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HOW EUSTATIC RAISED MARINE TERRACES OF CALABRIA CAN BE CONNECTED WITH CLIMATE OSCILLATIONS OCCURRING OVER THE MIS 5-MIS 4 PERIOD

ABSTRACT: DUMAS B. & RAFFY J., *How eustatic raised marine terraces of Calabria can be connected with climate oscillations occurring over the MIS 5-MIS 4 period*. (IT ISSN 1724-4757, 2006).

On the Calabria coast of the Strait of Messina, six major terraces (MT) have been shaped from the Late Pleistocene to the Holocene time. The four higher, stepped between about 180 m and 50 m a.s.l., are assigned to the MIS 5.5-MIS 4 period. Cross-sections and detailed mapping show that they consist of several terraces placed side by side: eleven for MT VI (MIS 5.5), four for both MT V (MIS 5.3) and MT IV (MIS 5.1) and finally three for MT III (MIS 4). The uppermost terrace of each series is termed head terrace. All over the study area, they were raised at a 1.3 m/ka mean uplift rate, without any important tilting or faulting occurring since the beginning of MIS 5. The characteristic thickness (CT) of the clastic marine deposits (= sea stacks) associated with each terrace is the vertical height between their top wall at the inner edge of the terrace (the coastline or shoreline angle) and their farthest seaward bottom (outer edge of their basal boundary). It clearly shows that the twenty-three studied terraces result from as many sea-level oscillations. So, a relative sea-level curve can be drawn. A comparison is attempted between sea-level changes and millennial-scale climate oscillations recognised from ice and marine records. A good correlation exists between head terraces, high CT, large amplitudes of sea-level rises and climatic orbital events at 128 ka, 105 ka and 84 ka plus a significant suborbital event at about 72 ka. Minor terraces (between head terraces), with small CT, have been generated by low-amplitude and high-frequency sea-level fluctuations. Most of them can be connected with suborbital and rapid climatic oscillations over the MIS 5-MIS 4 period.

KEY WORDS: Marine terraces, Sea-level change, Sea-level curve, Climate oscillations, MIS and OIS 5, MIS and OIS 4, Calabria, Southern Italy.

RIASSUNTO: DUMAS B. & RAFFY J., *Possibili correlazioni fra terrazzi marini eustatici della Calabria ed oscillazioni climatiche verificatesi fra il MIS 5 e il MIS 4*. (IT ISSN 1724-4757, 2006).

Fra il Tardo Pleistocene e l'Olocene, lungo la costa calabrese dello Stretto di Messina sono stati modellati sei terrazzi marini principali (MT). I depositi dei quattro più alti, disposti a gradinata fra 180 e 50 m s.l.m., sono stati attribuiti all'intervallo di tempo compreso fra il MIS 5.5 e il MIS 4. Sezioni geologiche e cartografia di dettaglio mostrano che ad essi corrispondono in effetti diversi terrazzi: undici corrispondono al MT VI correlato con il MIS 5.5; quattro al MT V e al MT IV correlati, rispettivamente, al MIS 5.3 e al MIS 5.1; in ultimo tre corrispondono al MT III, correlato al MIS 4. Il più alto in quota di ogni serie è definito terrazzo di testa. Tutta l'area considerata in queste pagine è stata sollevata con un tasso di 1,3 m/ka, senza che ci siano stati importanti basculamenti o fagliamenti a partire dall'inizio del MIS 5.5. Lo spessore caratteristico dei depositi marini (CT) di ogni terrazzo corrisponde all'altezza fra la sua parte più interna, la linea di costa, e la sua parte basale più esterna. I ventitre terrazzi rilevati sono conseguenza di altrettante oscillazioni del livello del mare riportate in una curva delle variazioni relative. Si propone una correlazione fra queste variazioni del livello del mare e le oscillazioni climatiche con periodo millenario riconosciute da dati marini e glaciali. Si riconosce una buona correlazione fra terrazzo di testa, alto spessore caratteristico, entità del sollevamento del livello del mare e eventi climatici orbitali in corrispondenza di 128, 105 e 84 ka ed a quello suborbitale di 72 ka. Terrazzi minori, con piccoli spessori caratteristici, sono stati generati da piccole fluttuazioni del livello del mare con alta frequenza. Molte di esse possono essere correlate alle rapide oscillazioni climatiche suborbitali verificatesi fra il MIS 5 e il MIS 4.

TERMINI CHIAVE: Terrazzi marini, Variazioni del livello del mare, Curva delle variazioni del livello del mare, Oscillazioni climatiche, MIS e OIS 5, MIS e OIS 4, Calabria, Italia meridionale.

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INTRODUCTION

Within the Italian Peninsula, Southern Calabria is one of the highly uplifted areas within the Quaternary period. On its western and north-western slope, from the Piani di Aspromonte (1300-1400 m a.s.l.), below the Montalto massif (1955 m high), down to present shore, its coastal landforms appear as an impressive flight of marine terraces. These ones result from a more than 1 m/ka Quaternary uplift rate (Dumas & *alii*, 1987a; 1987b; Montenat & Barrier, 1987; Ghisetti, 1992; Dumas & *alii*, 1999; Miyauchi & *alii*, 1994), which was coupled with sea-level change, involving large vertical and horizontal shifting of the coastline. As a consequence, step by step, emerged lands have been widened out and either have been shaped into shore platforms covered with only veneer beach deposits or have been built up into constructional terraces due to accumulated clastic sediments. A given terrace can shift laterally from one landform to the other. In a previous paper (Dumas & *alii*, 2005), we have explained how the thickness of such shallow marine deposits and their arrangement reveal sea-level changes. So not only the number and the age of these loose terraced deposits, but also their thickness, bear witness of the events that explain the coastal landforms.

The first aim of this paper is to deliver a detailed field survey relative to the stepped terraces on the Calabria coast of the Strait of Messina. Some of them are easily identified in the field when they are wide and when an indisputable sea cliff bounds them at their inner edge**.** The others need careful investigations. Sometimes, several coastline good exposures, along a linearly continuous and/or a sinuous landmark, are necessary to surely detect and locate them. When flat pebbly or sandy surfaces are narrow and vertically spaced from each other by metric scarps, they look like man-made terraces, a typical feature in Mediterranean landscapes. That explains why some marine terraces were not counted up in our own papers published before the mid-nineties (Dumas & *alii*, 1993) and in those written by other authors (for example Westaway, 1993 or Miyauchi & *alii*, 1994). Year after year, from field experience and from accurate surveys of new cross-section exposures such as quarries, road widening, house foundations, it has been possible to discriminate marine terraces from man-made terraces that obscure them. So joint examination of stepped topographies and geologic observations coupled with geomorphologic features (shoreline angles, marine notches, and especially indisputable links between terrace surface and beach deposits finishing at a coastline) provided the proofs that flat surfaces are distinct marine landforms. From these criteria, twenty-three raised marine terraces have been identified between ~180 m and 52 m above sea level. According to the available geochronological data (see later), such a vertical interval corresponds to Marine Isotope Stage 5 (MIS 5) and MIS 4, lasting from the sea level highstand at 128 ka to the MIS 3 high sea level at 58 ka. The geomorphologic and geological analysis of such raised landforms support a representative synthetic cross-section. That is the base for reconstructing the sea level history of the Tyrrhenian Sea in the Strait of Messina and for drawing up the sea level relative curve over the MIS 5-MIS 4 period.

The second objective of this paper consists in comparing our detailed sea-level curve with high-resolution records from ice-sheet and deep-sea cores that reveal millennial - or centennial-scale climate fluctuations, for exploring potential connections between sea-level change and climate. The question is to what extent glacio-eustatic terraces could be connected with some rapid climate oscillations over the same time interval.

FROM FIELD SURVEY TO A SYNTHETIC CROSS-SECTION OF STEPPED TERRACES

FIELD EVIDENCES AND AGE CONTROL AS DEDUCED FROM «MAJOR TERRACES»

Along the Calabria coast facing the Strait of Messina (fig. 1), stepped plateaus are the major characteristic features of the landforms, as well in the landscape as on aerial photographs. Their inner edges are separated by a vertical

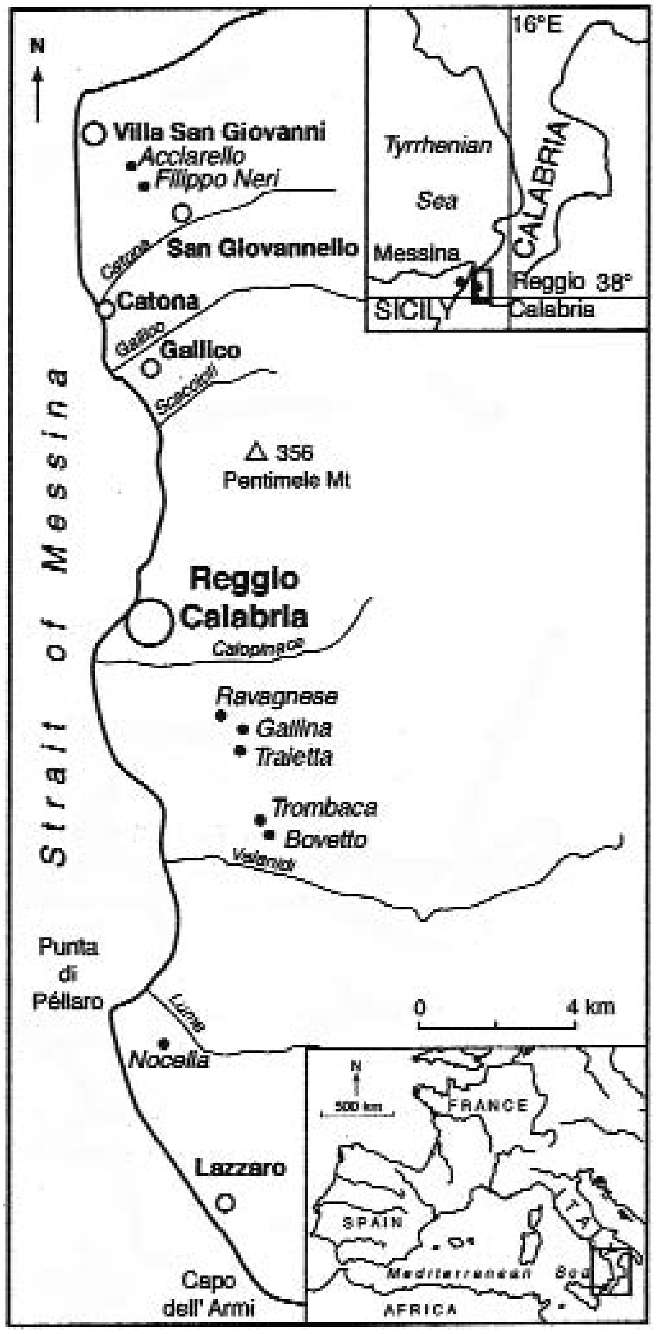


FIG. 1 - Location map of the study area.

distance ranging from about 10 m up to more than 50 m. Scarps limiting them at their outer edge are obvious on some traverses when their height exceeds 10 m but sometimes they are only 5 m high or less. Every plateau surface exhibits a low-gradient slope with small irregularities. Detailed mapping shows that each of them consists of several marine terraces, which are placed side by side and are separated from each other by a metric-high scarp.

TABLE 1

Major terrace	II	III	IV	V	VI
Head terrace elevation (m)	50-57	71-75	88-91	115-120	160-181
Max CT (m)	34	20	35	42	120

The number and age of major terraces (MT)

We name major terrace (MT) a lot of terraces, which together constitute a geomorphologic unit. At the head of each series of terraces, the upper one is called head terrace and its coastline head coastline. The others are termed minor terraces (fig. 2). Head terraces are associated with thick marine formations, which either rest upon truncated bedrock (wave-cut platform) or fossilize valley slopes. We have defined the characteristic thickness (CT) of the sea stack terraces (Dumas & *alii*, 2002a; Dumas & *alii*, 2005) as the difference in elevation between their top wall along the coastline (the top of beach deposits often at a sea cliff foot or shoreline angle) and their bottom upon a wave-cut platform or an unconformity surface. The elevation of this basal boundary is measured as far as it can be observed seawards. For lack of other exposures, it has been measured vertically at the outer edge of the marine terraces. Generally, depending on field exposures, the horizontal distance between the two measurement points ranges from 20-30 metres to 200 m, only. CT gives an estimation of the vertical space, which was available for sediment to accumulate during terrace construction. This space appears unequal for a given terrace as the characteristic thickness can laterally vary with respect to the coastal landforms. In cape location, when a terrace is mainly a shore platform, its characteristic thickness is thinner than that of a depositional terrace at the mouth of a valley or in bay position.

