their complete carving.

It appears that the amount of co-seismic deformation decreased during time in all sectors except for Capo Vaticano (Fig. 6). The reason for this similar behavior is unknown, but it points to higher seismic strain release in the coastal Calabrian Arc before than after ~2 ka. We exclude a contribution coming from a changing sea-level to the decreasing vertical separation between shorelines. Actually, because the sea-level during the Late Holocene and historical time was rising at steadily decreasing rates compared to the past (LAMBECK *et alii*, 2011), we would expect the opposite result in case it had influence on the shoreline distinction, and namely that their vertical separation should increase with younger ages.

A cyclic recurrence of comparable time extent is particularly evident for the Calabrian sectors, where it is estimated at ~1.8 ka at Scilla and Capo Vaticano (Tab. 1). In Sicily, the estimated recurrence is more variable. In eastern Sicily, the time lag between events ranges from 1-1.3 ka to ~1.7-1.9 ka. This double class of estimates probably reflects different earthquake sizes (or their effects on the coast). As an instance, event n. II at Taormina, which could possibly incorporate event n. I at Schisò was significantly larger than the other ones at this coast, and thus it could have given rise to a longer (1.9 ka) recurrence afterward (Fig. 6). Oppositely, the following event III at Taormina had a lesser uplift amount and thus recurrence was shorter (1.0 ka).

DISCUSSION

EARTHQUAKE CLUSTERS

When the age of the co-seismic uplift events is plotted on a diagram displaying the location of individual sectors along the extent of the Calabrian Arc (Fig. 7), an intriguing temporal and spatial pattern emerges. Specifically, the ancient earthquakes appear clustered within relatively narrow temporal intervals separated by longer quiescence periods (Tab. 3). For the aim of this discussion, we have included in Figure 7 historical events with macroseismic magnitude M≥6 occurred offshore or at the coast of the study region from the CFTI4Med (GUIDOBONI *et alii*, 2007) and CPTI catalogues (CPTI15, 2016). We have also included trench data from the Cittanova fault (Fig. 2) provided by GALLI & BOSI (2002) and GALLI & PERONACE (2015).

A first temporal cluster (n. 1) is envisaged at ~5.7-5.3 ka (Figs. 7, 8a). In Calabria, this cluster includes event n. I (5.7-5.5 ka) at Capo Vaticano and an inferred event at Scilla prior to 5.3 ka. Because this latter event is based on the existence of a polycyclic wave-cut terrace, but it is not documented by aged shoreline markers, we place a ~6 ka lower bound on it based on the statement about timing of Late Holocene paleoshorelines formation discussed in section 4. Assuming that the size of this event was comparable to that of younger ones, extrapolation of recurrence time established for later events yields a preferred age of 5.5 ka (Tab. 1). A displacement event recovered in trench from the Cittanova fault likely falls within this cluster (Fig. 7).

In Sicily, the oldest documented event at Taormina is the one that duplicated the uppermost notch before 5.1 ka. We place a conservative lower age bound for this event at ~6 ka with a ~5.6 ka preferred age (Fig. 7). Note that uplift could have also occurred at Schisò, but it has not been resolved there, and event I at this location spans the bracketed duration of both events I and II at Taormina. This is why we have assigned event I at Schisò a preferred age younger than the error bar mid-point (Fig. 7) and correlated it to a later cluster. In summary, cluster 1 possibly lasted an ~400 year interval between ~5.7-5.3 ka (Tab. 3).

Later on, two nearly coeval uplift events are well resolved at Capo Vaticano (3.9-3.5 ka) and Scilla (3.7 ka) during a second earthquake cluster (Figs. 7, 8b). Compared to the previous one, age constraints for this second cluster are tighter. There is however, no record of slip on the Cittanova fault. In Sicily, paleoshoreline displacement occurred at Capo Schisò and Taormina during a major earthquake that, by combining ages from the two sites, may be bracketed at 4.4-3.9 ka (SPAMPINATO *et alii*, 2012). However, as pointed out above, there is the possibility that uplifts at Taormina and Schisò occurred during two separate, but nearly coeval events. Within uncertainty, based on the preferred age of events this second earthquake cascade could have only lasted 500 years from 4.2-3.7 ka.

There is an apparent ~1.6 ka time lag between clusters 2 and 3 when no earthquake is recorded by raised shorelines (Fig. 7). Cluster 3 involves an almost coeval shoreline displacement in the whole region (Fig. 8c). In southern Calabria, two earthquakes occurred near simultaneously at ~1.9 ka at Capo Vaticano and Scilla. It is possible that also the M=6.2, 91 B.C. and the 361 A.D. earthquakes that hit the Messina Strait (Fig. 2) belong to this "coastal" cluster (although GALLI & BOSI (2002) and GALLI & PERONACE (2015) relate the latter earthquake, to which an ~374 A.D. age is assigned, to the onland Cittanova fault, Fig. 7).

In Sicily, shoreline displacement is documented at Taormina (event III) between 2.1-1.8 ka, nearly coeval with co-seismic coastal uplifts in southern Calabria. The age of event II at Schisò has a large uncertainty but it could fall within this cluster; it could correspond to event III at Taormina or be a separate event. At Capo Milazzo, a broadly coeval event is bracketed at 1.9-1.6 ka. Thus, also this third cluster may have a duration of 500 years between 2.1 and 1.6 ka (Tab. 3).

