G. TORTORICI*, M. BIANCA* & C. MONACO*

MARINE TERRACING AND TECTONIC UPLIFT RATES IN THE CAPO VATICANO AREA (SOUTHERN CALABRIA) DURING THE MIDDLE-LATE QUATERNARY.

INDEX

ABSTRACT

The Capo Vaticano promontory represents a structural high bordered by several normal fault segments mainly striking NE-SW and WNW-ESE and belonging to the Siculo-Calabrian Rift Zone. The northwestern coast of Capo Vaticano is characterized by the occurrence of a NE-SW striking, NW facing normal fault system. Southwards, the promontory is abruptly truncated by two main WNW-ESE trending, south facing normal faults (Coccorino and Nicotera faults) that separate the structural high from the Gioia Tauro basin. In the Capo Vaticano area six orders of marine terraces with preserved inner edges have been recognized. We mapped the inner edge and the outer edge of each marine terrace occurring in the whole area of Capo Vaticano peninsula. Stratigraphic information, combined with absolute dating recently proposed by some authors for the distinct orders of marine terraces, allow us to identify the Euthyrrenian marine terrace, related to the OIS 5.5 (125 kyr) of the global eustatic curve. Starting from this datum-line and considering the flight of marine terraces as a continuous set of morphological elements due to the interaction between tectonic uplift and eustatic sea level changes, the six inner-edges of the observed marine terraces have been ascribed to the last six principal high-stands of the eustatic curve occurred from 240 kyr to 60 kyr. The diagrams obtained by plotting the corrected elevations of the inner edges against time points out that the Capo Vaticano promontory has been affected by uplift rates changing in space and time, mainly related to the activity of the NE-SW trending major normal faults extending in the northern offshore of this area.

RIASSUNTO

Il promontorio di Capo Vaticano rappresenta un alto strutturale delimitato da diverse faglie normali, principalmente orientate NE-SW e WNW-ESE e appartenenti al Rift Siculo-Calabro. La costa nord-occidentale di Capo Vaticano è caratterizzata dalla presenza di un sistema di faglie dirette, orientate NE-SW e immergenti verso NW. Verso sud, il promontorio viene troncato bruscamente da due faglie dirette, orientate WNW-ESE e immergenti verso sud (faglie di Coccorino e Nicotera) che separano l'alto strutturale dal bacino di Gioia Tauro. Nell'area di Capo Vaticano sono stati individuati sei ordini di terrazzi marini con i rispettivi bordi interni ben conservati. Sono stati quindi cartografati sia i bordi interni che quelli esterni di ognuno dei terrazzi marini presenti nell'intera penisola di Capo Vaticano. I dati di tipo stratigrafico, integrati con le datazioni assolute recentemente proposte da diversi autori per alcuni dei terrazzi marini, consentono di individuare il terrazzo Eutirreniano, correlato allo stadio OIS 5.5 (125 ka) della curva eustatica globale. Partendo da questo livello di riferimento e considerando la sequenza di terrazzi marini come una serie continua di elementi morfologici derivanti dall'interazione tra sollevamenti tettonici e oscillazioni eustatiche del livello marino, i sei bordi interni dei terrazzi analizzati sono stati cronologicamente attribuiti alle ultime sei principali fasi di alto stazionamento marino della curva eustatica, nell'intervallo compreso tra 240 ka e 60 ka. I diagrammi raffiguranti l'andamento delle quote corrette dei bordi interni in funzione del tempo indicano che il promontorio di Capo Vaticano è stato interessato da tassi di sollevamento variabili nello spazio e nel tempo, legati principalmente all'attività delle principali faglie normali, a direzione NE-SW, che si estendendono lungo la costa settentrionale.

KEY WORDS: marine terraces, inner edges, eustatism, geochronology, tectonic uplift, Siculo-Calabrian Rift Zone, Capo Vaticano.

PAROLE CHIAVE: terrazzi marini, bordi interni, eustatismo, geocronologia, sollevamento tettonico, Rift Siculo-Calabro, Capo Vaticano.

1. INTRODUCTION

The Capo Vaticano promontory is a structural high bounded by several Quaternary normal fault segments, mainly striking NE-SW and WNW-ESE, belonging to the Siculo-Calabrian Rift Zone (Fig.1), a regional normal fault belt that contributes to a continuous extensional deformation from northern Calabria to the Ionian coasts of Sicily (MONACO & TORTORICI, 1999). Normal faults are due to a ESE-WNW regional extension (TORTORICI *et al.*, 1995; MONACO *et al.*, 1997) which is marked by a high level of crustal seismicity, producing earthquakes with normal focal mechanisms (CELLO *et al.*, 1982; GASPARINI *et al.*, 1982) and intensities up to XI-XII MCS and M ≥7 (BARATTA, 1901; POSTPISCHL, 1985; BOSCHI *et al.*, 1995).