Six major terraces, numbered from I to VI, are stepped between the present-day coastline and 180 m in elevation (Dumas & Raffy, 2004). Table 1 summarises the coastline elevation of their head terrace (except the Holocene one) and the highest CT value, which has been measured in the field for each of them. We note that CT equals or exceeds 20 m but we must keep in mind that it can be a minimum value. Indeed field exposures do not exhibit the initial seaward margin of the beach deposit base, which has usually been eroded by sea cliff retreating and sometimes by downcutting occurring subsequently.

South of Reggio Calabria, in these thick formations, some materials have provided geochronological data, which permit to constrain the flight of major terraces. The stratigraphic sequence outcropping at Nocella (Dumas & *alii*, 1987a) and on the Bovetto traverse (figs. 3 A and 3B) contains the *Strombus bubonius* fauna (Gignoux, 1913; Bonfiglio, 1972; 1973), which is referred to MIS 5 in Italy. A thermoluminescence age estimate (116±12 ka, cf. Balescu & *alii*, 1997a; 1997b) confirms this attribution. But the ratios of amino-acid racemization (from 0.46 to 0.39 at Bovetto and 0.44 at Nocella) allow to assign the Nocella-Bovetto formation to MIS 5.5, according to the Hearty amino-acid chronology (Hearty & *alii*, 1986; Dumas &

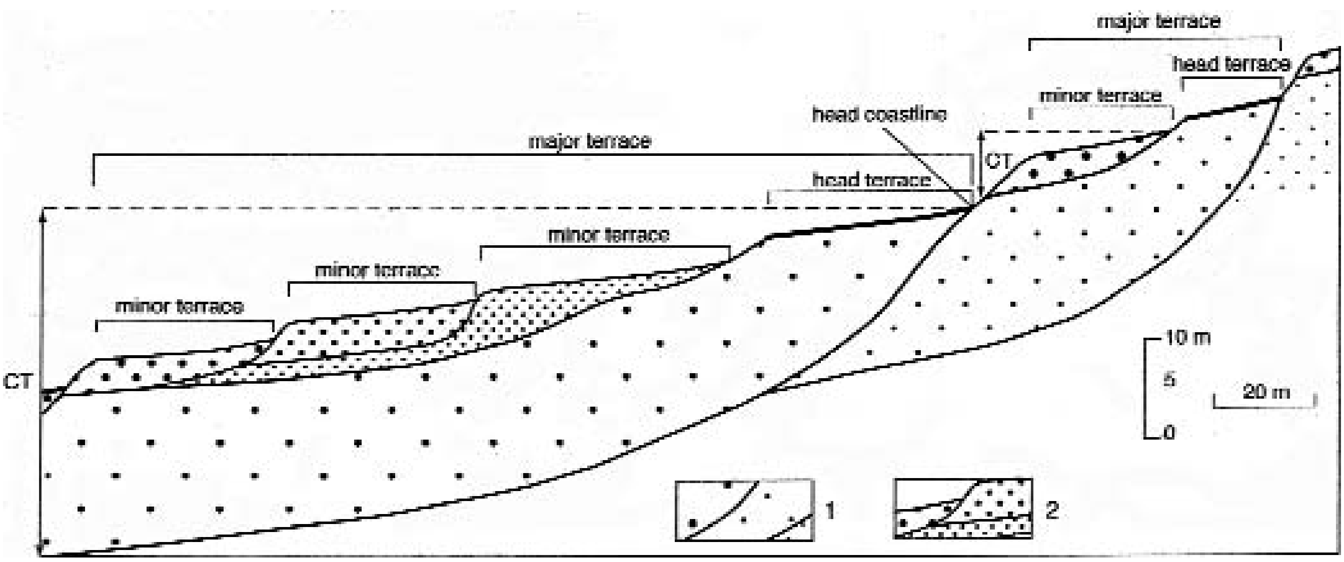


FIG. 2 - Setting of marine terraces. 1: Major and head terrace deposits; 2: Minor terrace deposit.

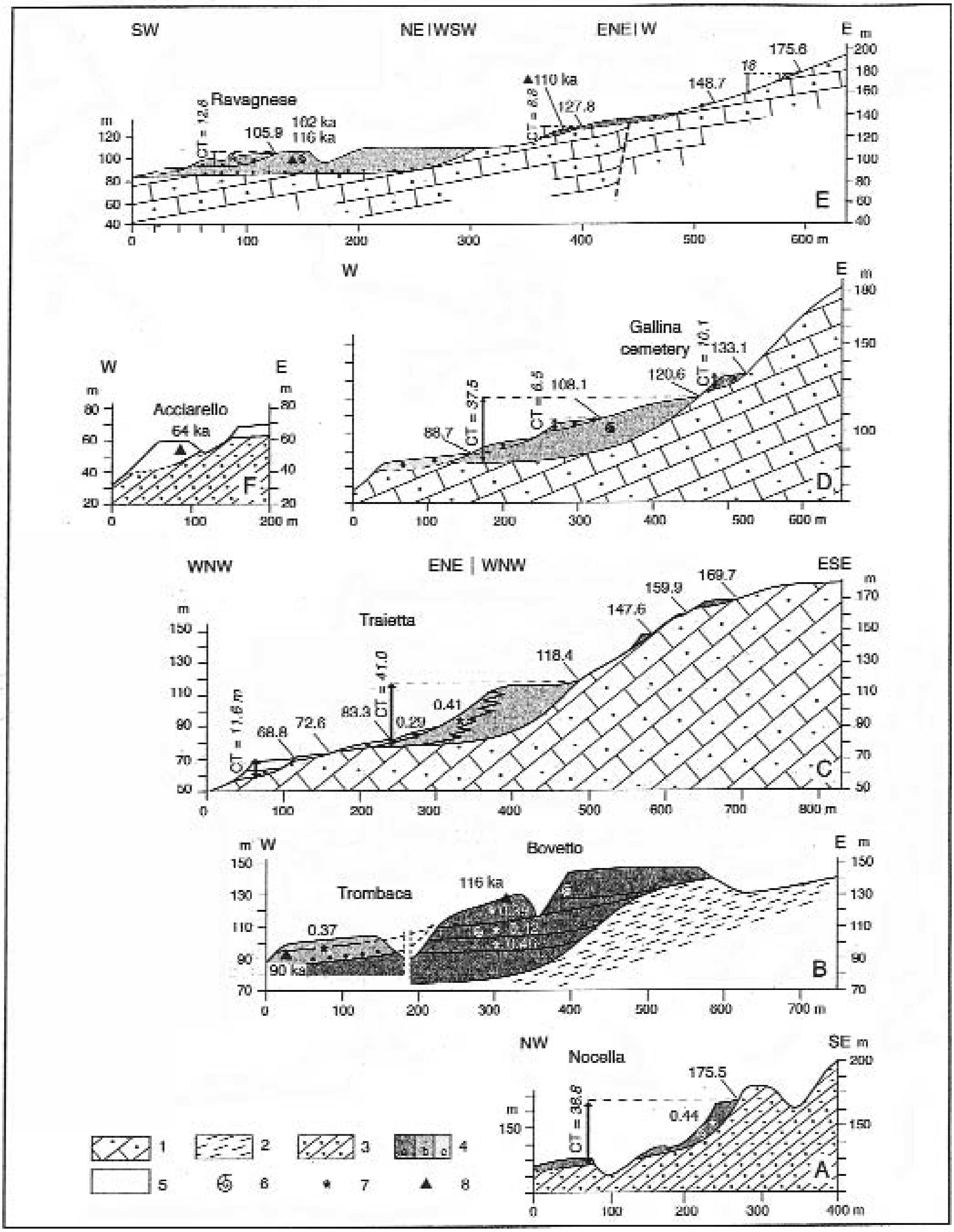


FIG. 3 - Three MIS 5 inset formations, South of Reggio Calabria (for location see fig. 1). 1: Messinian sandstones; 2: Middle Pleistocene white marls; 3: Pleistocene foreset beds; 4: MIS 5 deposits, (a) MIS 5.5, (b) MIS 5.3, (c) MIS 5.1; 5: marine deposits associated with MT III (MIS 4); 6: *Strombus bubonius*; 7: Amino-acid ratio; 8: OSL or TL age estimate. CT with italic numbers indicate the characteristic thickness of marine deposits in metres.

alii, 1988). At Bovetto, between ~ 75 m and 142 m a.s.l. (fig. 3B) the formation consists of alternating silty sands and sandy conglomeratic layers deposited in infralittoral shallow water, according to the fauna studied by Bellomo (1998). The corresponding coastline of part of it (the bottom layers) could be 178.8-m a.s.l., about 400 m upslope to the East, beyond the cut of Vallone Bovetto. This implies a 103-m characteristic thickness, at least. This formation could be associated with the MT VI head coastline, which has also been measured at 175.5 m a.s.l. at Nocella (CT = 38 m on fig. 3 A) and 175.6 m a.s.l. at Ravagnese (fig. 3E). From these data, a 1.3 m/ka mean uplift rate is calculated, if we assume a + 5 m initial relative sea level at 128 ka (Dumas & Raffy, 2004).

A second formation at Trombaca is deeply inset into the Bovetto formation (fig. 3B). Some 59-m below the local top of the Bovetto formation, it begins with a bed of boulders and pebbles, overlaid with highly fossiliferous fine sand. A TL age estimate (90±8 ka) distinguishes it from the MIS 5.5 formation (Balescu & *alii*, 1997a and b). This data, in agreement with a slightly lower amino-acid ratio (0.37), leads to an attribution to MIS 5.3. This deposit belongs to the same sequence as the thick sediments associated with the 118.4-m a.s.l. coastline at Traietta (CT = 41 m, fig. 3C) and the 120.6-m a.s.l. coastline on the Gallina cemetery traverse (CT = 37.5 m, fig. 3 D) or the Ravagnese traverse (fig. 3E), which contain the famous *Strombus bubonius* outcrops. In fine sands, at about 105 m a.s.l. (fig. 3E), a TL age estimate gives 116±13 ka corrected by OSL estimate at 102±8 ka (Balescu & *alii*, 1997b). After Gignoux (1913), Imbesi (1951) and Pata (1952) have described the fossiliferous shringle bar with typical beach fauna at the top wall of this formation, just at the Gallina cemetery level. It is the deposit and the coastline of the MT V head terrace.

At Traietta, a third marine deposit, inset into the MIS 5.3 formation, is associated with a ca 90-m a.s.l. coastline (fig. 3C). On the base of a much lower amino-acid ratio (0.29±0.04), it is assigned to MIS 5.1 (Dumas & *alii*, 1988). Here it is not possible to measure its characteristic thickness. But it undoubtedly belongs to MT IV formation (see later figs. 4C, 4D and 4F), the maximum measured CT value of which is 35 m (table 1).

Consequently, the high characteristic thickness helps to definitely distinguish between three different formations, which correspond to the three well-known sea-level rises occurring during stage 5 and ending at 128 ka, 105 ka, 84 ka, respectively, according to the 65 N mid-June maximum insolation curve (Berger, 1978). As a result, the thick marine formations (CT>20m), associated with broad terraces, provide a geomorphologic benchmark of orbital periodicity in the flight of marine terraces. This is an important observation because these features can be used as a guide into the staircase of marine terraces (Dumas & *alii*, 2000).

Below the MIS 5.1 formation and its associated major terrace (MT IV), another major terrace (MT III) has an about 20 m-CT value. No direct chronological data is available. But in the Acciarello quarry (just South of Villa San Giovanni, fig. 1) at about half height (fig. 3F, 48 m a.s.l.) of a fine sandy formation, a sample has provided a TL age estimate at 64±8ka (Balescu & *alii*, 1997a and b). According to the large error bar, it can be assigned either to MIS 4 or to MIS 3. In spite of this doubt, MT III head terrace (coastline 22 m to 25 m higher than the sample) has been shaped before or by that time (about 72 ka). So MT III can be assigned to MIS 4. It reveals an important suborbital event occurring between MIS 5.1 (84 ka) and MIS 3 (58 ka). The last studied head terrace (coastline = 52.4 m; CT = 34 m) can be correlated with the MIS 3 orbital event.

