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THE PROBLEM OF USING MARINE TERRACES WITH UNCLEAR INNER EDGE FOR PALAEO SEA-LEVEL DETERMINATION: A CASE STUDY FROM LIGURIA (NW ITALY)

Abstract - The marine terrace of Nervi (Liguria, North-Western Italy) was analyzed in order to state as accurately as possible the position of its inner edge to be used as a past sea-level altitude marker. In this case the platform-cliff transition is not sharp and the lack of an exposed section of the terrace makes impossible to evaluate the thickness of its sedimentary cover. The geomorphological survey of the terrace and its surroundings shows the presence of a «transition area» bounded seaward by the sub-horizontal surface and inland by a steep slope, interpreted as the palaeocliff. Subsurface data from mechanical drillings were collected for the area, both inside and outside the transition area; they provide evidence about the nature and features of the bedrock and of the deposits on and uphill the shore platform. Analysis of surface and sub-surface data permitted to interpretate the slope profile from 100 m a.s.l. down to the presently active cliff as the result of a long-term evolution of a four-stepped staircase of marine terraces. The inner edge of the terrace of Nervi results located on the bedrock at about 18 m a.s.l. The value obtained was compared with that calculated applying to the elevation of the profile knickpoint the error bar that the literature suggests to use in case of inner edge masked by deposit and with the error bar previously assumed for marine terraces located immediately easternward Nervi. Both comparisons underline the necessity of a case by case evaluation of the error bar acceptable for the marine terraces inner edge altitude, in particular if it is morphologically unclear.

Key words - Ligurian coast, marine terrace, inner edge, palaeo-sea level.

Riassunto - *Il problema dell'uso dei terrazzi marini con margine interno incerto per la determinazione di antichi livelli di stazionamento del mare: un caso di studio dalla Liguria (Italia nord occidentale).* Il terrazzo marino di Nervi (Italia nord-occidentale) è stato studiato con lo scopo di definire il più accuratamente possibile la posizione del suo margine interno in quanto esso rappresenta un importante indicatore di un antico livello di stazionamento del mare. In questo caso il margine interno del terrazzo è sepolto ed in particolare l'assenza di sezioni esposte impedisce una stima dello spessore della copertura sedimentaria. Il rilevamento geomorfologico dell'area ha messo in luce la presenza di una zona di transizione localizzata tra la superficie sub-orizzontale del terrazzo marino e una parte del versante più acclive interpretata come paleo-falesia. Sono stati raccolti i dati relativi ad indagini geo-meccaniche nella zona di transizione e nei suoi dintorni. Essi hanno fornito dati relativi alla profondità e alla natura del substrato che corrisponde alla piattaforma di abrasione e alla sua copertura. L'interpretazione dei dati di superficie e di sottosuolo ha permesso di interpretare il profilo del versante a partire da 100 m di quota sino al livello del mare attuale come il risultato di una gradinata di tre terrazzi marini. Il margine interno del terrazzo di Nervi è stato identificato sul substrato alla quota di 18 m s.l.m. Questa quota è stata messa a confronto con quella calcolata applicando all'altezza del margine interno identificato sul profilo topografico l'errore suggerito dalla letteratura nel caso di margini interni mascherati da deposito e con quello attribuito a terrazzi marini prossimi all'area di studio. In entrambi i casi il confronto sottolinea la necessità di una valutazione specifica caso per caso dell'errore da attribuire ad un margine interno sepolto.

Parole chiave - Costa della Liguria, terrazzo marino, margine interno, paleo livelli di stazionamento del mare.

Introduction

Marine terrace is one of the most widespread geomorphological evidence related to former sea levels highstands, useful to understand past sea level fluctuations and local tectonic movements. Each marine terrace is constituted by a nearly horizontal or gently seaward dipping erosional platform backed by a steep or degraded relict sea cliff (Fairbridge, 1968; Pirazzoli, 2005). The ideal scheme of a marine terrace also includes marine sediments overlapping the rock platform, whereas continental deposits, that in some cases may cover the terrace, are not considered part of it (Carobene, 1980). The intersection between the sea cliff and the platform is the inner edge that represents a former shoreline (Fairbridge, 1968; Lajoie *et al.*, 1986; Anderson *et al.*, 1999); the individuation of this feature is very important: in fact its elevation records the maximum altitude reached by the sea during an highstand (Cinque *et al.*, 1995). The marine terrace is contoured seaward by the outer edge which in most cases is the product of the backwearing of the original terrace seaward termination.

