Geogr. Fis. Dinam. Quat.
30 (2007), 43-53, 10 figg., 2 tabb.

TOMMASO DE PIPPO (*), CARLO DONADIO (*), PAOLO MIELE (*)
& ALESSIO VALENTE (**)

MORPHOLOGICAL EVIDENCE FOR LATE QUATERNARY TECTONIC ACTIVITY ALONG THE COAST OF GAETA (CENTRAL ITALY)

ABSTRACT: DE PIPPO T, DONADIO C., MIELE P. & VALENTE A., *Morphological evidence for Late Quaternary tectonic activity along the coast of Gaeta (central Italy)*. (IT ISSN 1724-4757, 2007).

The study of morphological evidence for palaeo sea-levels observed along the southern Lazio coastline NW of Gaeta showed the occurrence of tectonic movements in the time interval between Marine Isotope Stages (MIS) 11 and 3. On the basis of the heights, location and age of marine terraces and wave cut notches, both above and below current sea levels, examined in the various contiguous coastal zones, some considerations were made regarding the rates of differential rises and falls occurring at structural discontinuities in the past 400,000 years, especially between 150,000 years BP and the present-day. In particular, we distinguished a phase of generalised uplift in the coastal sector between MIS 11 and 5.5, followed by a more or less continuous fall phase between marine isotope substage 5.5 and stage 3, interrupted by a weak uplift with different rates between MIS 5.3 and 5.1. The dynamic model proposed, which differs from what has so far been hypothesised in the literature, is based on analysing all the forms observed along the coast north of Gaeta (Lazio, central Italy), whether those known from the literature or those indicated for the first time in this study.

KEY WORDS: Coastal geomorphology, Neotectonics, Sea-level change, Pleistocene, Gaeta, Italy.

RIASSUNTO: DE PIPPO T, DONADIO C., MIELE P. & VALENTE A., *Evidenze morfologiche di attività tettonica tardo-quaternaria lungo la costa di Gaeta (Lazio, Italia centrale)*. (IT ISSN 1724-4757, 2007).

Lo studio delle morfologie indicanti paleostazionamenti del livello marino, presenti lungo il tratto di costa del Lazio meridionale a NW di Gaeta, ha permesso d'individuare l'esistenza di movimenti tettonici protrattisi durante l'intervallo di tempo compreso tra gli stadi isotopici marini (MIS) 11 e 3. Sulla base delle quote, dell'ubicazione e dell'età di terrazzi marini e solchi di battente, sia emersi che sommersi, esaminati nelle varie zone costiere contigue, sono state fatte alcune considerazioni di carattere quantitativo circa i tassi dei movimenti differenziali di sollevamento ed abbassamento occorsi in corrispondenza di discontinuità strutturali negli ultimi 400.000 anni ed in dettaglio tra 150.000 anni fa ed il presente, secondo quello che in questo lavoro è definito "modello ad ascensore" della costa. In particolare, sono state distinte una fase di sollevamento generalizzato del settore costiero tra lo stadio isotopico 11 ed il substadio 5.5, seguita da una fase di abbassamento più o meno continuo tra il substadio 5.5 e lo stadio 3, interrotta da un debole sollevamento con tassi differenziali tra i substadi 5.3 e 5.1. Il modello dinamico proposto, che differisce da quanto sinora ipotizzato in letteratura, si basa sull'analisi di tutte le forme osservate lungo la costa di Gaeta, sia quelle ben note in letteratura che quelle per la prima volta indicate nel presente lavoro.

TERMINI CHIAVE: Geomorfologia costiera, Neotettonica, Variazioni del livello marino, Pleistocene, Gaeta, Italia.

INTRODUCTION

The Tyrrhenian coastline northwest of Gaeta in central Italy is characterised by a succession of rocky calcareous headlands and sandy pocket beaches. The latter develop in embayments connected to structural lines, transversal to the coastline. Along the cliffs, both active and fossil, many features of palaeo sea-levels are preserved: notches, terraces and fringes of *Lithophaga* sp. burrows.

The different heights of these forms, each assigned to a certain palaeo sea-level, could be explained by non-homogeneous movements of blocks. These movements are related to tectonic activity, which could have periodically affected one or more sectors between the Middle Pleistocene and Holocene. Evaluation of their rates and extent, as well as the direction of movement (downlift or uplift) of the different sectors, is connected to the position of sea levels estimated from eustatic curves, available in the literature, for the last 400 kyr.

The aim of this work is to report the results of a detailed geomorphological survey, which focused on various palaeo sea-level traces along this coastal stretch, some of them observed for the first time. Moreover, comparison of the collected data with a recent eustatic curve confirmed the various movements in this «unstable» area.

(*) *Dipartimento di Scienze della Terra, University of Napoli Federico II, Italy - depippo@unina.it.*
(**) *Dipartimento di Studi Geologici e Ambientali, University of Sannio, Benevento, Italy.*

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The investigated coast is situated in southern Lazio, between the coastal plains of Fondi and Formia-Garigliano, and extends some 14 km from the headland of Monte Orlando, in Gaeta, northwards to Torre Capovento (fig. 1). The coastal zone lies in a sector structurally limited to the NE by an important, albeit local, tectonic line with a NW-SE Apenninic trend. This line, called «Gaeta-Itri-Monte Calvo», sharply separates a northeastern area where Cretaceous limestone dominates from a southwestern area, where the coast in question is located and where Triassic-Jurassic dolomite outcrops prevail. Moving away from this line and upwards in the succession more limestone, Jurassic in age, is found, as may be observed along the slope of Mts. Lisantro and Dragone (De Riso, 1964). Finally in the coastal outcrop, that forms the top of the succession, represented by mainly Cretaceous limestones, Pleistocene and Holocene deposits, chiefly continental in origin, in limited outcrops, complete the sedimentary succession (Accordi & Carbone, 1988) in the investigated area.

The carbonatic succession heavily crossed by a network of structural discontinuity with NW-SE and NE-SW trends (Ambrosetti & *alii*, 1987; Cerisola & Montone, 1992; Carrara, 1995a, 1995b Carrara & *alii*, 1995), have a pronounced influence on the local geomorphological setting.

Owing to the strict correlation between the tectonic structure and the morphological evolution of the area, the slopes of the reliefs consist of fault scarps or fault-line scarps and separate valleys, developing along local tectonic lines, mainly with NW-SE and NE-SW trends (less frequently E-W). The landscape is therefore characterised by a series of hills often with a cone or truncated cone shape.

Along the coast the alternation of large and small pocket beaches (fig. 2) is also related to the presence of faults, chiefly NE-SW oriented, as well as cliffs, whose development was controlled by tectonics, as noted for the cliff of Monte Orlando and the fossil cliff of Monte Moneta, inland from the plain of Sant'Agostino (fig. 3).