Detailed survey of major terraces

North of Reggio Calabria, major terraces are better developed than in the South (fig. 4). Former studies (Dumas & *alii*, 1999; Dumas & *alii*, 2000) have shown that, despite slight differences, the stepped setting of major terraces, is raised at the same approximate elevation above sea level from a traverse to another, along the whole study area. Indeed, main fault scarps or fault-line scarps are inherited from Upper Pliocene-Early Pleistocene faults which have cross cut the crystalline basement and its Tertiary sedimentary cover. But despite the seismically high level, they have been scarcely revived since Middle Pleistocene period. Few Late Pleistocene reactivation throws have locally broken two terraces (Dumas & Raffy, 2004); but the offsets ranging from less than 1 m to eight metres, the fault-related movements neither disturb the flight of marine terraces nor generate significant tilting. So in spite of the lack of geochronological data, we consider that the major terraces I to VI are the same age from the North (Villa San Giovanni) to the South (Capo d'Armi) of the studied area and that they were raised at approximately the same uplift rate. To validate this conclusion two approaches have been used. Firstly, with a mathematical method (described in Dumas & *alii*, 1999; 2002b), it has been established that right links exist between coastline segments of each terrace, when their continuity is broken by several valleys. Secondly, all along the Strait of Messina (about 40 km), the elevation variation (from 160 m up to 181-m a.s.l) of the MT VI head coastline points out the low variation of uplift rate: 0.16 mm/yr (Dumas & Raffy, 2004). During time intervals between MT VI and MT V, MT V and MT IV, the variation is even weaker: 0.03 mm/yr. It is a second important conclusive result, which permits: (1) the identification of head coastlines even when the CT of the remnant deposits is lower than 20 m (for example, the 175.6 m coastline at Ravagnese, fig. 3E) and (2) the detection of missing major terraces (one or several) along some traverses.

The major terrace VI (MIS 5.5) is, in any case, the widest one (inset in fig. 4). In the North, it stretches for 1 to 2 km (figs. 4B, 4E, 4F) but becomes narrow in the South (~ 600 m, fig. 4, I). Except on the granite horst of Commenda- Campo Piale, it corresponds to thick Gilbert deltas. Nevertheless, it can disappear so far as a topographic unit in the upper part of the Ravagnese area (fig. 3E) and partly at Bovetto (fig. 3B). In both cases, peak MIS 5.5 sea level has struck against a high and steep fault-

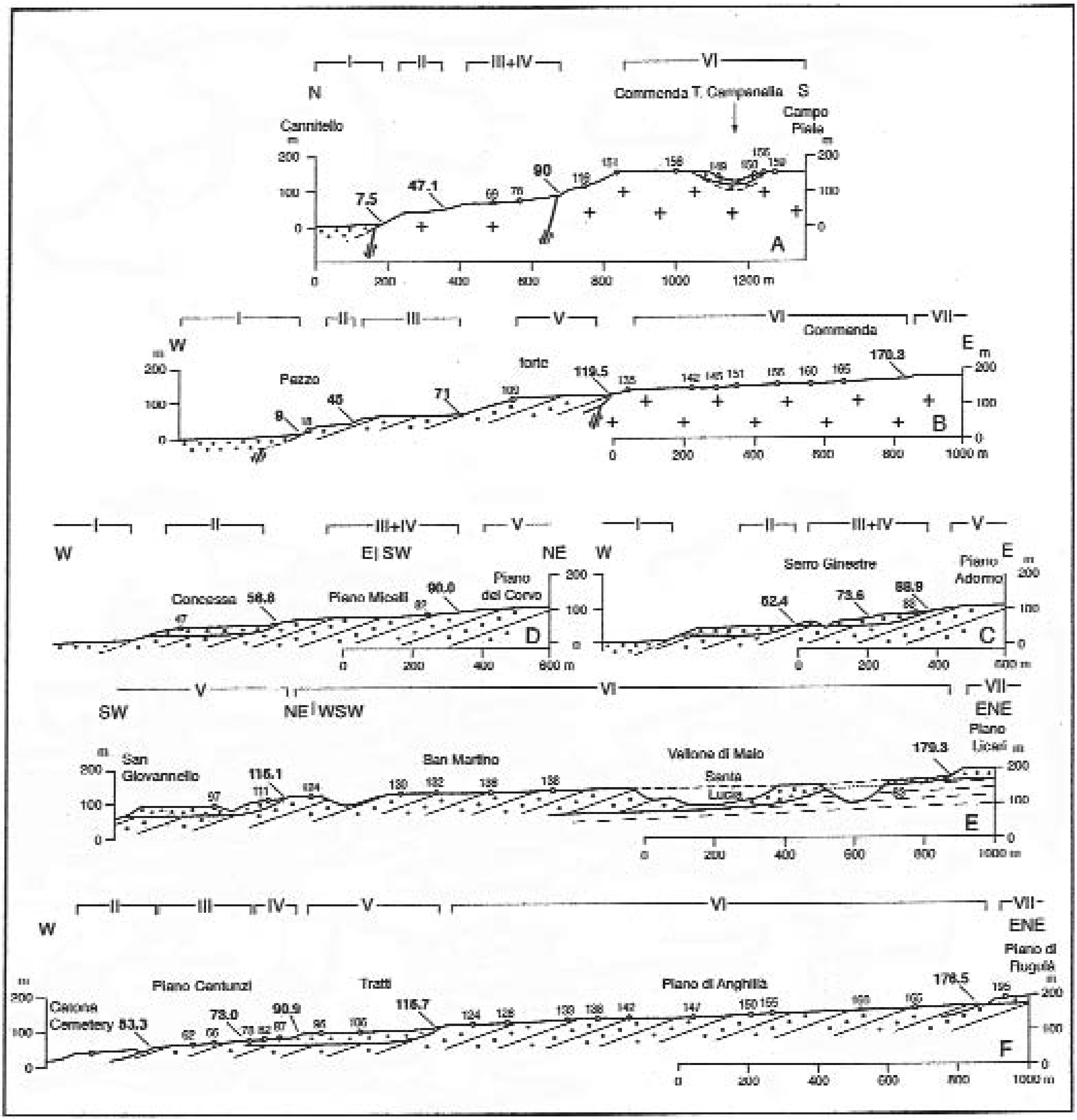
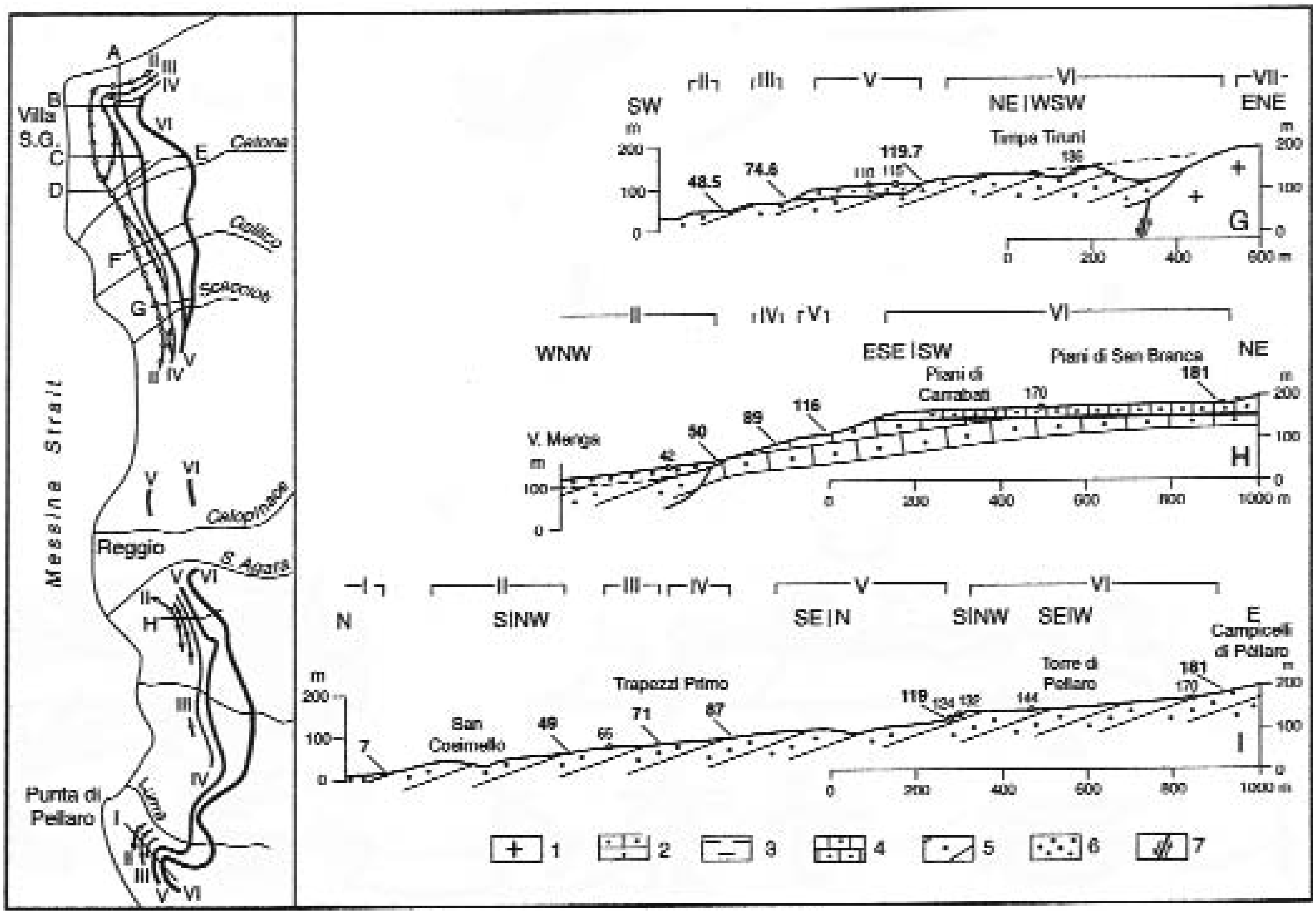


Fig. 4 (continue)

FIG. 4 - Serial cross-sections of the six Calabria stepped major terraces, from North to South, along the Strait of Messina. 1: Granite; 2: Sandstones (Messinian); 3: White marls (Lower Pliocene); 4: Calcarenite (Upper Pliocene-Lower Pleistocene); 5: Foreset beds (Pleistocene); 6: Late Quaternary and Holocene clastic marine deposits; 7: Fault. I, II, III: Major terrace numbering. Bold numbers indicate head coastline elevation, other numbers minor coastline elevation. At this scale, the thickness of stacking beach deposits is only represented when it exceeds 20 m, along the cross-sections. Inset: sketch of head terrace coastlines (except Holocene) and location of the cross-sections.



ed rocky coast that was cut into Messinian sandstone, Lower Pleistocene calcarenite or tight white marls. Locally, terrestrial supply was reduced compared to that which was elsewhere delivered by large rivers. Fine-grained sands rather than coarse sediments accumulate against the fault scarps and, later on, were easily swept away by selective erosion.

The major terrace V is so well preserved that it is often mentioned in the toponymy by the Italian words Piano or Piani: P. di Lastrico, P. Adorno, P. del Corvo, (fig. 4C, 4D). It also forms beautiful plateaus at Tratti (fig. 4F) and below Timpa Tiruni (fig. 4G) or again from Ravagnese to Traietta (fig. 3E, 3D, 3C). It disappears at the foot of the fault line scarp, which limits the Commenda horst northwards (fig. 4A).

When major terrace IV constitutes a plateau (P. Micelli for example, fig. 4D) it is not distinguishable from the successive major terrace III (MIS 4) for lack of a scarp between them. It happens that MT IV cannot be detected because it has been destroyed by the shore retreat during the shaping of MT III. This setting is observed to the east of Pezzo (fig. 4B) and below Timpa Tiruni (fig. 4G). In this case, at its inner edge, a 15 m-high sea cliff bounds MT III. The major terrace II is not studied in detail in this paper. Its head coastline is more or less easily detected in the field. At its mean elevation (53-56 m), and also at the elevation of MT III (73-75 m), human settlements (houses, roads, railway tracks, embankment for agriculture) may have concealed, cut, reduced, flattened the past sea cliffs. So it is more difficult to locate the head coastlines.

This comment outlines that it is necessary to carry out a comprehensive study of the geomorphologic and geological contexts to accurately count up the marine terraces. Only one indicator either depending on geomorphology (marine terrace) or morphometry (sea cliff height) or geology (thickness of deposits, sedimentary features) is not sufficient to link the stepping of marine terraces from one traverse to another.

FIELD DATA RELATIVE TO MINOR TERRACES

The high uplift rate (1.3 m/ka) explains why not only four head terraces were shaped all over the MIS 5-MIS 4 period, but also a series of other terraces termed minor terraces. Those are often inset into the thick formations of the head terraces while they have thinner sea stacks (= marine deposits), the characteristic thickness of which is less than 15 m. Some of them are difficult to discriminate from man-made terraces when only topographic features are available and when the embankments make the slope steeper or increase the height of an ancient sea cliff. All the minor terraces that are described below clearly exhibit a clastic wedge with beach deposits, the top of which exactly corresponds to the terrace surface and finishes at a shore angle.

