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GEOCHRONOLOGY OF PLEISTOCENE MARINE TERRACES AND REGIONAL TECTONICS IN THE TYRRHENIAN COAST OF SOUTH CALABRIA, ITALY

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RIASSUNTO - *Geocronologia e tettonica dei terrazzi marini della costa tirrenica della Calabria meridionale* - Il Quaternario, **7** (1), 1993, 17-34. Lungo la costa tirrenica della Calabria, dalla penisola di Capo Vaticano allo Stretto di Messina, sono stati distinti almeno dodici ordini di terrazzi marini contrassegnati da I a XII. La linea di costa del terrazzo più alto (I) raggiunge 1350 m sul versante sudoccidentale dell'Aspromonte. Sulla base di correlazioni geomorfologiche, biostratigrafiche e una datazione Torio-Uranio, tutti i terrazzi rilevati sono stati riferiti al Pleistocene. I terrazzi I-II si sono formati in corrispondenza di un alto livello del mare interglaciale, 1000÷1200 ka dal presente; il terrazzo IV, riferito allo stadio isotopico 25 (circa 950 ka), corrisponde ai depositi sommitali a *Globorotalia truncatulinoides* e *Hyalinea balthica*; il terrazzo VII è riferito allo stadio 9 o 11 (ca. 300-400 ka); il terrazzo X, con depositi a *Strombus bubonius* e un'età Uranio-Torio di 121±7 ka, ottenuta su Coralli, si colloca nello stadio 5e, corrispondente al picco principale dell'ultimo interglaciale (trasgressione eutirreniana). L'andamento delle quote delle linee di riva sollevate é variabile, gli spostamenti per faglia risultano diacroni e non uniformi. Nel Pleistocene inferiore (circa 1200-900 ka) sono prevalsi sollevamenti a duomo (dell'ampiezza di 50 km), causati probabilmente da intrusioni diapiriche dalla parte superiore del mantello, contemporanee a movimenti estensionali iniziati nel Pliocene. Sono stati individuati tre centri locali di sollevamento: Monte Poro, Le Serre, Aspromonte. In particolare, in corrispondenza dei versanti sudoccidentali dell'Aspromonte si sono sovraimposte faglie gravitazionali a faglie normali, simultaneamente a rapidi sollevamenti a duomo (tasso massimo di 3,8 m/ka). Le deformazioni gravitazionali implicano fenomeni di collasso verificatisi lungo i pendii del duomo crostale in rapido sollevamento. A partire dal tardo Pleistocene medio (ca. 300 ka), invece, è prevalso un sollevamento regionale generalizzato con un tasso di 0,9-1,1 m/ka dell'arco calabro accompagnato da lievi inarcamenti. Nel promontorio di Capo Vaticano si è verificato un notevole sollevamento differenziale testimoniato dal terrazzo eutirreniano, posto a m 50 a Vibo Valentia Marina e a m 120 a Capo Vaticano, forse provocato dal protrarsi del sollevamento a duomo. Le faglie normali non presentano evidenza morfologica, posteriormente al Pleistocene medio, sebbene terremoti distruttivi abbiano interessato la Calabria in tempi storici.

ABSTRACT- *Geochronology of Pleistocene marine terraces and regional tectonics in the Tyrrhenian coast of South Calabria, Italy* - Il Quaternario, 7(1), 1993, 17-34 - At least twelve orders of marine terraces (named Terrace I to XII in this paper) are identified along the Tyrrhenian coast, from the Capo Vaticano Promontory to the Messina Strait, in southern Calabria (Italy). The shoreline of the highest terrace (Terrace I) reaches 1350 m in altitude around Aspromonte. On the basis of geomorphological and biostratigraphical correlation and uranium-series dating, all marine terraces are ascribed to an emergence in Pleistocene times: - terraces I and II are assigned to interglacial high sea levels around 1000÷1200 ka; terrace IV probably to the oxygen isotope Stage 25 (~950 ka); terrace VII is related presumably to Stage 9 (or to Stage 11) (~300÷400 ka); terrace X with *Strombus bubonius*-bearing sediments and the uranium-series age of 121±7 ka of *Cladocora* is ascribed to Stage 5e (~125 ka) corresponding to the last interglacial peak (Eutyrrhenian transgression). Altitude changes in elevated shorelines and fault movements show disuniform and differential tectonic phases in Pleistocene. Doming uplift manifested by warping (wavelength: ~50 km) prevailed in the Early Pleistocene (~1200÷900 ka), probably originating from an upper mantle diapiric intrusion into the crust, contemporary with an extensional normal faulting that started in Pliocene. Three local uplifting centres are identified: Monte Poro, Le Serre, and Aspromonte. In particular, around Aspromonte local gravitational faulting is superimposed onto normal faulting and is simultaneous with rapid doming uplift (the maximum rate being 3.8 m/ka). The gravitational features imply brittle collapses on slopes of the rapidly up-domed upper crust. A generalized regional uplift (0.9 ÷ 1.1 m/ka) has been dominant since Middle-Late Pleistocene (~300 ka), suggesting arc-wide crustal deformations in the Calabrian ridge, accompanied by gentle warping. At the Capo Vaticano Promontory the marked doming uplift continued, as shown by the Eutyrrhenian shoreline varying in elevation from 50 m at Vibo Valentia Marina to 120 m at Capo Vaticano. There are no geomorphological evidence of active normal faults after the Middle Pleistocene, even if severe earthquakes have interested southern Calabria in historical times.

Key words: Pleistocene, marine terraces, geochronology, biostratigraphy, warping and doming uplift, normal and gravitational fault, diapir, Calabrian Arc, southern Italy.

Parole chiave: Pleistocene, terrazzi marini, geocronologia, biostratigrafia, sollevamento a duomo, faglie normali e gravitazionali, diapiro, arco calabro, Italia meridionale.

1. INTRODUCTION

The Calabrian Arc in southern Italy is known to be a tectonically active region in the Mediterranean Sea during Neogene times, resulting from interference between Eurasian and African plates and the Adriatic microplate (Fig. 1, inset, Dewey *et al.* 1973). Nevertheless, definite geometry and movement of plates are still obscure, and not widely discussed in previous works. The southern part of the Calabrian Arc is generally oriented in the NE-SW direction; a number of horst-graben features are arranged perpendicular to it: the Aspromonte-Serre range, the Mesima Gioia-Messina graben and the Capo Vaticano Promontory (Fig. 1). The Calabrian Arc is characterized by a NW-SE trending active extensional tectonics represented by normal faulting in

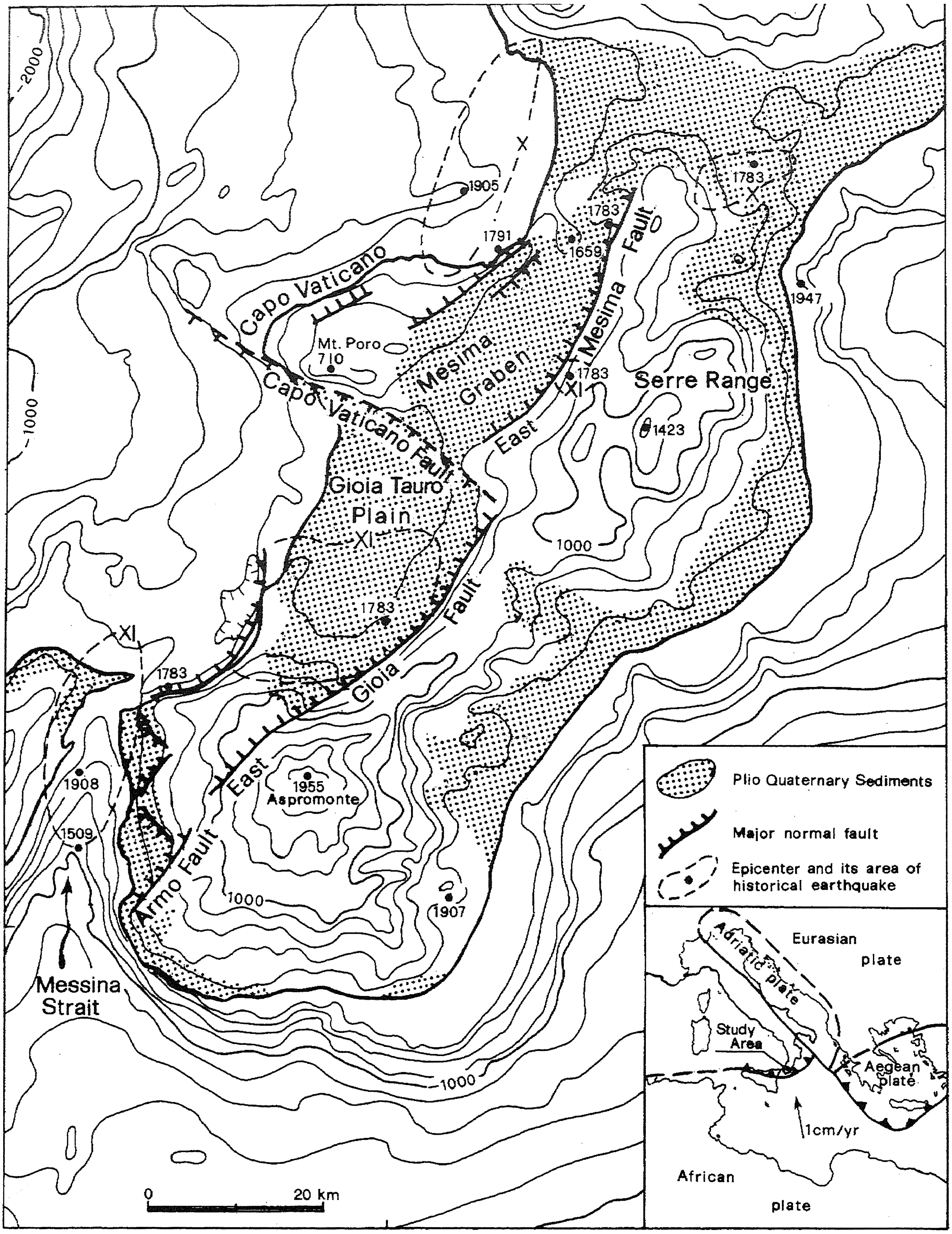

Fig. 1- Generalized topography in and around the South Calabria Promontory. Contour interval is 200 m. Historical earthquake data from Barbano *et al.* (1980). X and XI show intensity at the MSK scale, enclosed with fine dots. The inset shows the complex of plate configuration in central Mediterranean (simplified from Dewey *et al.*,1973). The arrow shows relative plate motion of African plate toward Eurasia plate. Plio-Quaternary sediments are adopted from Fabbri *et al.* (1980).