Inner edges indicate the palaeo sea level with an uncertainty which, also in the best state of conservation, is high if compared with that typical of other markers like tidal notches or lithophaga hole-bands (Carobene & Pasini, 1982; Pirazzoli, 1986; Antonioli *et al.*, 1999; Nisi *et al.*, 2003; Ferranti *et al.*, 2006; Pirazzoli, 2007). In fact marine terraces indicate the palaeoshoreline elevation with an accuracy which depends on their present-day displacement (e.g. degree of preservation and sheltering of the inner margin) but also on some of their

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originary features (e.g. the bedrock hardness; Thornton & Stephenson, 2006). On the other hand, in some areas, they are the unique marker of palaeoshorelines and for this reason it is important to better define the accuracy provided by them in their different conditions.

In a recent work that collects and compares data of ancient shorelines coming from different Italian regions, marine terraces are considered good quality markers (+3 m error bar) when the inner edge is clearly recognizable whereas they are considered less reliable markers when the inner edge is not preserved (+20 m) or masked by deposits (-20 m) (Ferranti *et al.*, 2006).

Although classifying different types of markers assigning them a fixed error bar is methodologically correct, the situations in the field are very different and a case by case evaluation of the uncertainty magnitude is necessary; therefore some options should be left to the method user, as some authors stress (e.g. Federici & Pappalardo, 2006).

Frequently the error bar of the inner edge is not indicated but there are enough examples that highlight the great variability of this parameter. Infact, also in the lucky cases, when the inner edge is visible, we can find in the literature different values of analytical error, evaluated by the authors in accordance with the sensitivity of the measuring instrument and the method employed to assess its elevation. It could be very small if measurements are carried out repeatedly with precision instruments (Merritts & Bull, 1989) or reach a couple of m using a pocket altimeter (Ota, 1996; Lucchi *et al.,* 2007). In addition they should consider the effect of tidal range. Of course, the difference in the error bar becomes greater when a knickpoint in the long profile highlights the existence of the terrace inner edge but this is sheltered by a secondary deposit. In these cases infact, the analytical error must be added with another error deriving from the estimation of the deposit thickness (Cucci, 2004; Feuillit *et al.* 2004). In Liguria we identified different kinds of marine terraces that provide data of palaeoshorelines with different accuracy depending on their degree of evolution and state of conservation. In particular the uncertainty assigned to the altitude of each terrace inner edge was chosen according to the following criteria (Biagioni *et al.*, 2007): when the marine terraces are uncovered the error bar is not wide and corresponds to the instrument error (± 1 m); when they are covered, the presence of a deposit constrains the value of the error bar between the upper limit of the altimeter accuracy (+1) and a value corresponding to the deposit average thickness added with the instrument error (on the whole +1/–6). The deposit average thickness was inferred from field observation of the terraces long and cross sections where the bedrock is exposed. In these cases a local estimation of the deposit thickness could be made and a realistic error indicated.

Even more problematic, also at local scale, is the determination of an error bar when the deposit thickness over the platform is unknown and inestimable. In this situation, information about the platform depth can be obtained through corings and geophysical surveys that can provide data useful for a geometric reconstruction of the inner edge original position and elevation (Alexander, 1961; Bradley & Griggs, 1976; Carobene & Firpo 2002; Shaller & Heron, 2004).

A further case is the one proposed in this paper, in which a wide coastal terrace is backed by a steep slope but the transition between the platform and the slope is not sharp and far from resembling the typical terrace-palaeocliff junction. Moreover no exposed section is available which shows the terrace cover thickness and nature. Recent geotechnical investigations carried out for the design of buildings foundations supplied new subsurface data for the area. Their analysis, associated to a detailed geomorphological survey of the terrace and of its surroundings, permitted to recognise in the long profile of the slope traces of terrace surfaces formed during four different highstands and to state their inner edge position and altitude with good confidence.

The results obtained from this work enable to infer some general features of the marine terraces of the area, useful to assess general guidelines for their employment as shoreline elevation markers.

