Raised marine terraces in the Northern Calabrian Arc (Southern Italy): a ~ 600 kyr-long geological record of regional uplift

Luigi Cucci
Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

Abstract
The Sibari Plain in the Northeastern Calabrian Arc displays a well-developed suite of marine terraces. This paper deals with i) the identification and correlation of the terraces; ii) their age assignment and a tentative reconstruction of the uplift history of the area; iii) the relationships between terraces and major faults in the study area and between uplift in the Plain and pattern of Quaternary uplift throughout the Calabrian Arc. Identifying wavecut platforms and inner-edge fragments over a linear extent of ~ 100 km was achieved by photo interpretation, 1:25 000 scale map analyses and field survey. Morphological evidence led to the correlation of the identified fragments into five complete strandlines (numbered #1 to #5 lowest to highest), at elevations ranging from 60 m to ~ 650 m. Analysis of two parameters of the emerged platform-cliff systems, namely the platform-cliff ratio and the dissection percentage, further testifies that the two lowest terraces are strongly correlative. A 130 kyr AAR age of *in situ* fossil samples of *Glycymeris* collected at 114 m elevation within the deposit of Terrace #2 indicates a key correlation of T#2 with MIS 5.5 (the peak of the last interglacial, 124 kyr), *i.e.* an uplift rate of ~ 0.98 mm/yr for this strandline. The other four terraces have been tentatively associated with MIS 5.3, 7, 9 and 15. Geological observations independent of geochronological evidence provide consistent lower age boundaries for the terraces and supply further constraints to this interpretation. Investigating the relations between setting of the terraces and location of major tectonic structures in the region is suggestive of no recent activity of two previously recognized faults, the «Sangineto Line» and the «Corigliano-Rossano Line». Instead, some limited anomalies that affect the terraces are tentatively associated with the activity of the Castrovillari Fault. Therefore, sustained uplift has been the long-term dominant process of tectonic deformation in the study area over the past 124 kyr, possibly 600 kyr. Rates and history of uplift in the Sibari Plain are largely comparable with those observed in the whole Calabrian Arc, confirming that the uplift driving mechanism is deep-seated and closely connected to the Tyrrhenian subduction as already pointed out by several authors. Despite a dearth of Holocene raised paleoshorelines, it is suggested that similarly to what was observed only few tens of kilometres north and south of the Sibari Plain, the Late Pleistocene rise is still active today and that without Holocene uplift the Plain should have been far less developed and attractive for human settlement.

Key words *Calabrian Arc – marine terrace – uplift – Pleistocene – active fault*

Mailing address: Dr. Luigi Cucci, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy; e-mail: cucci@ingv.it

1. Introduction

The Sibari Plain is located in the Northern Calabrian Arc (Southern Italy) at the boundary with the southern Apennines (fig. 1). This area is critical for the investigation of the processes directly related to the subduction beneath southern Italy of old Ionian oceanic lithosphere

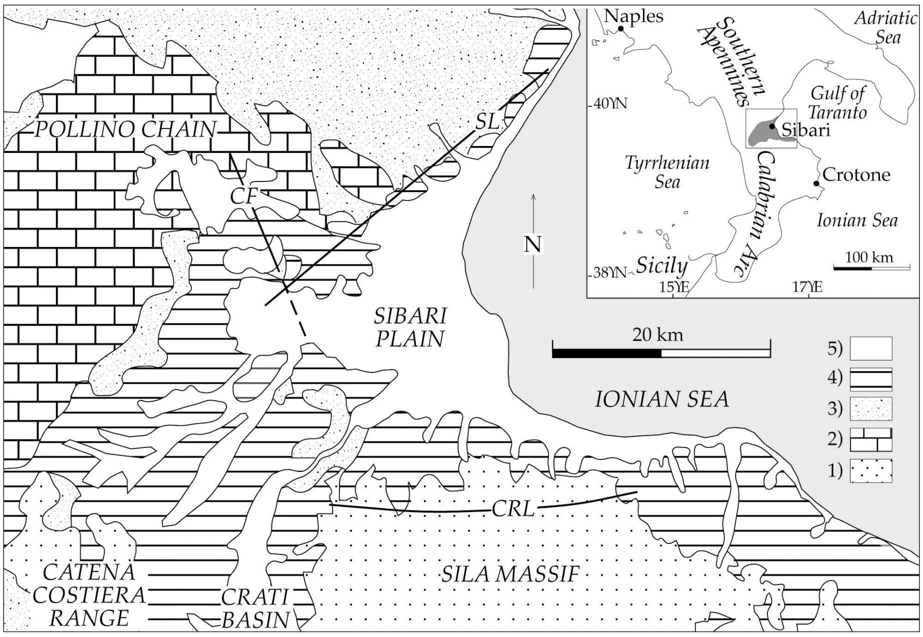


Fig. 1. Geological sketch of the study area. The grey zone in the inset shows the area occupied by the marine terraces. Legend: 1 – Calabride Complex (Paleozoic); 2 – Campania-Lucania carbonate platform (Mesozoic); 3 – liguride complex (Lower Cretaceous-Jurassic) and turbidites cover (Paleogene); 4 – marine terrigenous and fan deltas deposits (Middle Pleistocene-Upper Pliocene); 5 – continental and marine deposits (Holocene-Upper Pleistocene). Fault abbreviations: CF – Castrovillari Fault; SL – Sangineto Line; CRL – Corigliano-Rossano Line.

within the Tyrrhenian Benioff zone. Among these processes, the probable detachment of the subducting slab (Spakman *et al.*, 1993; Westaway, 1993; Hyppolite *et al.*, 1994; Gvirtzmann and Nur, 1999) or the slab retreat process (Malinverno and Ryan, 1986; Giunchi *et al.*, 1996; Meletti *et al.*, 2000) are responsible for active extension perpendicular to the chain and for rapid uplift in southern Italy (Gignoux, 1913; Bousquet, 1973; Brogan *et al.*, 1975; Aïfa *et al.*, 1988; Westaway, 1993).

The onset of uplift in Calabria and surrounding regions is a relatively recent feature, as raised marine Early Pleistocene deposits unconformably overlie Neogene compressional terrains. Emergent marine terraces are often associated with these deposits such that the resulting steplike landscape is a prominent characteristic of the coasts of peninsular southern Italy. In particular, in the study area the combination of Late Quaternary sea-level fluctuations and uplift caused the progressive filling of a wide embayment of the Ionian Sea and resulted in a spectacular flight of marine terraces.

Despite this, few studies have been undertaken on the marine terraces of the Sibari Plain and adjacent regions; on the Ionian side, the nearest values of uplift rate south of Sibari are located in the Crotone peninsula (fig. 1), where Gliozzi (1988) found 0.83 mm/yr of uplift rate since 123 kyr. Westaway (1993) suggested ~ 1 mm/yr uplift rate in the Plain since 360 kyr merely on the base of geomorphological correlations with nearby regions. Most recently, Cucci and Cinti (1998) calculated an average uplift of 0.67 mm/yr at the Calabria-Lucania border (~ 50 km north of the Plain) during a maximum age interval of ~ 0.7 Ma and provided evidence for a southward general increase of the rates of uplift.

2. Geology

The wide Sibari Plain (fig. 1) is surrounded by a mountainous amphitheatre formed by the Pollino Chain to the North, the Catena Costiera Range to the West, the Sila Massif and the northern Crati basin to the South; the Ionian Sea borders the Plain to the East. The overall setting of the study area is characterized by thrust units and nappes, deriving from oceanic and/or thinned continental margins, piled up and overthrust toward the Apulia foreland during Neogene. Terrains outcropping in this area belong to the Southern Apennines (Pollino Chain) and to the Calabrian Arc (Sila Massif and Catena Costiera Range) structural domains.