Going from E to W the headland of Monte Orlando, the highest coastal relief, is encountered first. It is made of cretaceous limestones with a prevalent eastward dip. The western slopes are modelled with gentle forms covered by clastic deposits, such as the red sands referable to the lithologic unity of *duna rossa antica* (Blanc & *alii*, 1953; Bergomi & *alii*, 1969; Bono, 1985; Dai Pra, 1995) assigned to Middle-Upper Pleistocene and colluvial detritus (Valente, 1999). The southern slopes, characterised by cliffs some 80-100 m in height, are however extremely steep and subject to active or quiescent rockfalls.

The cliff constituting the western side of the headland bordering Serapo beach, is at present fossil in its inner sector, whereas in the still active sector it continues under the sea down to –10 m with a monotonous sandy bottom. The southern side, by contrast, consists of a cliff which reaches about +120 m and continues down to –15/–30 m with a steeper bottom, characterised by terraced forms; at –40/–50 m a sandy bottom gently slopes downwards. The NE-SW trend (Antonioli, 1991; 1995; Valente, 1999; Miele, 2003) of such morphologic elements feels the effects of structural control by which the direction of the transversal elements is influenced, such as the wide aperture which tends to isolate stacks such as Montagna Spaccata. Inside the latter there are some caves, obviously reworked both

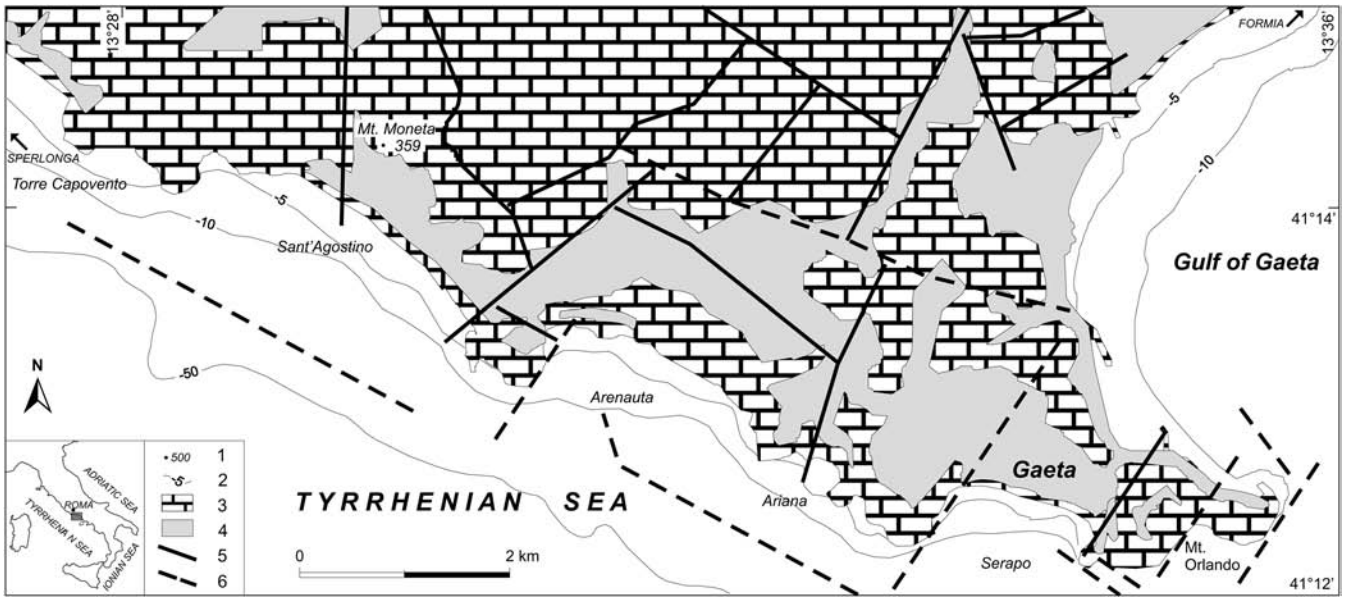

FIG. 1 - Geological outline of the Gaeta coastal sector (Latium, central Italy); 1) altitude (m a.s.l.); 2) isobath (-m); 3) Mesozoic carbonatic outcrops; 4) Pleistocene-Holocene deposits; 5) fault; 6) uncertain or buried fault.

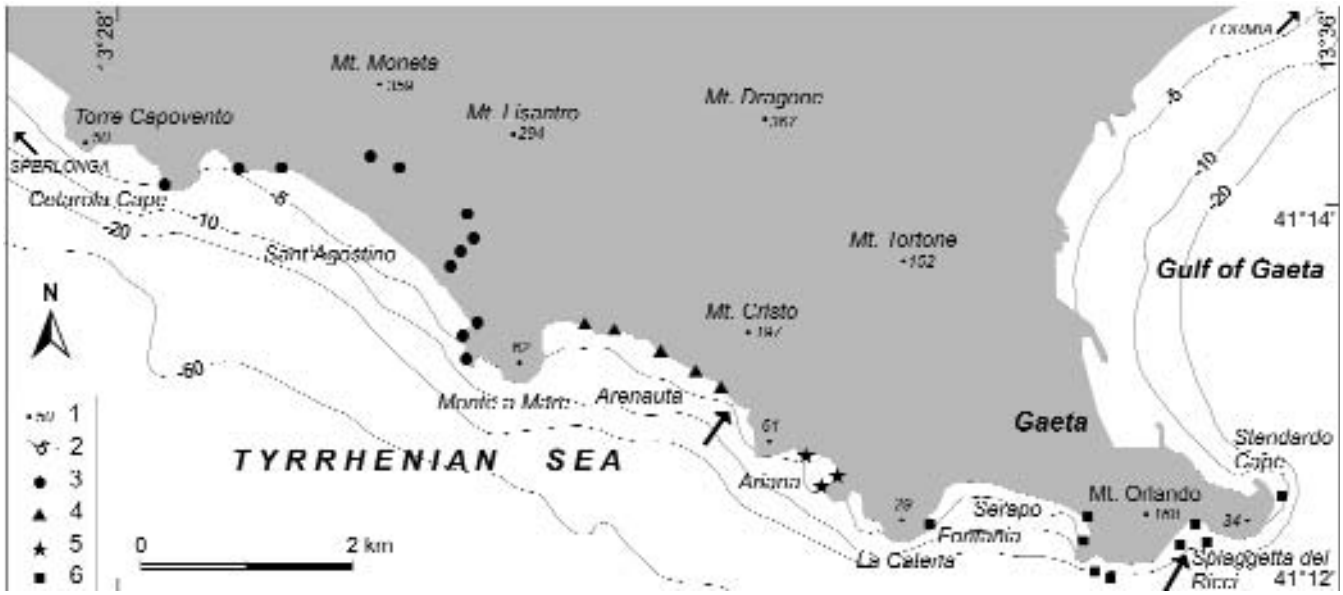

FIG. 2 - Features of ancient sea-level standings along the coastal zone of Gaeta; 1) altitude (m a.s.l.); 2) isobath (-m); ● Sant'Agostino; ▲ Arenauta; ★ Ariana; ■ Fontania - La Catena and Monte Orlando - Serapo. The arrows indicate the sections of Spiaggetta dei Ricci (fig. 5) and Arenauta (fig. 7).