General setting

The study area is located in the eastern outbank of the city of Genoa (Fig. 1). The coast of Liguria, facing the homonymous sea in NW Italy, is at the base of the seaward slope of an arch shaped mountain ridge separating the Mediterranean Sea from the Po Plain. From a geological point of view, the ridge can be divided into two parts: the western, NE-SW oriented is considered to be the southern continuation of the Western Alps (named Ligurian Alps, Vanossi *et al.*, 1986); east of the city of Genoa the Northern Apennine chain stretches NW-SE. Most of the chain is modelled in the so called Ligurian Units, and only in its easternmost part in the tectonic units of the Tuscan domain (Giammarino *et al.*, 2002). In the detail the study area is then located close to the westernmost edge of the Apennine chain, where Cretaceous to Eocene marls, limestones, calcarenites, sand-

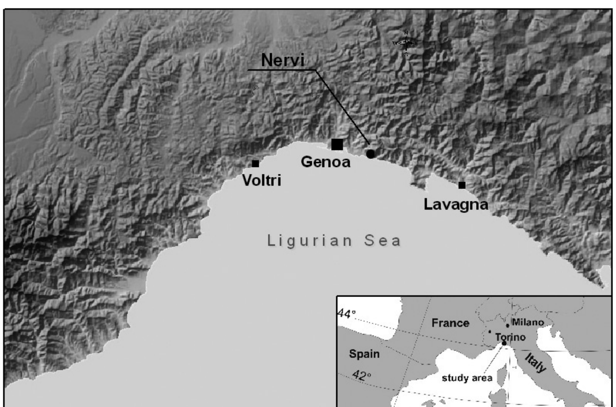

Fig. 1 - Geographic framework. The study area is indicated by the black dot.

stones and shales outcrop. From a tectonic point of view the area experienced the effects of the late orogenetic movements of the Apennine chain, being subjected to uplift movements probably decreasing in intensity with time. The strong influence of neotectonics in shaping the coastline of eastern Liguria was stressed, in particular during the 1980s when neotectonic studies were carried out (Fanucci & Tedeschi, 1982; Cortemiglia, 1982; Nosengo & Tedeschi, 1982, Fanucci (1987). It was supposed that this tract of the coast is dissected by transverse main faults that separate it in tectonic blocks, each characterized by a different vertical displacement. Being marine terraces included in these blocks, they could be used to measure the difference in vertical displacement among the blocks, provided the age of the different terraces is known; stating the precise altitude of their inner edge, thus, should be crucial.

Along the eastern ligurian coast, the presence of marine terraces was mentioned since the late 19th century (Issel, 1883; Rovereto, 1939), after those reports, the most important contributions were provided by the cited works focused on neotectonics. These papers recognize those marine terraces developed in the eastern sector of Genoa city as the most continuous and extended ones in eastern Liguria (Fig. 2), nevertheless they do not supply a record of inner edges measurements nor consider to state the uncertainty of the marker altitude value.

Recently a review of old and new data (Federici & Pappalardo, 2006) highlights the presence, throughout the sea-facing slope of eastern Liguria, of marine terraces with elevations ranging from 4 up to 34 m a.s.l, clustered into 3 orders around 27, 12.5 and 5 m a.s.l. (Biagioni, 2008). The most developed and laterally continuos set of terraces of the upper order can be observed in the study-area and in its immediate prosecution towards the east; it is characterized by an inner edge located at 27+1/-6 m a.s.l. (Biagioni *et al.*, 2007). To the same order belongs the only dated shoreline in eastern Liguria. It is represented by a marine terrace located at 28 ± 3 m a.s.l. (Lavagna). In the past it was ascribed to a Middle Pleistocene highstand (Federici & Pappalardo, 2001) and later to M.I.S 5 (Federici & Pappalardo, 2006). Currently, reliable OSL datings of its original deposit suggest that it was formed in MIS 9 or 11 (Biagioni, 2008). The age and position of this terrace account for a very small uplift rate for western Liguria since the Middle Pleistocene. Higher and undated terraces are present, but a careful assessment of their inner margin elevation has never been carried out. It is remarkable to notice that, apart from the Lavagna terrace case, no marine deposit outcrops on top of the terraces of eastern Liguria; their genetic interpretation, then, is based purely on morphological criteria. Nevertheless the original shore platform is currently buried by continental deposits that may be colluvial in origin or due to mass movements. Long-aged reworking for agricultural purposes (most of sea-facing ligurian slopes were terraced by man) and modern settlements often altered the original shape and grain-size of these deposits. The terraces inner edge, thus, is often tricky

Fig. 2 - Panoramic view of the Nervi marine terrace from the west. In the background the Portofino Promontory.