The northwestern coast of Capo Vaticano reflects the geometry of NE-SW striking, NW facing normal fault system which are located both onland (Tropea, Zaccanopoli and Vibo Faults) and offshore (Fig.1). The occurrence of a fault segment in the northwestern offshore has been proved by a seismic profile carried out by TRINCARDI *et al.* (1987), wherear the fault scarps extending onland show, in places, to have undergone at least one phase of marine erosion and, therefore, to have played a role of sea cliff during the Quaternary time.

(*) Dipartimento Scienze Geologiche, Università di Catania, Corso Italia 55, Catania 95129
Email: mbianca@mbox.unict.it

Southwards, the promontory is abruptly truncated by two main WNW-ESE trending and south-dipping normal faults (Coccorino Fault and Nicotera Fault) that bound the Capo Vaticano structural high from the Gioia Tauro basin whereas, landward, a NE-SW-striking, SE-facing normal fault segments (Mileto Faults) separate the promontory from the Mesima basin.

The Capo Vaticano area also shows several orders of marine terraces (Fig.1) represented by wave-cut surfaces and/or thin-depositional platforms, which, are the result of the interaction between tectonic uplift and eustatic sea level changes (WESTAWAY, 1993).

The Quaternary period was marked by cyclic glacio-eustatic global sea-level changes which are well recorded by the curve of the oxygen isotope time scale (OIT) (SHACKLETON & OPDYKE, 1973; IMBRIE *et al.*, 1984; MARTINSON *et al.*, 1987; BASSINOT *et al.*, 1994). Based on the variations of the ^{18}O / ^{16}O ratio (δ ^{18}O), this curve shows a cyclic trend characterized by peaks corresponding to distinct marine interglacial high stands, represented by the odd-numbered oxygen isotope stages (OIS), and marine glacial low stands, indicated by the even-numbered OIS (Fig.2). The absolute sea-level variations, calculated for the peaks related to the last 400 kyr of the OIT curve and represented by the eustatic curve (CHAPPEL & SHACKLETON, 1986; MERRITTS & BULL, 1989; CHAPPEL *et al.*, 1996), show a trend quite concordant to the isotopic curve for the last 400 kyr, and therefore can be assumed as a world-wide reference. The absolute sea-level variations range from about 130 m below the present sea-level, during the last glacial climax, up to 6 m above the present sea-level during the Eutyrrhenian interglacial period (Fig.2).

Since the inner edges of the terraced surfaces represent the paleo-shorelines corresponding to the main eustatic highstands of the reference global eustatic curve (BLOOM *et al.*, 1974; LAJOIE, 1986; BOSI *et al.*, 1996), related to the interglacial periods, the Quaternary marine terraces and paleo-shorelines are visible only in uplifted regions, with a number of orders rising with the increasing of the uplift rate. By combining ages and elevations of paleoshorelines with the oxygen isotope stages of the high sea-level stands and absolute sea-level variations, it is thus possible to accurately evaluate the uplift rates of rising coastal regions (WESTAWAY, 1993; ARMIJO *et al.*, 1996; BIANCA *et al.*, 1999). Moreover, data from the vertical distribution of the paleoshorelines can provide useful information on the deformation of a region patterns and their change with time.

The aim of this study is to quantify the uplift rates of the Capo Vaticano area and their changes in space and time during the Middle-Late Quaternary by the analysis of the marine terraced sequence. The mapping of the marine terraced surfaces and their relative inner and outer edges has been carried out by the accurate analysis of the 1:25.000 and 1:10.000 scale topographic maps of the Istituto Geografico Militare (I.G.M.), SPOT satellite images and 1:33.000 scale aerial photographs, integrated by a detailed field work.

2. MARINE TERRACES

Six different orders of well preserved Quaternary marine terraces and a top continental surface, here numbered I to VII starting from the highest and oldest, have been recognized both on the structural high of Capo Vaticano and along the northern edge of the Gioia Tauro Basin (Fig.1). The inner edges of the marine terraces have been mapped with an uncertainty in the elevation of ± 5 m. However, this uncertainty, which basically depends on erosional and depositional processes following the emergence of the terrace, is negligible when estimating the long term Quaternary uplift rates involving time span of tens to hundreds of thousands of years. This implies that the elevations of the inner edges reported in this paper must be considered as mean values useful for estimating the regional uplift of the entire area during the Late Quaternary (Tab.1).

The marine terraces show a good morphological continuity and extend with a concentric geometry on the Capo Vaticano promontory. The terraced wave-cut surfaces are carved both on coeval marine deposits, on the Mio-Pliocene sediments, and on the Paleozoic metamorphic basement. The Quaternary terraced deposits are generally constituted by silicoclastic sands and coarse sandstones with a fossiliferous content mostly represented by poor microfaunas.