The Southern Apennines are a fold-and-thrust belt consisting of a tectonic stack of rock units deriving from different sedimentary basins and shelves, like the thick succession of the Campania-Lucania carbonate platform that extensively outcrops in the Pollino Chain. This unit is tectonically overlain by a series of ophiolite-bearing low-grade metamorphic basalts, gabbros and serpentinites that form the allochtonous nappes of the Liguride Complex and are unconformably covered by late orogenic calcareous and/or siliciclastic turbidites.

The innermost crystalline units deriving from the Tethyan oceanic realm are piled up in the Calabrian Arc; in this area they are represented by the Calabride Complex made up of igneous and metamorphic rocks.

The youngest terrains in the whole region postdate the Tortonian compressive tectonic phase as during upper Pliocene-middle Pleistocene the Sibari basin has been progressively filled by fan deltas (Colella, 1988) and marine terrigenous sediments; these deposits are the bedrock into which the terraces are cut throughout the study area. Continental deposits of a modern braided fluvial system occupy the central part of the plain and attain a maximum thickness of ~ 1500 m.

3. The marine terraces

3.1. *Description*

In an uplifting region, an abrasional terrace or wave-cut platform will form during an interglacial highstand when the rate of global sea level rise slows down and matches that of the land uplift. Each platform is usually overlain by progradational and aggradational terrace deposits and is backed by a relict sea cliff. The intersection of the platform and the cliff is called inner edge (or shoreline angle): it closely approximates the paleoshoreline and is the datum mapped to determine subsequent tectonic or isostatic deformation.

A first step in the present reconstruction of the marine terraces has been provided by photogrammetric interpretation, analysis of 1:25 000 scale topographic maps (5 m best contour interval) and field observations (altimeter error < 10 m; survey closed every day to the starting position). The estimated errors in the elevations are ± 5 m. Then, the identified fragments of inner edge and wavecut platform have been associated with individual strandlines; the main criteria of morphological correlation were the lateral continuity for the best preserved terraces and the altitudinal spacing between adjacent interfluves. All this led to the identification of five marine terraces at elevations ranging from 60 m to ~ 650 m above present sea level; the terraces were numbered #1 to #5, lowest to highest (fig. 2). The wavecut platforms are generally well preserved, particularly in the northern half of the study area; the associated inner edges are often clearly recognizable for several kilometers, although locally a seaward-tapering veneer of colluvium from sea cliff decay mantles the terraces. Local height variations observed between neighbouring terrace inner margins are not large enough to originate uncertainties in the identification of each strandline and/or of the sequence of strandlines between adjacent interfluves, as their number, spacing, thickness and stratigraphy are distinctive. Because of prolonged subaerial slope degradation the higher (elevations > 300 m) and older terraces are geomorphologically less evident, and the inner edge of T#5 is no longer exposed. South of the Crati River the number and extent of the terraces decrease (fig. 2); in particular, no remnants of platforms #3 and #4 are found, and the outcrops of the lower terraces are reduced to narrow strips. This is due to local smaller thicknesses of the Pliocene-Pleistocene deposits into which the terraces are carved and to stronger ero-

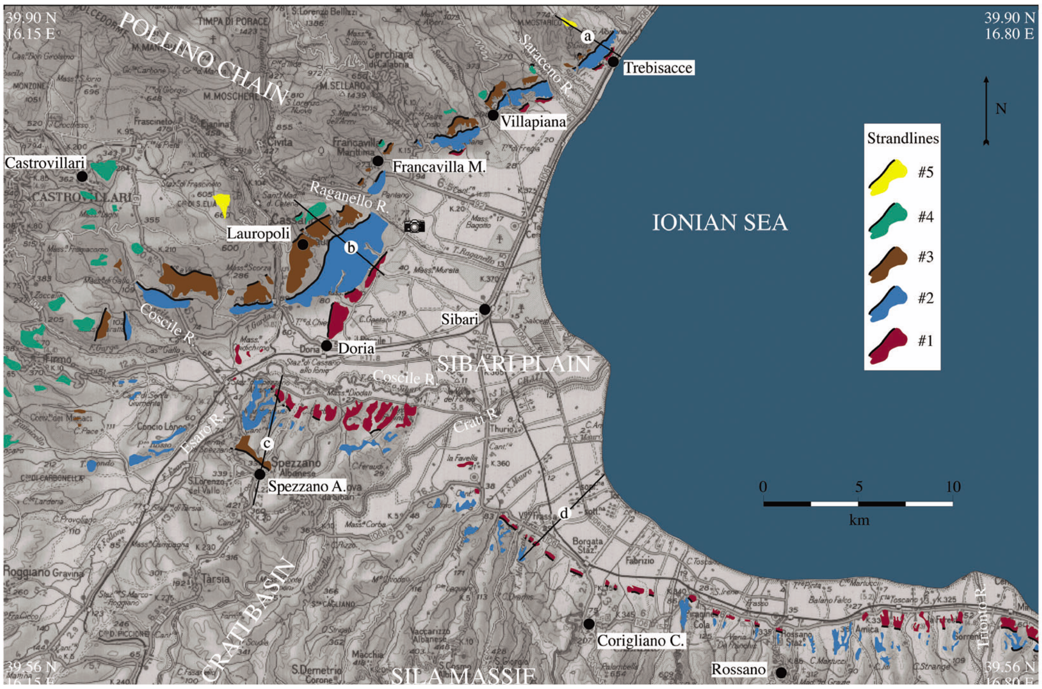


Fig. 2. Map of the five marine terraces (#1 to #5, lowest to highest) that contour the Sibari Plain; different colours are associated with the wavecut platforms and black thick lines mark the inner edges. Black segments marked by letters ‘a’ to ‘d’ indicate the traces of the four longitudinal profiles in fig. 5a-d. A camera marks the site location of the photo in fig. 4. The contour interval of the map is 100 m.

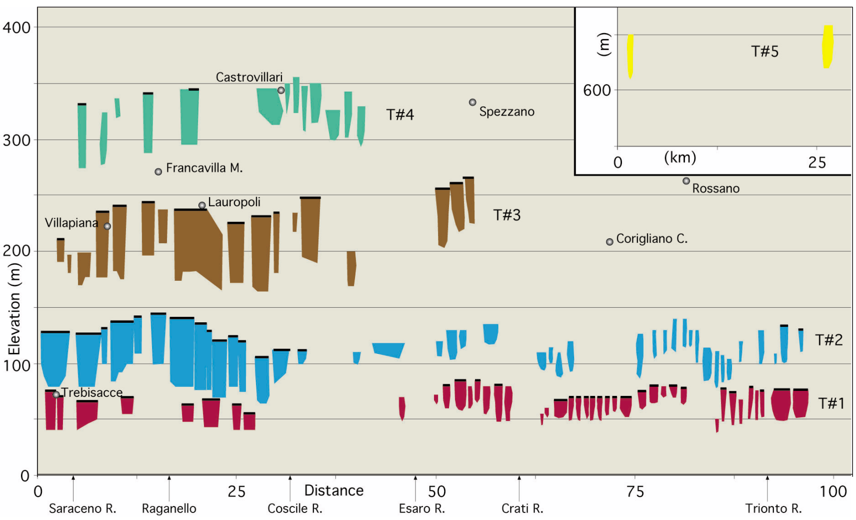


Fig. 3. Elevation profile of inner edges (black thick lines) and wavecut platforms (coloured areas) along a vertical section parallel to the coast.

sion along the many short ephemeral streams («fiumare») that flow to the sea.