FIG. 3 - View of the little coastal plain of Sant'Agostino with Punta Cetarola. The coastal plain is inland characterized by alluvial fan and talus deposits.

by waves and karstic phenomena, that also continue below sea level.

Serapo beach, sited west of the Monte Orlando headland (fig. 4), is the relic of a tombolo joining the headland to the mainland. Further west a system of pocket beaches is visible: Fontania, Ariana, Arenauta, San Vito and Sant'Agostino, in this order. Several features may be used to recognize ancient sea-levels along the cliffs of the rocky headlands that separate these beaches. At their base a sandy bottom is usually present, which gently slopes down to –18/–27 m. At such depths there are steep slopes in a range between –20/–25 m and –44/–48 m at Cape Capovento and near Monte a Mare as well as at –30/–35 m in the stretch between the beaches of Sant'Agostino and Arenauta. In the latter the slopes represent the greatest in the whole area. Careful observation of the isobaths, con-

FIG. 4 - View of Serapo beach and Monte Orlando. This littoral represents an example of pocket beach along the Gaeta coastline.

cave seaward in the area in front of the beach and convex and close together in the area where the rocky coast extends, confirms that under the loose sedimentary blanket, which currently covers the sea-bottom, the morphology of the submerged coast is controlled by the same structural pattern which controls the evolution of the emerged area.

The area behind the beach of Sant'Agostino is of extreme interest: the gradient of the southwestern slopes of Mts. Moneta and Lisantro and especially the presence of notches, as well as deposits interpretable as taluses, show that they were sea cliffs, at present fossilised. Along the entire stretch of coast there is considerable evidence of different sea-levels in the past. In particular, notches, marine terraces, and fringe-boring by bivalves such as *Lithophaga* sp. and drapes of sedimentary deposits have been observed. More specifically, in the last fifty years various authors have studied the relationship between these forms and the position of the sea-levels with the aid of increasingly accurate dating methods, as reported in table 1.

PREVIOUS KNOWLEDGE

From data reported in the literature it may be inferred that there is considerable evidence for palaeo sea-levels during the Upper Pleistocene, especially at MIS 5.5 and 5.1. These palaeo sea-levels have left evident traces along the coast north of Gaeta: their height, dating and morphology have been extensively described by several authors. Table 1 presents a schematic overview of findings especially related to position, location and the dating of palaeo sea-levels.

Those who have studied this stretch of coastline (Blanc & Segre, 1947; Segre, 1949; Hearty & Dai Pra, 1986; Ozer & *alii*, 1987; Antonioli, 1991; Dai Pra, 1995) converge in attributing to MIS 5.1 (Neotyrrhenian) the traces located at a current average of +2.5 m a.s.l., in accordance with findings for other sites along the coast of Lazio and Campania, namely the Circeo promontory (Durante & Settepassi, 1976-77; Vitagliano, 1984; Stiner, 1991), Marina di Minturno, and the Sorrentine Peninsula (Brancaccio & *alii*, 1990; Cinque & Romano, 1990; Riccio & *alii*, 2001). There is also the same convergence of data concerning the traces from MIS 5.5 (Eutyrrhenian) identified by many authors between +4.80 m and about +6 m.

In particular, for «Eutyrrhenian» forms, now MIS 5.5, interesting findings have been reported for several sites on the coast of southern Lazio, where two notches attributed to this stage are recognised. At the sites of l'Arenauta and Marina di Minturno this double notch is observed.

DATA ANALYSIS

During research carried out in the area (Miele, 2003) several hitherto undiscovered traces were identified and studied (wave cut notches and marine abrasion platforms with rockpools *sensu* De Pippo & Donadio, 1999) (table 2), which may indicate palaeo sea-levels. The wave cut notch between +5.70 m and +5.75 m visible on the fossil cliff delimiting the plain behind the beach of Sant'Agostino (fig. 4) was attributed to MIS 5.5, as well as that at +6.20 m located towards the end of the Monte Orlando promontory (Spiaggetta dei ricci: fig. 5). Both are well-preserved and completely perforated by lithodomes.

What occur much more commonly than suggested by the literature are the traces that may be attributed to MIS 5.3, sited immediately below those of the previous stage.

TABLE 1 - Elevation above present-day sea-level (± m), position and age or stage of palaeo sea-level standing forms detected by some Authors along the coast between Sperlonga and Gaeta; N: notch; C: sea cave; L: fringe of *Lithophaga* sp. bores; T: marine terrace

site	morphological element	elevation (m)	age or stage	main references	notes
Torre Capovento and Grotta dei Moscerini	C	about +6	«Eu-Tyrrhenian»	Blanc & Segre, 1947 Vitagliano, 1984 Zei, 2000	in the cave a beach deposit is present with senegalese fauna, subsequently dated with ESR and racemization methods
Sant'Agostino	L	+20/+22	before the last interglacial		aminoacid epimerization done in Gaeta and in the Grotta di Tiberio at Sperlonga (Antonioli & *alii*, 1988)
	N, L	+7	Tyrrhenian		
Monte Orlando	N, L	+5.30/+5.20/+4.80	«Eu-Tyrrhenian»		
	N, L	+1.30	«Neo-Tyrrhenian»	Antonioli, 1991	this element is correlated by the Author to a conglomerate with «warm fauna» and a notch at Torre Capovento, recognized by Ozer & *alii*, 1987
	T C, T N N, T N, T	–24/–25 –17/–21 –1.5 –10/–15 –7/–8	MIS 3 or eustatic rising phase after 18 kyr BP		
Arenauta	N	+7.52/+7.51/+7.43/+7.41/+7.39/+7.34/+7.29 +6.22/+5.81/+5.80	«Eu-Tyrrhenian»	Dai Pra, 1995	
Ariana		+5.85		Ozer & *alii*, 1987	presence of fossiliferous beach deposits
coast between Gaeta and Sperlonga	N	+2.50	«Neo-Tyrrhenian» (MIS 5° or 5c)	Dai Pra, 1995	on the basis of a correlation to marine deposits with «reduced fauna» (Durante & Settepassi, 1976-77; Ozer & *alii*, 1987)
	N, T	+29/+32 +60/+70 +95/+117 +150/+160 +178/+198 +205/+230	Middle Pleistocene	Antonioli, 1991	

The wave cut notches detected are found between +3.7 m and +3.9 m at the site of Sant'Agostino (fig. 6) and Ariana, while marine abrasion surface oscillates between +2.95 m and +3.1 m to the South (Fontania, west of the Serapo beach (fig. 7), and Spiaggetta dei Ricci, east of Monte Orlando). There is an interesting, albeit rather thin, deposit of laminated sand, rich in minute fragments of gasteropods, bivalves and corals, which is heavily bioturbed, at times covering the above terraced surfaces.