Eleven terraces included into MT VI

On the Anghillà Plateau (MT VI), eleven terraces were recorded (fig. 4F and Dumas & *alii*, 2005). Because of the lack of suitable exposures on the plateau margins, it is not possible to observe the best cross-section of every coastline, whereas better opportunities for surveying minor terraces and their deposits, included into major terrace VI (128-105 ka interval) are located in the Villa San Giovanni area (fig. 1). Both sides of the Campanella valley head and the right side of another near valley, South of Campo Piale, provide some good natural exposures (fig. 5). Comparing stepped topographies and geologic cross-sections on the one hand and linking, step by step, three traverses on the other hand, clearly reveals a series of eleven terraces.

Figure 5A shows the upper stepped terraces and their corresponding deposits along the Campanella valley (left side), from the head coastline (171-172 m a.s.l.) down to the fifth coastline, the elevation of which is ~149 m high on both sides of the valley. The deposit corresponding to the head terrace is much thicker than those of the lower terraces. Its characteristic thickness is at least 20 m high (topset beds) and it increases to about 90 m down to the bottom of the valley. On the contrary, the characteristic thickness of the minor terraces ranges between 5 m and 12 m. It is obvious that minor terraces are inset into the MT VI thick formation. Their setting shows that the present valley is hollowed into successive marine deposits, which have filled a series of successive paleovalleys invaded by the sea (ria type), the first of them being dug into the granite basement during MIS 6 lowstands. Downward, on the right side of the valley, three other terraces (fig. 5A) are observed from 146 m to 135 m a.s.l. As the terraces were cut into the granite bedrock, on the margin of the deep Campanella valley, they mainly appear as wave-cut platforms, with thin deposits.

On the left side, just south of the bridge spanning the Campanella valley, the former valley side, parallel to the downstream section of the present one, is first buried by base cobbles and boulders, leaning directly against a granite slope, then by a thick reddish sandy deposit resting on white sands in direction of the valley bottom. This deposit belongs to a marine terrace, the coastline of which is measured at ~146 m a.s.l., the CT being equal to 10.3 m (fig. 5B). Below, the coastlines of four other terraces have been measured at 142.1 m, 135.7 m, 128.8 m and 123.7 m a.s.l., respectively. So, eight successive marine terraces are identified on each side of the Campanella valley from 172 m to 135 m a.s.l.

Four terraces with their corresponding deposits are observed on the north and on the right side of a small valley, South of Campo Piale (fig. 5C). The marine deposits are lying on wave-cut platforms truncating older marine deposits looking like the oblique stratified beds of the Campanella valley. They are fining upwards, shifting from boulders and cobbles, above the wave-cut platforms, to gravel and yellow then red sand at the top of the terraces. Red sand results from pedogenic alteration near the upper surface of the terraces. Landwards, each wave-cut platform is often bounded by a low, steep sea-cliff partly buried by aggrading beach deposits up to the inner edge of the terrace, at the foot of a low sub-aerial sea cliff. This one is in the prolongation of the buried cliff but it appears less steep, because weathering has smoothed it. It also happens that these low past sea cliffs are more or less levelled or flattened by earthworks for cultivation.

The characteristic thickness of the four terrace deposits ranges from only 5.7 m to 9.7 m. The lowest terrace (coastline at 123.7 m a.s.l.) is stretching and continuous as far as the left side of the Campanella valley (horizontal distance: 300 m, figs. 5C and 5B). The above coastline, even if less continuous, has been measured at the same elevation on the two traverses. It can be concluded that both terraces belong to the MT VI minor terrace series. Consequently, it is likewise for the two terraces located above (133.4 m and 136.8-m a.s.l.). Compared to the 142-m coastline, at nearly the same elevation on both sides of the Campanella valley, the latter (136.8 m) is in the same relative position and at about the same elevation as the lowest terrace (135.4 m) on the right side of the Campanella valley. So it can be linked with it. From the head terrace it is the eighth of the series. The ninth is only preserved South of Campo Piale because it has been destroyed by a road cut across the Campanella left side (fig. 5B) and because a 20 m-high scarp overlooking the MT V inner edge bounds the Commenda plateau (fig. 5A).

In short, eleven terraces were shaped between the MIS 5.5 highest sea level at about 128 ka and the MIS 5.3 highstand, ca 105 ka old. One can note that the minor coastlines on the Anghillà Plateau (fig. 4F) have nearly the same elevation as in the Commenda and Campo Piale neighbourhood.

Minor terraces included into MT V, MT IV and MT III

The terraces included into MT V are recorded within a 20-30 m vertical interval between about 120 m and 90 m a.s.l. The Tratti plateau (fig. 6) and Timpa Tiruni area (fig. 7) exhibit both four stepped terraces on each traverse. In the Tratti area, natural exposures provide cross-sections for measuring coastline elevation but they are not long or deep enough to get good measurements of CT. Some observations in the Timpa Tiruni area give complementary information. The CT of the head terrace deposits (fig. 7) is 36.4 m, a value comparable to those measured on the Gallina cemetery (37.5 m, fig. 3D) and on the Traietta (41 m, fig. 3C) traverses where only one or two minor terraces are detected. In different points of the study area, the two lowest terraces of the series are well-preserved about 103-108 m a.s.l and 95-97 m in elevation, respectively. Figures

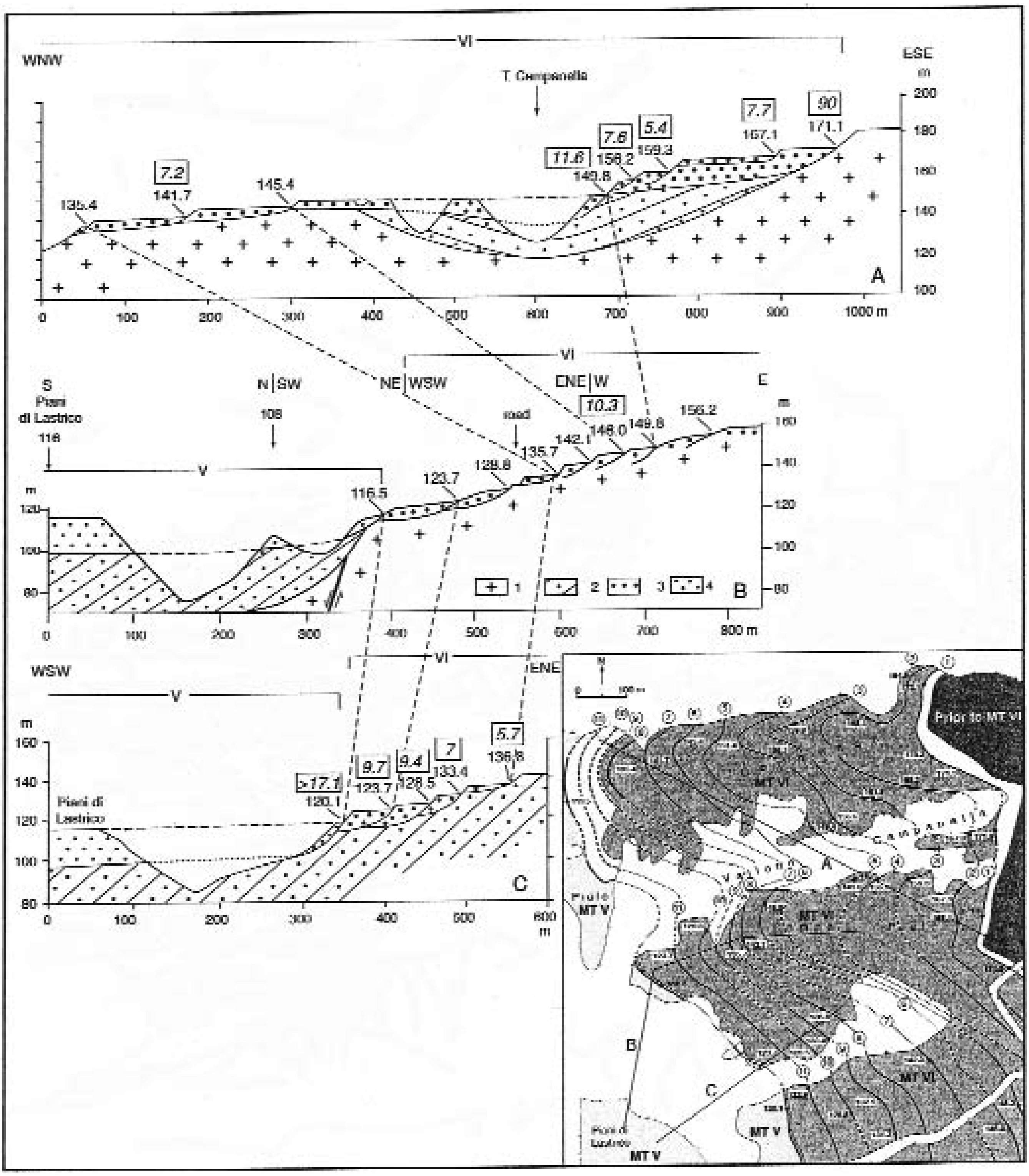


FIG. 5 - Eleven terraces included into major terrace VI, East of Villa San Giovanni. 1: Granite, 2: Foreset beds (Late Pleistocene); 3: Marine deposits belonging to major terrace VI; 4: marine deposits belonging to major terrace V. In boxes, above some coastline elevation, the characteristic thickness in metres of the corresponding marine deposits.

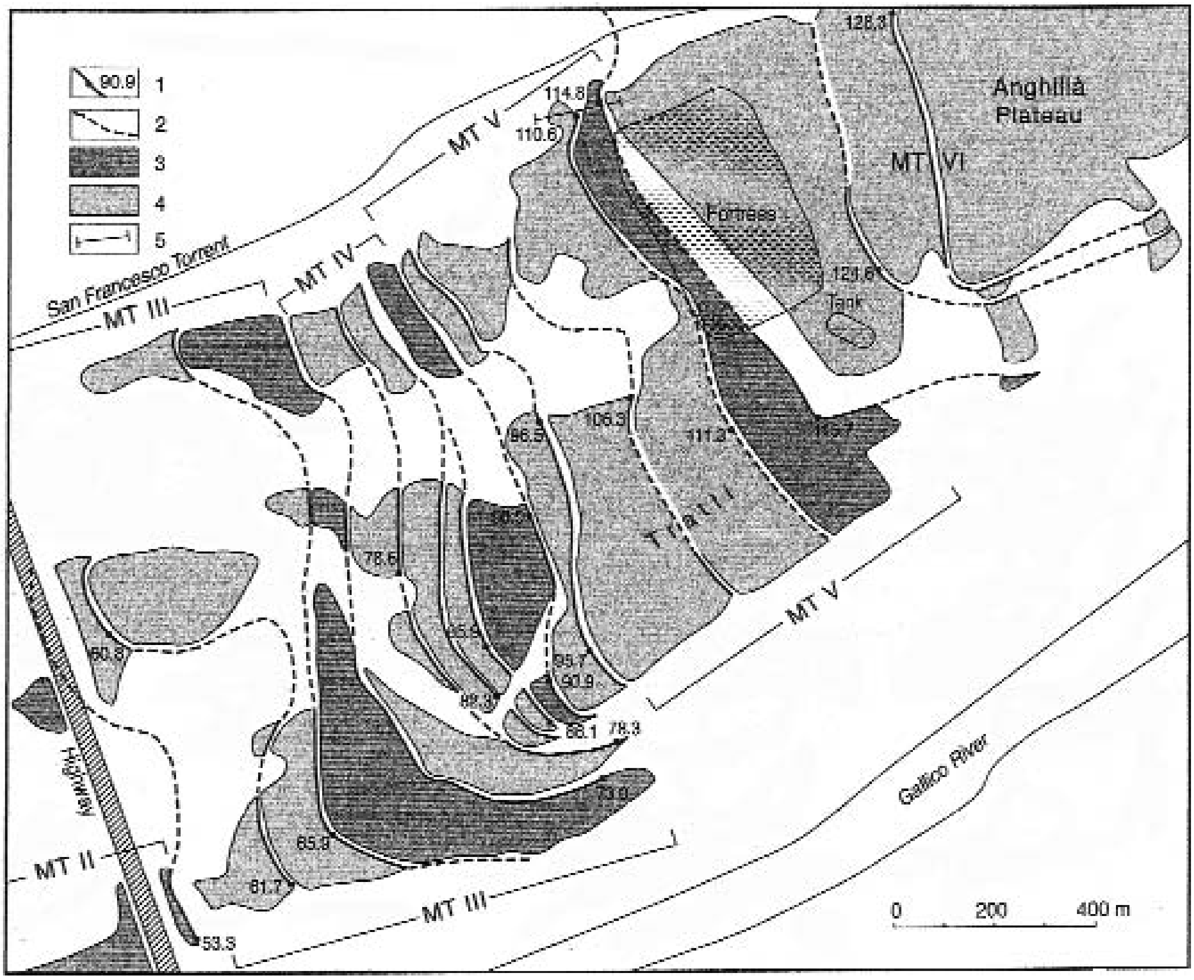


FIG. 6 - Series of terraces included into major terraces V, IV and III in the Tratti area (for location see fig. 4F). 1: Coastline with its elevation; 2: Inferred coastline and links between segments of the same coastline; 3: Head terrace; 4: Minor terrace; 5: Cross-section (see fig. 8).