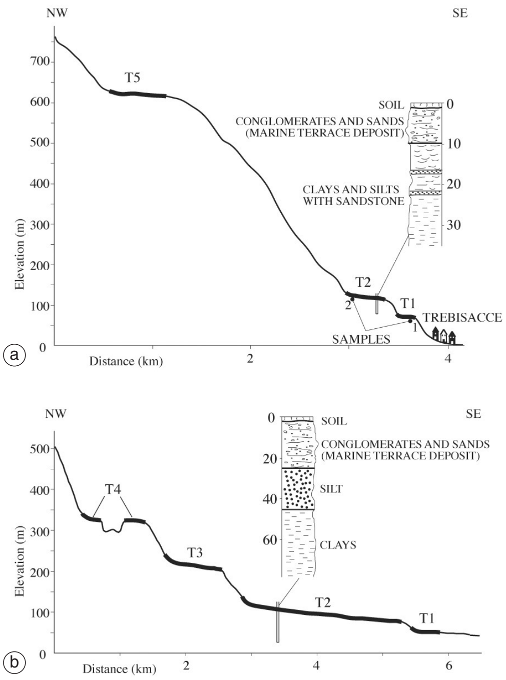
Figure 3 illustrates the elevation profile of the marine terraces along a vertical section parallel to the coast. Although the section of coast investigated is only ~ 50 km-long, the linear contouring of the innermost paleoshorelines reaches ~ 100 km; this is a consequence of the fact that the strandlines that contour the Sibari plain depart from the present coastline, so that the older and higher platforms are now found several kilometers inland.

Terrace remnants associated with strandline #1 are well expressed especially in the central part of the region, with inner edges at 75-80 m altitude and platforms that dip ~ 2° and attain a maximum width of 1350 m near the village of Doria (figs. 2,3 and 5a-d). In the Trebisacce-Villapiana zone the height of this strandline ranges from 60 to 75 m, while south in the Spezzano Albanese-Rossano zone is found between 70 and 80 m. This southern section is now densely populated and widely constructed (villages, roads, railway), so that additional narrow fringes of Terrace #1 identified by aerial photo (dated 1950's) are not mapped because no field control was possible.

Terrace #2 is the most continuous throughout the study area (fig. 2), with strandline at 130-145 m between Trebisacce and Francavilla Marittima, at 115-120 m between Lauropoli and the Coscile River, and finally again at 130-140 m west and south of this stream (fig. 3); 2° to 3° dipping broad wavecut platforms are associated with this strandline, up to 2500 m wide and more than 7 km laterally extended in the Lauropoli and Spezzano Albanese areas (fig. 4 and profiles b and c in fig. 5a-d). In the southern half of the region the inner edge remnants of Terrace #2 become more sporadic and scattered such that the terrace here is often represented by narrow elongated spurs between closely spaced interfluves (fig. 2).

Terrace remnants pertaining to strandline #3 are found almost continuously in the central-northern region between Trebisacce and Spezzano Albanese (fig. 2); this terrace is very well preserved and clearly recognizable for several kilometers (fig. 4). The elevation of this strandline varies from 220-245 m to the north to 245-260 m in the central-western zone (fig. 3); up to 880-1050 m wide, ~ 4° dipping terraced surfaces join the paleoshoreline (profiles b and c in fig. 5a-d).

Fig. 4. Westward view of the terraces in the Lauropoli area; coloured arrows (same colours as fig. 2) point to terraces T#2 to T#5. Location of the photo in fig. 2.



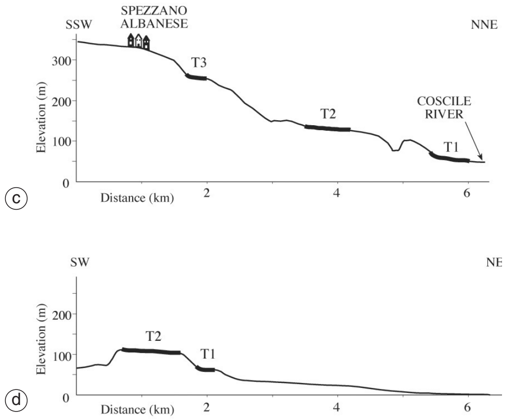
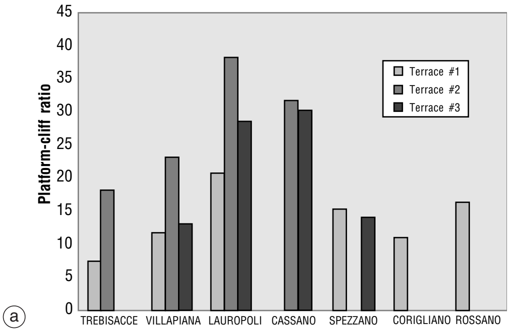


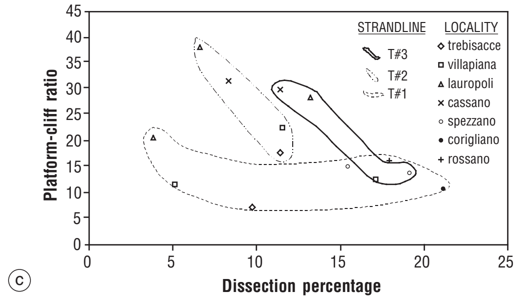
Fig. 5a-d. Topographic profiles along four sections representative of the area (see fig. 2 for location of the sections). Thicker lines mark the different terrace surfaces. Profiles ‘a’ and ‘b’ report the stratigrafies of two boreholes drilled along the direction of the sections; profile ‘a’ also shows the location of the samples used for the datings.

Altough sparser, the evidence of Terrace #4 resemble the geographical distribution of Terrace #3; the highest inner edges of the study area (maximum altitude at 340 m near Francavilla Marittima and Lauropoli, figs. 3 and 4) are associated with this strandline. The terrace slopes are usually 700-1150 m wide, with a dip of about 4-5° (profile b in fig. 5a-d); several other platforms devoid of inner edge occur between Castrovillari and Spezzano Albanese, about 25 kilometers inland from the modern coastline (fig. 2).

Two ~ 650 m high, ~ 1000 m wide, 3° dipping surfaces associated with the uppermost wavecut platform #5 are located 3 km northwest of Trebisacce (fig. 5a) and 5 km northwest of Lauropoli (figs. 2 and 4); both surfaces have no inner edge associated and look heavily affected by slope degradation.

Most of the deposits associated with the terraces include a series of beach sequences consisting of a progradational gravel body (beachface) and sands and silts (shoreface). The gravel bodies have a wedge-shaped geometry in a section perpendicular to the paleoshoreline. Their structure consists of lower low-angle clinostratified beds passing upward (with sigmoidal geometry) to subhorizontal, laterally continuous beds of well sorted sands and conglomerates. The latter is characterized by very platy to platy-bladed pebbles gently imbricated seawards and frequently bored by sponges. Such typical progradational gravel beach sequences are mainly connected with stillstand or regression phases of the sea (Massari and Parea, 1988). The thickness of the gravel bodies ranges from a few meters to a maximum of ~20 m. (*e.g.* stratigraphic logs of the wells along the longitudinal profiles a and b in fig. 5a-d). Though fossils are not abundant within the terrace deposits, they usually contain valves of *Glycymeris* and *Arca*, and less frequent remains of *Ostrea*, *Chlamis*, *Pecten* and *Cardium*. Alluvial debris close to the main streams and colluvium from scarp degradation along the interfluves locally cover with 1-2 m thickness the beach deposits.





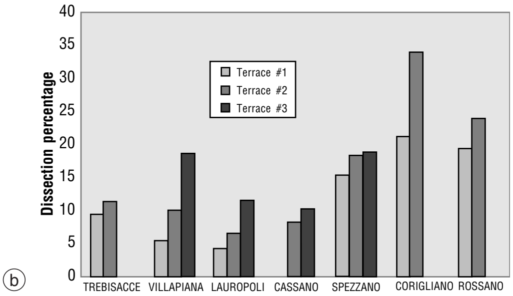


Fig. 6a-c. Geomorphological parameters of the cliff-platform systems. a) the platform-cliff ratio is the width of the terrace divided by the height of the above scarp; b) the dissection percentage is the rate between the area consumed by erosion and the initial area of the terrace. When present, T#2 is always characterized by higher values of PCR coupled with intermediate values of DP; this individuality makes the terrace a useful horizon for correlation along great distances; c) the plot of PCR against DP at seven localities of the Sibari Plain indicates a distinctive clustering of these two parameters for T#1.