Cluster 4 is separated from the previous one by a limited time lag of ~500 years (Fig. 6). We have placed an upper age limit on this last earthquake group by considering the completeness interval for the M~6.5-7 magnitude class, which for southern Calabria and eastern Sicily is thought to be ~600 years or shortly less (STUCCHI *et alii*, 2004). The limiting age bar means that seismic uplift events documented by raised shorelines, if occurred in the last ~600 years, should match earthquakes listed in the historical catalogues.

In southern Calabria, a seismic uplift event is constrained at Capo Vaticano to be younger than 1.9 ka, whereas there is no evidence of uplift at Scilla (Fig. 7). This event (n. IV) is the largest among those recorded at Capo Vaticano (Fig. 6), and in principle could be related to the M=6.7 1905 earthquake that struck this area and was likely

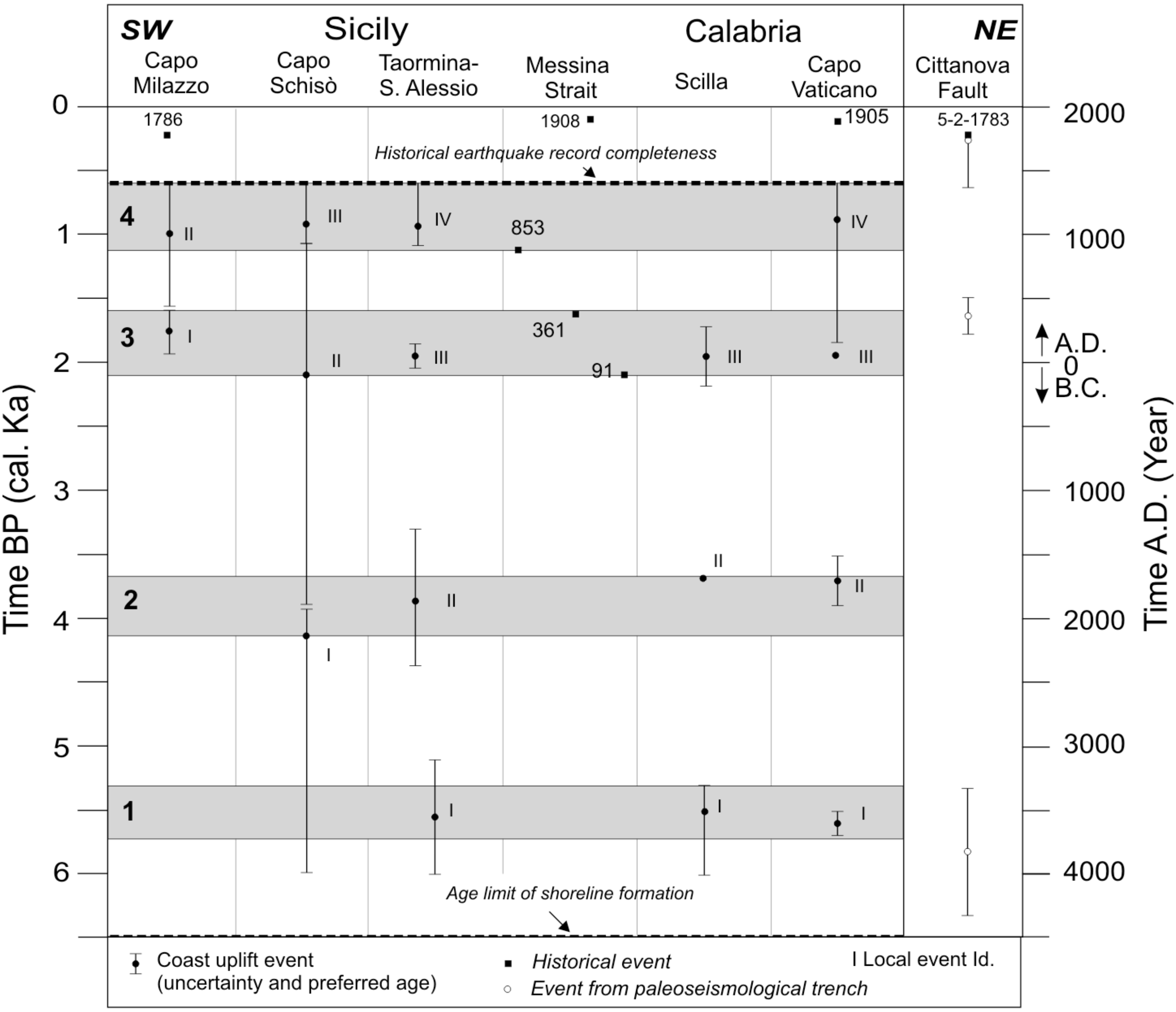

Fig. 7 - Time distribution of ancient earthquakes detected from coastal uplifts along a schematic transect from northeastern Sicily to southern Calabria. Dots and related bars indicate the preferred and bracketed age of seismic events, respectively. The numbered (1-4) horizontal grey bands span the duration of the inferred earthquake clusters in the region. Arabic numerals designate the sequence of individual events at each locality (see Table 1).

generated offshore (Fig. 2; Piatanesi & Tinti, 2002; Cucci & Tertulliani, 2010; CPTI15, 2016). Because there is no report of coastal uplift during the 1905 earthquake, event IV at Capo Vaticano is assigned to cluster 4 because of the completeness threshold.