In the MIS 5.1 (Neotyrrhenian) the sea-level left traces along almost the whole coastline in question, as may be seen from findings in the literature (tab. 1). However, besides those already known, we also found other traces that may be attributed to this palaeo sea-level stand, such as the wave cut notch detected at Ariana at +2.2 m and the abrasion surface observed both at Sant'Agostino between +1.6 m and +2.2 m and along the beach of Arenauta between +2.0 m and +2.5 m. The latter surface (fig. 8) stretches from the palaeocliff as far as the shoreline of the sandy beach and is easily visible both due to its morphology and the presence of rockpool*s* and lithodome perforations on the surface. Westwards the traces of this palaeo sea-level stand are poorly conserved or completely absent. Nevertheless, we observed an irregularly incised wave cut notch at +2 m on calcareous breccia at the site of Spiaggetta dei Ricci and to the east of Monte Orlando.

Besides these traces which are typical of Tyrrhenian levels, we recognised traces at greater and lower heights. The interpretation by which evidence increasingly close to the current sea level is the most recent is based on considerations of a general nature, such as the recognition of a decreasing trend of the height above sea level of high stands in the past 400 kyr. This hypothesis comes from comparing the trends of eustatic curves with what may be inferred from the Lazio neotectonic scheme (Ambrosetti & *alii*, 1987) in which «a more or less continuous uplift

TABLE 2 - Correlation between MIS, sea-level elevation (± m) related to present-day one and age (kyr BP) represented in the eustatic curves published by some Authors

MIS	references	elevation (m)	age (kyr BP)
11	Shackleton, 2000	–5	404
	Waelbroeck, 2002	+10	400
9.3	Shackleton, 2000	0	330
	Waelbroeck, 2002	+8	
7.3	Shackleton, 2000	–20	226
	Waelbroeck, 2002	–5	
	Martinsons & *alii*, 1987	+6	216
7.1	Shackleton, 2000	–14	196
	Waelbroeck, 2002	–5	
	Bard & *alii*, 2002	–18/–9	209/142
5.5	Shackleton, 2000	+8	126/130
	Waelbroeck, 2002	+10	
	Imbrie & *alii*, 1984	+8	122
		+8	125
	Martinsons & *alii*, 1987	+7	128/130
		+3	118
	Shackleton & Opdike, 1973	+20	123
	Labeyrie & *alii*, 1987	+17	121
	Shackleton, 1987	+3	123
5.3	Shackleton, 2000	–5	100
	Waelbroeck, 2002	–20	102
	Shackleton & Opdike, 1973	–10	
	Shackleton, 1987	–20	103
	Labeyrie & *alii*, 1987	–5	100
5.1	Shackleton, 2000	+15	83
	Waelbroeck, 2002	–5	
	Martinsons & *alii*, 1987	+2	80
	Shackleton & Opdike, 1973	–10	85
	Shackleton, 1987	–30	81
	Labeyrie & *alii*, 1987	–10	78
3	Shackleton, 2000	–36	52
	Martinsons & *alii*, 1987	nd	55/50
	Shackleton & Opdike, 1973	–50	55
	Shackleton, 1987	–55	59
	Labeyrie & *alii*, 1987	–25	60

zone» is recognised in the study area. The trend would appear already evident in the literature (Avellino & *alii*, 1987; Antonioli, 1991), both based on much more specific considerations on the morphostratigraphic correlations with already dated forms and on morphoevolutionary considerations on the individual forms. The latter show a progressive tendency towards more «ancient» morphologies starting from traces closer to the current sea level, towards increasingly higher traces. Thus, the highest Tyrrhenian forms may be interpreted as preceding MIS 5.5, while the lowest are interpreted as being younger than MIS 5.1.

In particular, wave cut notches at +30 m and +54 m are found in succession on the same cliff of Sant'Agostino on which Eutyrrhenian notches are incised. They may be chronologically correlated to MIS 7 and 9 respectively. However, the notch at +173 m, situated in a palaeocliff along the southern slope of Monte Moneta (fig. 9), close to that incised by notches at lower heights, is older than MIS 9 and could be attributed to a stage no more recent than 11. It should be noted that along the coast there are flat surfaces that correspond in height to these notches.

For example, a fairly wide sub-horizontal surface develops at 30 m at La Catena, west of the Serapo beach. Moreover, observing the succession of promontories on the coast west of Gaeta, even beyond the stretch in question, one notes a repeated surface at around 50 m, constituting the summits of Monte a Mare, Monte Scissura and the eastern end of Monte Orlando. There are smaller stretches behind the beach of Sant'Agostino. Lastly, clear examples of the higher surface at about 170 m are distinguished in the profiles of the promontory of Punta Cetarola, at the western end of the area in question, and that of Monte Orlando, of which it forms the summit.

Lower forms than those of the «Neo-Tirreniane», however, have been found on each promontory in of the coast examined. At Sant'Agostino and Arenauta the notches and

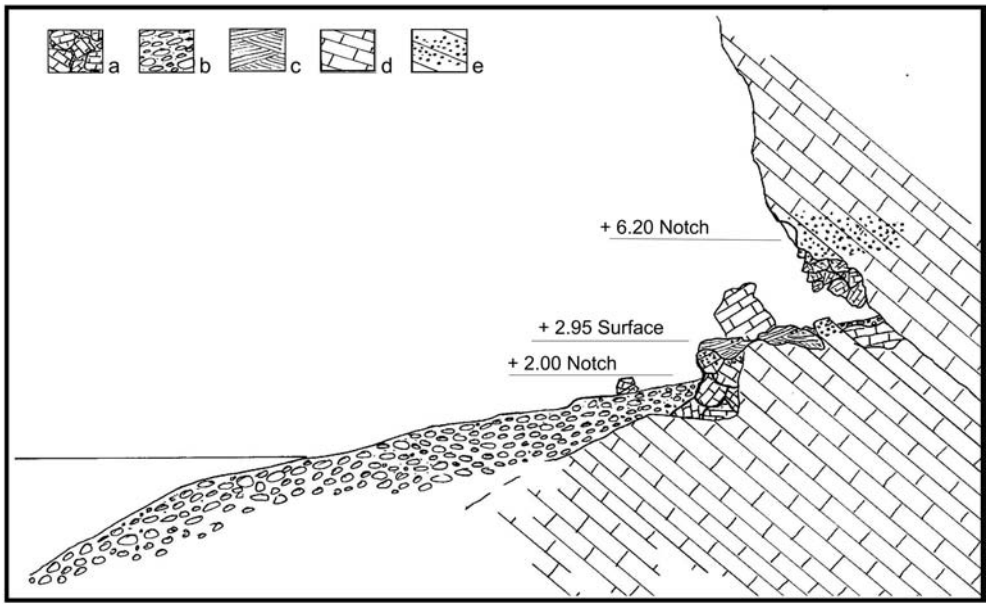

FIG. 5 - Sketch of the site of Spiaggetta dei Ricci, East to the Monte Orlando; a) slope deposits; b) actual gravelly beach deposits; c) old beach deposits; d) well stratified Cretaceous limestones; e) fringe of *Lithophaga* sp. bores.