to detect. By the western out banks of the city of Genoa (Voltri), a particularly favourable case-study enabled Carobene & Firpo (1994) to highlight shoreface deposits overlapping two shore platforms at 7 and 17 m a.s.l.; although the terraces inner edge elevation could not be measured and the deposits could not be dated, these sea-level markers should be considered high-quality ones in the general context of the Ligurian coast.
The identification of the correct inner edge elevation of the Nervi marine terrace is useful far beyond the importance of the single study-case. In fact, being this terrace the most continuous and extended one in eastern Liguria, it would be crucial to state if a correlation, based at least on the altitude of the inner margin, can be stated between it and the dated terrace of Lavagna, located about 40 km far from it and/or between it and the upper Voltri shore platform, highlighted west of the city of Genoa. This is at present the only way to correlate marine terraces in this area, being chronological correlation impossible with currently available dating methods.

Methods

Airphoto interpretation enabled preliminary geomorphological mapping of the study area, then fieldwork provided more information about surface processes and landforms.
Data about subsurface setting were collected from 15 mechanical drillings carried out in the area for slope stability evaluations and the design of foundations for new structures. Drilling points on the topographic surface range from an elevation of 85.00 m a.s.l down to 27.60 m a.s.l. (location in Fig. 3); they are clustered on the intermediate tract of the slope while unfortunately no drilling was available on the terrace surface. In Table 1 the main details about the cores are summarized. Four cores were examined directly by the Authors, whereas of the other ones a detailed stratigraphic log was available (Genoa Municipality database). In addition to relevant information on rock/sediment type and degree of weathering, cores logs provided fundamental geotechnical parameters.