In the Messina Strait, we include in cluster 4 the M=6.2, 853 A. D. earthquake, whose epicenter, although poorly located, is placed in the CPTI catalog at sea close to the Sicily side of the strait (Figs. 2, 7, 8d). In eastern Sicily, three uplift events are recorded at Capo Milazzo (n. II), Taormina (n. IV) and Schisò (n. III), respectively (Fig. 7). In these sectors no strong earthquake is on record in the historical catalogue after ~1000 A.D. (CPTI15, 2016), with the exception of the M=6.2, 1786 earthquake whose macroseismic epicenter is located ~20 km southwest of Capo Milazzo (Fig. 2). Because of the large distance, we regard the attribution of event II at Capo Milazzo to the 1786 earthquake as unrealistic. Event IV at Taormina was related by De Guidi *et alii*, (2003) to the 853 A.D. earthquake. However, the epicentral area of this earthquake lies ~40 km north of Taormina-S. Alessio (Figs. 2, 8d) and thus the attribution is weak. Notwithstanding, the 853 earthquake is placed within cluster 4, which, given uncertainty, occurred between 1.1-0.6 ka.

Cluster recurrence

The earthquake clusters defined here involved, within a time span of few hundred years, nearly all the abrupt coastal uplifts observed in southern Calabria and northeastern Sicily (Figs. 7, 8a to 8d). Overall, the earthquake

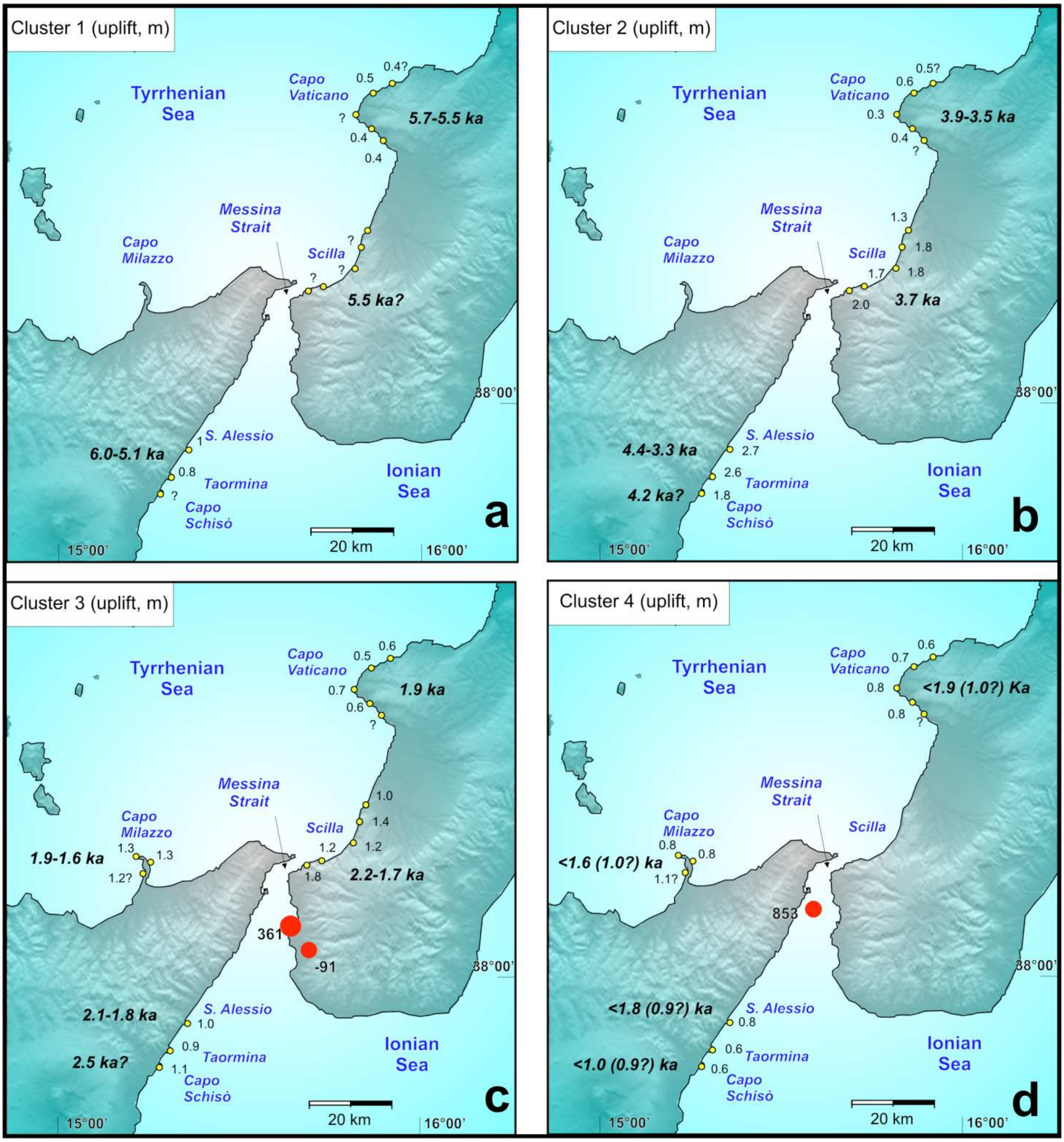

Fig. 8 - Space-time pattern of earthquake clusters in the southern Calabrian Arc, showing ages and amount of seismic uplift of individual earthquakes.

clusters took four intervals of ~500 years to be completed (Tab. 3), although there are large uncertainties on their precise timing. Notwithstanding, the estimated duration of these ancient clusters is consistent with the ~300 years time bracket of the apparently clustered historical seismic release in Calabria (JACQUES *et alii*, 2001; GALLI & BOSI, 2002).