Principali elementi orografici e strutturali della Calabria meridionale. L'quidistanza è di 200 m. I dati sui terremoti storici sono ricavati da Barbano et al. *(1980). Le intensità X e XI della scala MSK sono rappresentate dalle linee tratteggiate. Il particolare in basso a destra mostra l'assetto delle placche nel Mediterraneo centro-orientale (semplificato da Dewey* et al. *1973). La freccia mostra il movimento relativo della placca africana verso la placca eurasiatica. La distribuzione dei sedimenti plio-quaternari è ripresa da Fabbri* et al. *(1980).*

Late Pliocene-Quaternary times (Ghisetti, 1979; 1981). Plio-Quaternary sediments are present mostly in major fault grabens (the Mesima graben, the Gioia plain and the Messina strait graben), and overlie a crystalline basement (Fabbri *et al.*, 1980).

A fine marine terraces flight with more than ten levels may be found on the Tyrrhenian Sea side of southern Calabria. These terraces are significant to elucidate global climatic changes and regional tectonic uplift in recent geological times. Cortese (1886) first described 1000 m high marine terraces around Aspromonte; these probably belong to the highest marine terraces on earth, and are noteworthy from a geomorphological point of view because of the very good conservation of their surface even at so great elevation.

Good quality objective terrace correlation is required to establish geochronology and to evaluate tectonic features in quantitative terms. Aerial photography provides geomorphological continuity and sequence of terrace units, the recognition of which lead to regional terrace correlations and their classification. Using this procedure (air-photo scale 1 : 33,000), a regional correlation and geochronology of marine terraces in the area from the Capo Vaticano Promontory to the Messina Strait is developed (Fig. 1), supported by micro-and macro-paleontological evidence and uranium-series dating from related terrace deposits. At least twelve marine terraces may be recognized in this area. Terrace age is discussed with reference to $d^{18}O$ records from deep-sea cores indicating climatic changes. Correlation between terraces indicates Quaternary crustal movements, paleoshoreline deformations and fault movements in the southern Calabrian Arc.

2. PREVIOUS STUDIES

A number of geochronological studies on marine terraces and sediments have been carried out on Quaternary sea level changes in southern Calabria, frequently together with studies highlighting implications of tectonic uplift and local fault movement. In particular, the last interglacial Eutyrrhenian marine terrace (125 ka, corresponding to the oxygen isotope Stage 5e) has been biostratigraphically recognized at several sites, based on the occurrence of Senegalese fauna with *Strombus bubonius* (Pata, 1947; Bonfiglio, 1972; Bonfiglio *et al.*, 1986; 1988). Hearty *et al.* (1986) and Hearty & Dai Pra (1985; 1992) estimated the age of interglacial marine deposits in South Italy at mean value of 122±7 ka by calibrating aminoacid ratios using uranium-series coral dates from the *Strombus* beds in Mar Piccolo (Taranto) (analyses by B. J. Szabo, Boulder). Dai Pra *et al.* (1993) estimated at 121±7 ka the uranium-series of a coral sample from *Strombus bubonius* bearing deposits of Vibo Valentia Marina in southern Calabria, mentioned by Pata (1947).

Dumas *et al.* (1987; 1988) attempted to construct a geochronology of marine terraces and vertical uplift history in some areas of South Calabria by combining morphometric analysis with aminostratigraphy. Their morphological criteria for terrace classification and correlations are however obscure and the presented uplift rates in Late Quaternary remains problematic for lack of objectivity. Barrier (1987) and Barrier *et al.* (1986; 1987) describe a biostratigraphy of Early Pleistocene successions in the highest marine terraces around Aspromonte. Their biochronology indicates that the Early Pleistocene marine terrace was uplifted up to more than 1000 m and that marine sedimentation was controlled by tectono-sedimentary basin forming through normal faulting during Late Pliocene to Early Pleistocene times.

Several studies on regional tectonics have been performed with reference to the geological evolution of structures, seismotectonics and geodynamics in the crust. Ghisetti (1979; 1981) clarifies, using detailed analyses of fault geometry and its mechanism, that the Calabrian Arc has been controlled by a strong extensional stress field since Late Pliocene. Ghisetti (1984) sustains that upheaval of the Calabrian Arc originates from the overthrusting of the Tyrrhenian crust onto the African Crust, simultaneously with normal faulting along the Messina Strait. On the contrary, Locardi & Nicolich (1988) propose a unifying theory that the intrusion of fluidized mantle from an asthenolith dome into the crust-mantle boundary is the factor determining the uplift of the Calabrian and Apennine arcs.

3. MARINE TERRACES AND THEIR RELATED STRATIGRAPHY

Photogrammetric interpretation and field observations have allowed us to distinguish at least twelve orders of marine terraces. Recognized marine terraces have been numbered, I to XII, starting from the highest. In general, each terrace is more or less developed (Plate 1) and is bounded by morphological scarps. More rarely, marine terraces developed in depositional basins, such as the Gioia Basin, are not easily distinguishable due to a lack of clear terrace scarps. Three terraces (Terrace I, VII and X) are the most continuous, and are used as key terraces for regional terrace correlation in the wide study area (100 km long). Marine terrace features, subsurface geology and biostratigraphical analyses are descriptively outlined below, in several conveniently separated areas.

3.1 Capo Vaticano Promontory

In this promontory, twelve even-spaced marine terraces, with the exception of the wide Terrace I, are distributed 450 to 620 m a.s.l. around the Mt. Poro (710 m a.s.l.) composed of metamorphic rocks.

Most terraces are abrasion platforms carved on

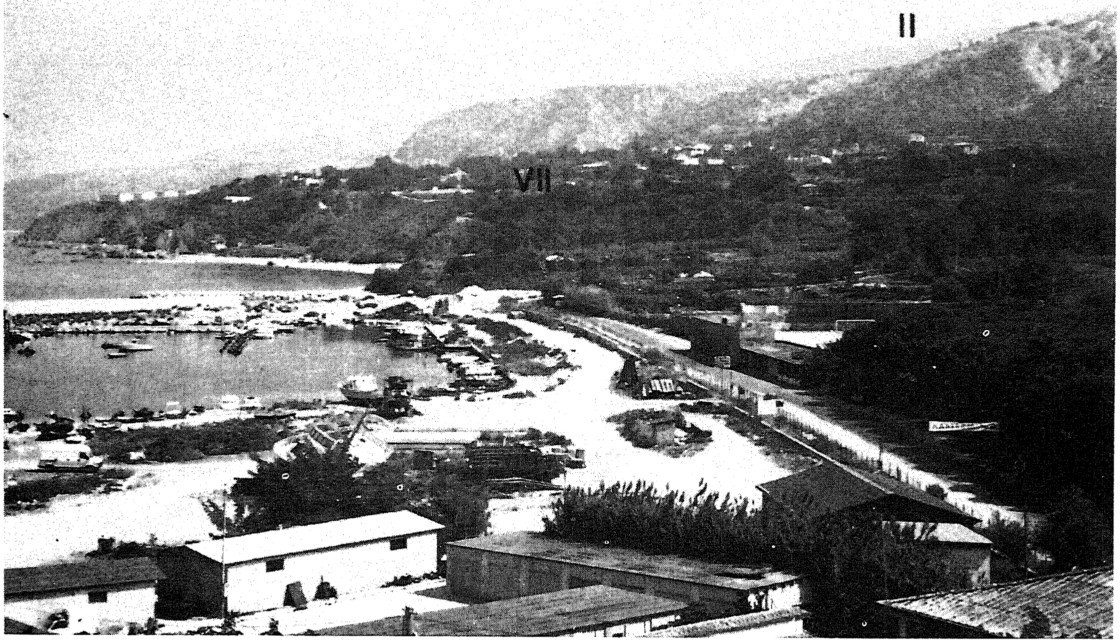

Fig. 2 - Marine terrace features near Pizzo Calabro viewed from Vibo Valentia Marina.
Terrazzi marini nei pressi di Pizzo Calabro visti da Vibo Valentia Marina.

either the crystalline basement or Miocene and Pliocene sediments. A thin deposit overlies the platform (Fig. 2 and 3; Plate 1, section A and B).