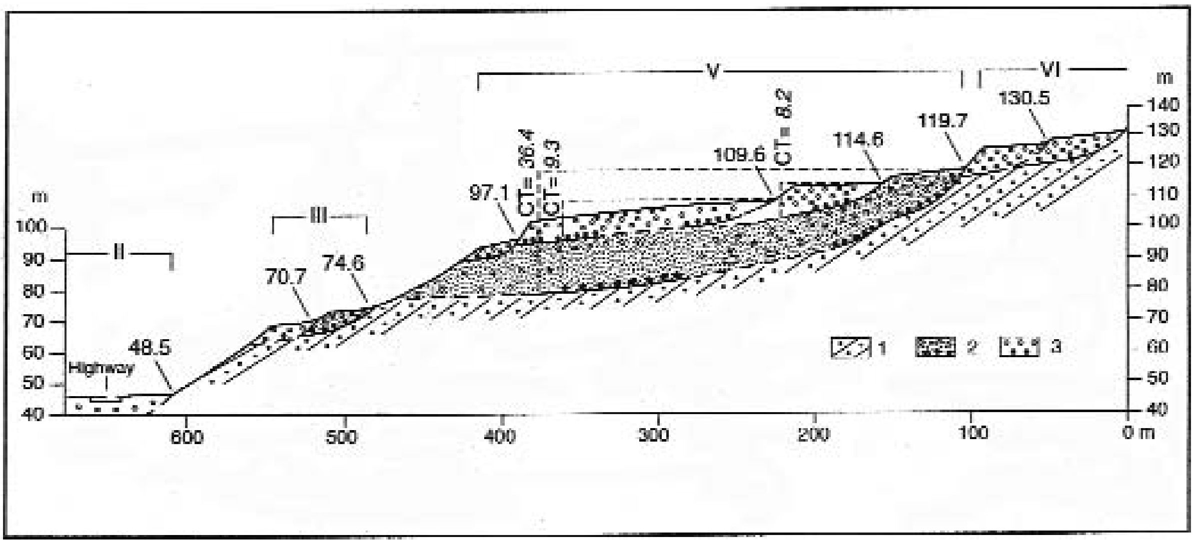


FIG. 7 - Staircase of marine terraces, west of Timpa Tiruni (for location see fig. 4G) 1: Foreset beds (Late Pleistocene); 2: Head terrace deposits; 3: Deposits of minor terraces.

6 and 8 show that below the north-west corner of an old fortress (today occupied by a fun fair park), the narrow head coastline and the following minor one can still be distinguishable but they are far from each other by a less than 20-m horizontal distance only and less than 4 metres vertically. It is easy to conceive that in some cases the retreating sea cliff has reached one or several previous coastline(s) and made it (or them) disappear. Under these conditions, it is necessary to compile the measurements carried out on different traverses to obtain the maximum CT values of each minor terrace: they range between 7 and 15 m for the first minor terrace and it is about 10 m for the two following ones.

The Tratti site also exhibits the best area for counting up the stepped terraces included into MT IV: below the head terrace three minor terraces have been identified between 90 m and 73 m a.s.l. (fig. 6). It is important to note that the fourth coastline of the series (78-m a.s.l.) enters the Gallico valley as the MT V head coastline and the two lower ones of the Anghillà plateau did. As in the Campanella Valley, here we observe a recurrent ria-type setting, which lasted at least over the MT III formation. This accounts for the fact that the terraces, which are not wide, become narrower, close to the Gallico right valley-slope and when they are in lateral position. It has been difficult to measure the characteristic thickness of their associated deposits, except that of the fourth terrace (CT = 7.3 m) and that of the second (10.5 m). On the North of the Gallico valley, in the Piano Micelli, only three terraces have been identified (fig. 9); they become so narrow beyond the Bolano valley that it is impossible to distinguish two of them, despite the natural and artificial exposures along both sides of the San Filippo Neri valley (fig. 10). Nevertheless the CT of the MT IV head terrace deposits has been measured (CT = 34.9 m) and also that of the 82.7 m coastline deposits (7.2 m). Once again this area outlines the fact that retreating coastlines may completely destroy the preceding terrace. It is the case of the second terrace of the series (narrow and ~ 86 m high at Tratti), which completely disappears below Piano del Corvo, as does perhaps the fourth terrace (~78 m high).

In the same areas (Tratti, Filippo Neri and Piano Micelli) MT III is well exposed with its three terraces between 73-75 m and the inner edge of MT II (52-57 m a.s.l.). The head terrace either merges into MT IV (fig. 9) or appears hardly inset in it. Its measured CT is 19.6 m. The deposits of the two successive terraces have a 10.4 m and a 5.6 m characteristic thickness, respectively.

In summary, including MT II head terrace, eleven terraces were shaped from 105 ka to 58 ka and twenty-three on the whole from 128 ka. In spite of the unequal number of terraces on every traverse, the detailed coastline mapping, cross-sections and morphometric results justify the drawing up of a synthetic cross-section (fig. 11A), which summarises the main features in order to make it easier to understand the origin of this impressive stepping of marine terraces.

FROM STEPPED TERRACES TO DEDUCED SEA-LEVEL CURVE AND CONNECTION WITH CLIMATE FLUCTUATIONS

EVIDENCE FOR LATE QUATERNARY SEA LEVEL CHANGES

Dumas & *alii* (2005) have shown in some detail evidence for the eustatic origin of the studied Calabria terraces and they have concluded that the twenty-three marine terraces, stepped from 52 to 181 m, are the result of glacio-eustatic sea-level change coupled with tectonic uplift rate (mean value: 1.3 m/ka).

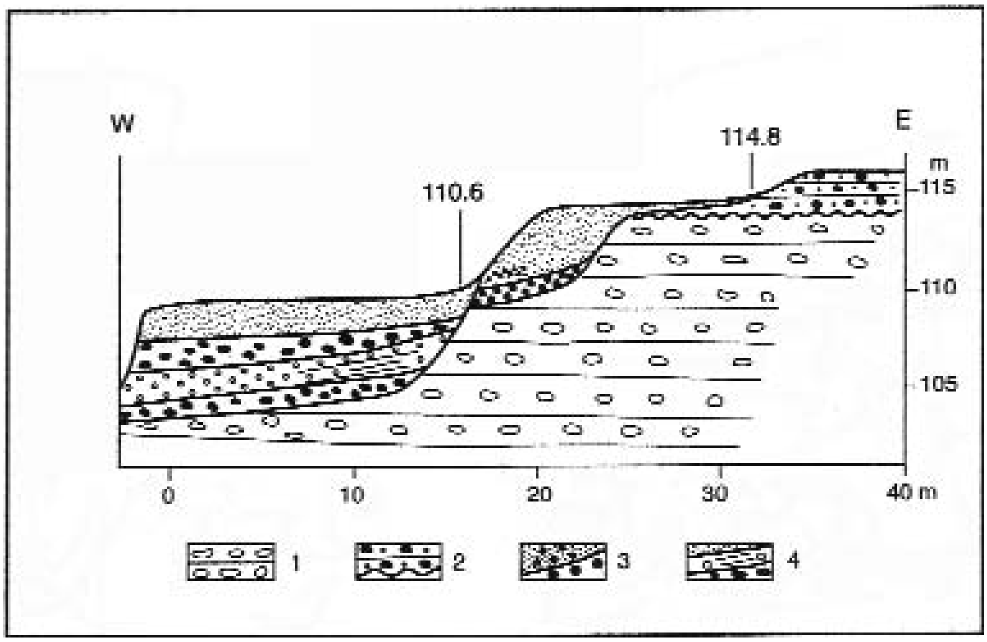


FIG. 8 - Two successive coastlines located close one from the other (San Francesco valley, location on fig. 6). 1: Anghillà formation (conglomerate) belonging to MT VI head terrace (MIS 5.5); 2: Marine deposit (sand and conglomerate) of the last MT VI minor terrace; 3: Marine deposit (conglomerate and sands) of the MT V head terrace; 4: Marine deposit of the second terrace belonging to MT V.

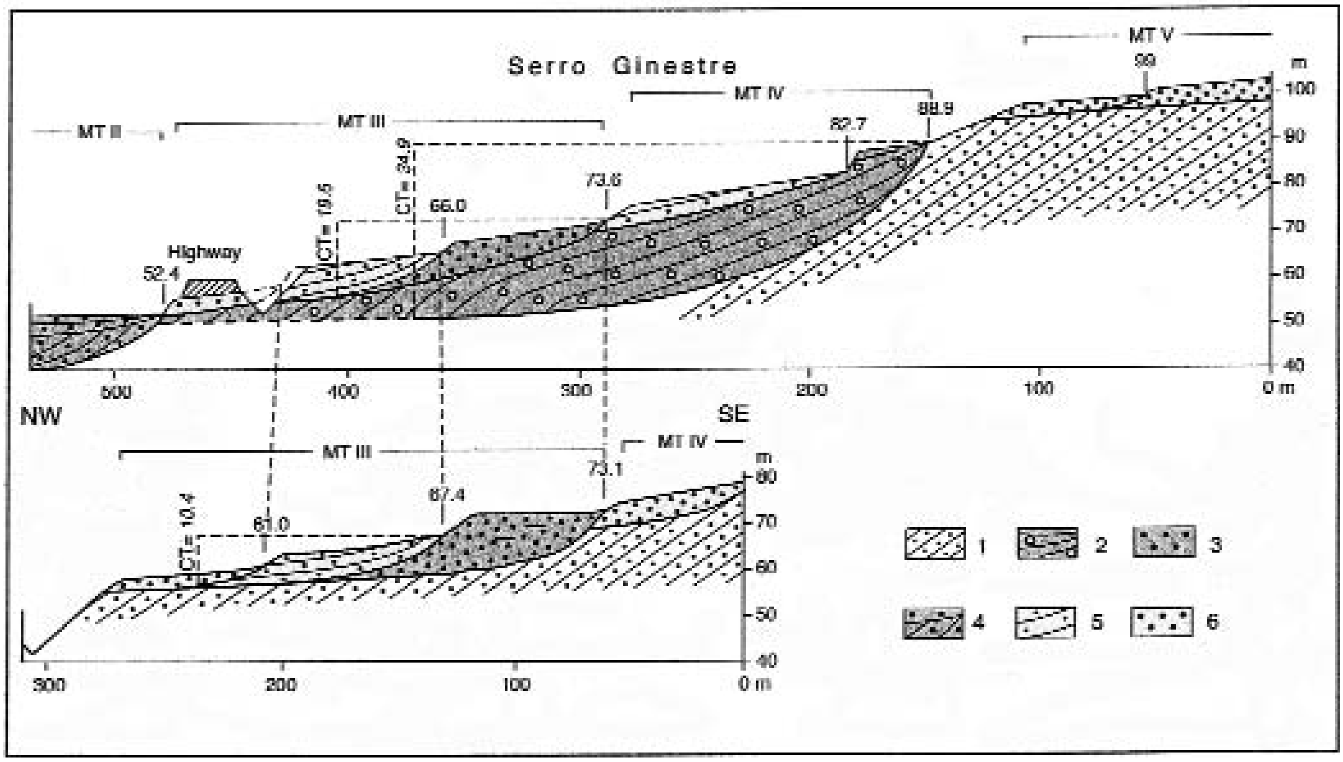


FIG. 9 - Stepped terraces on both sides of the San Filippo Neri valley (for location see fig. 4C and fig 10). 1: Foreset beds (Late Pleistocene); 2, 3, 4: Deposits of head terraces; 5, 6: Deposits of minor terraces.

How does the characteristic thickness (CT) of terrace deposits reveal sea-level changes?