Table 3 shows that the time lag between older clusters (1-2 and 2-3) is substantially larger (1.1-1.6 kyr) than that (0.5 kyr) between the more recent ones (3-4). We suggest that this difference is related to a regional variation in energy release, as suggested by the decreasing extent of uplift in more recent times (Fig. 6). The second cluster is associated to the largest uplift events at Scilla, Schisò,

TABLE 3

Time characteristics of Late Holocene earthquake clusters in the southern Calabrian Arc.

Cluster n.	time span (kyr)	duration (yr)	time lag (yr)
4	1.1-0.6	500	500
3	2.1-1.6	500	1600
2	4.2-3.7	500	1100
1	5.7-5.3	400	-

and Taormina (Fig. 6, Tab. 1), and a 1.6 ka quiescence time before the following cluster (Tab. 3) is conceivable. Basically, the 1.6 ka time lag is dictated by the recurrence of the large earthquakes occurred all over the region during the second cluster, and perhaps this reasoning applies to the substantial lag (1.1 ka) between clusters 1 and 2 as well. On the contrary, the magnitude of coastal uplift during the third cluster was minor (Fig. 6), and thus the time lag for the following fourth earthquake cluster was lesser (0.5 ka).

Open issues in defining seismogenic sources

The seismogenic structures responsible for abrupt coastal uplifts are not yet defined because they lie mostly offshore. Shoreline displacement was tentatively attributed to uplift in the footwall of normal faults (De Guidi *et alii*, 2003; Ferranti *et alii*, 2007; 2008; Spampinato *et alii*, 2012). However, this interpretation faces the discrepancy that observed individual uplifts appear in most cases too large (Tab. 2) for typical extensional earthquakes, where ratios of hanging–wall subsidence to footwall uplift ranges between 1:1 and 1:10, and are mostly observed in the lower range (King *et alii*, 1988; Armijo *et alii*, 1996; Papanikolaou *et alii*, 2010).

Under the view that the coastal uplifts are due to normal faulting, the hanging-wall subsidence would be missed in the coastal record. In fact, local faulting subsidence can be observed only when the effect of regional uplift prevails, and this can be only appreciated at the long-term (100-1000 ka) time span (Valensise & Pantosti, 1992; Roberts *at alii*, 2013). Because the Late Holocene sea-level rise (Lambeck *et alii*, 2011) was broadly equal to the regional uplift rate (Ferranti *et alii*, 2007), coastal sectors away from active faults are predicted to show no uplifted Holocene shorelines. On the other hand, sectors within and parallel to a normal fault would be characterized by uplifted or down-lifted (beneath the sea level) Holocene shorelines depending whether they reside in the footwall or hanging-wall block, respectively. The observation of uplifted shorelines in the sectors studied here indicate that, in the scenario that uplift is due to displacement on normal faults, the cost must reside in their footwall.

Within an extensional context scenario, a possible explanation of the large shoreline footwall throw per event would invoke that it does not result from a single coseismic displacement. Rather, it could be the sum of several events closely spaced in time, e. g. at the ≤100 yr scale that is the detection threshold of ages uncertainty. These earthquake sub-clusters have been proposed as an explanation for apparent large displacements of coastal notches in the footwall blocks of known normal faults (Boulton & Stewart, 2015, and references therein). Recently, the use of Terrestrial Laser Scanner (TLS- t-LiDAR), that offers very high spatial resolution, has demonstrated the existence of additional and morphologically subdue notches in between well-developed notches that are separated of ~1 m in the Gulf of Corinth, suggesting the observed uplift is the sum of multiple individual earthquakes (Schneiderwind *et alii*, 2017). Because of their lower vertical separation, some of these minor notches may have a locally inverted chronological order.

In the Calabrian Arc, the possibility that the observed shoreline separation results from several clustered events at sub-centennial scale should be tested using high-resolution measurement techniques. However, the displaced markers (balanid rims, loose coastal deposits) mostly found in the study region have a lower degree of preservation compared to notches, and thus only those displaced at sufficiently high elevation by the summed earthquake displacements invoked in this model could have escaped the ensuing destruction by the sea-waves. Thus, with the existing uncertainty in dating and in positioning of the paleoshorelines, displacements of few decimetres, separated of some to several years to decades, can hardly be recognized. In this tectonic scenario, only the uppermost part of a shoreline, which should have been uplifted after a long-enough time span between seismic clusters, would be recognized and dated, and would invariably yield an age older than the immediately underlying shoreline.

An alternative view may hold that the large coastline displacements are due to thrust earthquakes related to subduction processes, as occurs at Crete (Shaw *et alii*, 2008). Because the subduction interface between the African margin and the European plate lies ~100 km off the site of coastal uplift at Crete, Shaw *et alii* (2008) suggested that the structure responsible for uplift is a synthetic thrust fault in the overriding plate positioned close beneath the island.

