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Late Pleistocene to Holocene record of changing uplift rates in southern Calabria and northeastern Sicily (southern Italy, Central Mediterranean Sea)

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Abstract

A combination of published and new radiometric dates on uplifted Holocene fossil beaches from northeastern Sicily and southern Calabria (southern Italy) is compared with the altitude of the inner margin of the Last Interglacial (LIg) (Late Pleistocene, ~124 ka) and older marine terraces in order to gain a regional-scale outline of uplift rates and their temporal changes in a region which is one of the fastest uplifting sectors of the Central Mediterranean Sea. Late Holocene radiocarbon dates from Ioppolo (southern Calabria) and Ganzirri (northeast Sicily), two newly discovered sites are here presented for the first time. The Holocene uplift rates are highest at St. Alessio and Taormina in eastern Sicily (2.4 mm/y) and at Scilla in southwestern Calabria (2.1 mm/y), two sites located across the Messina Straits and which separate the island of Sicily from mainland Italy. Uplift rates decrease towards the south and north from this centre of uplift. Late Holocene uplift rates show an apparent increase of between 64 and 124% when compared with the longer-term uplift rates calculated from the LIg highstand terraces. Furthermore, we discovered that the locations of fastest Late Pleistocene and Late Holocene uplift rates spatially coincide. To what extent the Holocene increase in uplift rates results from incomplete elastic strain release along the major extensional faults which frame the seismotectonic of the area, or indicate a true change in regional tectonic processes, is not resolved. Nonetheless, the heterogeneity of uplift, with a well-defined centre that crosses the Messina Straits, and its persistence at different time-scales indicates a tight connection between wider regional processes and fault-related displacement in controlling crustal instability in this area.

Keywords: Holocene; Late Pleistocene; Sea level; Tectonic uplift; Messina straits; Central Mediterranean

1. Introduction

One aim of coastal studies is to identify the nature and rates of vertical tectonic motion using a combination of field observations, radiometric dates and predictive models of the deformation processes affecting the coastal region. Vertical rates of tectonic motion give important insights into the driving mechanisms and on the crustal response to these forces, and this can be achieved in the coastal zone by examining the history of sea-level change if non-tectonic contributions to the

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latter can be independently estimated. Thus, corrections must be applied for global eustasy and regional glacio-hydro-isostatic sea-level changes in order to obtain the rates of vertical tectonic displacements.

Vertical tectonic motions will usually include two main contributions: one is reflected in regional, large-amplitude motions which are commonly sustained over longer time spans, and the second includes more local effects mostly attributable to slip on faults or volcanic deformation, and whose rate may not correspond to the long-term rates.

Within the Mediterranean Sea, tectonic subsidence or uplift occurs in many locations (Westaway, 1993; Miyauchi et al., 1994; Dia et al., 1997; Kershaw and Guo, 2001). This paper focuses on the southernmost part of peninsular Italy (Calabria) and northeastern Sicily, which is an area of complex tectonics, and aims to (1) advance the understanding of processes and responses in coastal vertical motions and (2) to address the complex problems of such processes in this part of the Central Mediterranean Sea, using a range of approaches to the problems. For this region a wealth of information on accurate positional measurements and high-precision dating is available and has been used to constrain the uplift of tectonically active coasts (e.g. Dumas et al., 1987, 1988; Cosentino and Gliozzi, 1988; Miyauchi et al., 1994; Bordoni and Valensise, 1998; Cucci and Cinti, 1998; Bianca et al., 1999; Catalano and De Guidi, 2003; Catalano et al., 2003; Tortorici et al., 2003). Typically, estimates of tectonic uplift use the last interglacial (~124 ka BP, LIg) shoreline as reference level (e.g. Cosentino and Gliozzi, 1988; Bordoni and Valensise, 1998; Ferranti et al., 2006) but in other instances rates have been obtained for longer time intervals by fitting higher but undated shorelines to positive stillstands back to the Middle Pleistocene at ~0.7 Ma BP (e.g. Cucci and Cinti, 1998; Bianca et al., 1999) and such studies indicate that rates of tectonic uplift are approximately constant on time scales of $\sim 10^6$ years.

Constancy of uplift rates, may, however, not be valid when shorter time intervals are analysed, and short-term rate-changes suggest that the deformation may be controlled more by the local crustal response than by the long-term forcing (e.g. Catalano and De Guidi, 2003; Catalano et al., 2003). Also, corrections for eustatic and glacio-hydro-isostatic changes are likely to be important on these shorter time scales. In the last few years, absolute dating of Holocene shorelines has been performed in Calabria and Sicily (Fig. 1; Firth et al., 1996; Pirazzoli et al., 1997; Stewart et al., 1997; Antonioli et al., 2003; De Guidi et al., 2003; Ferranti et al., submitted for publication). Thus, it is now possible to compare the long and short-term rates of vertical tectonic motion for the area, one of the fastest uplifting sectors of the Mediterranean Sea. In addition to the global sea-level rise from the melting of the last ice sheets (the eustatic change), vertical motions of the crust caused by the glacial and melt-water loading/unloading, during the glacial cycle, have been calculated using model predictions calibrated against data from 30 sites in Italy (Lambeck et al., 2004a). Of these loading corrections, the glacial signature is caused by the

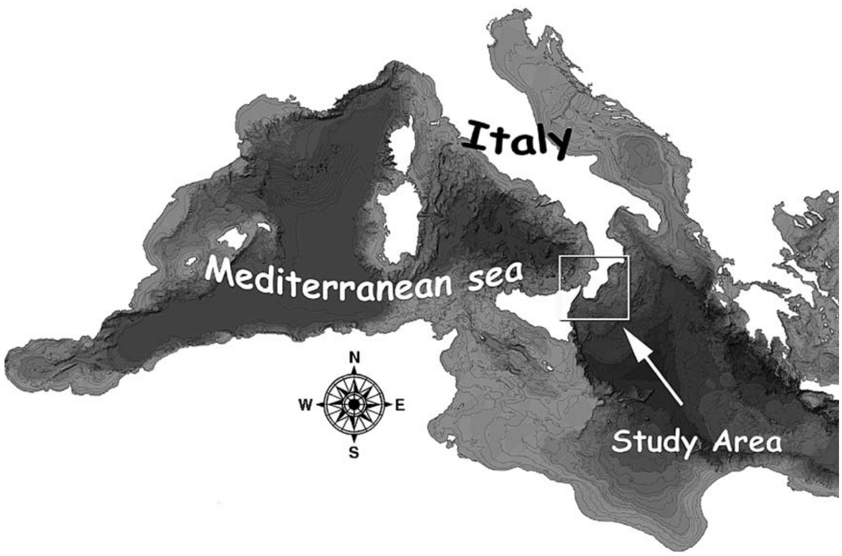

Fig. 1. Location of the study area in the Mediterranean Sea.