With regard to the areal extension of the terraced surfaces, it mainly depends on the duration of the relative sea level stand, the erodibility of the local substratum and its original morphology (e.g., fault scarps, large coastal plain, etc.). Taking into account the lithological homogeneity of the Capo Vaticano promontory, the original morphology of the substratum is the factor that mostly determines the width of a single marine platform. In fact, the width of the

Order of inner edge	Inner edge elevation in different sections (m)			OIT stage	Age (kyr)	Sea level correction
	Briatico	Tropea	Capo Vaticano			
VII	30	60	75	3.3	60	+ 28
VI	70	105	125	5.1	80	+ 19
V	100	175	175	5.3	100	+ 9
IV	216	300	300	5.5	125	- 6
III	270	360	360	7.1	200	+ 7
II	440	500	500	7.5	240	+ 10

Tab.1 - Elevations of the inner edges measured in Briatico, Tropea, Capo Vaticano.

marine surfaces ranges from few meters, if carved on a cliff, to several hundred meters, if formed on a flat or slightly inclined coastal plain.

In order to analyze the areal variation of the inner edge altitude, we have longitudinally projected the profiles of the inner edges on a ENE-WSW trending segment, extending for about 30 km from Pizzo to the western edge of Capo Vaticano, parallel to the present shoreline (A-A' in Fig.1). The strandlines of the terraces II - VII increase in elevation from ENE to WSW (Fig.3), displaying a deformation pattern characterized by a westward divergent geometry. South of M. Poro (Fig.1), the Coccorino Fault breaks the continuity of the marine terraces, that, on the hangingwall, are located at lower elevations.

Terrace I, the highest and oldest surface of the study area, is constituted by a gently undulated surface extending from M. Poro to Vibo Valentia at an elevation ranging from about 420 m to more than 650 m. Along the southern edge of the Capo Vaticano promontory, Terrace I is downdropped toward the Gioia Tauro basin, together with the other terraced orders, by the Coccorino Fault. Eastward, this terrace is cut by the NE-SW-striking, SE-dipping Mileto Faults,