Mollusca assemblage and a coral sample have been taken from beach sediments at 28 m a.s.l., on Terrace X at Vibo Valentia Marina (Plate 1, A, "Loc. 1"). The coral sample has been dated to 121±7 ka with the uranium-series method (Dai Pra *et al.*,1993). Senegalese fauna, *Strombus bubonius,* is also found at the same horizon. Barrier *et al.* (1990) report a few taxa of Senegalese fauna from 260 m a.s.l. in the sea cliff between Coccorino and Ioppolo, corresponding to our Terrace VII (Plate 1). A >3 m thick paleosol is distinctly observed with some cracked pedogenic sublayers on Terrace I and II around Mt. Poro.

Near the coast at Capo Vaticano (Plate 1, "Loc. 2"), an emerged abrasion platform is recognizable at 1.8 m a.s.l. (Fig. 4), partly overlain by thin calcareous cement deposits. Emergence of these features appears to be associated with uplift in mid-Late Holocene time, because no evidence of a sea level stand higher than present is visible in the post glacial transgression around the southern Italian Peninsula (Antonioli & Frezzotti, 1989; Dai Pra & Hearty, 1989).

Ulzega & Ozer (1980) described emerged beachrocks between 0 and 0.50 m a.s.l. in Sardinia.

3.2 Mesima Graben

Both the western and eastern sides of this graben are structurally bounded by fault scarps (West Mesima Fault and East Mesima Fault) oriented NE-SW (Fig. 1; Ghisetti, 1979), and face the Gioia plain on the southern side. Thick Neogene-Early Pleistocene marine sequences crop out in the graben. Terrace VII around 300 m a.s.l. is traceable into the graben as a fluvial terrace, though its surface is mostly removed due to easy erosion (Plate 1). On the foot of the East Mesima Fault scarp, marine terraces are often covered by alluvial fan deposits.

Fossil samples from five sites at different elevation along the cross section B (Plate 1) in the central part of the Mesima Graben have been taken. Littoral sediments underlying Terrace II include macro- and microfauna species of *Groborotalia truncatulinoides*[1], *Hyalinea balthica* at "Loc. 4" (580 m a.s.l., Spilinga), and *Globo-*

[1] Dr. Conato maintains that it is very difficult to distinguish Sicilian *Globorotalia truncatulinoides excelsa* from Late Pliocene *Globorotalia truncatulinoides.* We think that the taxa *Globorotalia truncatulinoides* identified by him is *Globorotalia truncatulinoides excelsa,* because *Hyalinea balthica,* which is typical of the Emilian stage of Early Pleistocene, is found together with it in the same horizons of most collected samples.

Fig. 3 - Marine terraces near Capo Vaticano, viewed to NW. The central flat Terrace X is correlated with Stage 5e. Arrow shows the location of Fig. 4.

Terrazzi marini a Capo Vaticano visti verso N W. Il piatto terrazzo centrale XI è riferito allo stadio 5e. La freccia indica l'ubicazione della Fig. 4.

rotalia hirsuta, *G. puncticulata, G. crotonensis* and *G. inflata* at "Loc. 5" (480 m a.s.l., S. Costantino). The altitude difference between Localities 4 and 5 on the same Terrace II is caused by differential uplift as mentioned in Chapter 5. At "Loc. 6" (Francica) on Terrace IV, quartzitic littoral sand contains *G. truncatulinodes* and *H. balthica.* Terrace VII is an abrasional terrace on the underlying silt deposits bearing assemblages of *Hyalinea balthica, Globigerina pachiderma and Globorotalia inflata* at Localities 7 (Mutari), and. 8 (S. Angelo) in the Mesima Graben.

At Contrada Iannì (Plate 1, C, "Loc. 3"), alternative continental layers of eolian sand with Neanderthal skeletal remains and lagoonal deposits with *Cerastoderma Lamarki, Loripes lacteus* and *Scrobicularia plana* unconformably overlie 62 m high a.s.l. littoral deposits bearing *Strombus bubonius* (Bonfiglio *et al.*,1986, 1988). The marine-lagoonal cover beds have been associated with the high sea level stage younger than the stage producing the littoral deposits with *S. bubonius* related to the formation of Terrace X.

3.3 Serre Range

This mountainous range, with the peak of Mt. Pecoraro (1423 m), is a granitic massif. The shorelines of Terrace I, II, III and IV below 850 m a.s.l. extend in parallel with the East Mesima Fault, and suddenly disappear in the northern part of the East Gioia Fault. Each terrace is originally an abrasion platform with very few terrace deposits, and its surface often shows undulations modified by fluvial erosion. At "Loc. 9" (Monsoreto) a 3 m thick beach sand underlies Terrace III. Cracked paleosol are deeply developed around Terrace II (Plate 1 B, "Loc. 10" and Fig. 5).

3.4 Gioia Tauro Plain

This coastal plain is originally a fault graben thickly filled by Neogene-Quaternary sediments. The Gioia Tauro plain is clearly divided from the Serre-Aspromonte mountainous range by the 500 m high scarp of the East Gioia Tauro Fault. On the foot wall side, only Terrace I is seen around 1000 m a.s.l. (Plate 1).

Wide alluvial fans outcrop on the eastern part of the plain, superimposed on several marine transgressions. In particular, Terraces IX and X are landward gradually covered by alluvial deposits (Plate 1, D). Along the Rivers Vacale and Petrace, a fluvial terrace (terrace XIII) has been mapped, downcutting old marine terraces. This terrace is ascribed to the last glacial period. Many landslides concentrate in the southern part of the plain, and occur along the terrace margins (Plate 1).

3.5 Aspromonte

The Aspromonte massif is composed of granitic rocks and gneiss. NE-trending normal faults, including the East Gioia Fault, divide the northwestern part of Aspromonte into several blocks. Some conjugate faults

Fig. 4 - Emerged abrasion platform on granitic rocks, 1.8 m high above present sea level at "Loc. 2" near Capo Vaticano. Site locations as in Plate 1.
Piattaforma di abrasione su rocce granitiche, 1,8 m sul livello del mare attuale in Loc. 2 a Capo Vaticano. I numeri delle località sono indicati in Tavola 1.

along the Messina Strait shred, in a zigzag pattern, even. Neogene-Quaternary strata overlying the basement, as represented by the Armo(-Oliveto) Fault. Marine terraces are distributed in a complex way in and around such faulted blocks on Aspromonte.

Terrace I is remarkably developed and preserved at the high altitudes, from 1000 to 1350 m, and is locally displaced by faulting in Piani di Aspromonte (Plate 1, Fig. 6 and Plate 1, E and F). From Mt. Embrisi to Case Embrisi, 60 m thick calcareous-organogenic littoral sediments (Fig. 7) overlie the crystalline basement (Plate 1, G, inset); Mt. Embrisi is situated on Terrace I and Case Embrisi on Terrace II. These Monte Embrisi-Case Embrisi biogenic sediments are stratigraphically successive and are associated with the formation of Terrace I while Terrace II is an abrasional surface with beach gravel overlying these sediments. Mollusca taxa *Pseudoamussium septemradiatum* and *Arctica Islandica* are reported from the bottom of this succession by Barrier *et al.* (1986). Thin beach gravel and sand originating from granitic basement rocks also underlie Terrace II in Piani di Aspromonte (Fig. 6, E, "Loc. 11").

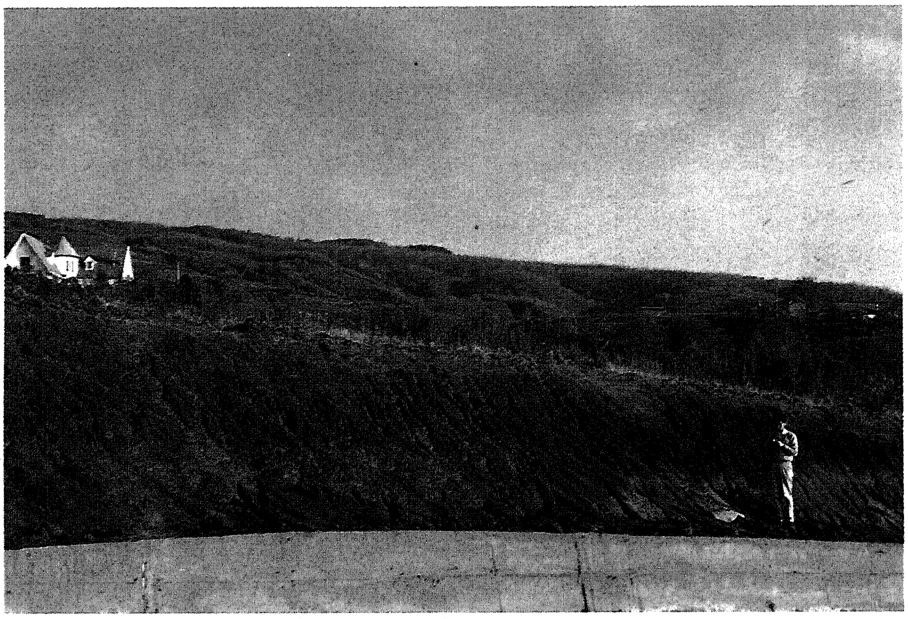

Fig. 5 - Well developed soil (2.5 YR 3/4) on Terrace II at "Loc.10" on the east of Arena in the Serre Range.
Suolo molto evoluto (2,5 YR 3/4) sul terrazzo II in Loc. 10 a Est di Arena (Le Serre).