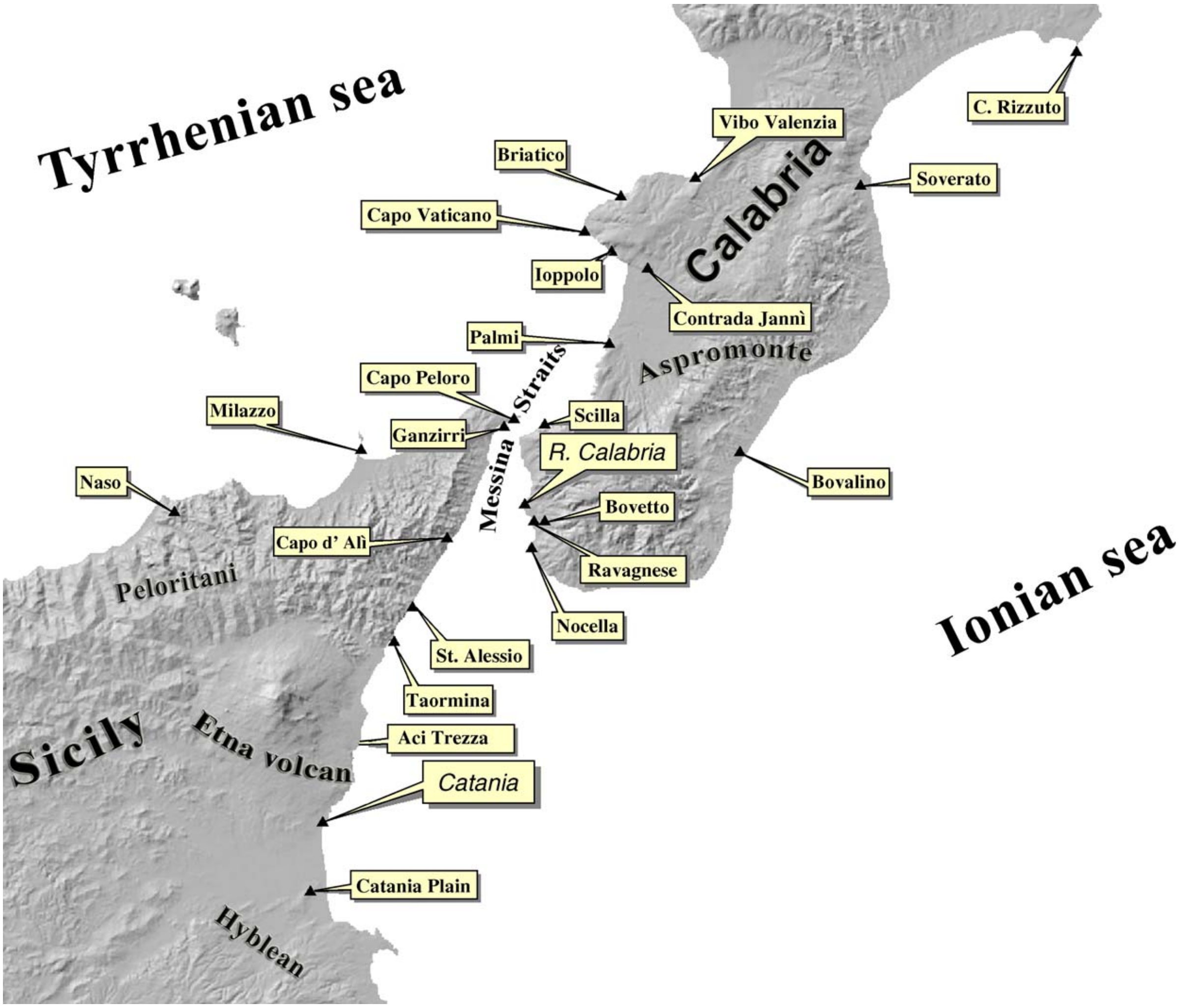

Fig. 2. Map of southern Calabria and northeastern Sicily showing the locations of the studied sites.

subsidence of the broad geoidal bulge that formed around the northern ice sheets during the last glaciation and the melt-water signature is the subsidence induced by the weight of the meltwater on the ocean and shallow sea floor, including the shelves.

For the locations considered here, these and the eustatic contributions, are additive.

This paper presents a refined picture of the uplift pattern in southern Calabria and northeastern Sicily (Figs. 1 and 2), by integrating published and new data on Holocene and older shorelines and including accurate corrections drawn from models of eustatic and glacio-hydro-isostatic processes. Generally we find a marked difference, of up to 100% in some instances, in the uplift rate between the Late Pleistocene and the Holocene.

This difference appears to be of regional extent, and suggests that the rate of uplift in the Holocene has increased. However, because the Holocene timescale is much shorter than the time since the last interglacial, it is unclear whether this difference results from the effect of scaling in the time resolution of the geological record (from 10 to 100 Ka), or indicates a true increase in regional deformation rates.

2. Regional Tectonic Setting

Calabria and northeastern Sicily are an arcuate portion of the Neogene Apennine–Maghrebide orogenic belt (the Calabrian Arc, Fig. 3A), which was emplaced to the southeast as a result of Africa–Europe collision (Ghisetti and Vezzani, 1982; Dewey et al., 1989), and north-westerly subduction and roll-back of the Adriatic–Ionian slab (Malinverno and Ryan, 1986; Royden et al., 1987; Doglioni, 1991). The present-day

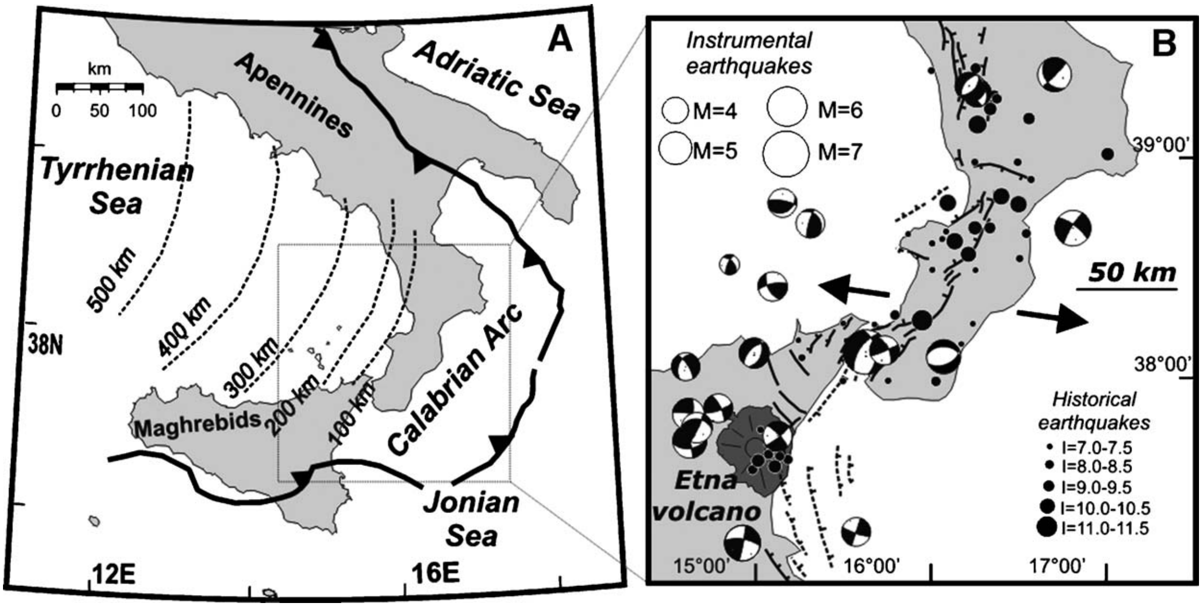

Fig. 3. Tectonic setting of Calabria and Sicily. (A) Location in the regional context of Southern Italy, with depth of the Ionian slab indicated by dashed lines (drawn after Giardini and Velona, 1988). Thick bold line is the thrust front of the Maghrebid–Apennines orogenic belt. (B) Seismicity and active tectonics of southern Calabria and northeastern Sicily. Thin lines: active normal and strike-slip faults, with barbs on hanging-wall block, dashed where inferred or buried (after Bigi et al., 1991; Tortorici et al., 1995; Catalano et al., 2003); large arrows: regional extension direction (after Monaco and Tortorici, 2000); filled circles: historical earthquakes (after Stucchi et al., 1993); beach-balls: focal mechanisms of $5<M<7$ earthquakes, after Gasparini et al., 1985; CMT Harvard and Mednet catalogues).

geometry of the northwest dipping slab has been imaged by seismic tomography and by earthquake locations that deepen to the northwest to depths of nearly 500 km (Fig. 3A) beneath the southeastern Tyrrhenian Sea (Giardini and Velona, 1988; Suhadolc and Panza, 1989; Cimini and Amato, 1993; Amato et al., 1993; Selvaggi and Chiarabba, 1995).

Since the Pliocene, contractional structures have been superimposed by extensional faults which have fragmented the orogen into structural highs and subsiding basins, such that today an array of active normal faults run southwards from Calabria to the Ionian coast of Sicily, and is spatially associated to destructive historical earthquakes (Fig. 3B; Tortorici et al., 1995; Monaco and Tortorici, 2000; Jaques et al., 2001; Galli and Bosi, 2002; Catalano and De Guidi, 2003; Catalano et al., 2003). Active extension along a ~ENE–WSW axis roughly normal to this belt is confirmed by earthquake focal solutions (Fig. 3B; Cristofolini et al., 1985; Gasparini et al., 1985) and GPS velocities (Hollenstein et al., 2003; D'Agostino and Selvaggi, 2004).