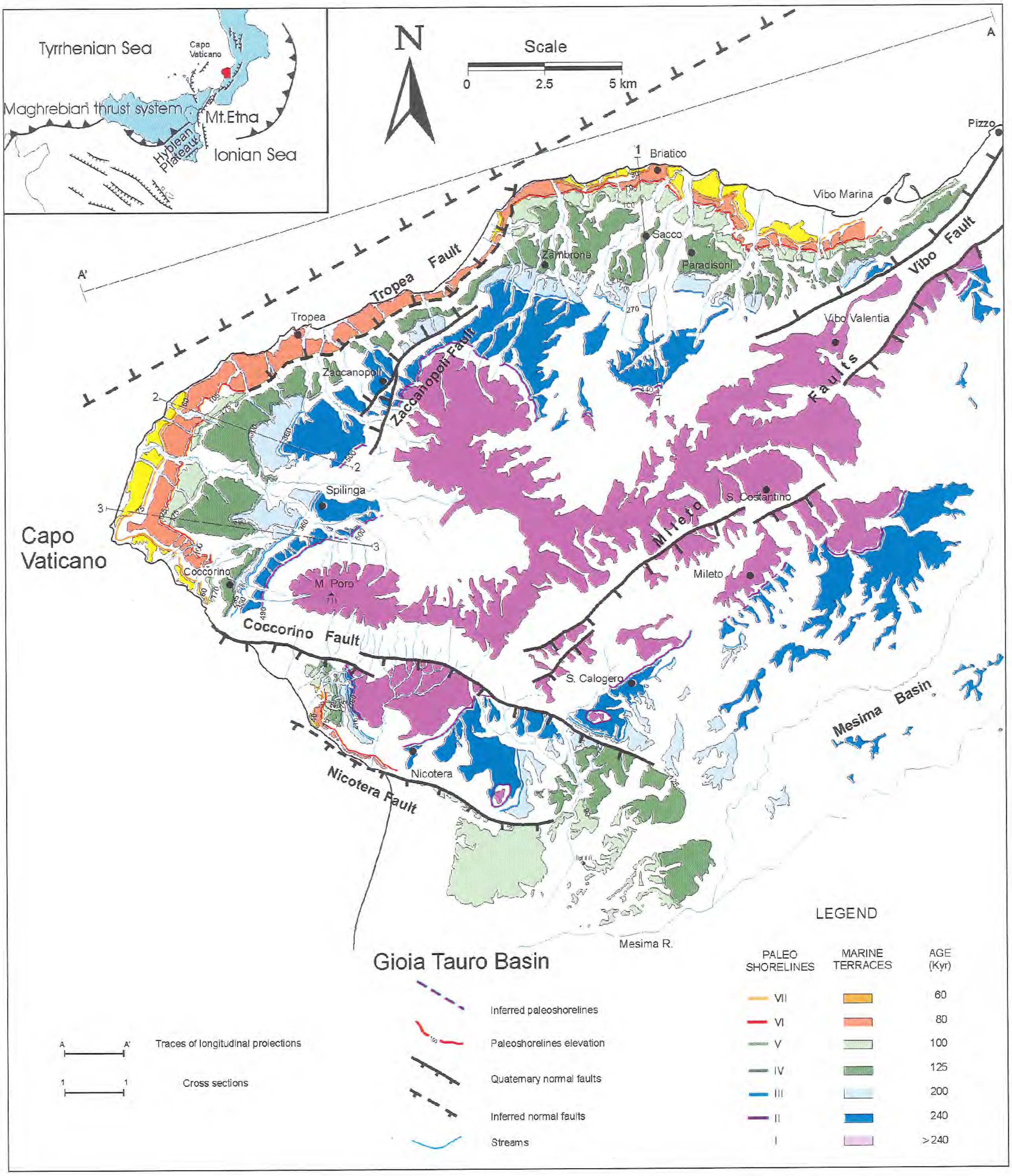

Fig. 1 - Morphotectonic map of Capo Vaticano promontory.

which separate the promontory from the Mesima basin. Unlike the other terraces, Terrace I shows a morphology characterized by large, smoothed valleys that, indicating a low energy relief, suggests a long period of continental erosion. Near Mileto, this surface is related to about 10 meters thick sequence made of cross-bedded fossiliferous calcareous sandstones and massive sands containing pumiceous and cineritic layers of calc-alkaline composition (CELLO *et al.*, 1983), capped by red to brown soil which in some places rest directly above the highly weathered Paleozoic crystalline basement.

Terrace II extends around the top relief of the Capo Vaticano promontory, both on the Tyrrhenian margin and along the Mesima valley, showing a width ranging from few meters, north of Vibo Valentia, to several hundreds meters, south of Tropea and east of Mileto. The inner edge of Terrace II is located at a minimum elevation of ~ 250 m and a maximum elevation of ~ 530 m. This surface is mainly erosional and only in a few places (i.e. near the Spilinga village) cross-laminated marine sands, belonging to Terrace II, occur. Although several patches occurring in the Mesima basin have been ascribed to Terrace II, based on their position in the terraced sequence, they show morphological features typical of the fluvial-coastal terraces (i.e. the inner edge characterized by an elevation decreasing downstream and by a trend parallel to the flanks of the basin, etc.). Moreover, along the Vibo Fault, Terrace II is represented only by a patch carved on the fault scarp, whereas, near the Zaccanopoli village, this terrace is displaced by the Zaccanopoli Fault, with a vertical offset of about 50 m.

Terrace III shows a trend similar to the terrace II and it is bounded landward by an inner edge that develops at elevations ranging from ~ 190 m to ~ 370 m. This terrace shows a good continuity in the Briatico area and between Tropea and Coccorino, where it is diplaced by the Coccorino Fault. Eastward, in the Mesima basin, several remnants of Terrace III are characterized by an inner edge which, extending perpendicular to the valley, can definitely be considered as a marine palaeoshoreline.

Terrace IV is characterized by the widest marine surface and the most continuous inner edge, that extends from ~ 110 m near Vibo Valentia up to more than 290 m, near Coccorino. It is usually represented by a thin depositional platform constituted by littoral sands with lenses of conglomerates. Furthermore, Terrace IV is the only one forming a wide wave-cut platform carved on the Vibo Marina sea-cliff, except Terrace V, which is represented by a narrow platform. Based both on its morphological continuity and on geochronological data (see below), this terrace can be considered one of the reference levels of the whole terraced sequence.

Terrace V is a narrow erosional platform bounded by an inner edge located at an elevation ranging from ~ 45 m to ~ 180 m. The continuity of this marine surface is interrupted between Tropea and Zambrone, where Terrace V is represented only by its inner edge, carved on the paleocliff of the Tropea Fault.

Terrace VI shows a very good morphological continuity and most of the coastal villages are located on its top surface. The inner edge extends parallel to the present coastline with an elevation of ~ 30 m up to ~ 120 m.

Finally, Terrace VII, the youngest and lowest order of the whole flight of marine terraces, is represented by a discontinuous and narrow surface, bounded by an inner edge extending from ~ 25 m a.s.l. in the Briatico area to a maximum elevation of ~ 75 m close to Capo Vaticano.