Fig. 6 - The highest Terrace (I) differentiated into 2 levels by movements of the E Gioia Tauro Fault, near Gambarie on Piani di Aspromonte.
Il terrazzo più alto (I) dislocato in due livelli dalla faglia Gioia Tauro Est, nei pressi di Gambarie a Piani di Aspromonte.

Terrace III (700 ÷ 800 m a.s.l.) and Terrace IV (500 ÷ 600 m a.s.l.) are also well developed to the northwest of Piani di Aspromonte (Fig. 8), the shorelines of which correspond with original fault lines by chance (Plate 1, E). Terrace IV around Bagnara Calabra is clearly faulted suggesting a gravitational slide, and a down-slid block shows back tilting (Plate 1).

The coastal area below 500 m a.s.l. along the Messina Strait presents difficulties for the exact mapping of marine terrace distribution, because fluvial processes have considerably affected geomorphic evolution (Plate 1, F, G).

Along zigzag conjugate faults, scattered remnants of eroded terraces are visibile (Fig. 9, Armo Fault). These are underlain by littoral-infralittoral gravel deposits (the Pozzi Gravel) with remarkable content of *Pseudoamussium septemradiatum, Globorotalia truncatulinoides, Chlamys* and *Pecten*, which unconformably cover Pliocene strata at about 400 m (Plate 1, G, "Loc. 14" and Fig. 10). Terrace VII and X are relatively preserved and are covered by alluvial fans landward along rivers. Terrace X yields characteristically Senegalese fauna with *Strombus bubonius* in its terrace deposits at several sites: Archi, Ravagnese, Bovetto (Plate 1, G, "Loc. 13") and Nocella, with sample positions ranging from 120 to 150 meters in altitude.

A thick gravel formation (the Messina Gravel) is distributed in the limited coastal area below the elevation of about 350 m a.s.l. The formation bears Early Pleistocene marine macrofauna and is inclined at most 30 degrees seaward. Between the "Pozzi Gravel"-terrace and the terrace X deposits, it is not confirmed which marine terrace is related to this formation, which is chronologically located.

4. GEOCHRONOLOGY OF MARINE TERRACES

With support of paleontological analyses and uranium-series dating the formation age of marine terraces and their related layers can be estimated. In particular,

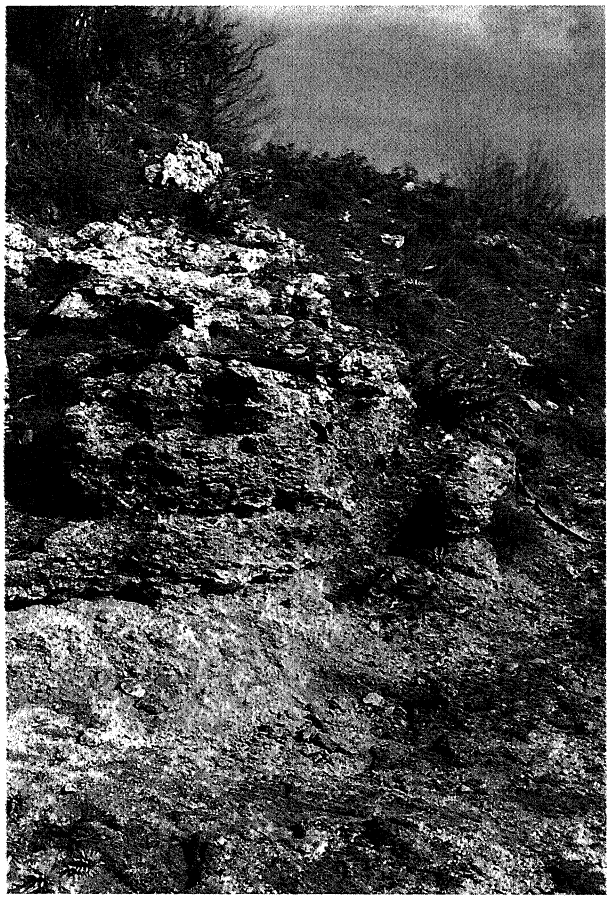

Fig. 7 - Fossiliferous littoral deposits at Monte Embrisi, 1040 m a.s.l.
Depositi littorali fossiliferi a Monte Embrisi, 1040 m s.l.m.

Fig. 8 - Terrace IV, about 600 m high a.s.l., near Melia, to the east of Villa S. Giovanni. This surface is back-tilted.
Terrazzo IV a circa 600 m di quota, a Piani di Melia a est di Villa San Giovanni. Questa superficie è tiltata verso monte.

Terraces I, IV, VII and X contain positive age information useful as reference terraces, in order to establish the chronological framework and to compare relative paleo-environments. A probable geochronology is proposed (Fig.11); this is discussed and compared with the ^{18}O (Oxygen isotope) record suggesting Quaternary sea level fluctuations and global climatic change. The biochronological scale by Shackleton *et al.* (1990) has been adopted since it includes recent reliable biostratigraphy and nomenclature. According to field investigations, the higher terrace tends to have more progressed pedogenesis, cementation and weathering of terrace deposits, which may be regarded as indices of terrace age.

4.1 Terraces I and II (Early Pleistocene around 1000÷1200 ka)

Barrier *et al.* (1986) firstly reported macro and microfauna from littoral sequences at Casa Embrisi (950 to 1020 m a.s.l.) and at Mt Embrisi (1051 m a.s.l.), Aspromonte. On the basis of the appearance of *Pseudo-amussium septemradiatum* and *Arctica islandica* in mollusca taxa, they considered the thick littoral deposition to date back to the Early Pleistocene. Present observations suggest that the formation of Terrace I is associated with these littoral deposits (Fig. 7) and Terrace II is an abrasion platform with beach gravel un-

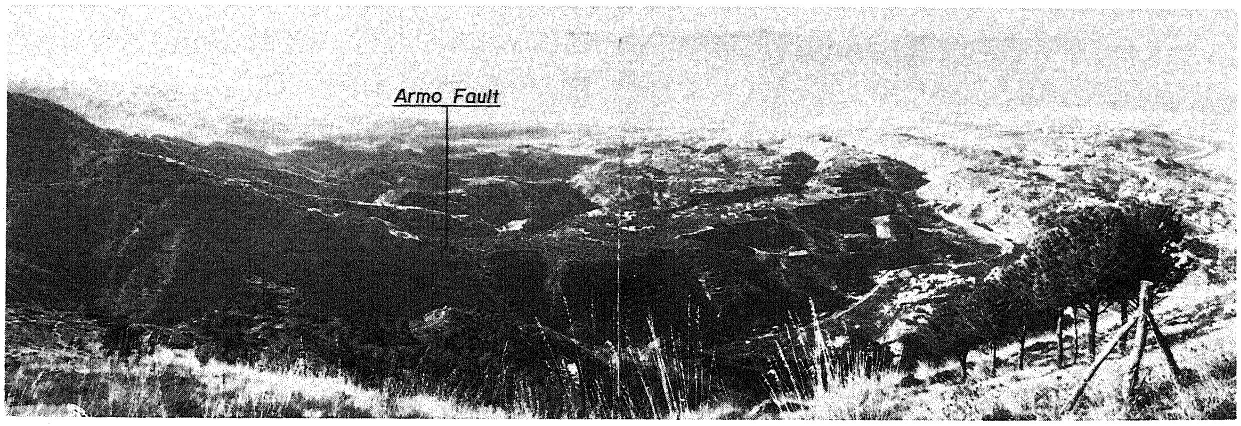

Fig. 9 - Southwest view of the fault scarp of the Armo Fault. Alluvial fans developed at the foot of the fault scarp; in the background, the Messina Strait and Sicily.

Vista sud-est della scarpata della faglia di Armo. Si possono osservare le conoidi alluvionali sviluppate al piede della scarpata di faglia e, sullo sfondo, lo Stretto di Messina e la Sicilia.

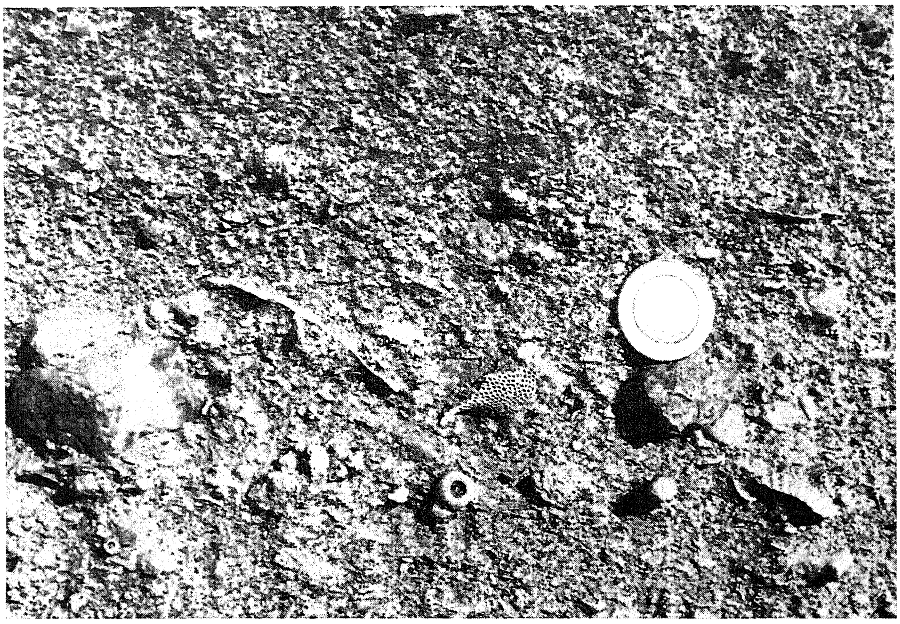

Fig. 10 - Circalittoral "Pozzi Gravel" deposit including many assemblages of macro- and microfauna, distinctly *Pseudoamussium septemradiatum* and *Globorotalia truncatulinoides*, at "Loc. 14" near Armo.