Since the Early-Middle Pleistocene, Calabria and northeastern Sicily were affected by strong uplift, which progressively decreases toward the north and the west (Ghisetti, 1981; Dumas et al., 1982, 1987; Westaway, 1993). Uplift was largely coeval with motion on the extensional faults that controlled local domains of subsidence including the Messina Straits between Calabria and Sicily (Ghisetti, 1984, 1992; Valensise and Pantosti, 1992; Monaco and Tortorici, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003).

The long-term uplift which affected the region is spectacularly documented by flights of marine terraces developed along the coasts (Fig. 4). Existing reconstructions of coastal uplift rates are essentially based on the altitude of markers of the LIg (Dumas et al., 1987; Cosentino and Gliozzi, 1988; Westaway, 1993; Miyauchi et al., 1994; Catalano and De Guidi, 2003; Catalano et al., 2003; Tortorici et al., 2003). Despite the weak radiometric control on the LIg terraces, they are well identifiable when associated with sediments hosting the gastropod *Strombus bubonius* L. This warm water gastropod species together with other species of the Senegalese fauna is found in the central and eastern Mediterranean Sea only at the time of the Last Interglacial highstand and it therefore provides a unique marker of the LIg horizon, which since Issel (1914) is known as the "Tyrrhenian Stage".

Terraces of LIg age have been uplifted across the region to elevation of tens to hundred of meters, and older uplift is documented by Lower Pleistocene marine deposits found at 1000–1200 m a.s.l. (Barrier et al.,

Fig. 4. Scilla (Calabria): the inner margin of the MIS 5.5. marine terrace, at an elevation of 125 m.

1986; Miyauchi et al., 1994). The longer-term uplift established on the Lower to Middle Pleistocene markers is ~0.6 mm/yr, but it has been suggested to have increased since the upper part of the Middle Pleistocene (Westaway, 1993; Miyauchi et al., 1994). According to Westaway (1993), post-Middle Pleistocene uplift of southern Calabria was at 1.67 mm/yr, 1 mm/yr of which due to regional processes and the residual to co-seismic displacement. Highest values have been found in areas located in the footwall of the main active faults, where a fault-related component is cyclically superimposed on the regional signal (Valensise and Pantosti, 1992; Westaway, 1993; Catalano and De Guidi, 2003; Catalano et al., 2003; Tortorici et al., 2003).

Long-term uplift has been viewed either as an isostatic response to slab break-off (Westaway, 1993; Wortel and Spakman, 2000), or as a result of convective removal of deep roots and decoupling of the Calabria forearc from the subducting plate (Doglioni, 1991; Gvirtzman and Nur, 2001), and it has been locally accommodated in the upper crust by repeated coseismic displacement along the major active faults (Monaco and Tortorici, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003).

3. Methodology

Methods used to interpret the relative sea-level changes and uplift history in the region include: geomorphological study of uplifted coastal features, radiometric dating of relevant biotic encrustations; crustal modelling for the various isostatic components. Important aspects of these methods are briefly discussed below.

Geomorphological features and altitude distribution of Quaternary marine deposits and terraces, and their relations with active normal faults in southern Calabria and north-eastern Sicily have been intensely investigated (Ascenzi and Segre, 1971; Bonfiglio, 1972, 1983, 1991; Selli et al., 1979; Ghisetti, 1981, 1984, 1992; Barrier et al., 1986; Hearty et al., 1986; IGAL, 1987; Dumas et al., 1987, 1988, 1999; Valensise and Pantosti, 1992; Westaway, 1993; Miyauchi et al., 1994; Monaco et al., 1996; Ricchetti and Ricchetti, 1996; Balescu et al., 1997; Galli and Bosi, 2002, Catalano and De Guidi, 2003; Catalano et al., 2003; Tortorici et al., 2003, De Guidi et al., 2003, Zecchin et al., 2004). In recent years, uplifted Holocene tidal notches and marine deposits have been studied in North-Eastern Sicily (Firth et al., 1996; Stewart et al., 1997; Rust and Kershaw, 2000; Antonioli et al., 2003; De Guidi et al., 2003; Monaco et al., 2004), and Southern Calabria (Pirazzoli et al., 1997; Antonioli et al., 2004), and radiometric dating has provided the first estimates of Holocene uplift rates. Recent more extensive investigation has led to the discovery of additional Holocene raised shorelines in other locales in the region.

In this study, we compare the elevation of the Holocene and the older uplift markers at all sites where both occur (Fig. 2). For the pre-Holocene shorelines, which are predominantly represented by marine terraces, we focus our attention on the elevation (including the uncertainty of elevation) of the inner margin of marine terraces. Relative error in altitude determination is minimised where the sea-level markers have been uplifted high above their formation position (Table 1); also the inner margins are sufficiently well-preserved to be identified clearly. During the LIg the shorelines in tectonically stable areas were generally a few meters higher than today, but, like the Holocene levels, some spatial variability will occur because of the isostatic response to past glacial cycles (Lambeck and Nakada, 1992); however, within the Mediterranean these are relatively small (Lambeck et al., 2004b) and their neglect does not

Table 1
Location, elevation and age data for uplifted Middle and Late Pleistocene shorelines on the Sicily and Calabria coasts

Location	Marker type	Shoreline elevation m	Eustatic correction	Eustasy corrected Elevation	Age Ka	Dating method	Average uplift rate, mm/yr	References
Sicily Naso	Inner margin	130±3	7±3	123±6	124±3	Geomorphic	0.99±0.11	1
Milazzo	Inner margin	120±10	7±3	113±13	124±3	Aminostratigraphy (aminozone E)	0.91±0.11	1, 2
C. Peloro Ganzirri	Inner margin	95±3	7±3	88±6	124±3	*S. bubonius*	0.71±0.11	3
Capo d'Alì	Inner margin	140±3	7±3	133±6	124±3	Geomorphic	1.07±0.11	4
St. Alessio	Inner margin	140±3	7±3	118±6	124±3	Geomorphic	1.07±0.11	4
Taormina	Inner margin	115±3	7±3	108±6	103.4/124.3	ESR/Uth age on marine shells	0.87±0.11	5
Aci Trezza	Inner margin	175±10	7±3	168±6	124±3	Age of lava: 180 ka	1.35±0.11	6
Catania	Inner margin	165±10	7±3	158±6	124±3	Age of lava: 180 ka	1.27±0.11	6
Pachino	Lagoonal deposits with *Cerastoderma*	5±1	7±3	−2±4	124±3	Aminostratigraphy (aminozone E)	0	5
Calabria Scilla	Inner margin	125±3	7±3	118±6	124±3	Geomorphic	0.95±0.11	3
Scilla	Inner margin	650±10	−6±6	656±16	Lower Pleistocene (MIS 19–25) 780–990	Geomorphic *G truncat. excelsa*	0.75±0.11	3
Palmi	Inner margin	100±3	7±3	93±6	124±3	Geomorphic	0.75±0.11	3
Contrada Iannì	Inner margin	100±3	7±3	93±6	MIS 5.5 124±3	Geomorphic and *S. bubonius*	0.75±0.11	3
Ioppolo	Inner margin	100±3	7±3	93±6	MIS 5.5 124±3	Geomorphic	0.75±0.11	3
Ioppolo	Inner margin	440±10	−6±6	446±16	Lower Pleistocene (MIS 19–25) 780–990	Geomorphic *G. truncat. excelsa*	0.51±0.11	3
Ioppolo Nord	Inner margin	120±3	7±3	113±6	124±3	Geomorphic	0.91±0.11	3
Vibo Valentia	Beach	48±3	7±3	41±6	124±3	*S. bubonius* U/Th on *Cladocora*	0.33±0.11	3
C. Rizzuto	Inner margin	110±3 84±3	7±3	90±6	124±3	Geomorphic and *S. bubonius*	0.62–0.83	7
Soverato	Inner margin	100±3 115±3	7±3	100±6	124±3	Geomorphic	0.75±0.11	7
Bovalino	Inner margin	85±3 90±3	7±3	81±6	124±3	Geomorphic	0.63–0.67±0.11	7
Ravagnese	Inner margin	160±3	7±3	153±6	124±3	Geomorphic and *S. bubonius*	1.23±0.11	3
Bovetto	Inner margin	150±3	7±3	143±6	124±3	Geomorphic and *S. bubonius*	1.15±0.11	3
Nocella	Inner margin	140±3	7±3	133±6	124±3	Geomorphic and *S. bubonius*	1.07±0.11	3

Observed elevations are relative to present sea level. References: (1) Catalano and Di Stefano, 1997; (2) Hearty et al., 1986; (3) Miyauchi et al., 1994; (4) This paper; (5) Antonioli et al., 2003; (6) Monaco et al., 2002; (7) Bordoni and Valensise, 1998.