In the Ionian subduction zone, aseismic motion may still be occurring at the toe of the accretionary prism ~300 km SE of Calabria, but active and possibly seismogenic displacement has been proposed on thrust faults within the accretionary wedge (Polonia *et alii*, 2011) ~100-150 km off the shore (Fig. 1). Hypocentral depth distribution of deep seismicity indicate that the subduction interface lies at ~30-40 km depth beneath the Tyrrhenian side of Calabria, before turning into the top of a very steep Benioff zone under the Tyrrhenian Sea (Fig. 1; Neri *et alii*, 2012). In this frame, synthetic and antithetic thrust faults akin to the Crete subduction could be present in the deep crust of Calabria above the Ionian slab.

Within this second scenario, some of the earthquake uplifts illustrated here could be duplicate events. Because the temporal resolution of dating is not enough adequate to handle broadly coeval events within distinct coastal sectors as separate events, the possibility exist that thrusting events that could be M>7.0 can significantly expand uplift over a larger area. Further constraints on the age of uplifts, as well as incorporation of geophysical datasets and modelling, is deemed to test this hypothesis.

CONCLUSIONS

Abrupt shoreline displacement related to ancient earthquakes occurred during the Late Holocene in the southern Calabrian Arc and permits to extend back in time the paleoseismological record for the region. Although significant uncertainties exist on the age of many events, they appear to be clustered during limited time intervals of few hundred years when several faults were probably activated in a cascade fashion. Four of these clusters are tracked in the last ~6 ka and are separated by ~500-1500 years periods of seismic quiescence.

Although previously attributed to co-seismic uplifts in the footwall of offshore normal faults, the throw per events appear too large to be caused by individual extensional earthquakes. A possible explanation would invoke temporally clustered (10 to 100 years) extensional ruptures, whose effects would be summed and not distinguishable in the shoreline record. Alternatively, these coastal uplifts might hinder the existence of an active thrust system occurring at lower crustal depth in the overriding plate of the Ionian subduction zone. Because attribution of the coastal uplifts studied here to (clusters of) extensional earthquakes would require the too fortuitous location of normal faults close to the coast of southern Calabria and Sicily, we regard Holocene displacements on thrust systems, possibly synthetic to the Ionian subduction front, as a viable explanation.

The possible existence of active thrusts at depth does not prevent activity of other type of faults in the overriding plate. No Holocene coseismic coastal uplifts are documented in the Messina Straits between Sicily and Calabria, and yet extensional historical earthquakes are recorded. Field and trench data document Holocene and historical ruptures on the Cittanova normal fault in between sites of coastal uplifts. All in all, the coupled shoreline uplift, trench offset, and seismicity datasets may record the joint activity of thrust and extensional faults.

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REFERENCES

Antonioli F., Kershaw S., Rust D. & Verrubbi V. (2003) - *Holocene sea-level change in Sicily and its implications for tectonic models: new data from the Taormina area, northeast Sicily*, Marine Geology, **196**, 53-71.

Antonioli, F., Dai Pra G., Segre A. G., and Sylos Labini S. (2004) - *New data on late Holocene uplift rate in Calabria and Messina Straits area, Italy,* Quaternaria Nova, **8**, 71– 84.

Antonioli F., Ferranti L., Lambeck K., Kershaw S., Verrubbi V. & Dai Pra G. (2006) - *Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and northeastern Sicily (southern Italy, central Mediterranean sea).* Tectonophysics, **422**, 23-40.

Antonioli F., Ferranti L., Fontana A., Amorosi A.M., Bondesan A., Braitenberg C., Dutton A., Fontolan G., Furlani S., Lambeck K., Mastronuzzi G., Monaco C., Spada G. & Stocchi P. (2009) - *Holocene relative sea-level changes and vertical movements along the Italian and Istrian coastlines.* Quaternary International, **206**, 102-133.

Antonioli F., Lo Presti V., Rovere A., Anzidei M., Deiana M., de Sabata E., Ferranti L., 66 Furlani S., Mastronuzzi G., Orrù P., Pagliarulo R., Sannino G., Sansò P., Scicchitano G., 67 Spampinato C., Vacchi M. & Vecchio A. (2015) - *Tidal notches in Mediterranean Sea: a 68 comprehensive analysis*. Quaternary Science Review, **119**, 66-84.

Anzidei M., Antonioli F., Benini A., Gervasi A. & Guerra, I. (2013) - *Evidence of vertical tectonic uplift at Briatico (Calabria, Italy) inferred from Roman age maritime archaeological indicators.* Quaternary International, **288**, 158–167.

Argnani A., Serpelloni E. & Bonazzi C. (2007) - Pattern of deformation around the central Aeolian Islands: evidence from multichannel seismics and GPS data. Terra Nova, **19**, 317-323.

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.

Bianca M., Catalano S., De Guidi G., Gueli A.M., Monaco C., Ristuccia G.M., Stella G., Tortorici G., Tortorici L. & Troja S.O. (2011) - *Luminescence chronology of Pleistocene marine terraces of Capo Vaticano Peninsula (Calabria, Southern Italy).* Quaternary International, **232**, 114-121.