Le "Ghiaie di Pozzi" di ambiente circalitorale con ricca associazione di macro e microfauna, tra cui Pseudoamussium septemradiatum *e* Globorotalia truncatulinoides, *in Loc. 14, vicino Armo.*

conformable on these littoral deposits (Plate 1, G, inset).

Furthermore, this deposition of successive sediments is retroactive to the Emilian transgressive stage as indicated by the appearence of *A. islandica,* and the shallow water lithofacies of the upper part of sediments is implicated with the Sicilian regressive stage, often recognized in Italy. Thus, the final emergence of Terrace I is estimated to be occurred in the Early Sicilian stage around 1100÷1200 ka (Fig. 11); Terrace IV, which is lower than Terrace I, is also placed in the Sicilian stage.

Terrace I therefore seems to have recorded the first transgressive stage during Pleistocene in southern Calabria. Around Scalea in northern Calabria, Carobene & Dai Pra (1990) described the first order (V) terrace, 4 km wide and 100 to 500 m high a.s.l from North to South, underlain by marine sequences dating to Emilian transgression-Sicilian regression. Such wide terrace morphology and depositional cycle bear some similarity with the morphology of Terrace I and the Monte-Case Embrisi geologic section. This is the basis for accepting a correlation between Terrace I and their first order terrace.

Terrace II is underlain by infralittoral sediments with *G. truncatulinoides* ("Loc. 4", Spilinga) and is also assigned to the Sicilian stage, an interglacial peak 1000÷1100 ka ago occurring between the formation of Terrace I and Terrace IV.

4.2 Terrace IV (Oxygen isotope Stage 25)

Distinct foraminifera fossils, *Globorotalia truncatulinoides* and *Hyalinea balthica,* are recognized in littoral deposits at "Loc. 6" (Francica) and belong to Early Pleistocene according to the recent biostratigraphy proposed for Italy (Ruggieri *et al.*, 1984). The samples of molluscs and foraminifera from "Loc. 14" (Pozzi Gravel, Armo) similarly indicate that these date to Early Pleistocene, as they characteristically contain *Pseudoamussium septemradiatum* and *Globorotalia truncatulinoides.*[2] Thus, it is biostratigraphically confirmed that the infralittoral "Pozzi Gravel" is contemporaneous with the formation of Terrace IV near Francica.

Terrace IV may therefore be assigned to the Late Sicilian stage, because of appearence of *Globorotalia truncatulinoides* [2] which characterizes the Sicilian stage (Ruggieri & Sprovieri; 1975, Ruggieri *et al.*,1984) The emergence of Terrace IV took place probably around an interglacial peak, Stage 25 (ca. 950 ka), which is the last peak in the Sicilian period (Fig. 11).

The Messina Gravel showing deltaic lithofacies is chronologically placed between Terrace IV and Terrace X. Its steep gradient and limited distribution in the Messina graben indicate that the deposition of those beds is associated with severe tectonic movements and rapid sea level lowering, probably at the end of Early Pleistocene, as mentioned hereafter in Chapter 5.

4.3 Terrace VII (Oxygen isotope Stage 9 or 11)

This terrace, 140 to 430 m high a.s.l. is the most continuous and best developed amongst middle terraces. This feature and configuration permits Terrace VII to be associated with a major transgressive event older than

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(2) See footnote 1.

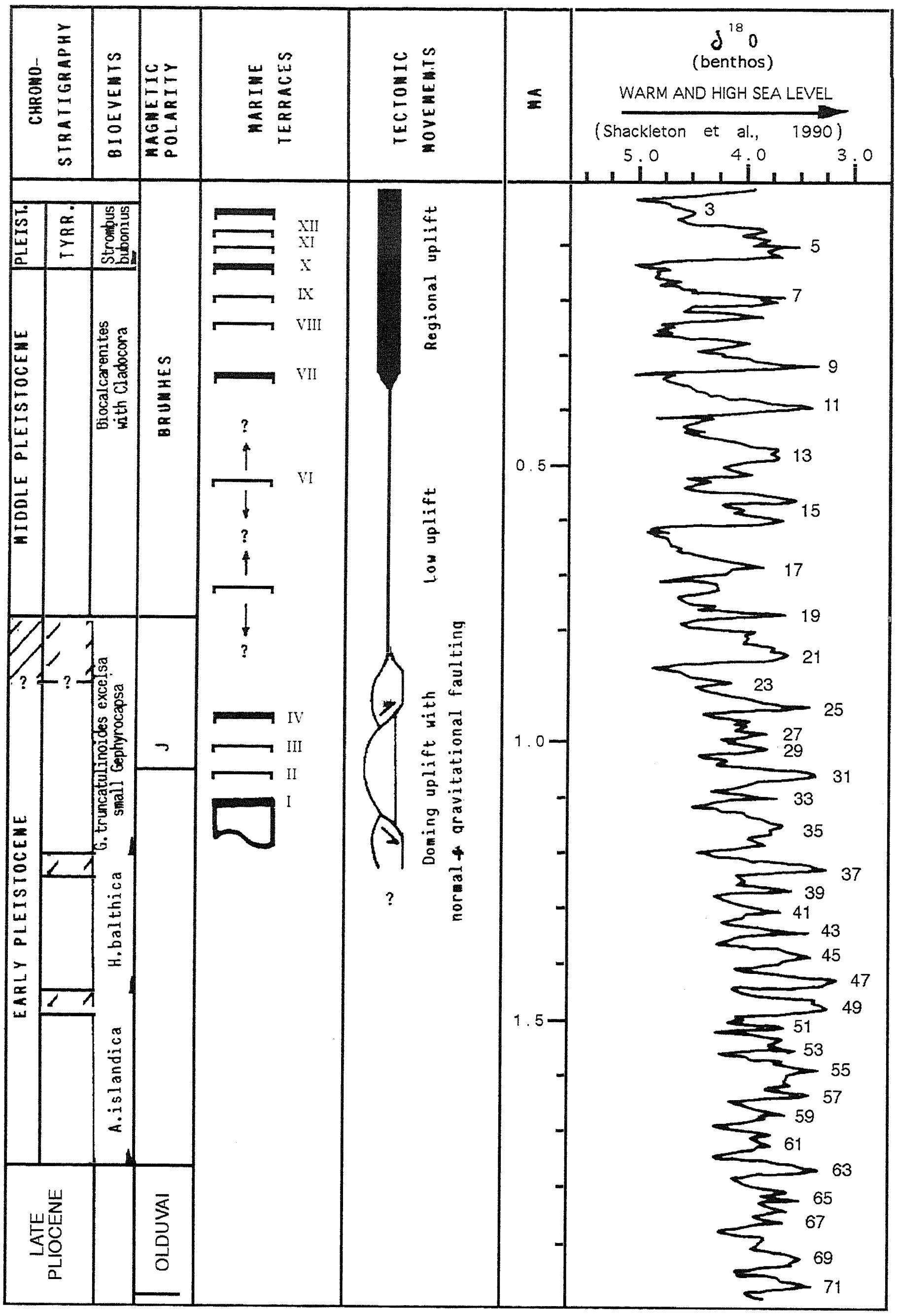

Fig. 11 - Geochronology of marine terraces and their relationship with the oxygen isotope curve (Shackleton *et al.*, 1990) and vertical movements.

Geocronologia dei terrazzi marini e loro correlazione con la curva isotopica dell'Ossigeno (Shackleton et al., *1990) e movimenti verticali.*

the last interglacial. Foraminifera and Ostracoda fossil samples (*Hyalinea balthica (Schr.), Globigerina pachyderma (F.), Bolivina pseudodigitalis (Di N.), Leptocythere multipunctata (Schr.*) taken from Locs. 7 (Mutari) and 8 (S. Angelo) show that Terrace VII was formed at a time younger than Early Pleistocene. Nannoplancton analyses performed by I. Raffi on terrace silt deposits at S. Angelo (260 m a.s.l.) showed the presence of *Gephyrocapsa oceanica*, which Rio *et al.* (1991) ascribed to the NN20 level corresponding to isotopic stages 9 - 11.

Barrier *et al.* (1990) found four species of Senegalese fauna not accompanied by the typical warm fauna of *Strombus bubonius*, at the 260 m high cliff between Ioppolo and Coccorino near Capo Vaticano, and ascribed them to the last interglacial Eutyrrhenian stage. This level is correlated with Terrace VII (Plate 1, B), here clearly higher and older than the 120 m high Terrace X, which corresponds to the last interglacial Eutyhhrenian stage, as mentioned below.

Appearance of these minor Senegalese fauna indicates that Terrace VII dates to a penultimate major interglacial either at Stage 9 (ca. 330 ka) or Stage 11 (ca. 400 ka), and is almost equivalent to Stage 5e in magnitude (Shackleton *et al.*, 1990; Hearty, 1991). This suggests that Stage 9 (as well as Stage 11) is volumet-rically the most important depositional event of Middle Pleistocene, after comparing the aminoacid geochronol-ogy in the Mediterranean Basin, Bermuda and the Bahamas.