Table 2
Location, elevation and age data for uplifted Holocene shorelines in the Sicily and Calabria coasts

Location	UTM coordinates	Lab N°	Fossil	Conventional ^{14}C age	Calibrated ^{14}C age 2σ	Elevation m	Depth sea bottom m	Predicted sea level m	Corrected sea level range	Uplift rate mm/yr	Average mm/yr	References
Sicily Milazzo	15.252 38.237	UTC 11356	*Patella*	5665±36	6065±100	2	−1	8.1	10.1–11.1	1.5–1.8	1.7	1
Sicily Ganzirri	15.603 38.253	UTC 12275	*Serpulids*	5557±43	5954±99	0.70	–	7.9	8.6	1.4	1.4	2
Sicily St. Alessio	15.346 37.915	β-81856	*Lithophaga*	4880±60	5149±180	4.9	−2	6.4	11.3–13.3	2.2–2.6	2.4	3
Sicily St. Alessio	"	β-81857	*Lithophaga*	4780±70	4989±210	4.5	−2	6.3	10.8–12.8	2.2–2.6	2.4	3
Sicily Taormina	15.294 37.850	UCL-362	*Cladocora*	4295±120	4399±320	3.4	−3.8	5.1	8.5–12.3	1.9–2.8	2.3	3
Sicily Taormina	"	β-81859	*Lithophaga*	3470±210	3331±510	2.0	−2	3.3	5.3–7.3	1.6–2.2	1.8	3
Sicily Taormina	"	β-81859	*Lithophaga*	5570±150	5963±390	1.5	−2	8.2	9.6–11.6	1.6–1.9	1.7	3
Sicily Taormina	"	GX 28038	*Lithophaga*	3160±50	2936±150	2.1	−1	2.6	4.7–5.6	1.6–1.9	1.8	4
Sicily Taormina	"	GX 28039	*Bolma rug.*	2500±50	2168±180	1.5	−1	1.7	3.2–4.2	1.4–1.9	1.7	4
Sicily Taormina	"	GX 28040	*Dendropoma*	2570±80	2229±150	2.8	0	1.7	4.5	2	2	4
Sicily Taormina	"	R-3540	*Dendropoma*	2203±62	1791±160	1.9	0	1.3	3.2	1.8	1.8	4
Calabria Scilla	15.703 38.253	GX 28045	*Spondylus*	2930±60	2665±164	2.5	−2.2	2.7	5.2–7.4	1.9–2.7	2.3	5
Calabria Scilla	"	GX 28332	*Spondylus*	3450±40	3318±103	2.9	−2.2	3	5.9–8.1	1.7–2.4	2.0	5
Calabria Scilla	"	GX 28331	*Hesaplex*	3930±40	3901±125	2.9	−2.2	4.2	7.1–9.3	1.8–2.4	2.1	5
Calabria Scilla	"	R-2625	*Spondylus*	2683±40	2370±105	2	−2.0	1.8	3.8–5.8	1.6–2.4	2	5
Calabria Ioppolo	15.886 38.579	GX 28045	*Dendropoma*	5120±50	5358±100	1.8	0	6.8	8.6	1.6	1.6	2
Calabria Ioppolo	"	GX 28332	*Columella*	5380±40	5667±80	1.8	0	7.3	9.1	1.6	1.6	2
Calabria C. Rizzuto	17.095 38.893	–	Algal rim	–	2990±50	0.6	0	2.9	3.5	1.17	1.2	6

Observed elevations are relative to present sea level. The sea level correction to present elevation (tectonic uplift) depends on the sea level change on the maximum depth of the sea floor.
The sea level change (predicted sea level column) includes eustatic and isostasy components and is drawn from Lambeck et al. (2004a) curves.
The seafloor depth estimation is based on direct measurement of the present day morphology. AMS ^{14}C age determinations, samples labeled GX were performed at Geochron Laboratories, USA; samples labeled UCL were performed at Utrecht Laboratories, Netherlands and samples labelled R, Department of Physics, La Sapienza University, Roma, Italy.
All data were calibrated using original conventional ages with program Calib 4 (Stuiver et al., 1998). A reservoir age of 400 years was added (Siani et al., 2000). References: (1) Gringeri et al., 2004; (2) This paper; (3) Stewart et al., 1997; (4) Antonioli et al., 2003; (5) Antonioli et al., 2004; (6) Pirazzoli et al., 1997.

significantly impact on the determination of the uplift rates.

For analysis of coastal markers, we use the maximum elevation of the inner edge of terraces and adopt an uncertainty between 0 and −1 m and between 0 and −3 m, when the LIg marker is well or poorly identifiable, respectively. Definition of older terrace inner margins is more problematic than those of the LIg markers and we use an uncertainty of between 0 and −10 m. These values results from actual survey and inspection of published data, and incorporates estimation ambiguity deriving from both terrace reshaping and cover of recent continental deposits.

The main contributor to the uncertainty of data quality is age determination. For the LIg and older terraces few absolute ages are available, but palaeontological dating and geomorphological correlation provide tight constraints. In several localities, the LIg terrace is associated with sediments containing *S. bubonius*. These include, from north to south, Vibo Valentia (where *S. bubonius* occurs at 28 m and the corresponding inner margin at 48 m with U-series on a coral found within the same sediments yielding an age of 119–122 ka (Dai Pra et al., 1993), Contrada Jannì (Bonfiglio et al., 1988), and the terraces of Ravagnese (Gignoux, 1913), Bovetto (Bonfiglio, 1972) and Nocella (Dumas et al., 1987) near Reggio Calabria (Fig. 2; Table 1).

For the geomorphological dating and altitude of the inner edge, we rely mainly on the correlation of all the terraces of southern Calabria performed by Miyauchi et al. (1994), who used constraints deriving from the presence of *S. bubonius* supported by U/Th ages on corals (Cladocora). In a few instances, these results do not correspond with those of TL age determination (Balescu et al., 1997; Tortorici et al., 2003), who produced younger ages for the same terraces hosting the *S. bubonius*. For our compilation we use only markers dated with the more reliable U/Th methodology.

Holocene shorelines are represented mainly by beach deposits and subordinately by tidal notches and abrasion platforms. Results of the most relevant studies are summarized, and additional geomorphological, stratigraphical and palaeontological observations, integrated with new radiocarbon dating, are presented for known or newly discovered sites (Table 2).

Holocene uplifted beaches are characterized by intertidal (*Vermetids*), mesolittoral (*Chthamalus*) or infralittoral fossils, and the accuracy of the shoreline altitude varies according to the evidence. Uncertainties of the sampling elevation are negligible but larger uncertainties arise from the age and inference of the altitude of palaeo sea-level. Uncertainty in radiocarbon age ranges between 1.5% and 9%, but usually are 3–4% for sites of late Holocene age (i.e. 6–2 ka cal BP, Table 2). Uncertainty of the coeval sea-level position established from sampled fossils is variable between different localities. In the best cases (e. g. Taormina or Ioppolo, Fig. 2) we use biological markers (*Dendropoma petraeum*) whose position relative to the sea level is well established and is limited within the local tide range. The measurements are therefore reduced to mean sea level using tidal corrections from the Instituto Geografico della Marina (Tidal Data Base 2002). The atmospheric pressure effect on sea level is calculated to allow for the difference in pressure between the time of observation and the mean annual pressure for the site. These corrections are based on the inverted barometer assumption using nearby station meteorological data (www.metoffice.com). On the contrary, most sites have larger uncertainty in paleodepth, which we estimate to be between 1 and 4 m based on observation of the sea-floor morphology (e.g. Antonioli et al., 2003). Our cumulative uncertainty in paleodepth determination ranges from 5% to 18%.