Southward, in the Gioia Tauro basin, a trough filled by a thick Neogene-Quaternary sedimentary succession, the terraces are down-dropped by the Nicotera fault and show inner edges marked by morphological scarps less evident than those occurring on the promontory. In a more detail, Terraces IV and V are the youngest marine terraces occurring in the basin and are bounded by inner edges which extend at mean elevations of 125 m and 90 m, respectively. The present elevations of these inner edges provide a mean value of uplift rate of about 1 mm/yr, which is high enough to preserve the whole Middle-Upper Pleistocene marine terraced sequence. Consequently, the occurrence of Terraces VI and VII beneath the alluvial deposits of the Mesima river can be inferred.

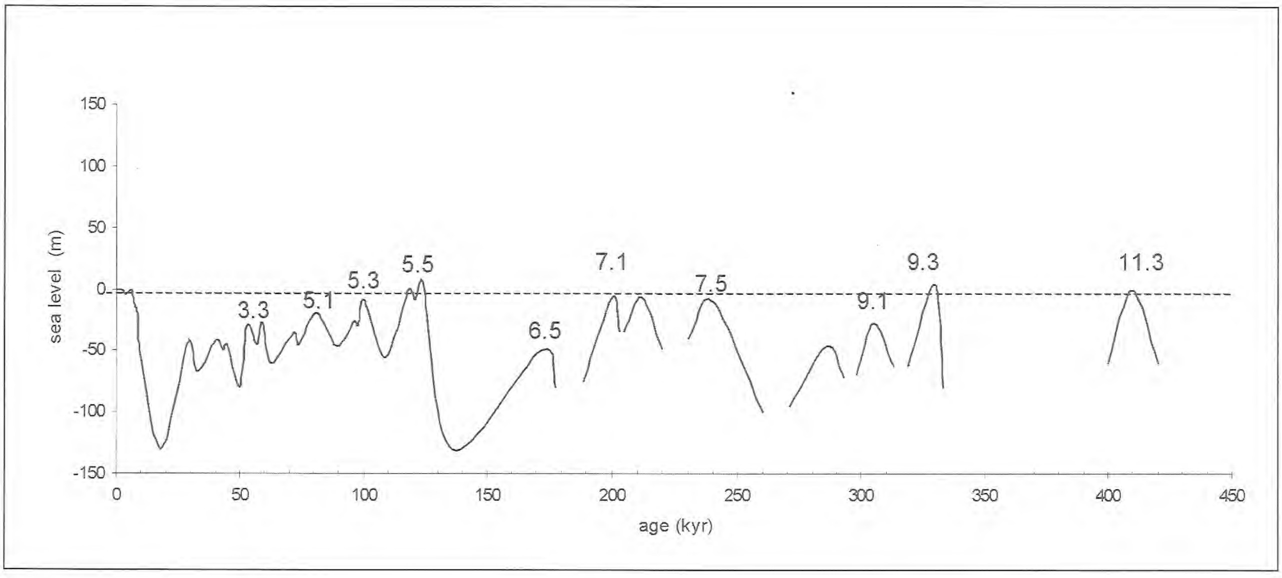

Fig. 2 - Reference eustatic curve. Numbers indicate the Oxigen Isotope Stages (OIS). From CHAPPEL & SHACKLETON (1986), modified.

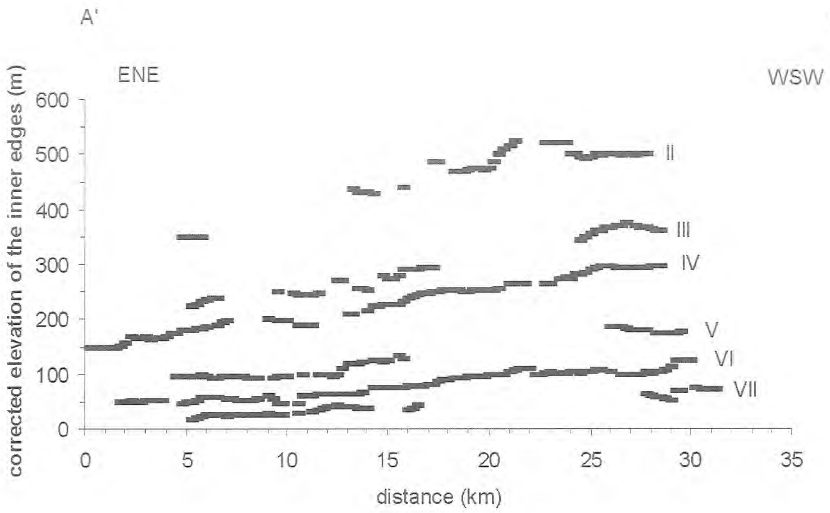

Fig. 3 - Longitudinal projection on a ENE-WSW direction (A-A' in Fig. 1) of the distinct inner edges.