Billi A., Barberi G., Faccenna C., Neri G., Pepe F. & Sulli A. (2006) - *Tectonics and seismicity of the Tindary Fault System, southern Italy: crustal deformations at the transition between ongoing contractional and extensional domains located above the edge of a subducting slab*. Tectonics, **25**, 1-20.

Billi A., Presti D., Faccenna C., Neri G. & Orecchio B. (2007) - *Seismotectonics of the Nubia plate compressive margin in the south-Tyrrhenian region, Italy: clues for subduction inception*. Journal of Geophysical Research Solid Earth, **112**, B08302.

Boulton S.J. & Stewart I.S. (2015) - *Holocene Coastal Notches in the Mediterranean Region: indicators of Palaeoseismic clustering?* Geomorphology, **237**, 29-37.

Camassi R. & Stucchi M. (1997) - NT4.1 un catalogo parametrico di terremoti di area italiana al di sopra della soglia del danno. CNR-GNDT. http://emidius.mi.ingv.it/NT/.

Carafa M.M.C., Barba S. & Bird P. (2015) - *Neotectonics and long-term seismicity in Europe and the Mediterranean region.* Journal of Geophysical Research Solid Earth, **120**, 5311-5342, doi: 10.1002/2014jb011751.

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.

Chiarabba C., Jovane L. & Di Stefano R. (2005) - *A new view of Italian seismicity using 20 years of instrumental recordings.* Tectonophysics, **395**, 251–268.

Chiarabba C., De Gori P. & Amato A. (2011) - *Do earthquake storms repeat in the Apennines of Italy?* Terra Nova, **23**, 300-306,

CPTI15 (2016) - Rovida A., Locati M., Camassi R., Lolli B., Gasperini P. (eds). *CPTI15, the 2015 version of the Parametric Catalogue of Italian Earthquakes.* Istituto Nazionale di Geofisica e Vulcanologia. doi: http://doi.org/10.6092/INGV.IT-CPTI15.

Cucci L. & Tertulliani A. (2010) - *The Capo Vaticano (Calabria) coastal terraces and the 1905 M7 earthquake: The geomorphological signature of regional uplift and coseismic slip in southern Italy*. Terra Nova, **22**, 378–389.

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**, B11402.

D'Agostino N., D'Anastasio E., Gervasi A., Guerra I., Nedimović M. R., Seeber L. & Steckler M. (2011) - *Forearc extension and slow rollback of the Calabrian Arc from GPS measurements*. Geophysical Research Letters, **38**, L17304.

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.

Devoti R., Riguzzi F., Cuffaro M. & Doglioni C. (2008) - *New GPS constraints on the kinematics of the Apennines subduction.* Earth Planet. Sc. Lett., **273**, 163-174.

Devoti R., Esposito A., Pietrantonio G., Pisani A.R. & Riguzzi F. (2011) - *Evidence of large scale deformation patterns from GPS data in the Italian subduction boundary*. Earth Planetary Science Letters, **311** (3-4), 230-241.

DISS Working Group (2015) - *Database of Individual Seismogenic Sources (DISS), Version 3.2.0: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas*. http://diss.rm.ingv.it/diss/, Istituto Nazionale di Geofisica e Vulcanologia; DOI:10.6092/INGV.IT-DISS3.2.0.

Evelpidou, N. & Pirazzoli P. A. (2016) - *Estimation of the intertidal bioerosion rate from a well-dated fossil tidal notch in Greece*. Marine Geology. DOI: 10.1016/j.margeo.2016.04.017.

Faccenna C., Molin P., Orecchio B., Olivetti V., Bellier O., Funiciello F., Minelli L., Piromallo C., & Billi A. (2011) - *Topography of the Calabria subduction zone (southern Italy): Clues for the origin of Mt. Etna*. Tectonics, **30**, TC1003.

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.

Ferranti L., Monaco C., Morelli D., Antonioli F. & Maschio L. (2008) - *Holocene activity of the Scilla Fault, Southern Calabria: Insights from coastal morphological and structural investigations*. Tectonophysics, **453**, 74-93.

Ferranti L., Antonioli F., Anzidei M., Monaco C. & Stocchi P. (2010) - *The timescale and spatial extent of vertical tectonic motions in Italy: insights from relative sea-level changes studies*. Journal of the Virtual Explorer, 36, 1–34.

Furlani, S. & Cucchi, F. (2013) - *Downwearing rates of vertical limestone surfaces in the intertidal zone (Gulf of Trieste, Italy)*. Marine Geology **343**, 92–98. DOI: 10.1016/j.margeo.2013.06.005.

Galli P. & Bosi V. (2002) - *Paleoseismology along the Cittanova fault: Implications for seismotectonics and earthquake recurrence in Calabria (southern Italy)*. Journal of Geophysical Research, **107**(B3), 2044, doi:10.1029/2001JB000234.

Galli P. & Peronace E. (2015) - *Low slip rates and multimillennial return times for Mw 7 earthquake faults in southern Calabria (Italy)*. Geophysical Research Letters, **42**, doi:10.1002/2015GL064062.

Galli P. Galadini F. & Pantosti D. (2008) - *Twenty years of paleoseismology in Italy*. Earth Science Review, 88, 89–117.

Gasparini, C., Iannaccone G., Scandone P. & Scarpa R. (1982) - *Seismotectonics of the Calabrian arc*. Tectonophysics, 84, 267-286.