The isostatic corrections may be less significant for longer-term estimates, but in studies dealing with Holocene relative sea level changes (Firth et al., 1996; Stewart et al., 1997; Rust and Kershaw, 2000; Antonioli et al., 2003, 2004) they may become a significant source of error if neglected. Table 3 shows the predicted sea

Table 3
Holocene predicted sea level data calculated for the sites of Scilla, Milazzo, Taormina and Capo Rizzuto (for locations see Fig. 2)

Time (ka)	Meters a.s.l			
	Scilla	Taormina	Milazzo	Capo Rizzuto
0	0	0	0	0
0.5	−0.323	−0.317	−0.312	−0.344
1	−0.688	−0.675	−0.664	−0.731
1.5	−1.094	−1.074	−1.057	−1.16
2	−1.567	−1.54	−1.516	−1.657
2.5	−2.098	−2.063	−2.031	−2.214
3	−2.724	−2.681	−2.64	−2.867
3.5	−3.481	−3.43	−3.379	−3.652
4	−4.308	−4.247	−4.186	−4.507
4.5	−5.201	−5.131	−5.056	−5.429
5	−6.176	−6.097	−6.007	−6.433
5.5	−7.207	−7.118	−7.012	−7.492
6	−8.297	−8.2	−8.073	−8.609
6.5	−9.964	−9.86	−9.71	−10.302
7	−13.274	−13.174	−12.989	−13.637
7.5	−19.24	−19.148	−18.924	−19.632
8	−23.574	−23.48	−23.222	−24.002
8.5	−29.438	−29.342	−29.049	−29.902
9	−34.223	−34.122	−33.795	−34.726
9.5	−39.047	−38.941	−38.581	−39.591
10	−49.841	−49.74	−49.328	−50.455

levels during the Holocene rise calculated for the sites under study on the assumption of zero tectonic deformation (Taormina, Milazzo, Scilla and Ioppolo).

4. Observational data

4.1. Uplifted Pleistocene coastlines

4.1.1. Southern Calabria

Along the coasts of southernmost Calabria facing the Messina Straits (Scilla, Fig. 2), the inner margin of a large marine terrace related to the LIg highstand (Miyauchi et al., 1994) occurs at 125 m (Table 1, Fig. 4). The existence of fan-deposits covering the inner edge of the terrace introduces a small uncertainty which we estimate between 0 and −3 m. An older terrace attributed to MIS 25 on the basis of geomorphic correlation (Miyauchi et al., 1994) occurs up to a maximum altitude of 650 m. For this datum, the uncertainty is larger (±10 m) due to combined effects of erosion and burial beneath more recent deposits (0–10 m). To the north (Ioppolo, Fig. 2) the inner margin of the LIg terrace occurs at ~100 m above sea level (Miyauchi et al., 1994). At this locality, a more elevated terrace attributed to the MIS 25 by Miyauchi et al. (1994) reaches an altitude of 425 m. The terrace is covered by marine deposits containing a distinct faunal assemblage of the Sicilian (Early Pleistocene) MIS 25 (*Globorotalia truncatulinoides excelsa*; Ruggieri and Sprovieri, 1975, Ruggieri et al., 1984) aged at 780–990 Ka.

Further to the north, along the Ionian coastline, the inner margin of the LIg terrace decreases in elevation, and near the Capo Rizzuto site (Fig. 2) it occurs at an altitude of between 84 and 110 m (Bordoni and Valensise, 1998; Zecchin et al., 2004).

4.1.2. Eastern Sicily

Along the Tyrrhenian coast of northeastern Sicily, the LIg terrace is preserved between Naso and Capo Peloro/Ganzirri (Fig. 2) at an altitude between 120 and 130 m (Catalano and Di Stefano, 1997). A well carved terrace occurs almost continuously around the Milazzo promontory (Fig. 2) at an elevation of 78–85 m, but the inner margin has not been preserved. This terrace is overlain by marine deposits including *Glycimeris*, which were assigned to the LIg based on aminostratigraphy (Hearty et al., 1986). On the basis of stratigraphy and geomorphic correlation, Catalano and Di Stefano (1997) assigned an altitude of 130 m to the inner margin of the LIg terrace found near Naso on the steep cliff immediately south of the Milazzo promontory. Since the terrace margin is covered by few meters of continental deposits (Catalano and Di Stefano, 1997), we use a 120 m altitude. Rust and Kershaw (2000) interpreted the Milazzo peninsula as having been uplifted at approximately half the long-term uplift rate of the Taormina area of east Sicily but the present results indicate that the uplift rates are similar, so that the uplift of northeast Sicily is probably more uniform than envisaged by Rust and Kershaw (2000). Temporal uplift variation is addressed later in this paper.

At Capo Peloro, the northeasternmost tip of Sicily, the fossil marker *Strombus bubonius* was found at 86 m elevation within a marine depositional sequence (Bonfiglio and Violanti, 1983), the onlap of which pinches out at 95 m. This sequence rests on a regionally extensive terrace, whose inner margin lies at an elevation of between 100 and 140 m along the eastern Sicily coast between Capo Peloro and Taormina, and reaches the maximum altitude of 140 m at Capo d'Alì (Fig. 2). Near the S. Alessio Holocene site (Fig. 2), we measured an elevation 140 m for the inner margin of the LIg terrace.

To the south, near Taormina town (Fig. 2), fossils were sampled from a beach conglomerate lying on a terrace whose inner margin is at 115 m, directly overlying the site of raised Holocene coastlines. The fossils yielded ESR and U/Th ages which point to an MIS 5 age, (Antonioli et al., 2003). Catalano and De Guidi (2003) and Catalano et al. (2003), attributed an altitude of between 210, 150 and 180 m to the LIg terrace in the area between St. Alessio, Capo d'Alì and Taormina, based on the correlation of the terraces found in the area with the sea level curve of Chappell and Shackleton (1986). Since their determination does not rely on radiometric dating, we adopt the previously established altitude of 115 m for the LIg terraces where ages are available.

On the south-eastern lower slopes of the Etna volcano (Aci Trezza, Catania, Fig. 2, 3), marine terraces whose inner edge occur at elevation of 165–175 m are carved in basalt flows of ~180 ka age, and are attributed to the LIg by Monaco et al. (2002). The elevation of the LIg terrace gradually decreases to the south of the Etna volcano, and at Pachino, the southernmost tip of Sicily, a deposit with *S. bubonius* is found at 8 m, close to the expected eustatic LIg level (Malatesta, 1985).

4.2. Uplifted Holocene shorelines

4.2.1. Southern Calabria sites

At the site of Scilla (Fig. 2), Holocene raised shorelines occur in two distinct outcrops along the rocky cliff of Punta Paci (Antonioli et al., 2004). Fossil shells from a beach deposit at an elevation of between 2 and 2.9 m a.s.l yielded calibrated ^{14}C ages of between

2.7 and 3.9 ka BP (Fig. 5, Table 2). In order to assign an error range to the fossil shells used for uplift rate estimation, scuba-diving transects were carried out down to a depth of −10 m. The sea floor slopes gently seaward from the coast and is covered by sand, gravels, and boulders shed from the cliff behind. Based on the subsurface morphology observation, a lower limit of 2 m for the positional uncertainties of the non subtidal sampled fossils has been established.

Subsequent to discovery of the Scilla outcrop (Antonioli et al., 2004), a search was made for marine Holocene deposits along the northern Calabrian coast in places where MIS 5.5 highstand terraces are presently uplifted. At Ioppolo (about 100 km north of Scilla, Figs. 2, 6, and 7) a raised Holocene shoreline was discovered, which includes an uplifted beach at an elevation between 1.8 m and 1 m above the present sea level. Samples of *Columella* sp. and *Vermetids* were extracted at 1.8 m, from a well cemented sand 3–5 cm thick. The fossil beach lay directly on the granitic bedrock and was covered (and preserved from erosion) by enormous granite blocks (2–5 m). The fossils yielded ^{14}C-based ages of between 5.3 and 5.7 ka cal BP (Table 2).