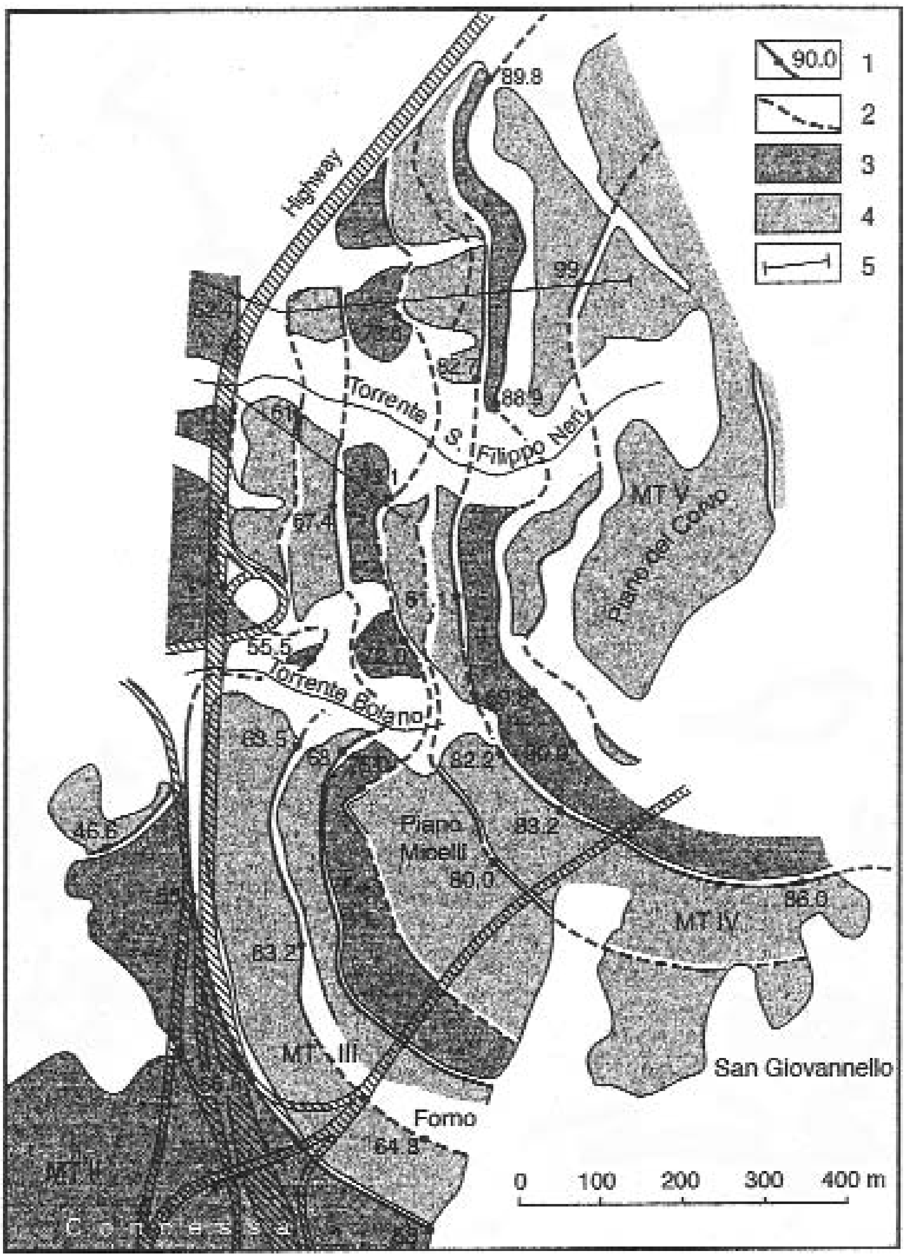
The argumentation firstly relies on the meaning of what they have named the characteristic thickness of coastal deposits. Along any coast, present-day current shore processes shaping the coastline control beach deposits. Those are the result of a dynamic equilibrium in the context of the present stable sea level. On present shores, without significant tide, as the coasts of the Strait of Messina are (tide range = 0.34 m), the mean height between the present wave-cut platform (under beach deposits) and the upper swash limit (coastline or shoreline angle) corresponds to the present space available for sedimentation. It is the present-day characteristic thickness of beach deposits. Any sea level rising would generate a landward and upward shifting of the beach, leading to an increasing characteristic thickness. In this case, the amplitude of sea-level rise would be equal to the difference between the new CT value and the present CT one. So, the latter constitutes a threshold, termed «critical thickness» (Tcr), associated with a stable sea level and fitted to a given coastal area. Along the Strait of Messina, the result of Tcr measurement is 5 ±1.4 m. Assuming that differences between coastal dynamics and those of the past are minimal, the present-day threshold, at a given location, can be compared with the characteristic thickness of Pleistocene marine deposits in the same area. So, every time CT exceeds Tcr (CT-Tcr>0), it indicates that the deposition of sediments is partly due to current shore processes and partly to a rise in sea level. Therefore it points out a sea-level change that is a eustatic event. In the study area, all the CT values exceed 5 m (fig. 11B). So, it can be deduced without any doubt that the twenty-three terraces (fig. 11A) have been generated when sea level was rising. However in raised areas, the characteristic thickness is not directly equal to the sea-level rise amplitude because upheaval reduces it (Dumas & *alii*, 2005). Consequently, the uplift magnitude occurring during the duration of sea-level rise (Ur) must be added to (CT-Tcr), the result being in our study area:

$$\text{Sea-level rise (slr)} = (\text{CT-5 m}) + \text{Ur}$$

Nevertheless, assuming that the uplift rate and the sedimentation rate were constant in time since MIS 5, (CT-5 m) may get a rough idea of sea-level changes. The greater CT values (≥ 20 m) yield the higher rises in sea level. They correspond with MIS 5.5, MIS 5.3, MIS 5.1 and MIS 3 orbital events plus an intermediate event between MIS 5.1 and MIS 3, each generating a sea-level highstand, while the others (less than 12 m) appear as short-lived eustatic events in time intervals.

Secondly, in the field, coastline cross-sections have shown that in many cases, the bottom of sea stacks consists of boulders and cobbles resting on a wave-cut platform truncating the bedrock or former Quaternary layers. These

FIG. 10 - Setting of marine terraces in the San Filippo Neri and the Piano Micelli areas (location see fig. 4D). 1: Coastline with its elevation; 2: Inferred coastline and links between segments of the same coastline; 3: Head terrace; 4: Minor terrace; 5: Cross-sections (see fig. 9).



features are the result of a transgressive sea. It is the basal boundary of the depositional terrace (= «*la superficie inferiore con conglomerato trasgressivo*» in Carobene, 2003). Upward and landward, the coarse sediment shifts into gravel and sands while the wave-cut platform gives place to a more or less plunging cliff buried under beach deposits. This setting is the signature of aggrading material accumulated during sea level rising up from a relative lowstand to a high sea level stand. The latter is associated with the sea stack top, the terrace topographic surface, the coastline and the sea cliff (= «*superficie superiore del terrazzo con paleofalesia*» in Carobene, 2003). As a consequence, each sea-level rise was necessarily preceded by a relative sea-level fall, the main component of which has a glacio-eustatic origin. Indeed, in different parts of the studied coastal area, some terraces have been shaped into rias of various sizes (figs. 5 and 6); that implies the valleys have been hollowed out before being invaded by the sea. Downcutting cannot only be a simple response to the 1.3 m/ka uplift rate, because upheaval can explain neither the amount of available space for sedimentation that is expressed by most of the (CT-5 m) values nor the difference in elevation (D) between two successive coastlines. For example, MT VI and MT V head coastlines are separated by 23 ka, during which the uplift of the oldest was about 30 m. Their 55 m-mean difference in elevation demonstrates

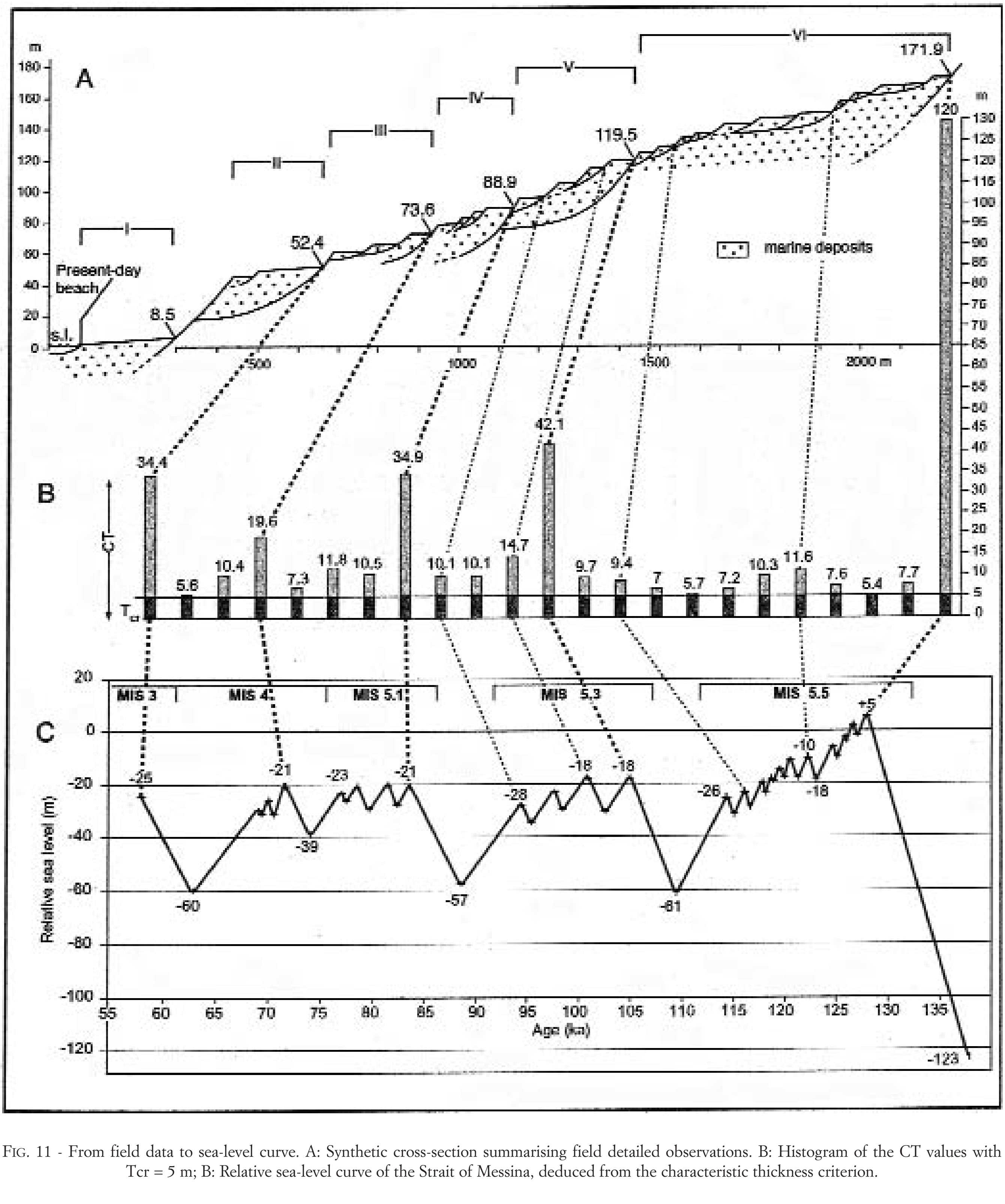


FIG. 11 - From field data to sea-level curve. A: Synthetic cross-section summarising field detailed observations. B: Histogram of the CT values with Tcr = 5 m; B: Relative sea-level curve of the Strait of Messina, deduced from the characteristic thickness criterion.

that they cannot be shaped without an at least 25 m-fall of the sea occurring in the time interval between their shaping. Moreover the characteristic thickness (42 m) of MT V head coastline indicates that before this second highstand, the level of the sea was indeed about 37 m (42-5) lower. So when (CT-5 m) is positive, the sum [(CT-5 m)+D] indicates a fall of the sea and its approximate amplitude. (To exactly calculate it, the uplift amplitude (Uf) occurring during the fall of the sea must be subtracted from [(CT-5 m)+D]). Consequently, if the characteristic thickness provides evidence of a sea-level rise, it also permits to indirectly prove a sea-level fall. As all the CT values of the twenty-three studied terraces exceed 5 m, we can deduce that twenty-three sea-level rises followed by as many sea-level falls have occurred from MIS 5 to MIS 3, determining twenty-three oscillations.