Faunal assemblage, stratigraphy, sedimentological structures, dip, thickness and map distribution of the terrace deposits clearly define that the terraces are indeed marine.

3.2. *Geomorphic properties*

The study of some characteristic geomorphic properties of the emerged cliff-platform systems was useful to better correlate remote terrace remnants and to discriminate between the identified strandlines: the observed parameters were the Platform-Cliff Ratio (PCR) and the Dissection Percentage (DP).

The PCR rates the width of the terrace to the height of the onlooking cliff; altough each of the two features could significantly vary depending on several factors, their ratio should be distinctive for each terrace level (Verma, 1973). The DP reflects how much of the initial platform surface has been dissected by stream erosion; it is a simple measure of the duration of subaerial processes on a given terrace (Muhs, 2000). Both PCR and DP can be greatly affected by the nature of the underlying substrate into which the terraces are cut; in this case, however, the bedrock lithology is the same across the region (upper Pliocene-middle Pleistocene marine terrigenous deposits).

The histograms in fig. 6a,b show the values of PCR and DP for the three lowest strandlines along seven different localities. Regularly higher figures for PCR coupled with intermediate values of DP mark Terrace #2, a distinctive peculiarity of this strandline that makes it a useful reference for terrace correlation between distant remnants. As expected, everywhere DP increases upward in the sequence providing indirect evidence of relative terrace ages (Kelsey and Bockeim, 1994; Rosenbloom and Anderson, 1994). The PCR-DP cross-plot shows that the data for the three terraces are clustered; in particular, the cluster for strandline #1, which occurs at six localities (figs. 2 and 6a-c), suggests that the remnants of this terrace are strongly correlative.

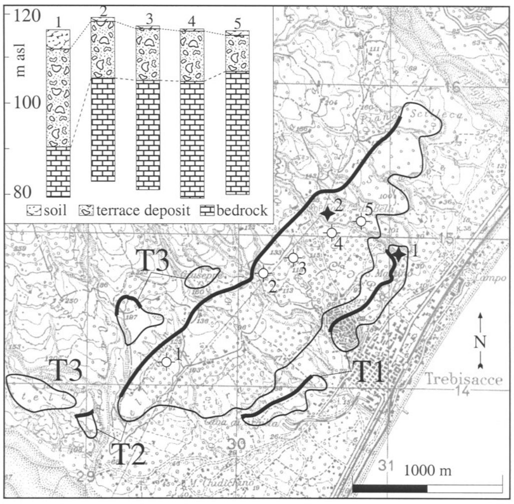


Fig. 7. Map of the Trebisacce area. Diamonds indicate the sites of the samples; dots are the location of five boreholes drilled onto T#2 for the construction of a highway. The stratigraphy of the boreholes is reported in the inset; at this location the thickness of the terraced deposits varies between 8 and 20 m. Eocene sandstones and calcarenites are the bedrock. The contour interval of the background map is 25 m.

4. Age and uplift rate of the terraces

No recent data about the morphology and chronology of Late Pleistocene terraces exist for the section of Ionian coast between Sibari and Crotone (fig. 1), as only Sestini (1930) recognized three terrace surfaces and Vezzani (1967) supposed a Tyrrhenian age for the lowest of them. Most recently, geomorphological reconstruction from Cucci and Cinti (1998) led to an estimated average uplift rate of 0.67 mm/yr during the last ~ 700 kyr in an area located ~ 50 km north of the Sibari Plain; Cucci and Cinti (1998) also provided evidence of a continuous, significant, northward drop in elevation of all the identified marine terraces, a feature that affects the whole Gulf of Taranto (Dai Pra and Hearty, 1988).

In this study, no tropical «Senegalese fauna» (index fossils like *Strombus bubonius* or *Conus testudinarius*) was found, preventing from dating the terrace deposits by paleontological means; the observed faunal assemblage always refers to fossils existing from Pleistocene to the present. Nevertheless, combining geological observations with the dating of fossil shells by aminostratigraphy yielded to uplift estimates of the terraces and provided a significant indication of the time extent of the uplift in the area.

The geological observations disclosed two comparable lower age boundaries for the marine terraces in the region: i) in the Lauropoli and Spezzano Albanese areas, the terraces are cut into and therefore postdate 1.0 Ma Gilbert-type fan deltas (Colella, 1988); besides the age constraint, this intriguing detail leads to the rationale that a unique mechanism of strong uplift likely provided at its early stage a high rate of sedimentation towards the Ionian Sea deriving the thick bottomset-foreset-topset delta sequences, and subsequently originated the marine terraces, when it started interacting with the glacio-eustatic oscillations; ii) at the northern extremity of the study area, marine deposits of the terraces contain magnetite (Massari and Parea, 1988) derived from the Vulture volcano (located about 150 km NW), which started activity around 0.73 Ma (Bonadonna *et al.*, 1998). These observations altogether indicate a post-Early Pleistocene age for the strandlines, which are therefore not older than 0.7-1.0 Ma.

4.1. *Aminostratigraphy*

Individual fossil samples have been dated by aminostratigraphy, which is a method of age estimation based on the phenomenon of amino acid racemization in geological specimens (see Wehmiller and Miller 2000, and references therein). Proteins in skeletal hard parts of living organisms contain negligible abundance of amino acids in the *D*-enantiomeric configuration; after death these amino acids undergo racemization, a spontaneous and reversible chemical reaction that proceeds to an equilibrium ratio (usually ~ 1.0) of *D*- and *L*-isomers. The measured *D*/*L* ratio is primarily a function of the diagenetic temperature history of the sample and of the type of the sample itself (*e.g.* shell, bone or wood and fossil genus). The theory of this dating method and many aspects of its methodology such as sampling, analytical strate-

Table I. Amino acid data and predicted age of the samples. AAR analyses are presented as mean *D/L* aspartic acid ratio (×), standard deviation (σ) and number of shells analyzed *N*. Predicted ages are calculated using a value of 17.0°C for the current mean annual temperature, which is a first approximation of the long-term effective diagenetic temperature at the site (see also Hearty *et al.*, 1986). There is good reproducibility among the shells in the sample, as suggested by the value for the coefficient of variation CV (CV=(σ*100/×) (measure of error).

Sample no.	Elevation (m)	Inner edge elev. (m)	Depth of burial (m)	×	σ	N	CV %	Predicted age (kyr)	Aminozone
1	65	77	0.6	0.734	± 0.004	4	0.578	139	E
2	114	128	1.7	0.730	± 0.041	4	5.648	130	E

gies, factors affecting the *D/L* ratios, presentation and interpretation of data and age estimates can be found in Wehmiller and Miller (2000).

In this study, I rely on the ratio of *D/L* aspartic acid of fossil specimens of *Glycymeris*; samples of this genus were selected because of their well-defined shell structure, widespread frequency of occurrence, and geological consistency of amino acid ratios (Hearty *et al.*, 1986). The samples were prepared according to the procedures outlined in Goodfriend *et al.*, (1996). Four different individuals from each sample were prepared to check for internal sample consistency; 1 uL of each processed sample was injected into an Agilent 6890 series gas chromatograph outfitted with a Chirasil-Val 50 m × 0.25 mm fused-silica column, using helium as the carrier gas. Amino acid abundance was measured via nitrogen-phosphorus detector.