Further north, the northernmost known occurrence of uplifted Holocene deposits occurs at Chiacolilli, located on the Ionian coast of Calabria near Capo Rizzuto (Fig. 2). This site was investigated by Pirazzoli et al. (1997), who sampled calcareous algae in growth position, which encrusted beach rock, at an altitude of 0.6 m. Radiocarbon analysis provided an age (uncorrected for δ^{13}C) of 2.7 ka cal BP.

4.2.2. Eastern Sicily sites

On the eastern side of the Milazzo promontory (Fig. 2), patches of beach deposits made of serpulid concretions and fossiliferous sands including *Patella* sp. and *Cerithium* sp. lap onto the crystalline bedrock at 2.2 m elevation. The calibrated radiocarbon age of a *Patella* shell sampled at 2 m a.s.l. is about 6 ka (Gringeri et al., 2004, Table 2).

At Ganzirri, on the eastern side of Capo Peloro, facing the Messina Straits (Figs. 2, 8 and 9), we discovered an uplifted conglomerate made of cm-size heterogeneous

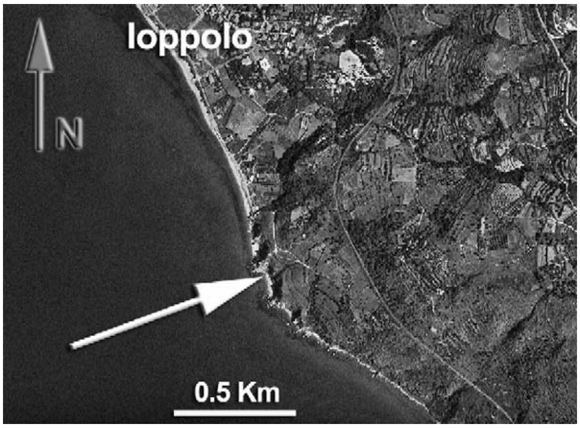

Fig. 6. The studied site on the coast of Ioppolo (Calabria), arrow indicate the outcropping coastal area. GPS coordinates (WGS 84): E 15.90058, N 38.56659.

Fig. 5. Scilla (Calabria): a Holocene fossil shell (Barnacle) presently uplifted at 2.1 m a.s.l.

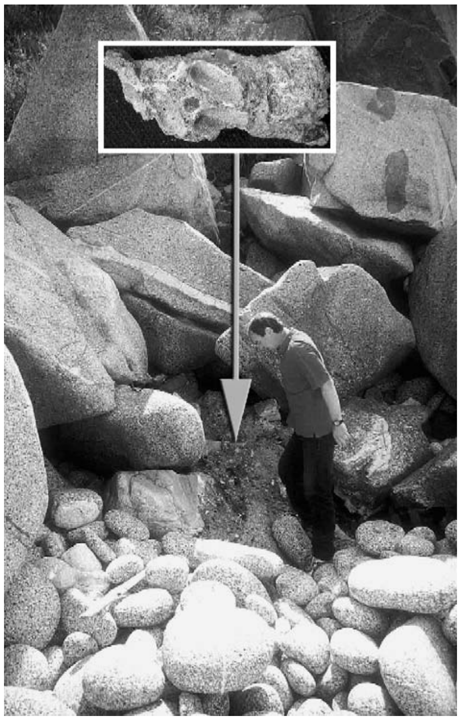

Fig. 7. Ioppolo (Calabria): fossiliferous Holocene sands (inset shows the dated *Dendropoma*).

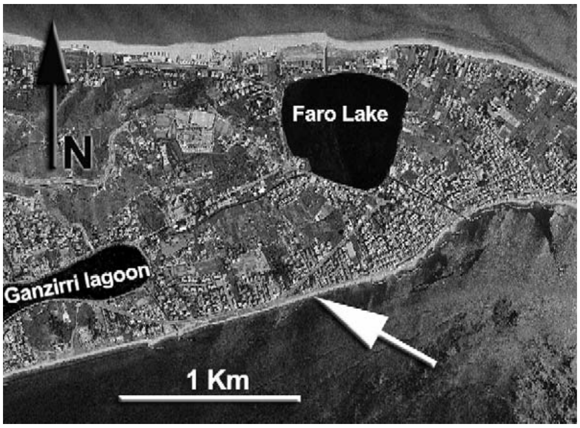

Fig. 8. Ganzirri (Sicily), arrow indicates the outcropping coastal area. GPS coordinates (WGS 84): E1563520, N3826153.

clasts. The conglomerate, clearly visible on the beach in the area of Ganzirri town, outcrops from −2 m to +0.70 m relative to present sea level, and displays a width of about 30 m along 1 km on the coastline north of Ganzirri**.** The deposit contains Gastrana. Serpulids encrusting the conglomerate were sampled close to the maximum elevation of the deposit and yielded a calibrated AMS radiocarbon age of about 5.9 Ka (Table 2). Archaeological remains younger than 5 ka (Antonioli et al., 2004) associated with the sand that covers the conglomerate, indicates that the 5.9 ka date is correct.

On the Ionian coast of Sicily, outcrops of raised Holocene fossiliferous deposits were found near Taormina and St. Alessio (Figs. 2 and 3). At Taormina, samples of *Lithophaga*, *Cladocora* and *Vermetids* collected on coastal outcrops between 1.5 and 3.4 m a.s.l. yielded calibrated radiocarbon ages of between 1.8 and 6.0 ka BP (Stewart et al., 1997; Antonioli et al., 2003). At St. Alessio, samples of *Lithophaga* at elevations of 4.5–4.9 m a.s.l. were dated at about 5 ka cal BP (Stewart et al., 1997). The finding of the Vermetid *Dendropoma* sp. at the Taormina site is particularly significant for rate determination, since this genus lives within an intertidal belt of ±0.10 m (Antonioli et al., 1999). In addition, scuba-dive transects carried in both locations provide lower limits for the non-infralittoral fossils of about 2 m (St. Alessio) and 3.8 m (Taormina), corresponding to the depth of the seafloor below the sample position (Table 2).

South of Taormina, Holocene uplift is documented at Aci Trezza (Fig. 2), where shells of *Lithophaga* within an early Holocene reef sampled at 1.55 to 6 m elevation yielded calibrated AMS ages of between 1.8 and 6.0 ka BP (Firth et al., 1996). These data however have large uncertainty since the *Lithophaga* holes are not related to a notch and the paleodepth cannot be accurately estimated. Unfortunately no fossils that provide accurate sea-level indicators have been found within the Aci Trezza reef.

Fig. 9. Ganzirri (Sicily): the Holocene conglomerate hosting marine gastropods of the Buccinidae family (inset).

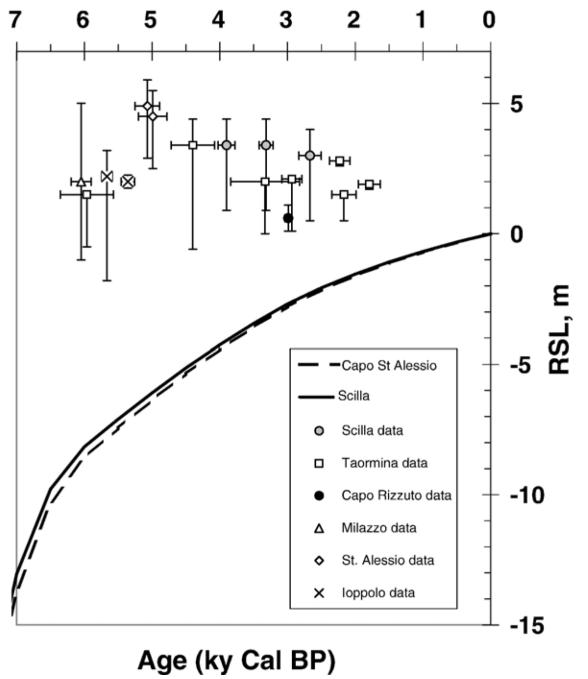

Fig. 10. Predicted Holocene sea level curves for the Scilla and Ganzirri sites compared with the observed data.