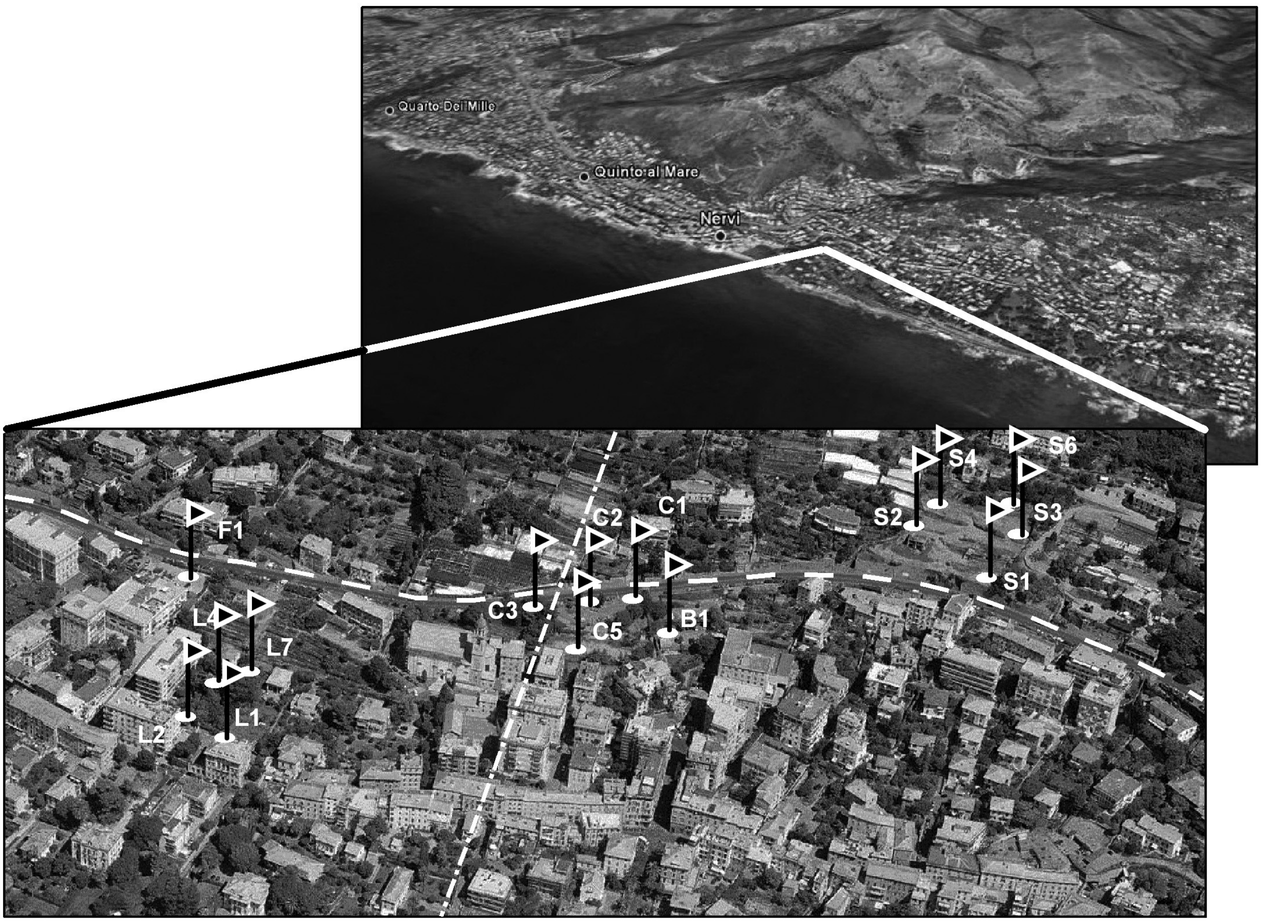

Fig. 3 - Location map of the drillings analysed in the text.

THE STUDY CASE

Geomorphology

The terrace of Nervi is an irregular shaped, gently seaward dipping surface about 2 km long and 0.5 km wide, located at the base of a steep slope. The slope crest reaches the elevation of 450 m and is at most 1 km far from the sea. The bedrock is formed by limestones and marly limestone with slate interbeddings belonging to the Mt. Antola Limestones fm. (Allazinas *et al.*, 1971). The long profile of the low part of the slope (Fig. 4) does not display the typical morphology of a marine terrace, i.e. a wide platform bounded by an inner and an outer edge. Based on the presence of 3 relevant knickpoints a subdivision of the profile in 5 tracts is possible:

a) The active cliff, the top of which reaches the altitude of 13 m a.s.l.
b) The sub horizontal surface of the marine terrace (dipping about 3°) bounded seaward by the outer edge, coincident with the active cliff top, and inland by a knickpoint (28 m a.s.l.). Along the cliff top the bedrock outcrops, whereas the marine terrace surface is sheltered by the long-aged human settlement (Nervi is nowadays a suburb of the City of Genoa).
c) The lower part of the slope (about 13° of dip) bounded by the lower (28 m a.s.l.) and an upper (50 m a.s.l.) knickpoint
d) An intermedite tract of the slope (about 24° of dip), between the two knickpoints at 50 m a.s.l. and 87 m a.s.l.
   Both c and d tracts are reshaped by ancient agricultural terracing. Nevertheless they display a smooth upward convexity (bulge).
e) The upper part of the slope (dip of about 40°) covered by a thin colluvial mantle.

None of the 3 knickpoints corresponds to the inner edge of the terrace because none of them marks the inner boundary of a flat surface and is backed by a palaeocliff. For this reason we consider as anomalous the tract of the long profile connecting these 3 knickpoints, characterized by an intermediate gradient. It represents a «transition area» between the subhorizontal surface typical of the marine terrace (b) and the slope, steep enough as to be considered the degraded palaeocliff (e). Morphological evidence suggests that it cannot be identified with a typical slope-bottom depositional landform. The upper part of the slope is on the whole very regular and only displays smoothed concavities, probably wide relict detachment niches. In connection with these niches we do not find at the slope foot a related positive accumulation (e.g. a landslide body). Being natural sections suitable for interpreting the sedimentary features of this body lacking, it is thus necessary to investigate the bedrock morphology.

Subsurface data

Subsurface data available for the area are presented in Table 1.

In all the cores the bedrock is capped by a layer of colluvium, formed by a silty matrix supporting scattered angular limestone pebbles. Underneath the bedrock is very fractured, which is consistent with its tectonic history (Fig. 5). Fractures acted as preferential ways for agents of chemical weathering and for karst dissolution. Alteration rinds affect fractures surfaces and from them cavities were created through karst processes affecting limestone; residual clay mostly fills in the voids created inside the solid rock.

The degree of weathering is different in the different cores and at different depths. The cores in the upper part of the transition area (70-85 m asl) display, below the top deposit, a very weathered layer, 4 m thick on average, in which also the argillitic strata of the rock (shales) are loose and the rock mass is on the whole disarticulated. Below this layer the bedrock displays intermediate weathering evidence, with alteration rinds and residual oxides and clay fillings affecting only fractures and dissolution cavities inside limestone and marl strata. This type of weathering is also characteristic of the bedrock in cores of the lower transition area (C1,2,3,5 and B1) down to the elevation of about 32 m a.s.l. In the deepest part of these cores the bedrock, still very fractured, is only moderately weathered. In the lowest cores (L1,2,4 and 7) fractures and weathering are observed in the rock down to the maximum depth reached by the drillings (10-13 m below the surface).