FIG. 6 - Wave cut notch at +3.9 m and at the present sea-level discovered along the cliff westward of Sant'Agostino beach. Between these two notches a karstified sea surface covered by a thin sedimentary deposit.

surfaces are arranged between +1.5 m and +0.4 m, while at the other sites only abrasion surfaces were recorded between +1.5 m and +0.9 m (fig. 10). These may at least partly be attributed to MIS 3 in that they are definitely more recent than the overlying forms of MIS 5.1, as is also borne out by their state of preservation, and older than the regressive Wurmian phases (or contemporary with their beginning), insofar as they are covered in unconformity by continental sediments (slope breccias) produced during the last glacial phase.

Finally, from the first underwater observations focussing on the submerged coast proximal to the whole promontory of Monte Orlando, in addition to the forms already known (Antonioli, 1991) and reported in table 1, there are some abrasion platforms at heights of –4/–6 m and –8.5/–9.5 m. The former, which commonly consists of rockpools, is evident from Punta Stendardo to Spiaggetta dei Ricci, that is at the eastern end. By contrast, the latter, consisting of many rockpools, is found only at Montagna Spaccata, at the western end of the promontory, and is associated with a previously reported wave cut notch. On the same stretches of the sea bottom, that is on the same vertical, we noted other subhorizontal surfaces, respectively eastward at greater depths (–11/–12 m), and westward at lower depths (–2/–2.6 m).

DISCUSSION

Traces of the ancient position of the sea-level are recognised and interpreted, and are thus assigned to certain chronological intervals. This assignment started with identifying the traces from the literature (MIS 5.5 and MIS 5.1), whose associated sedimentary deposits were dated with different methods, such as the racemization of amino acids and C^{14} (Hearty, 1986; Hearty & *alii*, 1986; Alessio & *alii*, 1996; Lambeck & *alii*, 2004; Ferranti & *alii*, 2006). We observed new evidence along the examined coast, firstly related to the Tyrrhenian stages, and then to other palaeo sea-levels. Subsequently, we carried out morphostratigraphic correlation of the elements sited above and below the well-known Tyrrhenian elements (notches, marine terraces and deposits). In particular, the morphological features formed during sea-level changes in the last 400,000 years are ranked above the present-day sea-level in decreasing altimetric position from MIS 11 to the younger stages.

Some considerable discrepancies in the altitude of palaeo sea-levels are noted throughout the studied areas.

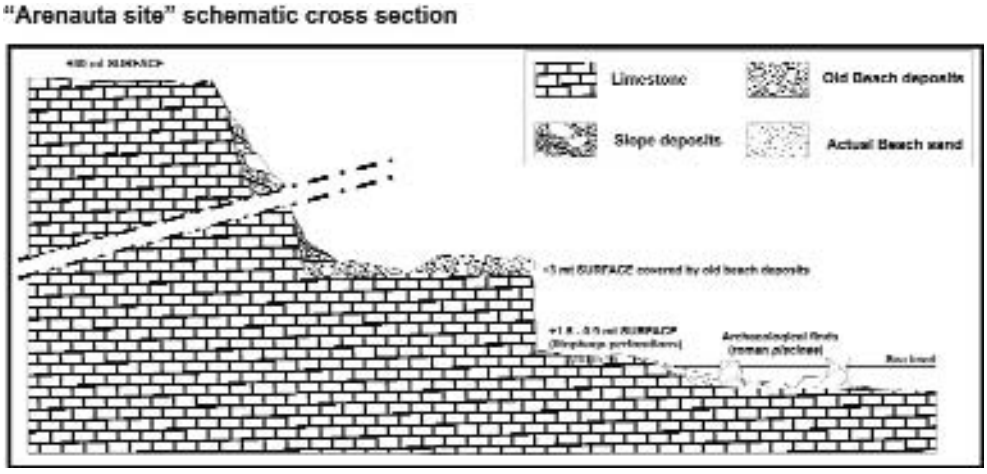

FIG. 7 - Sketch of the site of Arenauta. This coast is characterized by three main sea terraces and by archaeological ruins of Roman age, partially submerged.

FIG. 8 - Neo-Tyrrhenian (MIS 5.1) sea terrace, with rockpools and *Lithophaga* sp. bores, displaced at +2.5 m along the Arenauta beach.

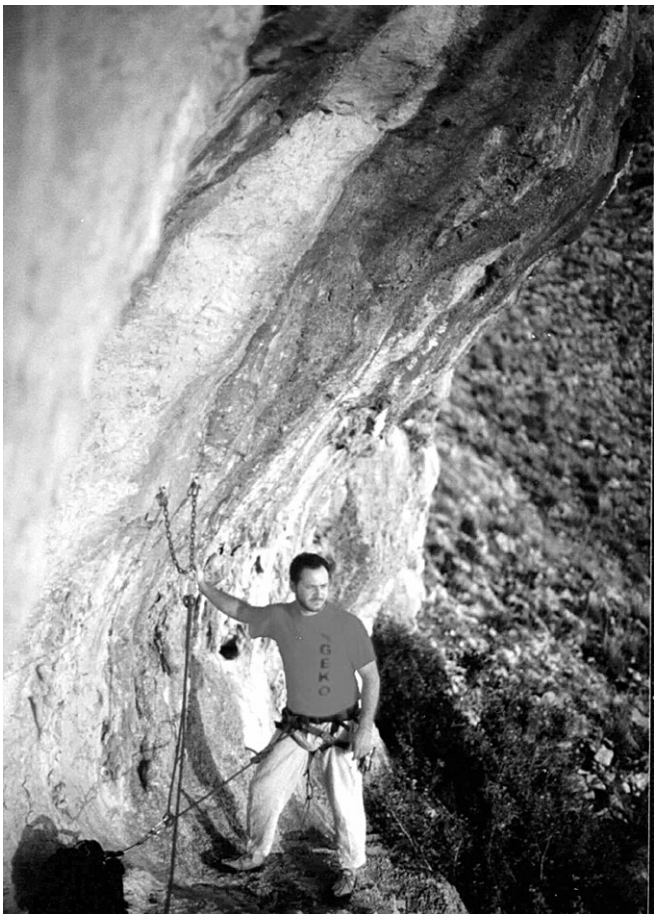

FIG. 9 - Wide wave cut notch at +173 m discovered along the palaeocliff of Monte Moneta, to the North of Sant'Agostino beach.