The *Glycymeris* specimens to be analyzed were collected close to the village of Trebisacce, at the northern extremity of the study area (figs. 2, 5 and 7); the close-up map in fig. 7 shows the location of the sampling sites and of five boreholes which depict the local stratigraphy beneath platform #2. The results of aminostratigraphy are summarized in table I; both the samples fall within the Aminozone 'E' of the Mediterranean Quaternary aminostratigraphy by Hearty *et al.*, (1986). Although the two sampling sites are very close to each other the two samples yielded different ages which are interpreted to reflect their different sampling conditions; in fact, shells from sample 2 were *in situ*, in connection and buried at the proper depth, while sample 1 specimens were collected near a gully (fig. 7) at shallower depth. Therefore, either i) the predicted age (139 kyr) and the consequent attribution to Aminozone E for this latter sample is reasonable, but the shells come from a higher terrace and are reworked by the stream, or ii) the dating of the sample is wrong because of heating of the shells due to their depth (heating accelerates the racemization of shallow shells at an exponential rate making them appear older). Consequently, I will rely on the results from sample 2.

4.2. *Rates of uplift*

It is not unusual to try to correlate a full set of observed terrace inner-edge elevations with reconstructed global sea-level histories, especially when a dearth of datable materials precludes direct dating of fossils. This common procedure is often used under the assumption that the uplift rate at the site is constant. Unfortunately, this assumption is not always valid, as demontrated in southern Italy by Miyauchi *et al.* (1994) on Late Pleistocene terraces in southern Calabria and by Antonioli *et al.* (2004) for Holocene uplifted fossil beaches in southern Calabria and eastern Sicily. It is therefore safe in this case to provide more robust estimations of uplift for the lower terraces and then to suggest a possible reconstruction of the uplift history of the area. The AAR dating for sample 2 indicates that the fossil was living during the marine isotope stage (MIS) 5.5, which corresponds with the peak of the last interglacial (124 kyr, see fig. 8); this yields an uplift rate of ~ 0.98 mm/yr for

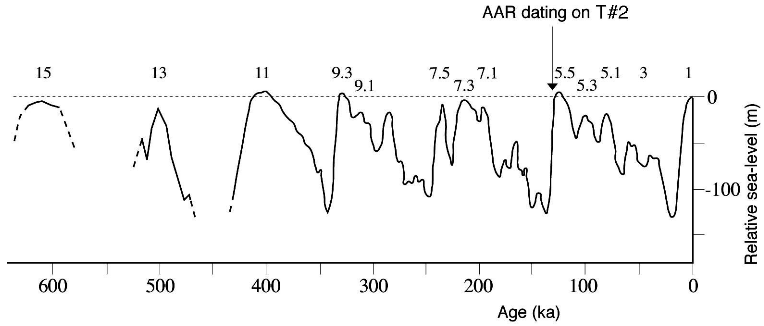


Fig. 8. Paleo-sea level curve during the past 0.6 Myr. The numbers denote marine isotopic stages. Data of relative sea-level from MIS 11 onward are from Waelbroeck *et al.* (2002), older data are from Lajoie *et al.* (1991). Measured AAR dating on T#2 is also shown.

the associated paleoshoreline at Trebisacce. A further constraint to the T#2 - MIS 5.5 correlation comes from the 130 kyr shells of sample 2 that were uplifted of ~ 134 m (114 actual elevation + ~ 20 m negative global sea level at 130 kyr, Waelbroeck *et al.,* 2002) (fig. 8): the ~ 1.03 mm/yr uplift rate calculated for the shells is consistent with that of the paleoshoreline. A final remark comes from the observation that best expressed geomorphic surface T#2 within the region is associated with the most prominent and constrained highstand of the paleo sea-level record (corresponding to MIS 5.5). Keying on this T#2 - MIS 5.5 correlation, it is concluded that T#1 is associated with MIS 5.3 highstand; the estimated uplift rate for this paleoshoreline at Trebisacce is 0.97 mm/yr. In this frame, a possible explanation of the absence of a terrace originated during MIS 5.1 is that the highstand was of short duration and/or the terrace was obliterated by erosion.

The age assignment of the three higher terraces leaves room for more uncertainties, nonetheless the ~ 0.98 mm/yr calculated uplift rate since the peak of the last interglacial and the 0.7 Ma as a lower bound age of the terraces provide interesting suggestions for a tentative reconstruction of the early uplift history of the area. Assigning each successively higher terrace to older sea-level highstands, the possible associations of T#3 and T#4 with MIS 7 and MIS 9 imply 1 mm/yr comparable rates of uplift, similar to the T#2 rate. As for T#5, the poor preservation of its remnants only allows us to speculate about a possible origin during MIS 15 (0.6 Ma, tentative uplift rate ≥ 1.1 mm/yr) on the base of the post-Early Pleistocene age indicated by geological constraints, or alternatively during MIS 11 as the long-lasting, high elevation formation, most recent highstand prior to 330 kyr (tentative uplift rate < 1.5 mm/yr).

As a conclusive remark, sustained uplift at ~ 1 mm/yr affected the area over the past 124 000 years, possibly 600 000 years.

4.3. *The Holocene*

No evidence of a Holocene paleoshoreline was found throughout the study area, a common feature in the whole Calabria peninsula. Despite the great number of papers on upper Pleistocene terraces, the only available dated Holocene paleoshorelines to date are from Pirazzoli *et al.*, (1997) (~ 0.67 mm/yr since 2.7 kyr in the Crotone region, Ionian side, central Calabria - ~ 80 km south of the Plain) and from Antonioli *et al.*, submitted (1.5-1.8 mm/yr close to Scilla, Tyrrhenian side, southern Calabria). Further values of uplift are provided by Westaway (1993) and Cucci and Cinti (1998), who estimated by geomorphological correlations ~ 1 mm/yr and 0.85 mm/yr uplift rates over the past 7.0 kyr at two locations ~ 70 km and ~ 50 km north of the Sibari Plain, respectively. However, these data consistently demonstrate that all around the study area and within the same structural domain the tectonic uplift over the past 2.7-7.0 kyr has been proceeding at an average rate that is fully comparable, when not slightly higher, than that determined for the Pleistocene. These observations suggest that the Late Pleistocene trend of tectonic uplift did not cease during the Holocene also in the Sibari Plain. Possible reasons for the lack of recent signals have to be searched in i) an extremely active coastal morphology, with exceptional quantity of continental sediments delivered by «fiumare» and rivers (the Crati river is the longest and most important in Calabria) that very rapidly modify the shape of the present coastline, and possibly concealed past Holocene shorelines, and ii) the comparable yet opposite rates of sea level rise and tectonic uplift since the Climatic Optimum (6000-5000 years BP), which prevented the formation of raised mid-Holocene shorelines.

5. Tectonic implications

5.1. *Marine terraces and major faults*

The data presented indicate a long-term rate of regional vertical tectonic deformation of ~ 1 mm/yr. However, marine terraces in seismogenic regions may also record local sharp deformations induced by active faults. As an example, Cucci and Cinti (1998) showed that the remarkable height variations observed in the terraces between Francavilla Marittima and the Coscile River are the result of cumulated coseismic deformation caused by the seismogenic normal Castrovillari Fault (Cinti *et al.*, 1997, 2002). In the study area, an additional general rise is recorded by the paleoshorelines between the Esaro River and Spezzano Albanese (figs. 2, 3 and 9), south of the Castrovillari Fault. Footwall uplift along the southern continuation of this fault (hypothesized by Cinti *et al.*, 1997)