The thickness of the colluvium layer was plotted over the profile of Fig. 2 in order to highlight the morphol-

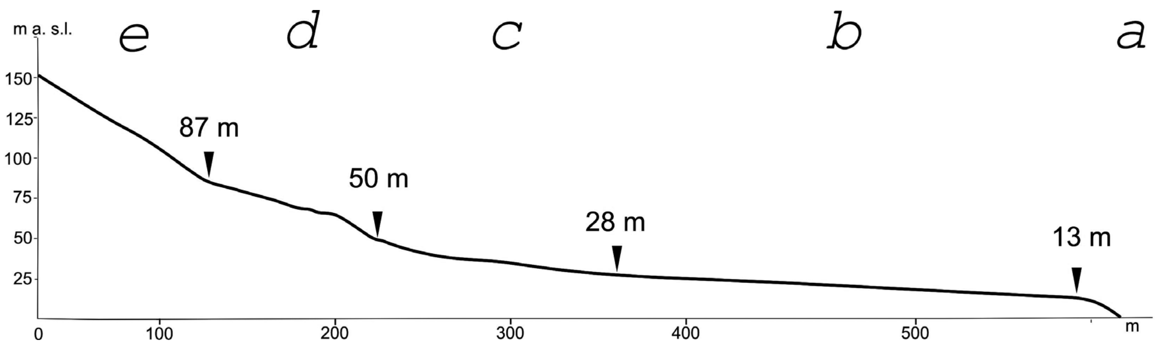

Fig. 4 - Long profile drawn along the grey dotted line indicated in Figure 3.

Tab. 1 - Synthesis of subsurface data from the examined the cores.

Code	Earth level elevation (m a.s.l.)	Thickness of sedimentary cover (m)
S1	70	4.8
S2	76.4	4.4
S3	78	4
S4	83	4.5
S6	85	5.4
F1	35	1.2
C1	51.4	3.2
C2	50	3.5
C3	48.6	4
C5	42.7	4.8
B1	43.95	4.2
L1	28	7.5
L2	27.6	9.5
L4	29.5	7
L7	31.6	7

Fig. 5 - The bedrock as appeared in a deep excavation performed in the site where core C3 was drilled.

ogy of the bedrock top (Fig. 6). This can be considered broadly representative of the overall bedrock morphology in the study area, although minor undulations in connection with plaeochannels dissecting the bedrock top are revealed by further corings, not considered in this work.

Discussion

Our data demonstrate that the morphology of the bedrock top closely resembles that of the surface. The knickpoints highlighted in the long profile, then, reflect similar features on the bedrock and represent vestiges of an ancient morphology smoothed by long lasting erosion.

The bulge in the profile (tracts «c» and «d» in Fig. 4) can thus be interpreted as the relict of two terraces developed during highstands older than Middle Pleistocene as to justify their enhanced lowering and degradation. The absence of a preserved original marine deposit and the presence of a thick (2-10 m) continental cover on this tract of the slope, accounts for a long lasting phase of exposure of the bedrock. During each interglacial the outer edge of the newly formed terrace was affected by backwearing, which reduced the original width of the platform; downcutting of the related surfaces took place both during the highstands and in the long lasting, intervening, cold climate phases, in which alternating different weathering processes exerted a differential lowering of the previously flat surfaces that became gradually more and more seaward dipping. Erosional landforms were created on which the position of the inner edge of the original terraces, though, is roughly the projection on the bedrock of the profile knickpoints. For this reason the two uppermost orders of terraces should be considered moderately reliable sea level markers: their inner margin was around respectively 82 and 45 m (measured on the bedrock), but it is impossible to assign them a reliable uncertainty; anyway, being they erosional landforms, the true value should be not lower than the elevation of the profile knickpoint which marks their past position.