3. UPLIFT RATES

In order to obtain quantitative information about the age and rates of vertical tectonic movements from the analysis of the flight of raised paleoshorelines, we need as many chronological constraints as possible. Although most of the marine surfaces in the Capo Vaticano area are represented by wave-cut platforms carved both on the metamorphic basement and on the Miocene and Pliocene sediments, some terraces are characterised by the occurrence of coeval marine deposits, mainly represented by littoral sands. Some of these terraced sediments have been object of several geochronological studies based both on biostratigraphical and absolute dating, this last mostly represented by U/Th, amino-acid and thermoluminescence (TTL) methods.

DUMAS *et al.* (1991) and DAI PRA *et al.* (1993) using the U-Th method, date to 130 ± 8 kyr and 121 ± 7 kyr, respectively, a coral sample of *Cladocora coespitosa* found, together with *Strombus bubonius*, in a terraced beach level (Terrace VI in this paper) near Vibo Valentia Marina whose shoreline is located at about 50 m a.s.l..

BONFIGLIO *et al.* (1988) report the presence of *Strombus bubonius* in terraced deposits of Contrada Iannì, near S. Calogero village, here referred to Terrace V, whose inner edge is located at 80 m.

On the basis of the occurrence of *Strombus bubonius* in several marine deposits, some authors have located the inner edge of the 125 kyr terrace at systematically lower elevations (COSENTINO & GLIOZZI, 1988; DUMAS *et al.*, 1991; MIYAUCHI *et al.*, 1994; etc.). In recent studies, the reliability of the attribution of the *Strombus bubonius*-bearing deposits to the OIS 5.5 (125 ky), largely accepted and considered almost certain, has been questioned and the possibility to correlate the *Strombus bubonius* to interglacials peaks younger than OIS 5.5 (i.e. 5.3 and 5.1; see Fig.2) has been suggested (MC LAREN & ROWE, 1996).

In this paper, Terrace IV has been related to the OIS 5.5 (125 kyr), corresponding to the Eutyrrhennian age, using TL age estimations recently obtained by BALESCU *et al.* (1997) for terraced marine sands outcropping in the Paradisoni and the Sacco area. This chronological attribution is confirmed by paleontological data of BARRIER *et al.* (1988) which, on the basis of the occurrence of a Senegalese fauna, date to the Tyrrhenian age the marine deposits cropping out near the Coccorino village, at an elevation of about 290 m, and belonging to Terrace IV. These chronological data are consistent with the deformation model of marine terraces (see Section 1) characterized by the correspondence between the inner edges and the main Quaternary interglacial high-stands of the global eustatic curve. For these reasons, Terrace IV has been chosen as a reference level, in order to reconstruct the geochronology of the terraced sequence of the Capo Vaticano area.

Since the present lowest elevation of the inner edge of Terrace IV indicate a minimum uplift rate sufficient to allow the recording of the entire sequence of the last major eustatic interglacial peaks, and considering the flight of marine terraces as a continuous set of morphological elements, the other five inner-edges of the observed marine terraces (Terraces II, III, V, VI and VII) have been ascribed to the other five main high-stands of the eustatic curve occurred from 240 kyr to 60 kyr (OIS 7.5, 7.1, 5.3, 5.1 and 3.3 respectively; see Tab.1).

In order to analyze the vertical distribution of the inner edges, three reference topographic sections, corresponding to the Briatico, Tropea and Capo Vaticano areas, have been carried out (Fig.4). The elevations of the inner edges of the terraces II to VII have been corrected for the sea level changes displayed by the reference eustatic curve and have been plotted against time. We obtained three velocity diagrams, showing the variations of the uplift rates along the reference sections during the last 240 kyr (Fig.5).

The estimated uplift rates displayed in these age-altitude diagrams range from 0.89 to 4 mm/yr. All the three diagrams show an almost similar trend, characterized by sudden acceleration and deceleration in the velocity of uplift. This feature, together with the very high values of uplift rate (up to 4 mm/yr) reached during certain time intervals, suggest a strong tectonic component in the total amount of uplift, probably related to the Late Quaternary