For instance, the Eutyrrhenian notch (MIS 5.5) in the western area ranges in height from +6.2 to +5.7 m, in the eastern area (Monte Orlando) from +5.3 to +4.8 m. Interestingly, the height of the notch is also visible at +6.2 m at the site of Spiaggetta dei Ricci close to the eastern border of the investigated area. Moreover, Neotyrrhenian traces (MIS 5.1) show some altimetric differences from West to East. Lower positions are measured at Sant'Agostino (+2.2/+1.6 m) as well as Fontania and Monte Orlando (+1.5/+0.9 m), whereas higher positions are revealed in the headland bordering Sant'Agostino (+2.5 m) to the west, at the sites of Arenauta and Ariana (+2.5/+2.0 m) and finally at the Spiaggetta dei Ricci (+2 m).

These examples suggest that the coastline did not behave homogeneously during the tectonic phases of the late Quaternary, as occurred in the southern sector of the Sorrentine Peninsula (De Pippo & *alii*, 1998) and has been hypothesized for the whole Campanian coastline (Esposito & *alii*, 2003). Homogeneity can be found within each individual block delimited by recognised structural elements, whose activity caused to differential movements, hence the dislocation of the notch or platform that had recorded the sea level at a time prior to the movement.

Such dislocations, occurred in the studied coast, coincide with a sector of the central Apennine included between two main coastal plains (Fondi and Formia-Garigliano). In these latter a light subsidence is recorded, which cannot be extended to the coastal reliefs. According to a recent paper, taking into account MIS 5.5 markers the whole eastern Tyrrhenian margin is considered from stable to slowly subsiding, even if in the southern Latium region local uplift movements, with a displacement rates of 0.2 0.01 mm/year, are estimated (Ferranti & *alii*, 2006).

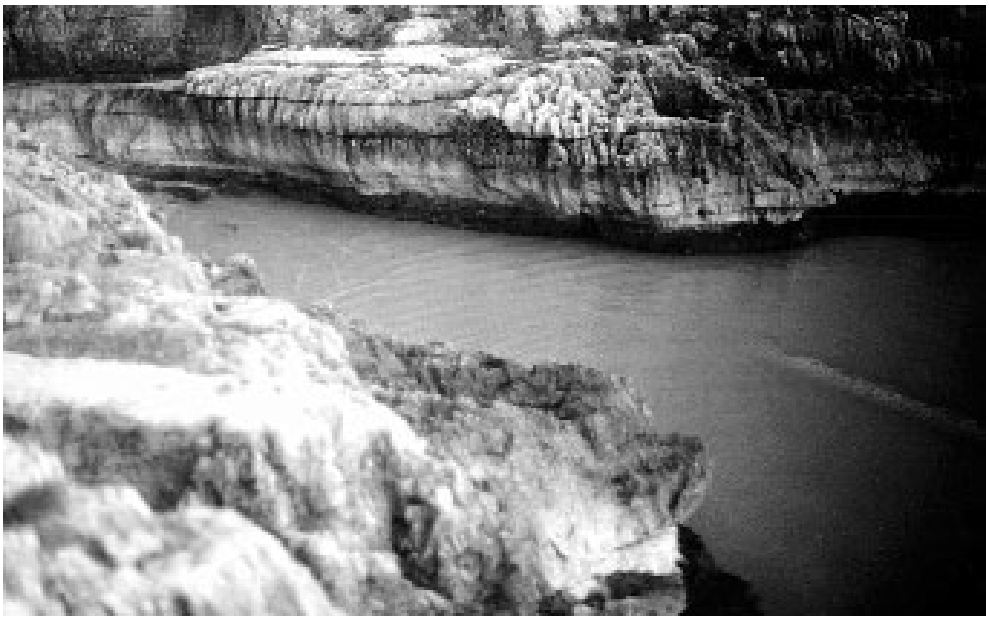

FIG. 10 - Sea terrace at +1.5 m modelled along the southwestern cliff Monte Orlando, close to the Serapo beach.

More specifically, returning to analyse the position of the traces attributed to MIS 5.5, the western area between the sites of Sant'Agostino and Ariana may be said to have behaved differently from Monte Orlando, whose western end did not follow the main movement of the headland. After MIS 5.1 the coastline seems to have become further segmented with movements in the area currently behind the plain of Sant'Agostino, in Serapo beach and in the area of Monte Orlando, compared with the rest of the area. Such considerations only allow for forms attributed with certainty to MIS 5.5 and 5.1. However, they may also be extended to the other forms, whose attribution to palaeo sea-levels derives from demonstrated morphological correlations.

So as to establish the rates and nature of differential movements it is necessary not only to consider the difference in height between the two morphologies that may be clearly attributed to two different sea level positions for the time interval during which the notch or surface was formed, but also to know the difference in eustatic level of the same time interval. Unfortunately, the differences encountered in the overlapping of the many eustatic curves published since the 1970s, obtained with various methods and data types as well as for different geographical areas, are often anything but negligible. The most significant data obtained from several curves are the following: the mean elevation of forms results 6.4 m for MIS 5.5 (126 kyr BP), with a sea-elevation of +10 m, and 2.1 m for MIS 5.1 (83 kyr BP), with a sea-level elevation of –5 m. Despite recognising a common general trend, differences are shown both in the eustatic level and in chronological attributions to the same stage. Thus, definition of the rate of fall and rise depends on the eustatic curve taken as reference.

For example, on comparing the eustatic curve of Waelbroeck & *alii* (2002) with wave cut notches and abrasion terraces found along the coastline, for MIS 5.5 a value of –0.03 mm/year is obtained for almost the whole area, with the exception of the Monte Orlando promontory which recorded a slightly higher value (–0.04 mm/year). The uplift rate would be almost halved if Shackleton's curve (2000) were taken into consideration, which sets the maximum Eutyrrhenian eustatic level at +8 m. The latter values are more compatible with those in the literature regarding uplift rates along the Italian coasts calculated by Bordoni & Valensise (1998) which, amongst other things, indicate differentiation between the coastline sector of Sperlonga and Arenauta (northwestern portion of the area in question) and that of Gaeta (+0.01 mm/y against –0.01 mm/y).

If we were to consider also the MIS 5.1 data, up to now the uplift rate, with the eustatic level of –5 m (Waelbroeck & *alii*, 2002), is about +0.09 mm/y for the sectors of Sant'Agostino and Monte Orlando and about +0.06 mm/y for Arenauta and Ariana. Also in this case the data would confirm the differential movements occurring also in this stretch of coastline subsequent to the position reached by the sea in the Neotyrrhenian.