4.4 Terrace X (Oxygen isotope Substage 5e)

This major transgressive terrace, 50 to 150 m high above sea level, is confidently correlated with the last interglacial Eutyrrhenian stage (corresponding to oxygen isotope Stage 5e), judged by the appearance of *Strombus bubonius* (Senegalese fauna) at many sites: Vibo Valentia Marina ("Loc. 1"), Contrada Iannì ("Loc. 3"; Bonfiglio *et al.*, 1986, 1988), Archi (Bonfiglio & Berdar, 1986), Bovetto (Loc.13), Ravagnese (Bonfiglio, 1972), and Nocella (Dumas *et al.*, 1987). Its presence suggests that winter sea surface temperature in this stage was 4° to 7°C warmer than present around Italy (Hearty & Dai Pra, 1987).

Dai Pra *et al.* (1993) presents the first uranium-series date of *Cladocora* (121±7 ka) at "Loc. 1" in southern Calabria. This absolute age corresponds well with those (ca.125 ka) from substage 5e deposits recognized worldwide. Such age correlation agrees with calibration age by aminoacid geochronological method in South Italy and in the Mediterranean (Hearty *et al.*, 1986; Hearty & Dai Pra, 1987; Dumas *et al.*, 1988).

4.5 Terrace XI (Oxygen isotope Substage 5c)

At Contrada Iannì (Plate 1, C, Loc. 3), lagoonal sediments with *Cerastoderma* on eolian sand, bearing a *Neanderthal* skull, overlie littoral sediments with *Strombus bubonius*. This indicates that the *Cerastoderma* bearing sediments, ca. 70 m a.s.l., is related with the next transgressive stage implied by Terrace XI after emergence of Terrace X. Ascenzi & Segre (1971) report that, also at Archi (Reggio Calabria), transgressive brackish sediments with *Tapes decussata*, ~90 m a.s.l. overlie fluvio-continental layers bearing *H. Neanderthal* remains; these transgressive sediments are stratigraphically over Tyrrhenian marine deposits and correspond to Terrace XI. These stratigraphic and morphological situations are very similar to each other, and imply a subsequent "post Eutyrrhenian transgressive stage", probably equivalent to Substage 5c, ~100 ka ago.

4.6 Other marine terraces

By comparing the above age estimates on reference terraces to recent, reliable ^{18}O record (Shackleton *et al.,* 1990), the remaining terraces can be allocated to odd-numbered oxigen isotope stages recording interglacial environments with high sea level stands, respectively

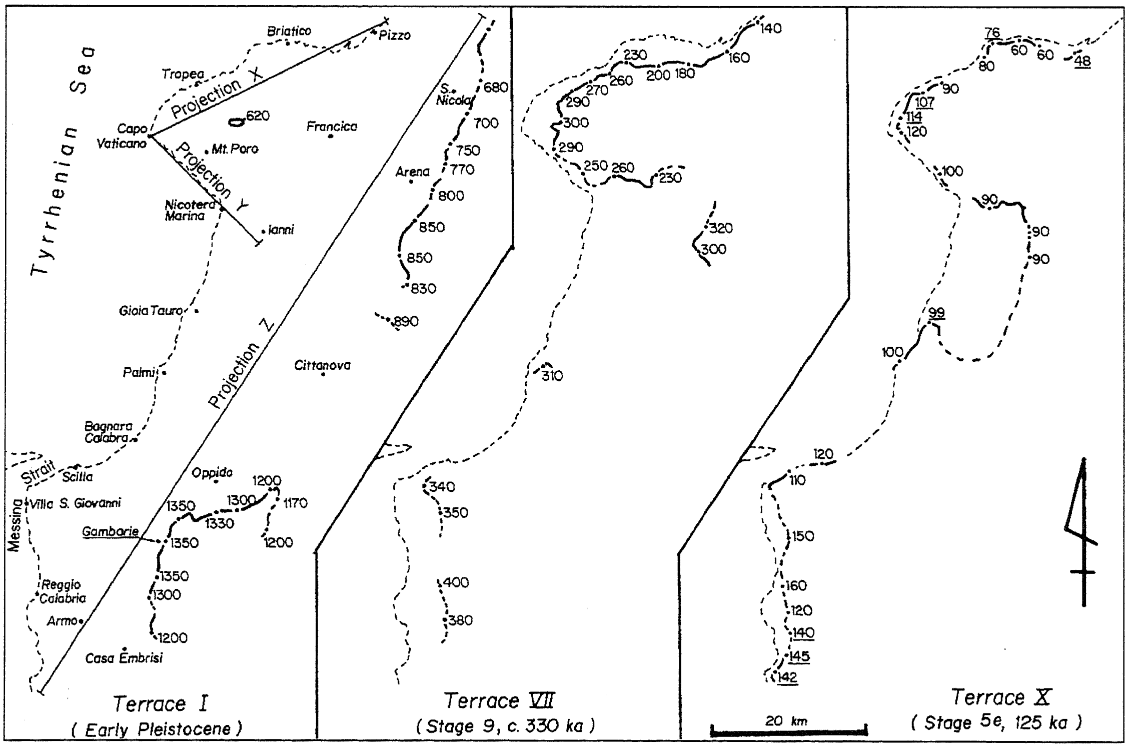

Fig. 12 - Areal distribution of paleoshorelines (solid thick lines) and height in meters of Terrace I, Terrace VII and Terrace X. Lines of "Projection X, Y and Z" show location and direction of the vertical planes in Fig. 13 where paleoshoreline is projected.

Distribuzione areale delle paleolinee di riva (linea spessa) e loro quota in metri per il Terrazzo I, il Terrazzo VII, e il Terrazzo X. Le rette X, Y e Z mostrano la direzione delle tracce dei piani verticali, riportati in Fig. 13, sui quali sono state proiettate le paleolinee di riva.

(Fig. 11). The following correlation and age estimates are probable, but remain uncertain:

Terrace III:	~1000 ka in Early Pleistocene
Terrace V and VI:	~900 to 400 ka in Middle Pleistocene
Terrace VIII:	Stage 7 or 9 ?
Terrace IX:	Stage 7
Terrace XII:	Substage 5a ? (interstadial)

5. REGIONAL TECTONICS

Data on paleoshoreline altitude and distribution help to clarify regional or local uplift patterns and their change with time. Data are presented in detail and discussed in terms of regional tectonics accompanied by crustal uplift and normal and gravitational faulting.

5.1 Changed uplift modes induced from marine terrace deformation

Figure 12 shows the horizontal distribution of inner edge altitude, almost the same as paleoshoreline altitude, selecting the three continuous key terraces: Terrace I, VII and X. Figure 13 displays vertical changes of inner edge altitude for all marine terraces.

The general deformation pattern is apparently of a warping uplift, with the relative altitude maxima of the older shorelines clearly apparent for three areas: Aspromonte, the Southern Serre and the Capo Vaticano Promontory. This warped crustal uplift has a wavelength of about 50 km after emergence of Terrace I, similar to the general undulation of local topography. In particular, severe deformation of Terrace I in Aspromonte leads us to interpret that it is equivalent to doming uplift. High heat flows have been measured offshore just near Capo Vaticano and may indicate local mantle pluming (Locardi, personal comm.). This suggests that warping uplift at Capo Vaticano results from vertical doming caused by this pluming.

On the contrary, such morphotectonic deformation is not clearly recognized in shoreline of younger terraces below Terrace IV in the Serre Range, and below Terrace III in Aspromonte. The shorelines of the lowest three terraces — X, XI and XII — depict a regional uplift with gentle warping and extending for 100 km along the coast from Pizzo to Reggio Calabria. The emergence of the Gioia Plain after Terrace VII indicates that regional uplift started after Middle Pleistocene replacing previous warping and doming uplift. The occurrence of gentle warping features indicates that Early Pleistocene doming contin-