Further south, in the Catania Plain (Fig. 2), Holocene infralittoral and lagoonal mollusks have been recovered in a borehole (Monaco et al., 2004). Taking into account the uncertainty in paleodepth determination of between 1 and 10 m, and assuming no significant displacement of the sampled fossils, the sea-level corrected elevation of the sampled fossils suggests a mild uplift of the plain (Monaco et al., 2004).

South of Catania plain, Holocene raised shorelines are not observed and the modern tidal notch is well developed from Augusta southwards (Fig. 2). Therefore, the Hyblean coast, which has suffered uplift since the Middle Pleistocene (Bianca et al., 1999), can be considered still suffering a slow uplift.

5. Discussion

Age and elevation of uplifted Late Holocene (6–2 ka cal BP) shorelines in Southern Calabria and northeastern Sicily are plotted in Fig. 10, together with the curve of sea-level rise predicted by the glacio-hydro-isostatic model of Lambeck et al. (2004a) for the sites of Scilla (Calabria) and St. Alessio (Sicily). The accuracy of these predicted values are functions of the model parameter uncertainties that define the earth response function and the ice load history, and the estimates adopted in Lambeck et al. (2004a) are used here. All the Holocene shorelines are displaced upward, and the amount of vertical displacement is given by the distance between the point-data and the calculated sea-level curve (Fig. 10). The resulting spatial distribution of site uplift rates is shown in Fig. 11. For the sake of simplicity, we have calculated the average of the

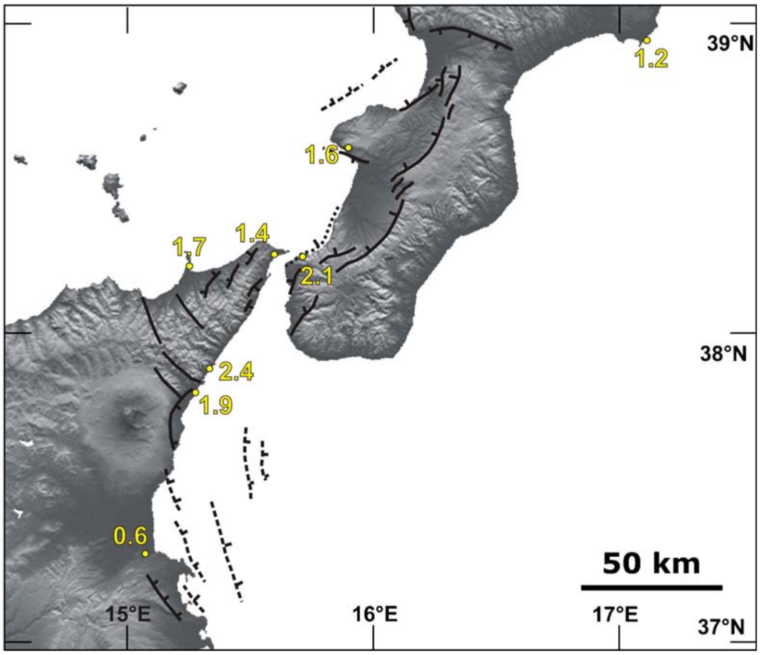

Fig. 11. Map of NE Sicily and Calabria, showing the average site Holocene uplift rates (in mm/yr).

individual estimates for each site (Table 2). We estimate that the cumulative uncertainty on Holocene uplift rate determination (Table 2), derived from the combined age and eustasy-loading corrected elevation error, ranges from 0.05 to 0.3 mm/yr. For the Catania Plain we used the average rate estimate of 0.56 mm/yr from Monaco et al. (2004).

Overall, the late Holocene uplift rate pattern is centred on the Messina Straits (Fig. 11). In Southern Calabria, rates grow steadily toward 2.0–2.3 mm/yr at Scilla (Table 2). On the Sicily side, rates increase from north (Milazzo: 1.7 mm/yr; Ganzirri: 1.4 mm/yr) and south (Taormina: 1.9 mm/yr) toward a central location near S. Alessio (2.4 mm/yr). The uplift rates decrease at the edges of the region with a different asymmetry. The rates decrease smoothly in northern Calabria (Capo Rizzuto: 1.2 mm/yr) and more sharply in southeastern Sicily (Catania Plain: 0.56 mm/yr).

These rates record the total vertical displacement at each site that may be the result of more than one process. In general, uplift of Calabria and northeastern Sicily results from a combination of sources located in the deep crust, as a response to removal of mantle lithosphere and asthenosphere upwelling (e. g. Gvirtzman and Nur, 2001; D'Agostino and Selvaggi, 2004), or breaking off of the slab (Westaway, 1993; Wortel and Spakman, 2000), and of sources located in the brittle upper crust and expressed as an array of seismogenic normal faults (Fig. 3; Monaco and Tortorici, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003). For sites located on the coastal extension of the active Etna volcano, where uplift rates up to 3 mm/yr were estimated by Firth et al. (1996), a contribution derived from magma inflation probably accounts for these high values. For most of the other sites, however, we are not able to unravel the contribution of deep sources, which are responsible for the so-called regional uplift, versus that related to displacement on faults.

Work in progress by Ferranti and others on the Scilla outcrops shows that uplift of two different Holocene shorelines result from the interplay between steady regional uplift and recurrent co-seismic displacements. Using geomorphological analysis and radiometric dating on shells, these authors have identified two abrupt co-seismic displacements at ~1.8 and 3.5 Ka which are attributed to footwall uplift along the offshore Scilla fault. On the other hand, when corrected for eustatic and glacio-hydrostatic sea-level changes for Scilla the results indicate that steady uplift occurred during the interseismic intervals at ~1.0 mm/yr, a value consistent with existing long-term estimates (Westaway, 1993; Tortorici et al., 1995; Catalano and Di Stefano, 1997). Thus, Late Holocene total uplift of the Scilla coastline at ~2.1 mm/yr is nearly equally balanced between steady and stick-slip components. A comparable partitioning of uplift may be inferred for the Taormina and S. Alessio sites (Stewart et al., 1997; De Guidi et al., 2003).

Apart from the Scilla and Taormina–St. Alessio locations, where total uplift is at a maximum, total uplift rates in nearby sites around the Messina Straits show consistent values of between 1.4 and 1.7 mm/yr. Assuming a constant Holocene steady uplift at 1.0 mm/yr derived from the Scilla study (Ferranti et al., submitted for publication) and long-term analysis (Westaway, 1993), these sites may record an elastic component of uplift of between 0.4 and 0.7 mm/yr, similar to the long-term estimate of Westaway (1993).

Additional perspectives on the regional significance of Holocene uplift rates may be gathered by examination of the spatial distribution of long term rates, mainly represented by the LIg marker (Table 1, Fig. 12). For the Scilla and Ioppolo sites, in Southern Calabria, observations of the Lower Pleistocene (MIS 19, 21 and 25) markers may be made. At all sites where the comparison is possible, the uplift rates averaged over the past 125 ka since the LIg highstand formation are consistently less than the Late Holocene rates. However, the average uplift rates since ~125 ka display a spatial pattern similar to the Late Holocene rates (compare Figs. 11 and 12). In particular, the rates averaged over the last glacial cycle increase progressively to the south in Calabria from Capo Rizzuto (0.62 mm/yr) to Ioppolo (0.75 mm/yr) and Scilla (0.95 mm/yr) and in Eastern Sicily, the LIg rates also increase from the Tyrrhenian coast at Milazzo (0.63 mm/yr) toward the Ionian coast, where they reach 0.95 mm/yr at St. Alessio and 0.92 mm/yr at Taormina. The maximum uplift rates along the Eastern Sicily coast occurs over the Etna volcano (Figs. 11 and 12), and contribution of the volcano-tectonic deformation (Monaco et al., 2002) is clearly superimposed on the regional signal.