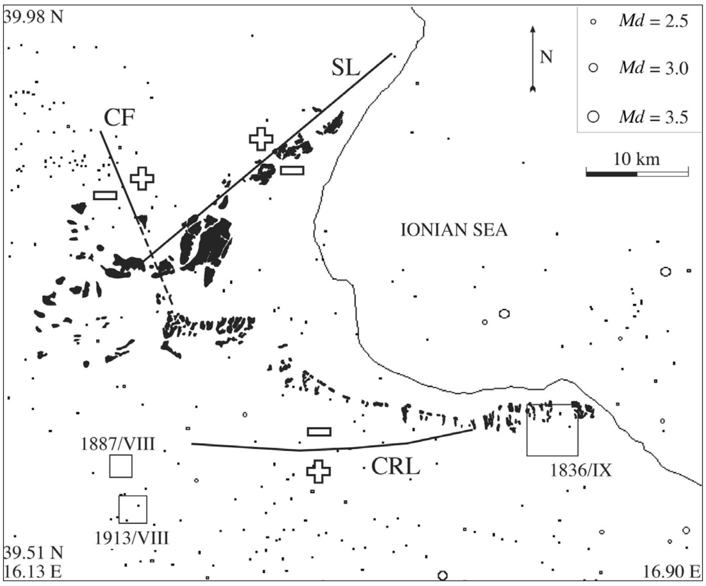


Fig. 9. Seismicity, major faults (see text) and marine terraces in the study area. The map shows historical events with intensities ≥ VIII MCS since 1000 A.D. from Boschi *et al.* (2000), and the 1985-2000 $Md \geq 2.0$ instrumental earthquakes from the bulletin of the INGV seismometric network. Fault abbreviations as in fig. 1; the dashed line is the CF's southern continuation hypothesized by Cinti *et al.* (1997). The relative sense of displacement across the faults is also indicated.

might be responsible for the anomaly observed in the elevation pattern of the strandlines. In this sector of the study area, older strandlines are more affected than younger ones by this increase of uplift, supporting the hypothesis that the fault-induced deformation was already active at the times of the formation of T#3 (~ 215 kyr). The lack of terraces immediately west of the Esaro River (hangingwall) does not allow the estimation of a reliable long-term slip rate across the fault, although the limited anomaly observed suggests a modest value for this rate (~ 0.1 mm/yr).

With the exception of the Castrovillari Fault, in the study area the terraces are only crossed by a short number of small normal faults usually displaying a vertical separation that is negligible at the scale of the present work. Although the elevation pattern of the strandlines shows some variations there is no evidence of strong vertical deformation or lateral deflection. Also this lack is significant because it can be interpreted as the negative evidence for recent activity along known tectonic lineaments that are mapped in the study area. In the region, the «Sangineto Line» and the «Corigliano-Rossano Line» (fig. 9) are two major discontinuities quoted, with different rates of reliability, by the most recent inventories and compilations of tectonic features such as «active faults» (Galadini *et al.*, 2000), «capable faults» (Michetti *et al.*, 2000), and «seismogenic sources» (Valensise and Pantosti, 2001). However, I believe that evidence against the present activity of these two faults comes from the following reasons: i) the absence of important local deformations of the strandlines adjacent to the Corigliano-Rossano Line (fig. 3); ii) a slight rise of the terraces (fig. 3) instead of the general subsidence expected east of the Sangineto Line; iii) the poor geomorphological expression of both faults, especially of the Sangineto Line, so that the cliff separating two adjacent marine platforms has been misinterpreted and mapped in the past as the fault trace; iv) the very limited instrumental seismicity and the moderate size historical earthquakes in the region across the two faults (fig. 9).

5.2. *Quaternary uplift pattern in the Calabrian Arc*

Based on the above data, regional uplift in the northern Calabrian Arc is about one order of magnitude faster than fault-related slip and therefore can be considered the principal source of tectonic deformation in the region. With 1 mm/yr long-term rate of uplift, the Sibari Plain is the final step of a ~ 150-km long southward progressive rise already pointed out by several Authors (Dai Pra and Hearty, 1988; Bordoni and Valensise, 1998; Cucci and Cinti, 1998). Moving southward along the Arc, the rise stops and the uplift gets almost steady for about 200 kilometres (fig. 10), showing only minor fluctuations within similar rates. Then, south of the Messina Straits uplift starts decreasing again and tapers to zero with a trend that is specular to the northern rise. The total extent of this regional doming (about 400-500 kilometres) constrains to a comparable scale the dimensions of its driving mechanism and strenghthens the hypothesis of the Tyrrhenian Benioff zone beneath the Calabrian Arc as its deep-seated engine. Not coincidentally, the extent of the maximum uplift matches that of the Arc (fig. 10), and major changes in the process of subduction (still debated: Sengor, 1993; Westaway, 1993; Hippolyte *et al.*, 1994; Kruse and Royden, 1994; Miyauchi *et al.*, 1994; Giunchi *et al.*, 1996) are therefore the most probable cause of the uplift.

Apart from the controversial driving mechanisms of uplift and despite the difficulties to find Holocene raised paleoshorelines, it is suggested that the process that raised the strandlines during the Pleistocene has continued through Holocene, similarly to what observed only few tens of kilometers north of the Sibari Plain (Westaway, 1993; Cucci and Cinti, 1998) and south of it (Pirazzoli *et al.*, 1997; Antonioli *et al.*, 2004). A quantitative evaluation of the Holocene evolution of the region would be worth another paper, as it should take into account, besides the neotectonics, a number of geomorphological 'events' such as the glacio-hydro isostatic changes, the sedimentary cycle and the local subsidence. Nevertheless, I emphasize the qualitative contribution of tectonic uplift as 'landscape maker' in the Plain. As a matter of fact, many authors generally accept a slow but contin-

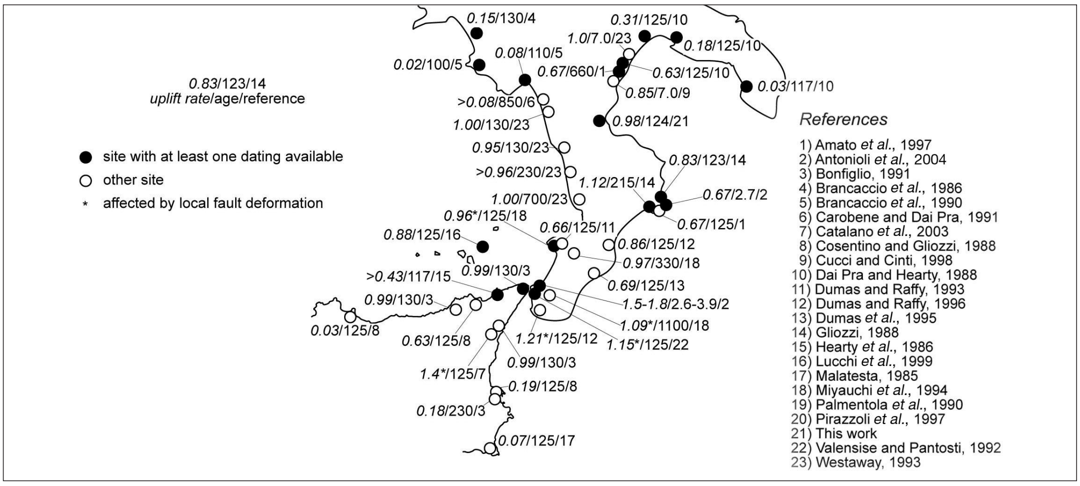


Fig. 10. Summary of Holocene and Pleistocene uplift rates in peninsular Southern Italy and Sicily. Figures shown are mean values (in mm/yr) calculated over the corresponding time (in thousands of years). Solid circles indicates sites where at least one dating (usually AAR or U-Th) was used to assess the uplift; white circles represent other sites where the rates were evaluated through paleontology and/or stratigraphic-geomorphological correlation. For a complete overview of the rates of uplift over the last 125 kyr see Bordoni and Valensise, (1998).

uous rise of the sea-level since mid-Holocene (Fairbanks, 1989; Pirazzoli, 1991; Alessio *et al.*, 1998; Morhange *et al.*, 2001). Therefore, only when regional uplift outpaced sea-level changes some 5-6 kyr did active coastal progradation cause the filling of the former embayment, originating the plain as we can see it today. As a consequence, the coastal setting became morphologically attractive firstly for prehistoric human settlement and subsequently for the foundation in 709 B.C. of Sybarys, one of the most famous and wealthy Greek colonies (Herodotus: *The Histories*, V, 2; Strabo: *Geography*, VI, 1, 13).