Thirdly, it is assumed that the duration of each sea-level rise and each sea-level fall is proportional to CT (after subtraction of Tcr) and to [(CT-Tcr)+D] respectively. As every eustatic oscillation, which generates a terrace, is composed of a sea-level fall followed by a sea-level rise, the duration of an oscillation is equal to the sum of both event durations and can be considered proportional to [2(CT-5)+D]. It is proportional to the ratio between the whole duration during which *n* terraces were shaped (for example between two orbital events) and the sum of their [2(CT-5)+D]. From the tie-points, an approximate dating for each terrace (or highstand) can be inferred. Knowing the age of each highstand and the uplift rate, each relative sea level height is calculated with the usual formula (uplift rate multiplied by the age minus the shoreline elevation). The age and the height of each relative lowstand follow directly by subtracting from the duration and the amplitude of each sea-level rise, which are easily calculated as indicated above.

With these data, a relative sea-level curve is drawn (fig. 11C); it reveals the sea-level history along the Strait of Messina with the minimal amplitude of each sea-level change. As deduced from the numerous collected field data which are reported on the synthetic cross-section, it appears more detailed, chiefly for MIS 5.5, than any other published sea-level record that is deduced from coral-reef raised marine terraces (Esat & *alii*, 1999; Lambeck & Chappell, 2001; Lambeck & *alii*, 2002; Potter & Lambeck, 2003). But it is more akin to the record obtained from benthic $\delta^{18}O$ Ceara Rise core EW9209-1 (Cutler & *alii*, 2003) after subtracting the temperature component.

Sea level history of the Messina Strait

On the sea-level curve (fig. 11C), the substages are well delimited by very low relative sea levels: –123 m for the penultimate glaciation event, about –60 m for both MIS 5.4 and MIS 4-MIS 3 transition, then –57 m for MIS 5.2. An intermediate lowstand (–39 m) precedes MIS 4. The largest amplitudes of sea-level rises (more than 35 m) follow them. The classical MIS 5.3, MIS 5.1 plus MIS 4 sea-level maxima are at about –18 m, –21 m, –21 m, respectively. All these values are similar to those deduced from recently published eustatic curves (Cutler & *alii*, 2003; Lambeck & *alii*, 2002; Potter & Lambeck, 2003). They correspond to the head shorelines (fig. 11A).

The curve is divided into four periods that appear different because they have unequal duration with unequal number of events of unequal amplitude.

The large time interval (23 ka) and the large difference between their respective relative sea level (23 m) explain that MT VI and MT V head terraces are clearly distinguished in the landscape. The most striking feature is the ten short-lived oscillations over MIS 5.5. Between 128 ka and ~ 114 ka, they are inscribed in a «descending» curve, which puts relative sea-level highstands lower and lower from + 5 m to –26 m. Lowstands follow more or less the same progressive drop of the sea. As eustatic gaps (difference between two successive highstands) range between 2 m and 4 m, even short-lived events can be recorded in the landforms. After the MIS 5.5 sea-level maximum and until ~ 125 ka, through three low-amplitude oscillations, sea level progressively fell until ca. –10 m. Three terraces are stepped within a ~11 m-high vertical interval. A greater drop (~ 12 m) was the onset of a second period, lasting about 6 kyr (125-117 ka) and including five oscillations. The first of them has the greatest amplitude of all the short-lived MIS 5.5 oscillations, sea level rising from –18 m to –10 m. It has generated the terrace at 149 m-150 m a.s.l., the coastline of which is well preserved on the Anghillà Plateau (fig. 6 in Dumas & *alii*, 2005). Through the next four, both rises and falls of the sea decreased, and relative sea level varied between –10 m and –20 m. Then in the third part of the curve, it dropped and oscillated between –20 and –30 m through two oscillations, during which both fall and rise amplitudes increased, before the MIS 5.2-minimal lowstand (–61 m). That corresponds to the nearly 10 m-CT value of the two last terraces in the Campo Piale valley (fig. 5C and fig. 11).

With peak MIS 5.3, sea level rose up to –18 m and the curve consists of four oscillations within 10 kyr. Contrary to the MIS 5.5 period, they are not inscribed in a slowly falling of the sea. The first two oscillations have similar amplitude. The small difference between the relative highstands is balanced by a greater time interval between terrace age estimate (~ 3.3 kyr). That explains the terraces can be witnesses of the eustatic events, thanks to the uplift amplitude, which prevents each coastline to be concealed or destroyed by the successive one. The drop of the sea intervenes with the third and fourth oscillations. Five and ten metres separate the first MIS 5.3 highstand from the third and fourth ones, respectively. This fact could explain that the terraces, the coastlines of which rise at about 103-105 m a.s.l. and 95-97 a.s.l. respectively are well preserved in the landscape.

During MIS 5.1, the sea remained below –20 m and its variations were so weak that its fourth and last highstand was only 2 m lower than the first: –23 m against –21 m. It is noticed that after MIS 5.1-MIS 4 transition sea level rose up again to –21 m. It means that the relative sea-level highstands were nearly the same over 10 kyr and they were less spaced in time, compared with MIS 5.3. Under these conditions, probably the shorelines have not been well recorded all along the Strait of Messina or maybe the low sea cliffs they have generated can easily escape to observation today. In the same order of ideas, a 5.5 kyr duration and an eustatic gap of –2 m separate the last MIS 5.1 minor terrace from the MT III head terrace against ca.10 kyr and –8 m or –7 m for MIS 5.3-MIS 5.1 or MIS 5.5-MIS 5.3 intervals. Apart from the variations of coastline indentation, all these facts could explain why in the Piano Micelli-San Filippo Neri areas for example (fig. 10) one or two terraces are not detected or why the major terrace III could not be in some cases morphologically distinct from MT IV because they might merge into the same terrace unit.

Connecting the relative sea-level curve of southern Calabria with climate fluctuations

What do climate curves reflect?

During the last twenty years, numerous papers dealing with either deep-sea material or terrestrial sediments or ice-cores focused upon the rapid climate variability all through Late Pleistocene (Lorius & *alii*, 1985; Jouzel & *alii*, 1987; Winograd & *alii*, 1992; Dansgaard & *alii*, 1993; An & Porter, 1997; Bond & *alii*, 1997; Chapman & Shackleton, 1998; Yokohama & *alii*, 2000; Wang & *alii*, 2001; Heusser & Oppo, 2003; Sánchez-Goñi & *alii*, 2005; Tzedakis, 2005). This now well established fact relies upon lots of indicators: composition and rate of biomarkers embedded in marine (*Neogloboquadrina pachyderma*) or terrestrial sediments (fossil pollen assemblages), percentage of lithic tracers (IRD, hematite-stained grained, detrital carbonate), of gas content (CO^2, CH^4) in air bubbles trapped in ice-sheets, isotopic ratios from air (δD), from speleothems ($\delta^{13}C$), from benthic ($\delta^{18}O$, $\delta^{13}C$) or planktonic ($\delta^{18}O$) foraminifera. Most of these proxies are considered as indirect palaeothermometres, from which changes in atmospheric or sea surface temperatures are derived while others reveal variations in deep-oceanic circulation and global ice volume. Nevertheless the signal interpretations are seldom simple. For example, the isotopic composition of planktonic foraminifera records both surface temperature and salinity of local sea water; benthic $\delta^{18}O$ reflects both deep-sea temperature and global ice volume. On a given curve, which comprises unequal amplitude peaks, it is difficult to determine the exact influence of both parameters, which do not necessarily oscillate in phase.

The published results are plotted on different curves showing fluctuations with unequal frequencies and unequal amplitudes. An important feature is the similarity of these curves that naturally leads to compare them despite they are not plotted on the same time scale. Most of them are orbitally tuned on SPECMAP, others on ice-layer counting and ice-flow models; other isotope records are calibrated making use of radiometric dates (mainly obtained from fossil corals). This disadvantage is circumvented by calculating an adjusted age-model based upon the alignment of the low-amplitude sharp peaks and troughs of the different curves or by using the synchronisation of some proxies (atmospheric methane variations in ice-cores, benthic $\delta^{18}O$ in deep-sea cores) to connect the prominent peaks of some curves with the major peaks of another one. Analysing all the signals from the same samples along thick core sequences taken off from the Atlantic ocean: MD95-2042 (Sánchez-Goñi & *alii*, 1999; Shackleton & *alii*, 2002; Shackleton & *alii*, 2003), MD99-2331 (Sánchez-Goñi & *alii*, 2005) and ODP site 1059 (Oppo & *alii*, 2001; Heusser & Oppo, 2003) is another way to get over the difficulty. In the case of ODP site 1059, they «allow a direct comparison of vegetation changes in the southeastern United States with those in the western subtropical Atlantic and with global ice volume» (Heusser & Oppo, 2003).

Joint examination of several high-resolution curves has led Earth scientists to establish strong links between marine, terrestrial and atmospheric climatic proxies and to point out rapid climatic event records, everywhere in the world. A reliable correlation is confirmed between 65 N orbital June insolation maxima, climate optimum highlighted by high percentages of tree pollen (Europe, Southeast USA) and low ice-volumes that mark the MIS 5 isotopic substages. But the most important result is related to the higher-frequency suborbital events (from 4-10 kyr to 1-2 kyr) that occurred between them even if the origin of suborbital oscillations is not understood (Keeling & Visbeck, 2005) and even if there is yet any doubt about the perfect synchronisation between all these events (Tzedakis, 2005).

Coral-reef-terrace U dating (Lambeck & *alii*, 2002; Cutler & *alii*, 2003) i.e. geomorphologic and radiometric criteria have shown that orbital events control rises in sea level. The complex interplays between the climatic parameters make it difficult to directly deduce sea-level changes from benthic isotopic curves, which include an ice volume component. Nevertheless, on the one hand attempts to isolate the influence of ice volume on global sea level (Shackleton, 2000; Lea & *alii*, 2002; Waelbroeck & *alii*, 2002) have shown few connections between climate suborbital fluctuations and sea level change except that of Siddall & *alii* (2003). On the other hand, new investigations about MIS 3 coral terraces at Huon Peninsula (Chappell, 2002) and MIS 5 terraces at Barbados (Potter & *alii*, 2004; Schellmann & Radtke, 2004) concluded to suborbital frequency of sea-level rises during these span times. Potter & *alii* (2004) find agreement between MIS 5.3 and MIS 5.1 terraces at Barbados and climate events recorded from GISP2 ice-core ($\delta^{18}O$), from V29-191 (McManus & *alii*, 1994) and NEAP18K (Chapman & Shackleton, 1999) deep-sea cores (percentage of *N. pachyderma s.* and IRD, respectively). As Southern Calabria has recorded twenty-three sea level oscillations from MIS 5 to the onset of MIS 3, that allows to compare them (fig. 11C) with the several climate high-resolution records during the same time period into which millennial-scale climate oscillations have been recognized.

Selected climate curves and sea-level oscillations

For a comparison with our sea-level curve, recent high-resolution isotopic records have been selected (fig. 12).