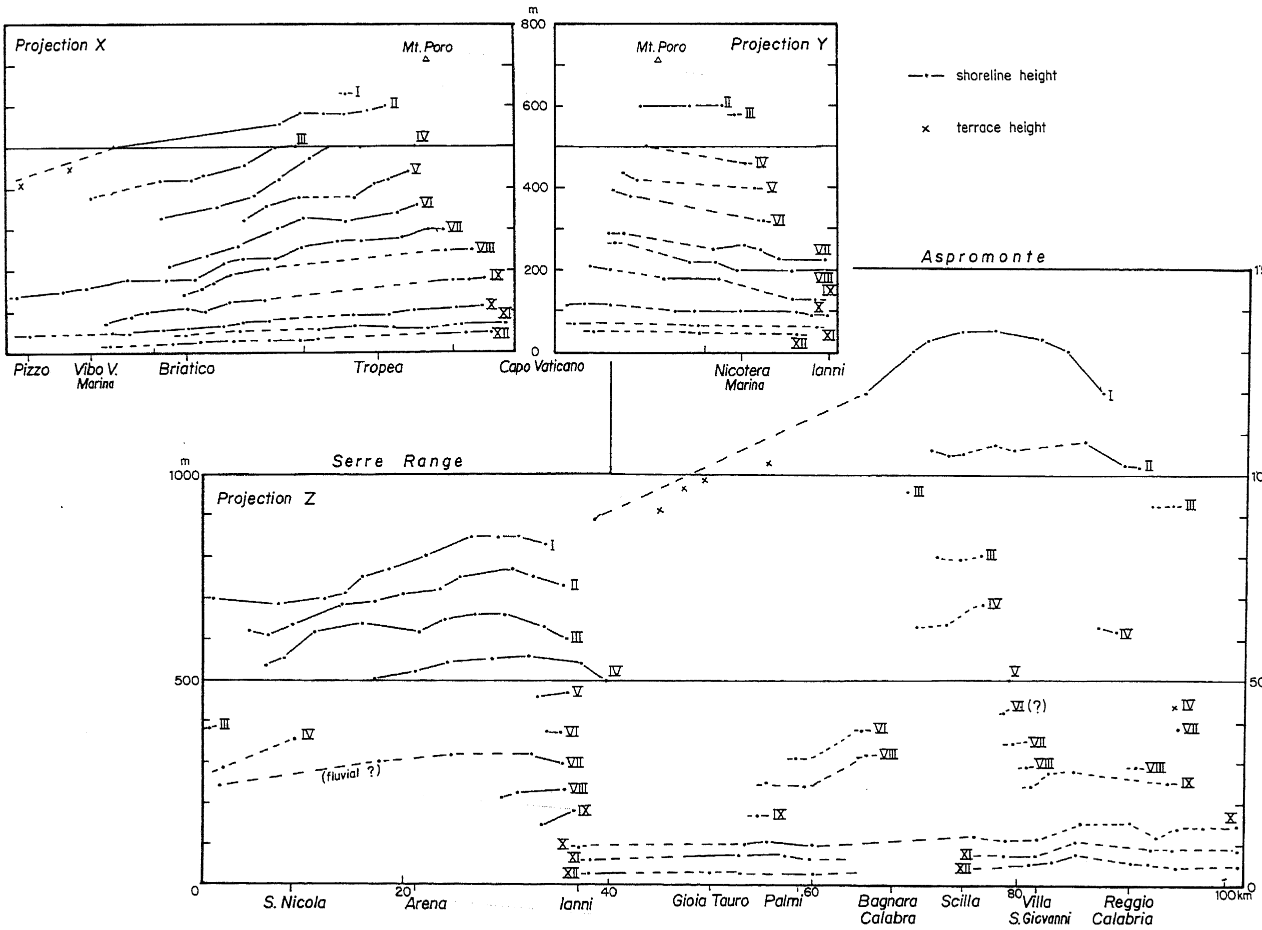

Fig. 13 - Vertically projected profiles of paleoshoreline height and terrace order for reference. Projected vertical planes are shown in Fig. 12.
Proiezione su piano verticale delle paleolinee di riva e indicazione dell'ordine dei terrazzi. Le tracce dei piani verticali sono indicate in Fig. 12.

ued with a lower activity also after Middle Pleistocene. In fact, the shoreline altitude of the Eutyrrhenian Terrace X ranges from 50 to 150 m a.s.l between Vibo Valentia Marina and Nocella.

As to the tectonic activity of the Tyrrhenian coast of northern Calabria and of Basilicata, 200 km to the north of Reggio Calabria, Carobene & Dai Pra (1990, 1991) discuss the 4 to 8 m high Eutyrrhenian shorelines, on the basis of aminoacid chronological stratigraphy. This means that a differential, large magnitude movement with northward tilting occurs in addition to a generalized regional uplift in the Calabrian Arc.

Figure 14 shows age-altitude plots of paleoshorelines; the figure outlines the tectonic history associated with changed uplift modes in the last one million years, although sea level stands at the peak of transgression are not considered because of their uncertainty.

Uplift rate in the Early Pleistocene is evaluated to be 3.8 m/ka in Aspromonte, 1.3 m/ka in the Serre Range and 0.7 m/ka in the Capo Vaticano Promontory. The lowest uplift rate (0.1 to 0.3 m/ka) dates to Middle Pleistocene (Fig. 14); in the following 330 ka the regional uplift rate increased up to 0.9 ÷1.4 m/ka. This tendency of change in uplift rates corresponds with a transition of tectonics, from rapid warping (doming) to regional uplift. The Early Pleistocene uplift rate (3.8 m/ka) in Aspromonte is possibly exaggerated by the fault movement with vertical slip rate of ~1.0 m/ka, as mentioned below for the Armo fault. Thus, the Aspromonte uplift rate is assumed to be no more than 3.0 m/ka.

The Calabrian Arc has clearly been uplifted, changing tectonic phases from local warping (doming) uplift to regional uplift in Pleistocene times. Ghisetti (1984) interprets that upheaval of the Calabrian Arc results from the overthrusting of the Tyrrhenian crust onto the African Crust. Her crustal uplift model is attractive since it explains the mechanism of regional uplift in the arc as a whole, but does not explain local previous warping or doming uplift. Strong compressional tectonic features in Quaternary times, reverse faults and severe folds, and Quaternary volcanism are not recognizable in southern Calabria. This suggests that warping (doming) features in southern Calabria are not associated with horizontal crustal shortening, and therefore require other more persuasive explanations of crustal uplift by geodynamically originating vertical movements.

A possible explanation is that diapiric intrusions into the crust determined doming uplift in Aspromonte and in the Capo Vaticano Promontory, probably affecting the Serre Range. Locardi & Nicolich (1988) propose an unique theory that the intrusion of fluidized mantle from asthenolith dome into crust-mantle boundary causes the uplift of the Calabrian Arc. In geodynamic terms, diapiric doming appears to result from a kind of intrusion of partially fluidized mantle, and agrees with their theory. However, the presence of diapirism is not clearly detected in seismic reflection profiles with velocity structures as shown by Schutte (1978) and Chabellard (1984), due to rough and discontinuous data. Further detailed geophysical surveys should verify the existence of diapirism, and the cause of warping must be tested.

Another tectonic scheme is required to understand

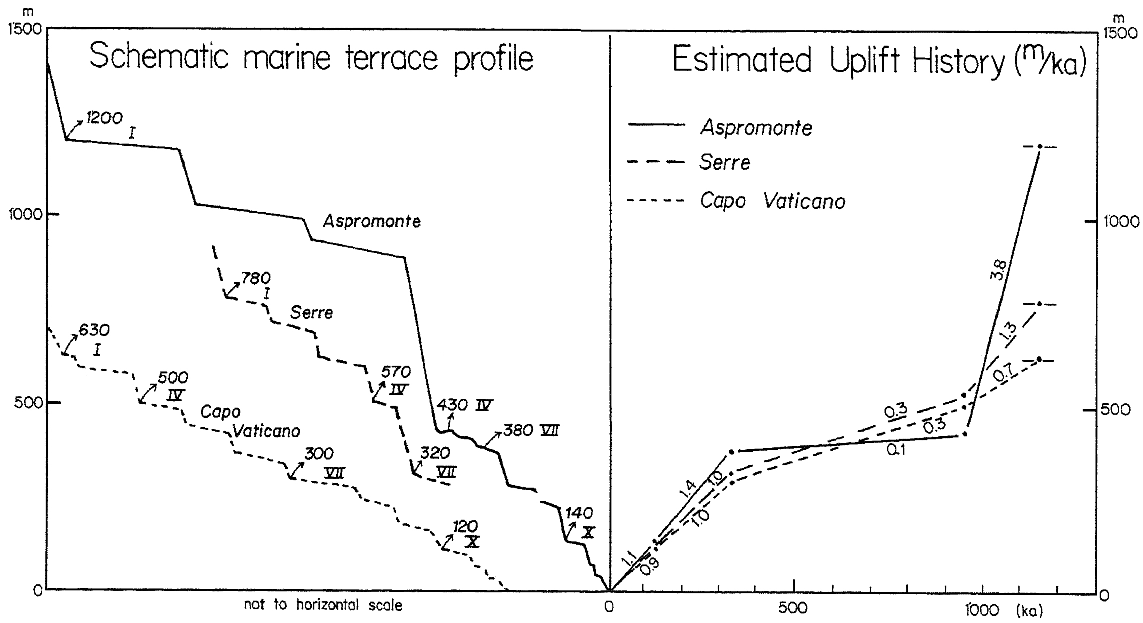

Fig. 14 - Estimated uplift rate obtained from the age-altitude ratio in Aspromonte, the Serre Range and Capo Vaticano Promontory.
Andamento del tasso di sollevamento ricavato dal rapporto fra quota e età per l'Aspromonte, Le Serre e il promontorio di Capo Vaticano.

regional uplift with northward tilting since the Middle Pleistocene, as identified along a 200 km long section of coast. Wideness of the affected area would seem to indicate an arc-wide crustal deformation. Such extensive uplift seems to reflect crustal shortening, such as that caused by convergent plate motion, phenomena frequently observed in the circum-Pacific tectonic zones.

5.2 Tectonic implications with uplift modes, normal and gravitational faulting

Major faults observed in the study region (Fig. 15) are geometrically categorized into two types: the NE-SW normal fault system prevailing in South Calabria, and the conjugate zigzag normal fault system between the Messina Strait and Aspromonte (Ghisetti, 1979; 1981). Ghisetti reports that normal fault movement initiated in Pliocene, as indicated by detailed structural analyses of faults.