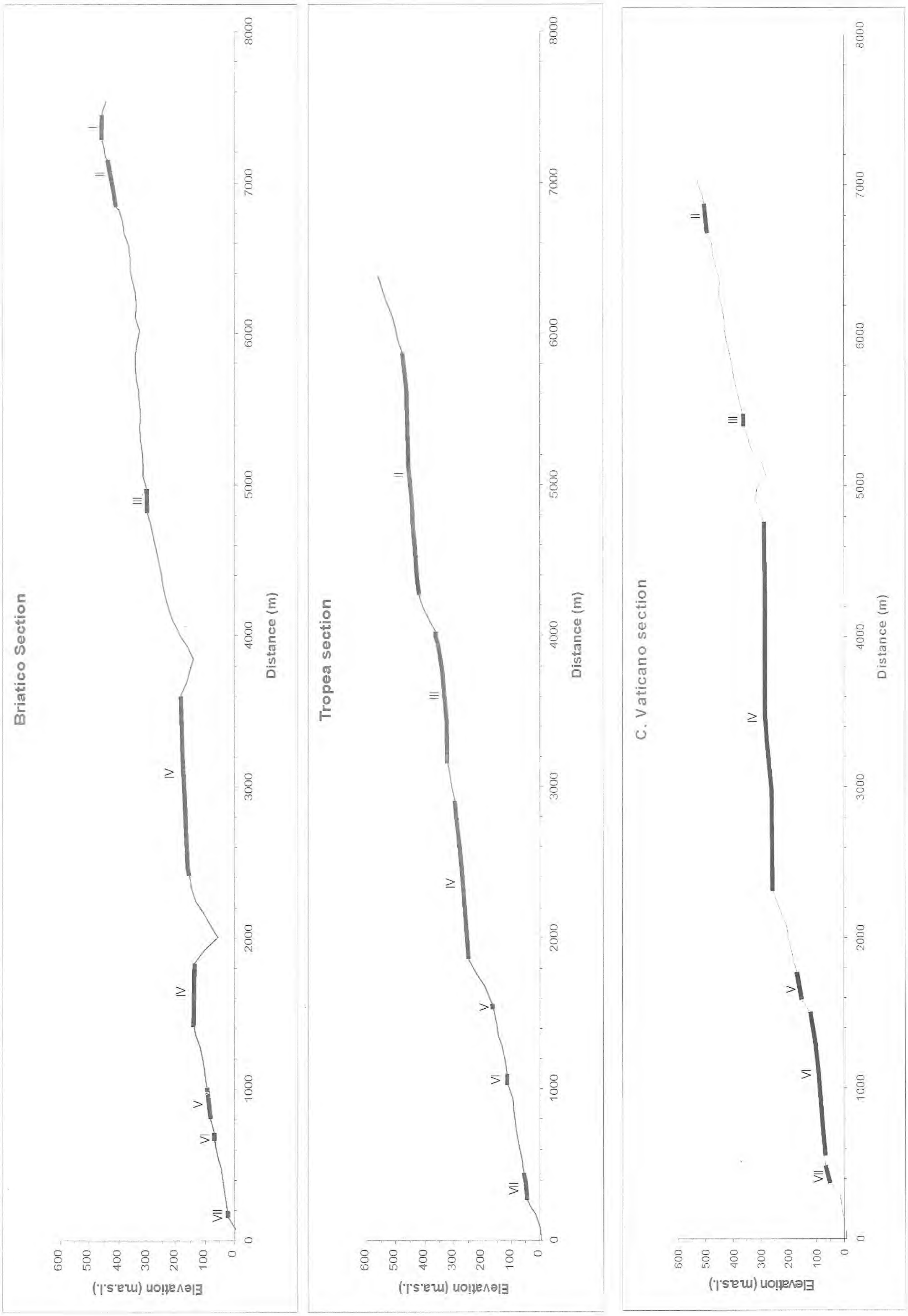

Fig. 4 - Topographic sections of Briatico, Tropea and Capo Vaticano areas (1, 2 and 3, respectively, in Fig. 1). The black segments indicate the distinct terraced surfaces.