6. Conclusions

Five marine terraces contour the Sibari Plain at elevations ranging from 60 to 650 m above present sea level. One main finding of the present work is that during Late Pleistocene this area experienced sustained uplift at a long-term rate of ~ 1 mm/yr since the peak of the last interglacial (124 kyr). Field survey, geological observations, geomorphological analyses and AAR datings support this result. Geological observations also provide evidence for a post-Early Pleistocene (*i.e.* not older than ~ 0.6 Ma) maximum age of the uplift phenomenon; if the highest terrace in the area was carved at that time, then the rate of uplift has never been lower than 1.0 mm/yr over the past 600 kyr.

No evidence was found of local fault-induced deformation across the Sangineto and the Corigliano-Rossano Lines; this observation, along with some geomorphological and seismological remarks, indicate that these two faults are no longer active. Vice versa, anomalies in the pattern of the strandlines between the Esaro River and Spezzano Albanese have been related to a ≥ 215 kyr-long activity along the southern prolongation of the Castrovillari Fault; however, no reliable estimate of a long-term slip rate across the fault was possible.

The mean ~ 1 mm/yr long-term uplift rate in the Sibari Plain fits well when compared with the pattern of Quaternary rise in the Calabrian Arc and surrounding regions. The studied area is the northern extremity of a 200 km-long stretch of crust, roughly corresponding to the extent of the Arc, displaying similar high uplift rates. It is therefore suggested that major changes in the process of Tyrrhenian subduction be the large scale causative mechanism of the uplift.

I found no evidence of Holocene uplifted paleoshorelines, mainly because of the extremely active coastal deposition. Notwithstanding, data from Holocene and Late Pleistocene uplifted strandlines all round the study area and throughout the Calabrian Arc allow to hypothesize that the process is still active and almost unchanged. Sustained uplift at the short-term rate of ~1 mm/yr might have originated dramatic coast progradation during the past 5-6000 years and provided the Plain the present configuration, establishing a suitable environment for early human occupation settlements and for subsequent wealthy archeological sites.

Acknowledgements

I want to thank F. Marra for constructive suggestions and comments that strongly improved the paper, and F.R. Cinti for having read and corrected a first draft of the manuscript. Special thanks to F. Luci who was my guide on the fan deltas outcrops and to F. Castrovillari who provided the stratigraphies of the boreholes. UCEA (Ufficio Centrale di Ecologia Agraria) supplied the data of mean annual temperature. Aminostratigraphic datings were performed by Amino Acid Geochronology Laboratory at the University of Massachusetts.

REFERENCES

Aïfa, T., H. Feinberg and J.P. Pozzi (1988): Pliocene-Pleistocene evolution of the Tyrrhenian arc: paleomagnetic determination of uplift and rotational deformation. *Earth Planet. Sci. Lett.*, **87**, 438-452.

Alessio, M., L. Allegri, F. Antonioli, G. Belluomini, S. Improta, L. Manfra and L. Preite (1998): La curva di risalita del Mare Tirreno negli ultimi 43 kyr ricavata da datazioni su speleotemi sommersi e dati archeologici. *Mem. Descr. Serv. Geol. Naz.*, **52**, 235-265.

Amato, A., G. Belluomini, A. Cinque, M. Manolio and F. Ravera (1997): Terrazzi marini e sollevamenti tettonici quaternari lungo il margine ionico dell'Appennino lucano, *Il Quaternario*, **10** (2), 329-336.

Antonioli, F., A.G. Segre and S. Sylos Labini (2004): New data on Late Holocene uplift rate in the Messina Straits area, Italy, *Quaternaria,* **8** (in press).

Bonadonna, F.P., D. Brocchini, M.A. Laurenzi, C. Principe and G. Ferrara (1998): Stratigraphical and chronological correlations between Monte Vulture volcanics and sedimentary deposits of the Venosa Basin, *Quatern. Int.*, 47-8, 87-96.

Bonfiglio, L. (1991): Correlazione tra depositi a mammiferi, depositi marini, linee di costa e terrazzi medio e tardo pleistocenici nella Sicilia orientale, *Il Quaternario*, **4**, 205-214.

Bordoni, P. and G. Valensise (1998): Deformation of the 125 kyr marine terrace in Italy: tectonic implications, in *Coastal Tectonics*, edited by I.S. Stewart and C. Vita-Finzi, *Geol. Soc. London, Spec. Publ. 146*, 71-110.

Boschi, E., E. Guidoboni, G. Ferrari, D. Mariotti, G. Valensise and P. Gasperini (2000): Catalogue of strong Italian earthquakes, *Ann. Geofis.*, **43** (4), pp. 268 (with full database on CD-ROM).

Bousquet, J.C. (1973): La tectonique récente de l'Apennin Calabro-Lucanien dans son cadre géologique et géophysique, *Geol. Rom.*, **12**, 1-103.

Brancaccio, L., A. Cinque, G. Belluomini, M. Branca and L. Delitala (1986): Isoleucine epimerization dating and tectonic significance of Upper Pleistocene sea-level features of the Sele plain (Southern Italy), *Z. Geomorphol. Suppl.*, **62**, 159-166.

Brancaccio, L., F. Russo, G. Belluomini, M. Branca and L. Delitala (1990): Segnalazione e datazione di depositi marini tirreniani sulla costa Campana, *Boll. Soc. Geol. It.*, **109**, 259-265.

Brogan, G.E., L.S. Cluff and C.L. Taylor (1975): Seismicity and uplift of Southern Italy, *Tectonophysics*, **29**, 323-330.

Carobene, L. and G. Dai Pra (1991): Middle and Upper Pleistocene sea-level highstands along the Tyrrhenian coast of Basilicata (Southern Italy), *Il Quaternario*, **4**, 173-202.

Catalano, S., G. De Guidi, C. Monaco, G. Tortorici and L. Tortorici (2003): Long-term behaviour of the late Quaternary normal faults in the Straits of Messina area (Calabrian Arc): structural and morphological constraints, *Quatern. Int.*, 101-102, 81-91.

Cinti, F.R., L. Cucci, D. Pantosti, G. D'Addezio and M. Meghraoui (1997): A major seismogenic fault in a 'silent area': the Castrovillari Fault (Southern Apennines, Italy), *Geophys. J. Int.*, **130**, 322-332.

Cinti, F.R., M. Moro, D. Pantosti, L. Cucci and G. D'Addezio (2002): New constraints on the seismic history of the Castrovillari fault in the Pollino gap (Calabria, Southern Italy), *J. Seismol.*, **6**, 199-217.

Colella, A. (1988): Fault-controlled marine Gilbert-type fan deltas, *Geology*, **16**, 1031-1034.

Cosentino, D. and E. Gliozzi (1988): Considerazioni sulle velocità di sollevamento di depositi eutirreniani dell'Italia Meridionale e della Sicilia, *Mem. Soc. Geol. It.*, **41**, 653-665.

Cucci, L. and F.R. Cinti (1998): Regional uplift and local tectonic deformation recorded by the Quaternary marine terraces on the Ionian coast of Northern Calabria (Southern Italy), *Tectonophysics*, **292**, 67-83.

DAI PRA G. and P.J. HEARTY (1988): I livelli marini pleistocenici del golfo di Taranto. Sintesi geocronostratigrafica e tettonica, *Mem. Soc. Geol. It.*, **41**, 637-644.

DUMAS B., P. GUEREMY, R. LHENAFF and J. RAFFY (1995): Reconstitution morphometrique d'un dispositif de paléorivagés soulevés dans un relief de dissection en Locride (Calabre Ionienne, Italie), *Geodin. Acta*, **8**, 185-198.

DUMAS B. and J. RAFFY (1993): Validité et précision de la mesure des mouvements verticaux par référence aux paléoniveaux marins: exemples en Calabre méridionale, *Bull. Inst. Géol. Bassin Aquitaine*, **53**, 141-150.

DUMAS B. and J. RAFFY (1996): Enregistrement géomorphologique de maxima glacio-eustatiques dans la région soulevée de Soverato (Italia du Sud), *Bull. Soc. Géol. Fr.*, **167**, 285-293.