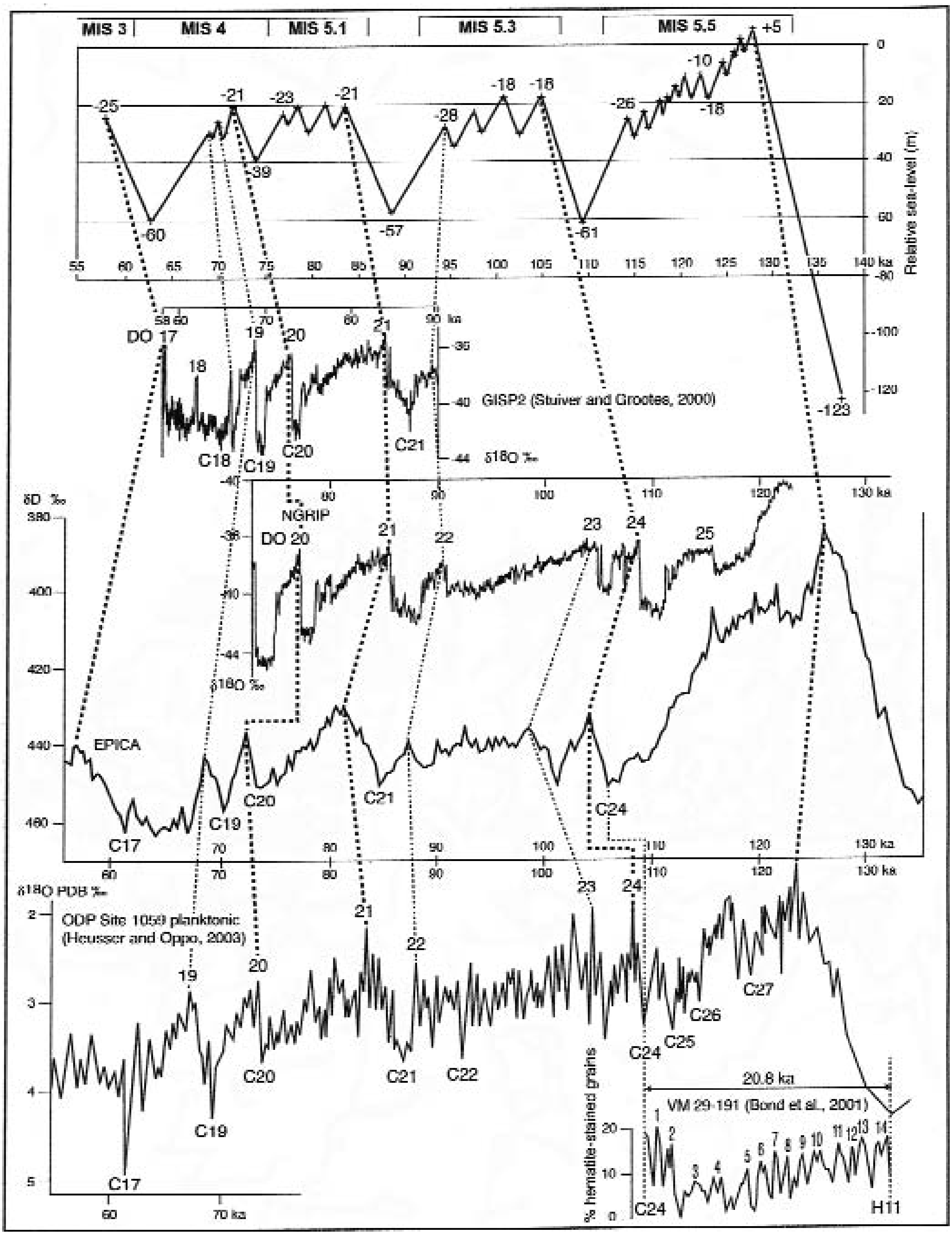


FIG. 12 - Comparing the Calabria sea-level curve with some ice records (GISP2, NGRIP, EPICA) and isotopic (ODP 1059) or lithic (V29-191) marine curves.

Only ODP Site 1059 and EPICA (2004) extend over the whole MIS 5-MIS 4 period. The ODP 1059 planktonic curve is associated in the Heusser & Oppo's paper (2003) with benthic curves ($\delta^{18}O$ and $\delta^{13}C$) and pollen taxa diagrams. It outlines some suborbital marine cold events already labelled as C27 to C19 (McManus & *alii*, 1994; Chapman & Shackleton, 1999) that are «mirrored» or «have counterparts in the pollen records» but also «additional millennial (cold) events» between them «marked by small decreases in Quercus» all through the whole MIS 5. «Nearly every positive planktic $\delta^{18}O$ event, whether it is a named cold event or occurred in-between those events, falls on or close to a negative $\delta^{13}C$ excursion», that closely links sea surface temperature and suborbital variations in NADW/SOW contribution. Compared to GISP 2 (now supplemented by NorthGRIP) Heusser & Oppo (2003) show that in the subtropical Atlantic, planktic $\delta^{18}O$ minima, associated with oak peaks, correspond with GISP2 interstadial events. Nevertheless, «the parallel high-frequency oscillations in pollen and planktic $\delta^{18}O$ concur with suggestions that climate variations were more frequent than recognized in Greenland ice core record».

Figure 12 represents the Heusser & Oppo's main comparisons between ODP 1059 and GISP2 curves; the results are reported on NorthGRIP (North Greenland Ice Core Project members, 2004) and correlated with EPICA curve. On this last curve, main warm events are more easily discriminated from minor peaks even if they are not labelled as IS (= DO or Dansgaard-Oeschger events). Labelled or not, interstadial events DO 20 and DO 21 are depicted as prominent peaks on every curve just as DO 24 and DO 19 appear on three of them. The stadial events C 24, C 21, C 17, which precede the climatic optima labelled respectively as DO 24, DO 21 and DO 17, can be linked with the about –60 m lowstands on our sea-level curve. With C20, they limit four unequal duration periods, during which climate fluctuations appear unequal by their number, their amplitude and their arrangement. Between the extreme lowstands, the sea-level curve looks like them with its unequal oscillations. So linking the MIS 5.5 warmest event with the + 5 m relative sea-level highstand is indisputable as are also the connections between the orbital DO 24, DO 21, DO 17 with the MIS 5.3, MIS 5.1, MIS 4 maximum sea-level highstands respectively. A suborbital warm event, DO 20, involved sea level rising up to –21 m.

The Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}O$ record, with its very high-resolution (Stuiver & Grootes, 2000) yields the most accurate information available on past climates, from present-day up to 90 ka. From 58 ka (DO 17) to 84 ka (DO 21) five numbered Dansgaard-Oeschger warm events are recorded. In the same time interval, our sea-level curve presents eight high sea levels. During MIS 4, two (out of three) prominent warm events are labelled: DO 18 and DO 19. It is probable that the first marine oscillation occurring after DO 20 could be linked to DO 19 (fig. 12). For the subsequent one, we have the choice between DO 18 and a non-numbered peak. DO 18 event does not seem to be the best candidate. Indeed if it had involved an about –30 m relative highstand, ~ 4 ka before orbital DO 17, the terrace could not be raised enough to emerge and be preserved above the coastline shaped by the large subsequent orbital sea-level rise (36 m). In other words, either DO 18 has not given a terrace expression or may be the terrace deposits were eroded or covered by younger ones. More probably, the last MIS 4 sea-level oscillation could be assigned to the 5‰ variation peak (at ca. 66 ka on GISP2) occurring during the fall of sea level until the C18 cold event. In this case, there is no correspondence between a marine terrace and a labelled DO event; conversely a non-named warm event can be linked to a eustatic event.

Between DO 21 and C20, (about 10 kyr duration), there are on all the curves numerous low-amplitude oscillations with decreasing $\delta^{18}O$ values and some little warmer oscillations (2‰ isotopic value difference at ~ 76 ka, on GISP2). Two of them are better depicted on ODP site 1059 curve. None of these MIS 5.1 small oscillations is labelled as DO. In comparison the Calabria sea-level curve shows four MIS 5.1 oscillations with nearly equal relative sea-level heights. Except the first (Early MIS 5.1 peak) it is impossible to surely assign the three others to one climate fluctuation rather than another.

For the MIS 5.3 period, there is a better agreement between the three climatic curves and the eustatic one. DO 24 and DO 23 appear as equally prominent peaks separated by a pronounced cold event. The sea-level curve exhibits an about –30m lowstand between two highstands at the same height (–18 m). Near the end of MIS 5.3, DO 22, before C21, is strongly marked on all the curves. It would correspond to the high sea level at –28 m. There only remains some uncertainty for the third sea-level maximum. The warm event closely following DO 23 on the ODP 1059 curve would be a good candidate because it has nearly the same amplitude as DO 23; but in the low decline in temperatures, lasting from 10 to 15 kyr, between DO 23 and DO 22, the more prominent peak, which appears just before C22 and which is at about 93 ka on EPICA curve, could be another possibility.

For MIS 5.5, our attempt for connecting the curves only depends on EPICA, ODP Site 1059 and VM 29-191 curves. EPICA and our sea-level curve are geometrically similar but only five significant warm peaks can be candidates for eleven highstands. Indeed the youngest peak is the counterpart of DO 25 revealed in NGRIP record at ~115 ka after an abrupt cooling at about 119 ka (NorthGRIP members, 2004). On the sea-level curve, the last MIS 5.5 relative highstand (–26 m) is also about 115 ka old. So, over a ~13 kyr-long period, from MIS 5.5 early peak, eleven sea-level changes occurred (frequency: 1,3 kyr), that is approximately the number of main climate variations on ODP 1059 curve, up to C24. Moreover fourteen drift ice indices (hematite-stained grains) have been identified by Bond & *alii* (2001) from two Atlantic marine cores (VM29-191 and JPC 37) between H 11 and H 9 (= C24) events, some of them (3 or 4) probably occurring during Termination II. Over 20.8 kyr (fig. 12) they appear as small events compared with the labelled successive younger Heinrich events. But they have counterparts neither in *Neogloboquadrina pachyderma* (sinistral coiling) nor in IRD grains relative abundance. Nevertheless they bear witness of low-amplitude climatic variations every 1.5 ka. We note that the smallest sea-level oscillations are documented from Calabria terraces during the same time interval. All these observations lead to the conclusion that many suborbital climatic events, which have been recorded in some ice or marine cores, may be connected with sea-level oscillations that occurred over MIS 5.5.

Finally, one can note that the sea-level curve deduced from the stepped marine terraces of Southern Calabria reveals strong similarities with prominent climatic events. Sea-level changes do not reflect all the detailed and weak climatic oscillations but several millennial-scale suborbital events have caused alternating rises and falls of the sea. This result remains an intriguing question because sea level oscillated between an interglacial state and a glacial one, i.e. during the inception and/or the growth of the North and South ice-sheets. It demonstrates that the ice-cap building up was not a linear phenomenon. Indeed as for the climate variability, we cannot understand the origin of such high-frequency sea-level changes, especially during MIS 5.5. In a recent paper, Kukla & Gavin (2005) show that the combination of obliquity and precession control the amount of insolation in the Tropics and temperature gradient variability between low and high latitudes; that influences the heat and vapour fluxes. Solar insolation in June at latitude 65 N would not be sufficient to explain climatic changes. For example, «the build-up of polar ice accelerated when low obliquity coincided with perihelion in Northern Hemisphere in winter». «During the first millennia, (after an interglacial maximum), the early glacial ice build-up was most likely accompanied by global warming» (Kukla & Gavin, 2005). This climate condition might increase annual snow precipitation in high latitudes and high elevations explaining the first small oscillations of the sea. Moreover the response of the Southern Hemisphere to climatic changes in the North is not clearly known. If some Antarctic warm events are more or less a response to ice discharge in the North Atlantic (Keeling & Visbeck, 2005), it is possible to infer an Antarctic ice-sheet contribution to global sea-level fluctuations. All these assumptions need to be proven.

CONCLUSION

In Southern Calabria, the numerous marine terraces inscribed within the 70-kyr time interval (128-58 ka) result from the interplay between sea-level change and a high uplift rate (1.3 m/ka). This conclusion relies on the analysis of twenty-three constructional terraces, consisting of loose deposits, which are stepped between 181 m and 52-m a.s.l. and are related to the MIS 5 and the MIS 4 periods. Comprehensive geomorphologic and geological surveys show that they are distributed into four wide major terraces (MT), which are the main landscape units. The uppermost (head) terrace of the series, associated with each major coastline, can be distinguished from the others, termed minor terraces, on the basis of the characteristic thickness of their marine deposits (CT). The four head terraces with more than 20-m thick marine deposits have been generated by orbital high-amplitude sea-level rises that occurred respectively at about 128 ka, 105 ka and 84 ka plus an important suborbital event at about 72 ka. In these time intervals, minor terraces, with generally less than 12 m-CT values, are often inset into the head terrace thick formations. This setting results from short-lived sea-level rises preceded by sea-level falls, the respective minimal amplitude of which is deduced from CT. Sediments of each terrace have accumulated in the accommodation space created by previous sea-level falls and they piled up during each sea-level rise, involving the landward and upward migration of the coastlines. In spite of unequal oscillations, and except for the orbital ones, the rise amplitude of sea level was always lower than that of the preceding sea-level fall. So the stepped coastlines appear as the record of the westward and the lower and lower successive shifts of the Calabria shoreline during the Late Pleistocene period. As a consequence, a sea-level history along the Strait of Messina can be reconstructed. The relative sea-level curve, which is drawn up, reveals an unexpected record of unequally time-spaced sea-level oscillations: eleven over MIS 5.5, four during both MIS 5.3 and MIS 5.1 and three during MIS 4. With its eighteen suborbital short-lived oscillations, it looks in a way like some high-resolution isotopic ice and marine records so that connections between each other may be attempted. Globally they seem in good agreement. From 105 ka to about 62 ka, eight eustatic oscillations out of eleven can easily be linked with a warm event on the climatic curves. Within the MIS 5.5 period, there are at least five and possibly up to a dozen-climate fluctuation between about 128 ka and about 115 ka to match the eleven sea-level oscillations. Finally, it seems established that rapid suborbital climatic events can be reflected in the low-amplitude and high-frequency sea-level changes occurring over a large part of the Late Pleistocene period in Southern Calabria.

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