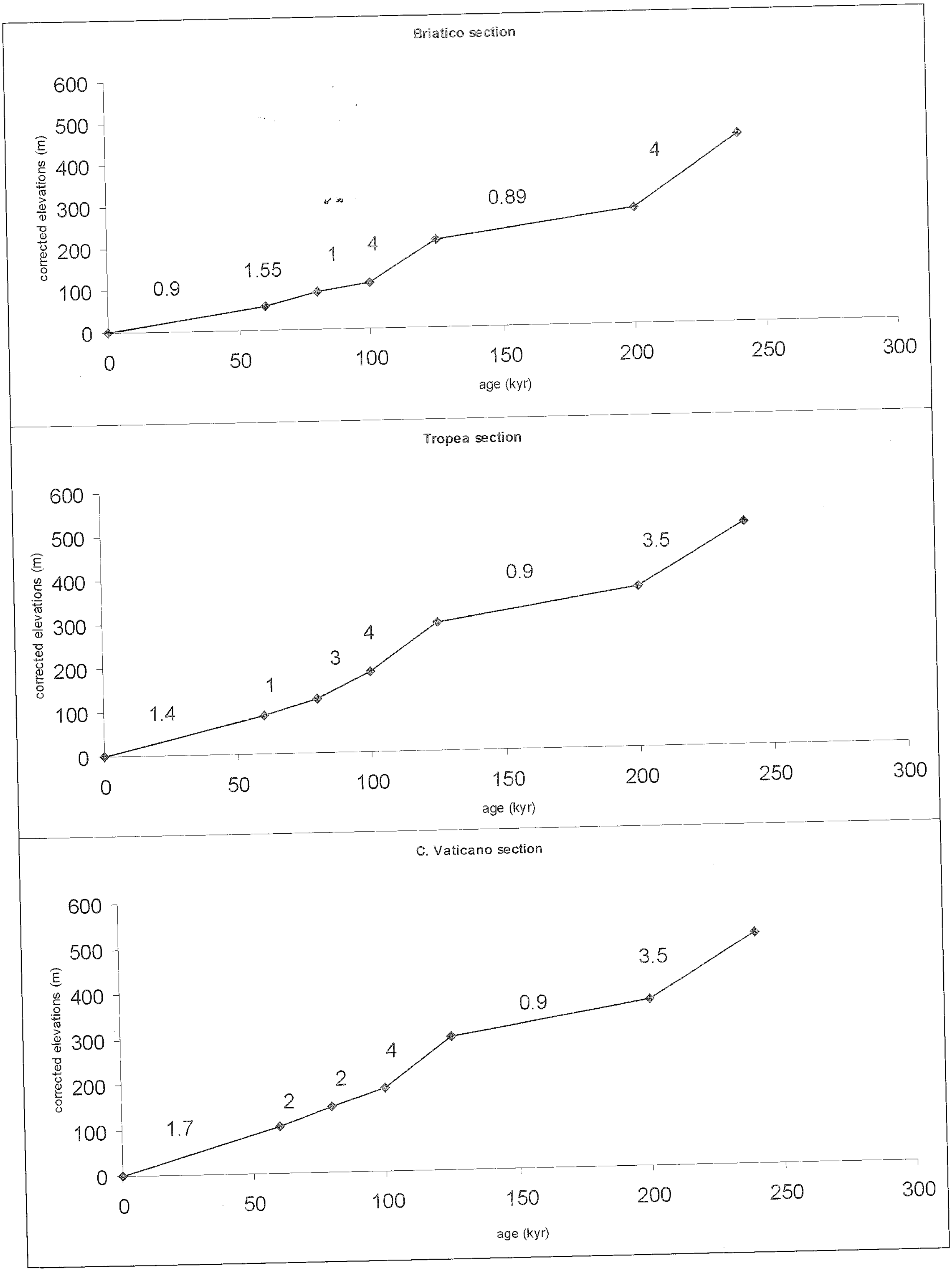

Fig. 5 - Diagrams showing uplift rates along the Briatico, Tropea and Cape Vaticano sections (1, 2 and 3, respectively, in Fig. 1). Uplift rates, expressed in mm/yr, are obtained for the last 240 kyr fitting the elevations of the different inner edges corrected for sea-level changes.

activity of the normal fault system located in the northern offshore of Capo Vaticano. The differences in the uplift rates recorded in the three distinct sections during the same time intervals may indicate that the rates of activity of the fault system changed in space and times during the last 240 ky. On the other hand, the lowest values of the uplift rates (less than 1 mm/yr) could approximate the regional component of uplift in the overall amount of vertical movement (WESTAWAY, 1993).

4. CONCLUSIONS

The geomorphological analysis of the Capo Vaticano promontory allowed us to recognise seven orders of terraced surfaces, here named Terrace I to VII from the oldest to the youngest. Terrace I is interpreted as an ancient continental surface, whereas the other six orders are represented by marine terraces with their relative inner edges.

The six orders of paleoshorelines, wich bound handward the terraces II to VII, have been ascribed to the last six main OIT stages and sub-stages (OIS) of the reference eustatic curve: Terrace II to OIS 7.5 (240 kyr), Terrace III to OIS 7.1 (200 kyr), Terrace IV to OIS 5.5 (125 kyr), Terrace V to OIS 5.3 (100 kyr), Terrace VI to OIS 5.1 (80 kyr) and Terrace VII to OIS 3.3 (60 kyr).

The longitudinal projection of the paleoshorelines and the velocity diagrams carried out in three reference sections (Briatico, Tropea and Capo Vaticano) indicate a tectonic deformation pattern of Capo Vaticano area changing both in space and time during the last 240 kyr. The tectonic uplift recorded along the northern coast of the promontory is characterized by rates increasing southwestward and ranging from 0.89 mm/yr to 4 mm/yr. The overall uplift rate of this area since 240 kyr can be considered mainly as the result of the combined tectonic activity of the ENE-WSW striking normal faults occurring along the northern offshore of Capo Vaticano and the WNW-ESE trending Coccorino and Nicotera segments, all belonging to the Siculo-Calabrian Rift Zone.

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