Each normal fault has not clearly deformed terraces younger than Terrace VII (300÷400 ka). This suggests that most fault systems were activated before Middle Pleistocene, probably retroactive to Pliocene times. For example, terraces older than VII are not recognized on the fault foot in the Gioia Plain. This fact supports the hypothesis that the plain was progressively lowered by high activity of the East Gioia Tauro Fault before the emergence of Terrace VII (by regional uplift). Therefore, the NE-SW trending grabens have been formed by these normal faulting, controlled by a regional extensional stress field.

Several faults are narrowly spaced, encircling the northwest margin of Aspromonte in a parallel fashion (Fig. 15). Each fault scarp is about 400 to 500 m high (Plate 1, G, Armo Fault). The littoral deposits (Pozzi Gravel) of late Sicilian age are not deformed as much as the underlying strata of Pliocene age that are dragged by the Armo fault movements. We consider that the Armo fault activity started in Pliocene times, and that its main activity developed in Early Pleistocene (1200÷800 ka) before the formation of Terrace IV. Therefore the Armo fault slip rate can be evaluated at 1 m/ka, at the most. Terrace IV is back-tilted near Bagnara Calabra, associated with landslides (Plate 1). This fault geometry and movement bearing high scarps probably indicate that local gravitational collapses are partly superimposed on normal faults, originally generated by regional extension. This gravitational feature is recognized only on the Aspromonte slopes where Early Pleistocene paleoshorelines are high because of doming uplift. This implies that strong and rapid up-doming caused the appearance of gravitational movements on the wing of upper crust around Aspromonte (Fig. 16).

In synthesis, up to Middle Pleistocene, local warping and doming, occasionally producing gravitational faults, coexisted with regional extensional tectonics begun in Pliocene times in the southern Calabrian Arc.

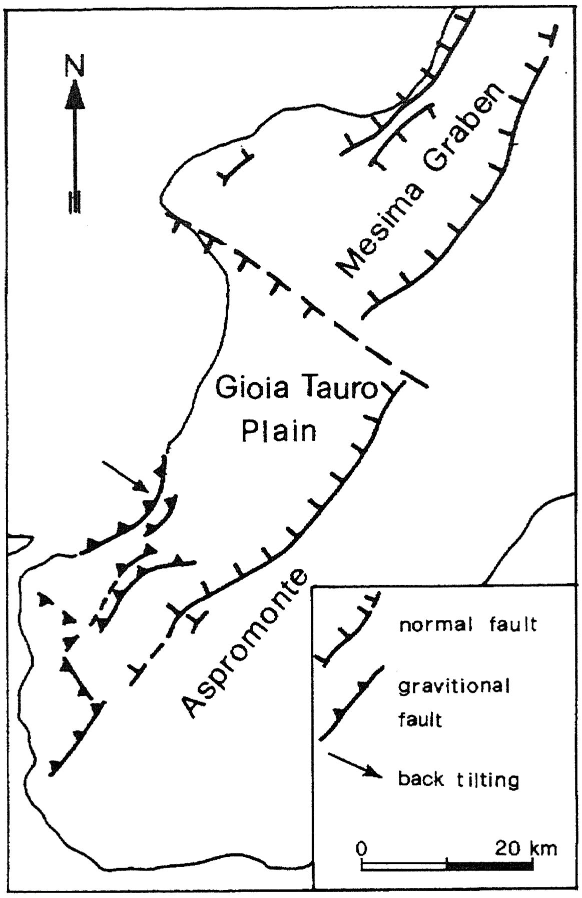

Fig. 15 - Fault geometry in South Calabria.
Geometria delle faglie nella Calabria meridionale.

Since Middle Pleistocene, a generalized regional uplift along 200 km of coast has instead taken place, with low activity of normal fault systems.

5.3 Seismotectonic implications with recent regional tectonics

Large earthquakes (M 6÷7) occurred in the Messina Strait and the Gioia Plain in historical times (Fig. 1). The implications of focal characteristics to seis-mogenic faults remain problematic due to a lack of surface faults, although several studies presented normal fault models to explain surface movements during earthquakes. Valensise & Pantosti (1992) reexamine previous fault models of the 1908 Messina Earthquake (Ms 7.5), and propose a model indicating that the Eutyrrhenian paleoshoreline along the Reggio Calabria coast is deformed by coseismic vertical changes at repeatedly occurring 1908-type earthquakes. It has not been possible to distinguish the paleoshoreline displacement similar to the coseismic one, because of difficulties of accurately identifying shoreline position since covered by thick alluvial deposits in the coastal area of South Calabria.

Recent seismicity in South Calabria is characterized by shallow earthquakes with dominant normal faulting,

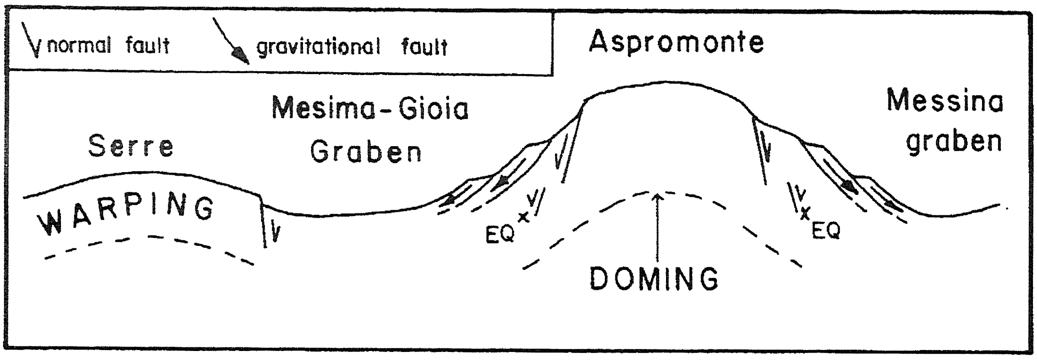

Fig. 16 - Early-Middle Pleistocene tectonic scheme of uplifting accompanied by normal and gravitational faulting in the South Calabrian Arc. EQ: earthquakes.

Schema del sollevamento tettonico dell'arco calabro meridionale, accompagnato da faglie normali e gravitazionali, durante il Pleistocene inferiore medio. EQ: terremoti.

while in the Tyrrhenian Sea seismic activity is characterized by intermediate earthquakes with dominant reverse faulting (Gasparini *et al.* 1982). The shallow earthquakes indicate a still in-progress brittle destruction of the upper crust of the southern Calabria Arc, as evidenced by the 1908 Messina Earthquake and the 17-18th century earthquakes along both the East Gioia Tauro and East Mesima Faults. During these events strong shaking probably caused many landslides, which are visible on the terrace edges in the southern Gioia Tauro Basin (Plate 1).

An alternative hypothesis is that brittle destruction originates either from regional extensional tectonics or local gravitational movements. No surface faults appear to be connected with shallow earthquakes, suggesting that their movements do not have enough potential to generate fault scarps (Fig. 16). Recent vertical slip rate of normal faults (in the order of 0.1 m/ka) in the Messina Strait (Ghisetti, 1992) is much less than that (~1.0 m/ka) induced by Early-Middle Pleistocene gravitational fault movements around Aspromonte (~400 m in ~400 ka: see the Armo fault). This rate difference indicates that normal faulting represented by recent seismicity essentially varies with previous gravitational faulting. The former hypothesis of extensional tectonics is, therefore, more acceptable in explaining the weak fault activity (seismicity) which is associated with brittle destruction processes in the upper crust, and which coexists with recent regional uplift having an intermediate rate of 1.0 m/ka.

6. CONCLUDING REMARKS

Morpho-biostratigraphical criteria are used to develop the correlation and geochronology of marine terraces along the Tyrrhenian coast of South Calabria. The proposed geochronology shows that all marine terraces, recognized at twelve orders (Terrace I to XII), emerged in succession since Early Pleistocene, about 1 million years ago. Terrace I and II are assigned to Early Pleistocene, slightly older than 1million years ago; Terrace IV to Stage 25 (~950 ka); Terrace VII to Stage 9-11 (300÷400 ka) and Terrace X to Stage 5e (~125 ka, corresponding to the last interglacial culmination). Thus, Early Pleistocene marine terraces reliably exist at high altitude in South Calabria. Biostratigraphic information on the marine terraces sequence confirms the gap in marine sedimentation during Middle Pleistocene (800÷400 ka) that was already evidenced in other Tyrrhenian coastal areas (Carobene & Dai Pra,1990).This gap is related to cold peaks (16, 14, 12; Fig. 11) and to a low tectonic uplift (Fig. 14).

Paleoshoreline analyses indicate that the tectonic deformation pattern of the investigated area has changed both with time and space during the last million years.

The NE-SW trending horst-graben features are essentially linked to a regional extension determined by crustal uplift, which has been active since Pliocene. An Early Pleistocene doming uplift (maximum rate: 3.8 m/ka) occurs in South Calabria — three doming centers are: Monte Poro, the Serre Range and Aspromonte. A rapid doming uplift around Aspromonte supports for speculative implications of local gravitational movements with crustal bending by diapiric intrusion. Doming uplift has been replaced by regional uplift (rate of ~1 m/ka) since Middle Pleistocene, with a still active gentle warping in the Reggio Calabria and Capo Vaticano areas, showing a more than 100-km-long northward tilting.

Recent seismicity in South Calabria is regarded as due to normal faulting in the upper crust, controlled by regional extensional fields synchronous with prevailing regional uplifting since Middle Pleistocene.

Neotectonics of the Calabrian arc will be geodynamically detailed with reference to the origin and mechanism of doming and regional uplift reflecting kinematics conditions in the upper crust in a forth-coming article.

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