Where uplift rates since the MIS 25 highstand are available (Scilla and Ioppolo sites) the uplift rates appear also lower than the LIg rates (Table 1), and the southward increase from Ioppolo (0.51 mm/yr) to Scilla (0.75 mm/yr) is indicative of a pattern similar to that provided by the younger markers. Clearly, more point data are needed before a compelling comparison to the ~1 Ma scale is possible.

Given the limited understanding of uplift rates pattern prior to 125 Ka, we restrict our discussion to

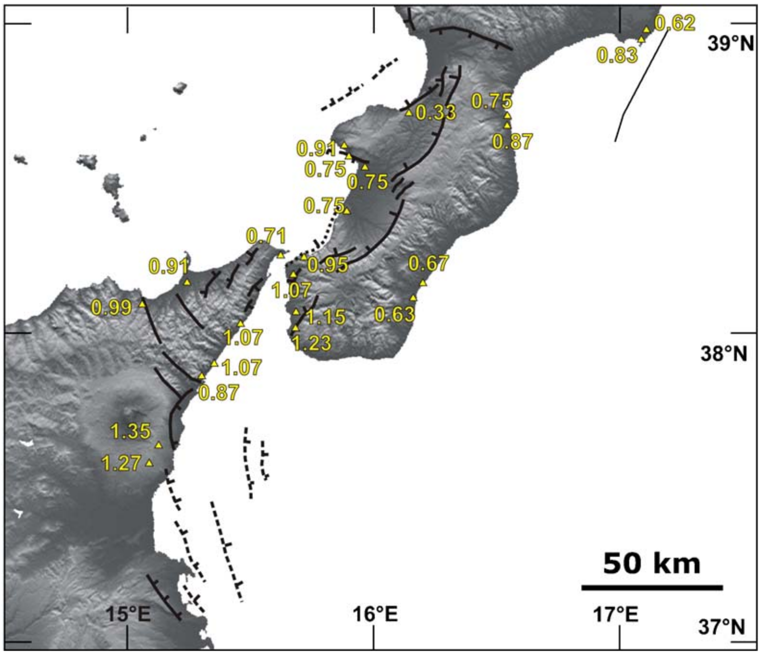

Fig. 12. Map of NE Sicily and Calabria showing the average site MIS 5.5 uplift rates (yellow numbers), in mm\yr. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the uplift rate changes between the LIg and the Holocene (Tables. 1 and 2). The difference in the rates of uplift for the two epochs, normalised by the uplift rate at MIS 5.5 is defined as:

$$\text{Uplift rate changes} = U_{\mathrm{H}} - U_{5.5}/U_{5.5} \times 100$$

where U_{H} is the Holocene uplift rate and $U_{5.5}$ is the uplift rate at the same site for MIS 5.5.

The area of maximum increase in uplift rates (>100%) occurs across the Messina Straits and extends toward the Tyrrhenian coast of Southern Calabria. Such increase has a stronger spatial gradient to the southwest than to the northeast (Table 4).

The pattern of rate change outlined in Figs. 11 and 12 is intriguing and stimulates different interpretations. On one hand, it might be argued that the whole region has undergone an increase in deformation rates since the Late Pleistocene, with a locus of maximum upwarping that has remained fixed throughout the interval. Be that the case, and given the dome shape of the region of uplift rate change, it is conceivable that the source of the increasing deformation lie in the deep crust or in the mantle. Within the upper crust, this

Table 4
Comparison between late Holocene (6.0–1.8 ka cal BP) and MIS 5.5 (124±3 ka BP) uplift rates. MIS 5.5 uplift was calculated subtracting 7±3 m to the observed altitude

Late Holocene uplift mm/yr	Holocene reference	MIS 5.5 altitude	MIS 5.5 uplift mm/yr	MIS 5.5 reference	MIS 5.5/late Holocene	Acceleration (%) between MIS 5.5 and Holocene
Milazzo 1.7	1	120	0.91±0.06	7–8	0.53	86.5
Ganzirri 1.4	2	95	0.71±0.06	9	0.51	97.3
St. Alessio 2.4	3	140	1.07±0.06	2	0.45	124.3
Taormina 1.9	4	115	0.87±0.06	10	0.46	118.4
Scilla 2.1	5	125	0.95±0.06	9	0.45	121.0
Ioppolo 1.6	2	100	0.75±0.06	2	0.47	113.3
Capo Rizzuto 1.2	6	84–110	0.73±0.11	11	0.61	64.4

For Scilla and Ioppolo sites longer term (MIS 25, about 900 ka BP) data are also provided.
References: (1) Gringeri et al., 2004; (2) This paper; (3) Stewart et al., 1997; (4) Antonioli et al., 2003; (5) Antonioli et al., 2004; (6) Pirazzoli et al., 1997; (7) Hearty et al., 1986; (8) Catalano and Di Stefano, 1997; (9) Miyauchi et al., 1994; (10) Antonioli et al., 2002; (11) Bordoni and Valensise, 1998.

might be accommodated either by increasing regional uplift, perhaps related to magmatic underplating, or by a more vigorous activity of brittle faults. The flat shape of the Moho underneath this region (Nicolich et al., 2000), however, suggests that magmatic underplating is unlikely. In this scenario, the Holocene increase in uplift rates likely reflects a large contribution from the upper crustal faults.

An alternative interpretation envisions the apparent increase in uplift rate between the 100 and the 10 Ka time span as a result of the different temporal scales of observation. Since the higher increase in uplift rates occurs across the Messina Straits and extends toward the Tyrrhenian coast of Southern Calabria, parallel to the elongation of the seismogenic belt (Fig. 3), it can be argued that large (M > 7) historical earthquakes produced co-seismic displacements (Monaco and Tortorici, 2000; Jaques et al., 2001; Galli and Bosi, 2002) that have not been averaged along the entire seismic cycle. When viewed at the 100 Ka timescale, the effects of several seismic cycle would be summed and the resulting average uplift rates would be likely different from the short-term rate.

The data presented here do not permit distinction between these different scenarios. We note however, that the shape of the domain of increasing uplift would suggest a rather fortuitous coincidence of incomplete elastic strain release for all the main faults of the region (Fig. 3). Clearly, at local scale, complex fault displacement relations occurs, but at the regional scale a coherent domain of larger displacement is accommodated by the brittle faults in the central region of higher uplift (e.g. Tortorici et al., 1995; Monaco and Tortorici, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003). Since the steady component of total uplift appears constant since 124 ka, and perhaps 700 Ka (Westaway, 1993; Ferranti et al., submitted for publication), footwall uplift on normal faults may accommodate a significant proportion of vertical strain during periods of increased vertical displacement, which, based on the Scilla case (Ferranti et al., submitted for publication), may have duration of 10–20 Ka and thus encompass the Holocene dataset. Similar time relations are found in other locations in the region (Catalano and De Guidi, 2003; Catalano et al., 2003; Tortorici et al., 2003). Thus, although the possibility that incomplete seismic cycles are documented by high Holocene uplift rates recorded at some of the studied sites certainly exists, a short-term change in the regional geodynamics processes, accommodated by footwall uplift along the major active faults of the area may not be excluded.

6. Conclusions

The present study combines new dates and older information to provide a framework for interpretation of vertical tectonic motion of southern Calabria and northeastern Sicily.

Holocene uplift rates in these areas may be greater than the longer term ($\sim 10^5$ years) rates, the latter rate calibrated from the position of the last (LIg) and earlier interglacial shorelines. Holocene uplift rates increase from 64% up to 124% relative to rates calculated on the 124 ka marker.

However, for the Holocene rates, since the available data do not provide a high enough temporal resolution, it has not been possible to separate the effects of brittle deformation due to faults, from that due to regional uplift caused by deep processes. The spatial coincidence between the belt of highest uplift rates and the main seismogenic faults in the region supports models of vertical deformation as being mainly accommodated by footwall uplift on normal faults, but more work in specific sites is needed to quantify the relative contribution of the two processes.

The sites of highest Holocene uplift rate are spatially coincident with the sites of highest 124 Ka and possibly older uplift rates, indicating that the region of increase in uplift rates is constant over a 100 Ka interval. Ambiguity remains on the significance of this constancy of pattern in uplift rates, whether it is related to true changes in the intensity of regional deformation, or is an apparent result of seismic cycle incompleteness at the short term scale.

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