A further calculation may be made for the interval between MIS 5.5 and MIS 5.1, which reveals an average rate of absolute altimetric variation of the whole stretch of coastline amounting to about –0.27 mm/year, with the Monte Orlando area showing a slightly higher rate.

CONCLUSIONS

Analysis of the Eu- (MIS 5.5) and Neotyrrhenian data (MIS 5.1), now accepted as correct, shows the presence of tectonic activity along the southern Lazio coastline, differentiated by adjacent coastal sectors. These sectors are those delimited by recognised structural elements or those

where the morphologies of subsequent stages retain their original reciprocal geometric ratios.

If we wish to extend our analysis to the others detected, assigned to other stages of the late Quaternary, we obtain fairly comforting values showing the vertical variation over time, designed to better display the data.

The adoption of data concerning the forms of palaeo sea-level stands attributed not only to MIS 5.5 and MIS 5.1, but also to higher ones, up to +173 m, and to lower, up to about +0.4 m, gives a more thorough picture of vertical movements involving various sectors of the coastline than that which could be reconstructed on the sole basis of MIS 5.5 data. The picture emerging thus implies a series of vertical movements within an uplift phase lasting from stage 11 up to substage 5.5, followed by a subsidence phase between MIS 5.5 and 5.3, by a new uplift phase between MIS 5.3 and 5.1, a new subsidence phase between MIS 5.1 and 3 and lastly a final uplift phase between MIS 3 and the present.

Furthermore, although the differences between the values of vertical variation rates were not very marked from sector to sector, nevertheless they were recorded, demonstrating that the various blocks of coastline were in some way disjointed. For each time interval considered, the rate may vary according to the eustatic curve chosen. The trend of variation rate over time at the studied sites, adopting different curves (Shackleton & Opdike, 1973; Shackleton, 2000; Waelbroeck & *alii*, 2002), results the same for all the curves, although the values vary according to eustatic levels and, to a lesser extent, according to chronological differences attributed to several MIS.

Our results thus suggest supplementing a model of «tectonic stability» of the stretch of coastline examined with a more dynamic model that includes a succession of shoreline uplift and fall phases throughout the Upper Pleistocene. In this work we have defined this scheme as a «lift model».

REFERENCES

ACCORDI G. & CARBONE F. (1988) - *Sequenze carbonatiche meso-cenozoiche.* In: ACCORDI G., CARBONE F., CIVITELLI G., CORDA L., DE RITA D., ESU D., FUNICIELLO R., KOTSAKIS T., MARIOTTI G. & SPOSATO A. (eds.), *Note illustrative della Carta delle litofacies del Lazio-Abruzzo ed aree limitrofe.* C.N.R., Quaderni de «La Ricerca Scientifica», 114, 11-92.

ALESSIO M., ALLEGRI L., ANTONIOLI F., BELLUOMINI G., IMPROTA S., MANFRA L. & PREITE MARTINEZ M. (1996) - *La curva di risalita del mare Tirreno negli ultimi 43Ka ricavata da datazioni su speleotemi sommersi e dati archeologici*. Memorie Descrittive della Carta Geologica d'Italia, 52, 261-276.

AMBROSETTI P., BOSI C., CARRARO F., CIARANFI N., PANIZZA M., PAPANI G., VEZZANI L. & ZANFERRARI A. (1987) - *Neotectonic map of Italy*. Foglio n. 6, scala 1:500.000, Progetto Finalizzato Geodinamica, C.N.R., Roma.

ANTONIOLI F. (1991) - *Geomorfologia subacquea costiera del litorale compreso tra Punta Stendardo e Torre S. Agostino (Gaeta)*. Il Quaternario, 4(2), 257-274.

ANTONIOLI F. (1995) - *Ricostruzione di variazioni climatiche quaternarie attraverso indagini subacquee*. In: *Lazio Meridionale - Sintesi delle ricerche geologiche multidisciplinari*. ENEA, Dipartimento Ambiente, 52-58.

AVELLINO B., BIETTI A., BRUCCHIETTI M., CASSOLI P., GIACOBINI L., GUADAGNALI F., LENTINI A., MONTERO D., SEGRE A.G. & VICARI M. (1987) - *Riparo Salvini a Terracina: una stazione di cacciatori-raccoglitori del Paleolitico superiore*. Edizioni Quasar, Roma, 35-41.

BARD E., ANTONIOLI F. & SILENZI S. (2002) - *Sea-level during the penultimate interglacial period based on a submerged stalagmite from Argentarola Cave (Italy)*. Earth and Planetary Science Letters, 196, 135-146.

BERGOMI C., CATENACCI V., CESTARI G., MANFREDINI M. & MANGANELLI V. (1969) - *Note illustrative alla Carta Geologica d'Italia. F°171 - Gaeta e Vulcano di Roccamonfina*, Servizio Geologico d'Italia.

BLANC A.C. & SEGRE A.G. (1947) - *Nuovi giacimenti tirreniani e paleolitici sulla costiera fra Sperlonga e Gaeta*. Historia Naturalis, II.

BLANC A.C., SEGRE A.G. & TONGIORGI E. (1953) - *Le Quaternaire de l'Agro Pontino*. Atti IV Congresso Internazionale INQUA, Roma-Pisa.

BONO P. (1985) - *Seminario informativo sui risultati del progetto «laghi costieri». Sintesi della relazione finale.* Università degli Studi «La Sapienza», Roma, vol. 1, 163 pp.

BORDONI P. & VALENSISE G. (1998) - *Deformation of the 125 ka marine terrace in Italy: tectonic implications*. In: STEWART I. & VITA FINZI C. (eds.), *Late Quaternary coastal tectonics*. Geological Society Special Publications, 146, 71-110.

BRANCACCIO L., CINQUE A., RUSSO F., BELLUOMINI G., BRANCA M. & DELITALA L. (1990) - *Segnalazione e datazione di depositi marini tirreniani sulla costa campana*. Bollettino della Società Geologica Italiana, 109, 259-265.

CARRARA C. (1995a) - *Elementi di Geologia regionale*. In: *Lazio Meridionale - Sintesi delle ricerche geologiche multidisciplinari*. ENEA, Dipartimento Ambiente, 23-33.

CARRARA C. (1995b) - *Elementi di neotettonica*. In: *Lazio Meridionale - Sintesi delle ricerche geologiche multidisciplinari*. ENEA, Dipartimento Ambiente, 34-36.

CARRARA C., DAI PRA G. & PAGANIN G. (1995) - *Lineamenti di tettonica plio-quaternaria*. In: *Lazio Meridionale - Sintesi delle ricerche geologiche multidisciplinari*. ENEA, Dipartimento Ambiente, 151-155.

CERISOLA R. & MONTONE P. (1992) - *Analisi strutturale di un settore della catena dei monti Ausoni - Aurunci (Lazio, Italia centrale).* Bollettino della Società Geologica Italiana, 111, 449-457.