Guidoboni E., Ferrari G., Mariotii D., Comastri A., Tarabusi G. & Valensise G (2007) - *CFT14Med, Catalogue of Strong Earthquakes in Italy (461 B.C. – 1997) and Mediterranean area (760 B.C. – 1500)*. INGV-SGA, Bologna. Available at http://storing.ingv.it/cfti4med/.

Gvirtzman Z. & Nur A. (2001) - *Residual topography, lithospheric structure and sunken slabs in the central Mediterranean*. Earth and Planetary Science Letters, **187**, 117-130.

Jackson J.J., Gagnepain A., Houseman G., King G.C.P., Papadimitriou P., Soufleris C. & Virieux J. (1982) - *Seismicity, normal faulting, and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981*. Earth Planetary Science Letters, **57** (2), 377–397. DOI: 10.1016/0012-821X(82)90158-3.

Jackson J.A., White N.J., Garfunkel Z. & Anderson H. (1988) - *Relations between normal-fault geometry, tilting and vertical motions in extensional terrains: an example from the southern Gulf of Suez*. Journal of Structural Geology, **10,** 155–170.

Jacques E., Monaco C., Tapponnier P., Tortorici L. & Winter T. (2001) - *Faulting and earthquake triggering during the 1783 Calabria seismic sequence*. Geophysical Journal International, **147**, 499-516.

Keller E. A. & Pinter N. (2002) - *Active tectonics: Earthquakes, uplift and Landscape* (second edition): Englewood Cliffs, New Jersey, Prentice Hall, p. 362.

King, G.C., Stein, R.S. & Rundle, J.B. (1988) - *The growth of geological structures by repeated earthquakes 1. Conceptual framework*. Journal of Geophysical Research: Solid Earth (1978–2012), **93**, 13307–13318.

Lambeck K., Antonioli F., Anzidei M., Ferranti L., Leoni G. & Scicchitano G. (2011) - *Sea level change along the Italian coast during the Holocene and projections for the future*. Quaternary International, **232**,1-2.

Loreto M.F., Fracassi U., Franzo A., Del Negro P., Zgur F. & Facchin L. (2013) - *Approaching the seismogenic source of the Calabria 8 September 1905 earthquake: New geophysical, geological and biochemical data from the S. Eufemia Gulf (S Italy)*. Marine Geology, **343**, 62–75.

Mattia M., Palano M., Bruno V. & Cannavò F. (2009) - *Crustal motion along the Calabro-Peloritano Arc as imaged by twelve years of measurements on a dense GPS network*. Tectonophysics, **476**, 528-537.

Michelini A., Lomax A., Nardi A., Rossi A., Palombo B. & Bono A. (2005) - *A modern re-examination of the locations of the 1905 Calabria and the 1908 Messina Straits earthquakes*. Geophysical Research Abstracts, **7**.

Minelli L. & Faccenna C. (2010) - *Evolution of the Calabrian accretionary wedge (central Mediterranean)*. Tectonics, **29**, TC4004.

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.

Natawidjaja D., Sieh K., Ward S., Cheng H., Edwards R. L., Galetzka J. & Suwargadi B. (2004) - *Paleogeodetic records of seismic and aseismic subduction from central Sumatran microatolls, Indonesia*. Journal of Geophysical Research 109, B04306, doi 10.1029/2003JB0002398.

Neri G., Barberi G., Oliva G. & Orecchio B. (2005) - *Spatial variation of seismogenic stress orientations in Sicily, South Italy*. Physics of the Earth and Planetary Interiors **148**, 175-191.

Neri G., Marotta A. M., Orecchio B., Presti D., Totaro C., Barzaghi R. & Borghi A. (2012) - *How lithospheric subduction changes along the Calabrian Arc in southern Italy: geophysical evidences*. International Journal of Earth Sciences, DOI 10.1007/s00531-012-0762-7.

Nur A. & Cline E.H. (2000) - *Poseidon's horses: plate tectonics and earthquakestorms in the Late Bronze Age Aegean and Eastern Mediterranean*. Journal of Archaeological Science, 27, 43–63.

Palano M., Ferranti L., Monaco C., Mattia M., Aloisi M., Bruno V., Cannavò F. & Siligato G. (2012) - *GPS velocity and strain fields in Sicily and southern Calabria, Italy: Updated geodetic constraints on tectonic block interaction in the central Mediterranean*. Journal of Geophysical Research, 117, B07401, doi:10.1029/2012JB009254.

Papanikolaou I.D., Foumelis M., Parcharidis I., Lekkas E.L. & Fountoulis I. (2010) - *Deformation pattern of the 6 and 7 April 2009, Mw = 6.3 and Mw = 5.6 earthquakes in L' Aquila (central Italy) revealed by ground and space based observations*. Natural Hazards and Earth System Sciences, **10**, 73–87.

Pepe F., Bertotti G., Ferranti L., Sacchi M., Collura A. M., Passaro S. & Sulli A. (2014) - *Pattern and rate of post-20 ka vertical tectonic motion around the Capo Vaticano Promontory (W Calabria, Italy) based on offshore geomorphological indicators*. Quaternary International, **232**, 85-98.

Piatanesi A. & Tinti S. (2002) - *Numerical modelling of the September 8, 1905 Calabrian (southern Italy) tsunami*. Geophysical Journal International, **150**, 271-284.