FAIRBANKS, R.G. (1989): A 17 000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, *Nature*, **342**, 637-642.

GALADINI, F., C. MELETTI and E. VITTORI (2000): Stato delle conoscenze sulle faglie attive in Italia: elementi geologici di superficie, in *Le ricerche del GNDT nel campo della pericolosità sismica (1996-1999). Internal report of CNR-Gruppo Nazionale per la Difesa dai Terremoti*, edited by F. GALADINI, C. MELETTI and A. REBEZ, Roma pp. 397.

GIGNOUX, M. (1913): Les formations marines Pliocènes et Quaternaires de l'Italie du Sud et de la Sicile, *Ann. Univ. Lyon*, **36**.

GIUNCHI, C., R. SABADINI, E. BOSCHI and P. GASPERINI (1996): Dynamic models of subduction: geophysical and geological evidences in the Tyrrhenian, *Geophys. J. Int.*, **126**, 555-578.

GLIOZZI, E. (1988): I terrazzi del Pleistocene superiore della penisola di Crotone (Calabria), *Geol. Rom.*, **26**, 17-79.

GOODFRIEND, G.A., J. BRIGHAM-GRETTE and G.H. MILLER (1996): Enhanced age resolution of the marine Quaternary record in the Artic using aspartic acid racemization dating of bivalve shells, *Quat. Res.*, **45** (2), 176-187.

GVIRTZMANN, Z. and A. NUR (1999): Plate detachment, asthenosphere upwelling, and topography across subduction zones, *Geology*, **27**, 563-566.

HEARTY, P.J., G.H. MILLER, C.E. STEARNS and B.J. SZABO (1986): Aminostratigraphy of Quaternary shorelines around the Mediterranean basin, *Geol. Soc. Am. Bull.*, **97**, 850-858.

HYPPOLITE, J.C., J. ANGELIER and F. ROURE (1994): A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy), *Tectonophysics*, **230**, 199-210.

KELSEY, H.M. and J.G. BOCKHEIM (1994): Coastal landscape evolution as a function of eustasy and surface uplift rate, *Geol. Soc. Am. Bull.*, **106**, 840-854.

KRUSE, S.E. and L.H. ROYDEN (1994): Bending and unbending of an elastic litosphere: the Cenozoic history of the Apennine and Dinaride foredeep basins, *Tectonics*, **13**, 278-302.

LAJOIE, K.R., D.J. PONTI, C.L. POWELL, S.A. MATHIESON and A.M. SARNA-WOJCICKI (1991): Emergent marine strandlines and associated sediments, coastal California; a record of Quaternary sea-level fluctuations, vertical tectonic movements, climate changes, and coastal processes, in *Quaternary Non-Glacial Geology: Conterminous United States*, edited by R.B. MORRISON, *Geological Society of America Decade of North America Geology*, vol. K-2, 190-214.

LUCCHI, F., N. CALANCHI, L. CAROBENE and C.A. TRANNE (1999): I terrazzi marini dell'Isola di Panarea (Isole Eolie): loro utilizzo nella definizione dell'eustatismo e del sollevamento Tardo-Pleistocenico. *Boll. Soc. Geol. It.*, **118**, 545-562.

MALATESTA, A. (1985): *Geologia e paleobiologia dell'era glaciale* (La Nuova Italia Scientifica, Firenze).

MALINVERNO, A. and W.B.F. RYAN (1986): Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the litosphere, *Tectonics*, **5**, 227-245.

MASSARI, F. and G.C. PAREA (1988): Progradational gravel beach sequences in the hinterland of the Gulf of Taranto, in *Excursion guidebook of the International Workshop on Fan Deltas*, Calabria, Italy, edited by A. COLELLA, C.N.R., 97-137.

MELETTI, C., E. PATACCA and P. SCANDONE (2000): Construction of a seismotectonic model: the case of Italy, *Pure Appl. Geophys.*, **157**, 11-35.

MICHETTI, A.M., L. SERVA and E. VITTORI (2000): ITHACA (Italy hazard from Capable Faulting), a database of active capable faults of the Italian onshore territory, *Internal report of ANPA-Agenzia Nazionale Protezione Ambiente*, Roma (CD-ROM).

MIYAUCHI, T., G. DAI PRA and S. SYLOS LABINI (1994): Geochronology of Pleistocene marine terraces and regional tectonics in the Tyrrhenian coast of South Calabria, Italy, *Il Quaternario*, **7** (1), 17-34.

MORHANGE, C., J. LABOREL and A. HESNARD (2001): Changes of relative sea level during the past 5000 years in the ancient Harbour of Marseilles, Southern France, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **166**, 319-329.

MUHS, D.R. (2000): Dating marine terraces with relative-age and correlated-age methods, in *Quaternary Geochronology: Methods and Applications,* edited by J. STRATTON NOLLER, J.M. SOWERS and W.R. LETTIS (American Geophysical Union, Washington, DC), 434-446.

PALMENTOLA, G., L. CAROBENE, G. MASTRONUZZI and P. SANSÒ (1990): I terrazzi marini pleistocenici della penisola di Crotone (Calabria), *Geogr. Fis. Dinam. Quat.*, **13**, 75-80.

PIRAZZOLI, P.A. (1991): *World Atlas of Holocene Sea-Level Changes* (Elsevier, New York), pp. 300.

PIRAZZOLI, P.A., G. MASTRONUZZI, J.F. SALIÈGE and P. SANSÒ (1997): Late Holocene emergence in Calabria, Italy, *Mar. Geol.*, **141**, 61-70.

ROSENBLOOM, N.A. and R.S. ANDERSON (1994): Hillslope and channel evolution in a marine terraced landscape, Santa Cruz, California, *J. Geophys. Res.*, **99**, 14013-14029.

SENGOR, A.M.C. (1993): Some current problems on the tectonic evolution of the Mediterranean during the Cainozoic, in *Recent Evolution and Seismicity of the Mediterranean Region*, edited by E. BOSCHI, E. MANTOVANI and A. MORELLI, *NATO ASI Ser. C*, 1-51.

SESTINI, A. (1930): La Piana di Sibari, in *Proceedings of the XI Congress of Italian Geographers*, vol. 2, 124-131.

SPAKMAN, W., S. VAN DER LEE and R. VAN DER HILST (1993): Travel-time tomography of the European-Mediterranean mantle down to 1400 km, *Phys. Earth Planet. Inter.*, **79**, 3-74.

VALENSISE, G. and D. PANTOSTI (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.

VALENSISE, G. and D. PANTOSTI (Editors) (2001): Database of potential sources for earthquakes larger than 5.5 in Italy, *Ann. Geofis.*, **44** (suppl. to no. 4), pp. 175.

VERMA, V.K. (1973): Map Parameters for correlation of marine terraces in California, *Geol. Soc. Am. Bull.*, **84**, 2737-2742.

VEZZANI, L. (1967): I depositi Plio-Pleistocenici del litorale ionico della Lucania, *Atti Acc. Gioenia Sc. Nat. Catania*, **6** (18), 159-179.

WAELBROECK, C., L. LABEYRIE, E. MICHEL, J.C. DUPLESSY, J.F. MCMANUS, K. LAMBECK, E. BALBON and M. LABRACHERIE (2002): Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records, *Quat. Sci. Rev.*, **21**, 295-305.

WEHMILLER, J.F. and G.H. MILLER (2000): Aminostratigraphic dating methods in Quaternary geology, in *Quaternary Geochronology: Methods and Applications*, edited by J. STRATTON NOLLER, J.M. SOWERS and W.R. LETTIS (American Geophysical Union, Washington, DC), 187-222.

WESTAWAY, R. (1993): Quaternary uplift of Southern Italy. *J. Geophys. Res.*, **98**, 21741-21772.

(received April 15, 2004;
accepted June 10, 2004)