CINQUE A. & ROMANO P. (1990) - *Segnalazione di nuove evidenze di antiche linee di riva in Penisola Sorrentina (Campania)*. Geografia Fisica e Dinamica Quaternaria, 13, 23-25.

DAI PRA G. (1995) - *Geomorfologia e stratigrafia dei depositi del Pleistocene e dell'Olocene*. In: *Lazio Meridionale - Sintesi delle ricerche geologiche multidisciplinari*. ENEA, Dipartimento Ambiente, 36-50.

DE PIPPO T. & DONADIO C. (1999) - *Morphology, genesis and evolution of rockpools along italian coasts*. Geografia Fisica e Dinamica Quaternaria, 22, 129-141.

DE PIPPO T., DONADIO C. & SGROSSO A. (1998) - *Geomorfologia sottomarina di una settore della Penisola Sorrentina (Campania)*. Geografia Fisica e Dinamica Quaternaria, 21, 103-110.

DE RISO R. (1964) - *Osservazioni geologiche sui monti di Gaeta*. Memorie e Note dell'Istituto di Geologia Applicata, Università degli Studi di Napoli Federico II, 9, 5-21.

DURANTE S. & SETTEPASSI F. (1976-77) - *Malacofauna e livelli tirreniani a Grotta Guttari, M. Circeo (Latina)*. Quaternaria, 19, 35-69.

ESPOSITO C., FILOCAMO F., MARCIANO R., ROMANO P., SANTANGELO N., SCARMIGLIA F. & TUCCINEI P. (2003) - *Late Quaternari shorelines in southern Cilento (Mt. Bulgheria): morphostratigraphy and chronology*. Il Quaternario, 16 (1), 3-14.

FERRANTI L., ANTONIOLI F., MAUZ B., AMOROSI A., DAI PRA G., MASTRONUZZI G., MONACO C., ORRÙ P., PAPPALARDO M., RADTKE U., RENDA P., ROMANO P., SANSÒ P. & VERRUBBI V. (2006) - *Markers of the last interglacial sea-level high stand along the coast of Italy: tectonic implications*. Quaternary International, 145-146, 30-54.

HEARTY P.J. (1986) - *An inventory of last interglacial (s.l.) age deposits from the Mediterranean basin: a study of isoleucine epimerization and U-series dating.* Zeitschrift für Geomorphologie N.F., Suppl.-Bd., 62, 51-69.

HEARTY P.J. & DAI PRA G. (1986) - *Aminostratigraphy of Quaternary marine deposits in the Lazio Region of Central Italy*. Zeitschrift für Geomorphologie N.F., 62, 131-140.

HEARTY P.J., MILLER G.H., STEARNS C.E. & SZABO B.J. (1986) - *Aminostratigraphy of the Quaternary shorelines in the Mediterranean basin*. Geological Society of America Bulletin, 97, 850-858.

IMBRIE J., HAYS J.D., MARTINSONS D.G., MCINTYRE A., MIX A.C., MORLEY J.J., PISIAS N.G., PRELL W.L. & SHACKLETON N.J. (1984) - *The orbital theory of Pleistocene climate: support from a revised chronology of the marine d ^{18}O record*. In: BERGER A., IMBRIE J., HAYS J., KUKLA G. & SALTZMAN B. (eds.), *Milankovitch and Climate*, Part 1, D. Reidel Publication Company, Dordrecht, 269-305.

LABEYRIE L.D., DUPLESSY J.C. & BLANC P.L. (1987) - *Variations in mode of formation and temperature of oceanic deep waters over the past 125000 years*. Nature, 327, 477-482.

LAMBECK K., ANTONIOLI F., PURCELL T. & STIRLING C. (2004) - *MIS 5.5 Sea level in the Mediterranean and inferences on the global ice volumes during late MIS 6 and MIS 5.5.* In: Proceedings of the 32nd International Geological Congress, Florence, Italy.

MARTINSONS D.G., PISIAS N.G., HAYS J.D., IMBRIE J., MOORE JR. T.C. & SHACKLETON N.J. (1987) - *Age dating and the orbital theory of the ice ages: development of a high resolution 0 to 300,000-year chronostratigraphy*. Quaternary Research, 27, 1-29.

MIELE P. (2003) - *Relazione tra linee di riva e tettonica durante il Quaternario nel tratto di costa tra Marina di Minturno e Gaeta (Lazio meridionale)*. Tesi di dottorato di ricerca, Dipartimento di Scienze della Terra, Università degli Studi di Napoli Federico II, Napoli, 219 pp.

OZER A., DEMOULIN A. & DAI PRA G. (1987) - *Les indices morphologiques témoins de la stabilité tectonique de la bordure litorale du Lazio méridional (Italie)*. Zeitschrift für Geomorphologie N.F., Suppl., 63, 103-117.

RICCIO A., RIGGIO F. & ROMANO P. (2001) - *Sea level fluctuations during Oxygen Isotope Stage 5: new data from fossil shorelines in the Sorrento Peninsula (Southern Italy)*. Zeitschrift für Geomorphologie N.F., 45, 1, 121-137.

SEGRE A.G. (1949) - *Tracce di morfologia subaerea sul fondo marino litoraneo del Lazio meridionale.* Historia naturalis, 3(1), 1-3.

SHACKLETON N.J. (1987) - *Oxygen isotopes, ice volume and sea level*. Quaternary Science Reviews, 6(3/4), 183-190.

SHACKLETON N.J. (2000) - *The 100,000-year Ice-Age cycle identified and found to lag temperature, carbon dioxide and orbital eccentricity*. Science, 289, 1897-1902.

SHACKLETON N.J. & OPDIKE N.D. (1973) - *Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 105 year and 106 year scale*. Quaternary Research, 3, 39-55.

STINER M. (1991) - *The faunal remains from Grotta Guttari: a taphonomic perspective*. Current Anthropology, University of Michigan, Ann Arbor, 32, 2.

VALENTE A. (1999) - *Aspetti geologici e geomorfologici del Parco Regionale di Monte Orlando (Lazio meridionale, Italia).* Memorie Descrittive della Carta Geologica d'Italia, 54, 101-110.

VITAGLIANO S. (1984) - *Nota sul Pontiniano della Grotta dei Moscerini Gaeta (Latina)*. Atti XXIV Riunione Scientifica II PU «Il Paleolitico nel Lazio».

WAELBROECK C., LABEYRIE L., MICHEL E., DUPLESSY J.C., MC MANUS J.F., LAMBECK K., BALBON E. & LABRACHERIE M. (2002) - *Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records*. Quaternary Science Reviews, 21, 295-305.

ZEI M. (2000) - *Preistoria del litorale formiano*. In: *Storia illustrata di Formia*. Sellino Editore, vol. I, 17-34.

(Ms. received 15 March 2006; accepted 15 December 2006)