Pirazzoli P.A., Stiros S.C., Laborel J., Laborel-Deguen F., Arnold M., Papageorgiou S. & Morhange C. (1994) - *Late-Holocene shoreline changes related to palaeoseismic events in the Ionian Islands, Greece*. Holocene **4**, 397–405.

Pirazzoli P.A., Mastronuzzi G., Saliege J.F. & Sansò P. (1997) - *Late Holocene emergence in Calabria, Italy*. Marine Geology, **141**, 61-70.

Polonia A., Torelli L., Mussoni P., Gasperini L., Artoni A. & Klaeschen D. (2011) - *The Calabrian Arc subduction complex in the Ionian Sea: Regional architecture, active deformation and seismic hazard*. Tectonics, **30**, TC5018.

Polonia A., Torelli L., Gasperini L. & Mussoni P. (2012) - *Active faults and historical earthquakes in the Ionian Sea*. Natural Hazards and Earth System Sciences, **12**, 2311–2328.

Polonia A., Torelli L., Artoni A., Carlini M., Faccenna C., Ferranti L., Gasperini L., Govers R., Klaeschen D., Monaco C., Neri G., Nijholt N., Orecchio B. & Wortel R. (2016) - *The Ionian and Alfeo-Etna fault zones: New segments of an evolving plate boundary in the central Mediterranean Sea?* Tectonophysics, **675**, 69-90.

Postpischl D. (1985) - *Catalogo dei terremoti italiani dall'anno 1000 al 1980, Consiglio Nazionale delle Ricerche, Progetto Finalizzato Geodinamica (CNR-PFG)*. Quaderni de "La Ricerca Scientifica", **1145**, 239.

Roberts G., 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.

Rust D. & Kershaw S. (2000) - *Holocene tectonic uplift patterns in northeastern Sicily: evidence from marine notches in coastal outcrops*. Marine Geology, **167** (1-2), 105–126. DOI: 10.1016/S0025-3227(00)00019-0.

Scarfì L., Messina A. & Cassisi C. (2013) - *Sicily and Southern Calabria focal mechanism database: a valuable tool for the local and regional stress field determination.* Annals of Geophysics, **56**, 1, D0109; DOI:10.4401/ag-6109.

Schneiderwind S., Boulton S. J., Papanikolaou I. & Reicherter K. (2017) - *Innovative tidal notch detection using TLS and fuzzy logic. Implications for palaeo-shorelines from compressional (Crete) and extensional (Gulf of Corinth) tectonic settings*. Geomorphology **283**, 189-200. DOI: 10.1016/j.geomorph.2017.01.028.

Scicchitano G., Spampinato C. R., Ferranti L., Antonioli F., Monaco C., Capano M. & Lubritto C. (2011) - *Uplifted Holocene shorelines at Capo Milazzo (NE Sicily, Italy): evidence of co-seismic and steady-state deformation*. Quaternary International, **232**, 1-2.

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 Planetary Science Letters, **298**, 347–360.

Shaw B., Ambraseys N.N., England P.C., Floyd M.A., Gorman D.J., Higham T.F.G., Jackson J.A., Nocquet J.M., Pain C.C. & Piggott M.D. (2008) - *Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake*. Nature Geoscience, **1**, 268-276.

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.

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.

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.

Stucchi M., Albini P., Mirto C. & Rebez A. (2004) - *Assessing the completeness of Italian historical earthquake data.* Annals of Geophysics, **47**, 659-673.

Subarya C., Chlieh M., Prawirodirdjo L., Avouac J. P., Bock Y., Sieh K., Meltzner A. J., Natawidjaja D. H. & McCaffrey R. (2006) - *Plate boundary deformation associated with the great Sumatra-Andaman earthquake*. Nature, **440**, 46–51.

Stuiver M. & Reimer P. J. (1993) - *Extended 14C database and revised CALIB radiocarbon calibration program.* Radiocarbon, **35**, 215-230.

Tiberti M.M., Vannoli P., Fracassi U., Burrato P., Kastelic V., & Valensise G. - *Understanding seismogenic processes in the Southern Calabrian Arc: a geodynamic perspective.* Italian Journal of Geosciences 10.3301/IJG.2016.12.

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**, 269-278.

Tortorici L., Monaco C., Tansi C. & Cocina O. (1995) - *Recent and active tectonics in the Calabrian Arc (southern Italy).* Tectonophysics, **243**, 7–55.

Valensise G. & Pantosti D. (1992) - *A 125 Kyr long geological record of seismic source repeatability: The Messina Straits (southern Italy) and the 1908 earthquake (MS 7 1/2)*. Terra Nova, **4**, 472–483.

Wells D.L., Coppersmith K.J. (1994) - *New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement*. Bulletin Seismological Society of America, **84**, 974–1002.

Westaway R. (1993) - *Quaternary uplift of Southern Italy*. Journal of Geophysical Research, **98**, 21741-21772.

Westaway R. & Bridgland D. (2007) - *Late Cenozoic uplift of southern Italy deduced from fluvial and marine sediments: Coupling between surface processes and lower-crustal flow*. Quaternary International, **175**, 86-124.

Wortel M.J.R. & Spakman W. (2000) - *Subduction and slab detachment in the Mediterranean-Carpathian region*. Science, **290**, 1910-1917.

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