The wide gently dipping surface (b tract, Fig. 4) extending between present-day cliff top (13 m) and the lower knickpoint (28 m) was already identified with a marine terrace (e.g. Rovereto, 1939; Cortemiglia, 1982); the original marine deposit is unpreserved and the bedrock is covered by continental colluvium whose thickness, according to Fig. 6 reaches 10 m close to the inner edge. The terrace surface is sheltered by very dense and long-aged settlement, so its original form is not clearly detectable. Nevertheless it is exceptionally wide (over 300 m) if compared to other terraces at similar elevation along the coast of Liguria; moreover the shift in elevation between its inner and outer edge (15 m) seems too great to account for a shore platform developed during only one highstand. These evidence suggest that the terrace of Nervi could be policyclic, and formed during two different highstands. The more elevated part of the terrace, formed in an earlier highstand, can be assigned an inner edge elevation of 18 m. The lower part of

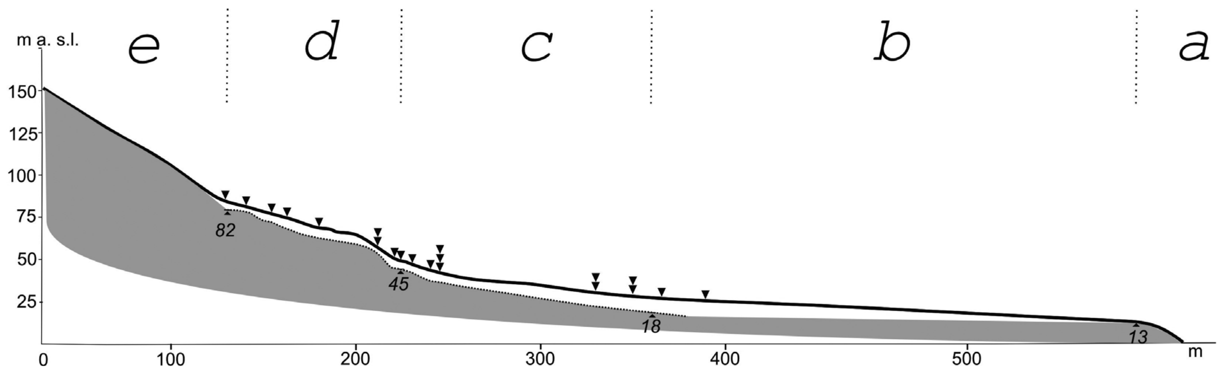

Fig. 6 - Essential geological section along the profile of Figure 4 with the location of the cores of Table 1.

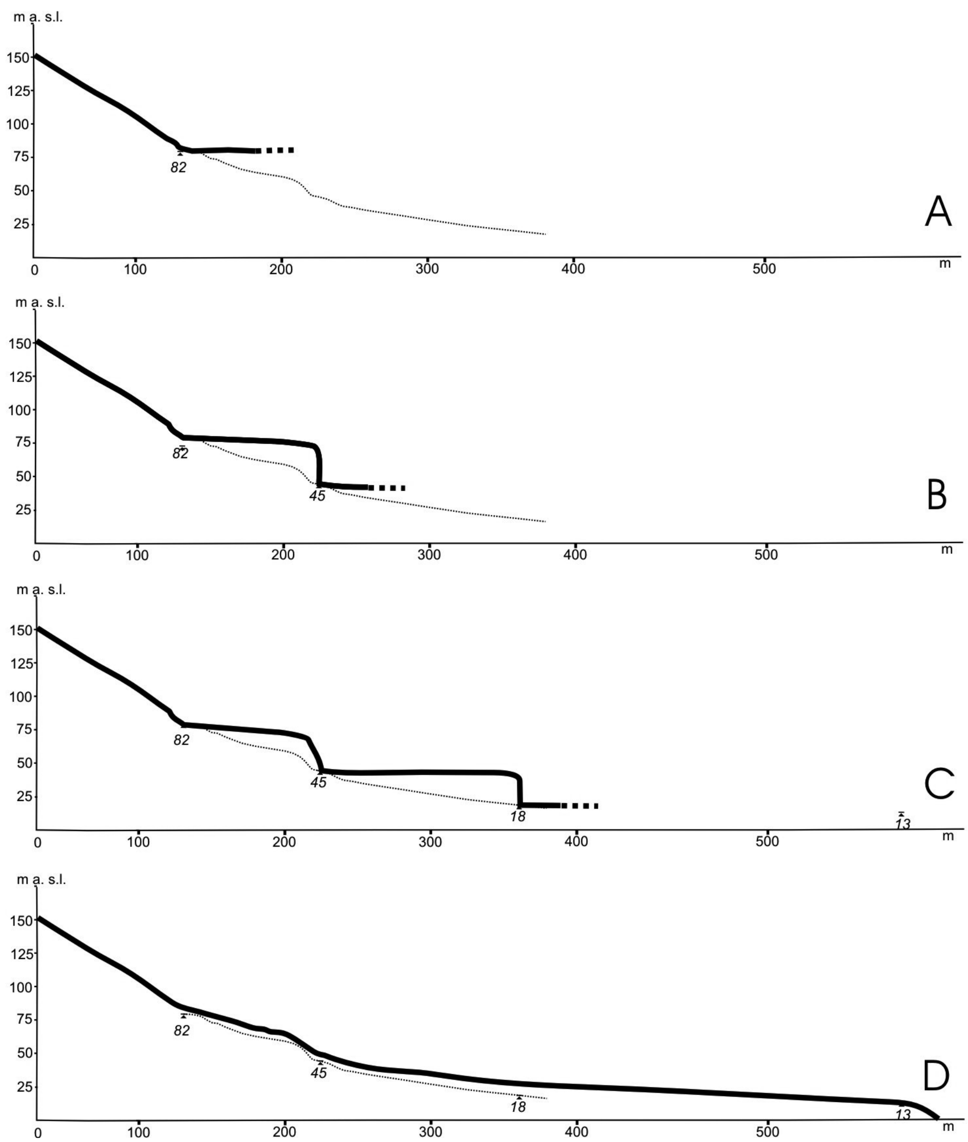

Fig. 7 - Reconstruction of the slope evolution in the study area.

the terrace has not a detectable inner edge, because no subsurface data are available to state the bedrock morphology in this tract. Thus it can not be considered a reliable sea level marker, but the original elevation of its inner edge can be assumed not much higher than that of its outer edge (13 m).

The preservation of a staircase of four marine terraces is consistent with previous work for the area (Biagioni *et al.*, 2007) and, more in general, in all Liguria (Fanucci, 1987; Carobene & Firpo, 2002; Federici & Pappalardo, 2006). This supports the evidence that the two uppermost orders of terraces are likely to be much older than the lower one, as they are quite high and morphologically badly preserved.

In Fig. 7 a reconstruction of the morphological evolution phases of the study area is attempted, using the representative profile of Fig. 2 added with the bedrock top reconstruction as in Fig. 6. As discussed above the most reliable inner margin elevation is the one located at 18 m a.s.l., backing the wide terrace known as the Nervi terrace.

Conclusions

The elevation of the marine terrace of Nervi inner edge was detected as accurately as possible, in order to use it as a past sea-level altitude marker.

Being the platform-cliff transition not sharp and an exposed section to evaluate the thickness of its sedimentary cover missing, investigation was focused on the interpretation of the anomalous displacement of the slope profile, uphill and downhill the terrace.

Both the geomorphologic setting and subsurface evidence are consistent with the genetic interpretation outlined in Figure 7. The current slope profile is the result of a long-term evolution of a four-stepped staircase of marine terraces. Speculating about the ages of these terraces is far beyond the purpose of this paper, especially because there are no datable materials to be related to them and the current knowledge of ligurian marine terraces chronology is for the moment too poorly refined to allow any kind of correlation. It is worth noticing, though, the similarity between the inner margin elevation of the Nervi terrace and that of the Voltri shore platform (Carobene & Firpo, 1994), located 23 km west of the latter. Also those terraces located immediately east of the Nervi terrace were a assigned an inner margin elevation (27+1/-6 m a.s.l. according to Biagioni *et al.*, 2007), which is consistent with that stated for the Nervi terrace in this work.

Only the inner edge altitude of the Nervi terrace could be stated with a reasonable accuracy, deriving from the evaluation of the terrace sedimentary cover thickness. The other terraces (at 82 and 45 m a.s.l.) are unsuitable as reliable sea level markers, although they can be indicative of sea level highstands the elevation of which can be broadly constrained at the related knickpoints.

This case-study proves that altitudinal assessment of a terrace inner edge can be very tricky and assigning a wide error bar is in many cases useless: this is true especially if the cliff toe is buried and the backing cliff-platform junction is not very clear in the profile. In fact if we attribute to the maximum elevation of the flat or gently dipping tract of the slope profile (first knickpoint, 28 m) an error of -20 m to remove the effect of deposit sheltering, according to the prescriptions of Ferranti *et al.* (2006), the datum loses its significance and any correlation with other surrounding terraces belonging to different orders becomes impossible. On the opposite side, if we attribute to this first knickpoint, assumed as inner edge, an error of +1/-6 m, as attributed to the same order of terraces in the same area for a tract of coast about 20 km long (Biagioni *et al.*, 2007), the real inner edge value results overestimated of 4-11 m because of the relevant sedimentary cover over the rock platform.

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