JOURNAL OF QUATERNARY SCIENCE (2003) **18**(8) 709–721

Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/jqs.803

Coastal deformation between the Versilia and the Garigliano plains (Italy) since the last interglacial stage

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Nisi, M. F., Antonioli, F., Pra, G. D., Leoni, G. and Silenzi, S. 2003. Coastal deformation between the Versilia and the Garigliano plains (Italy) since the last interglacial stage. *J. Quaternary Sci.*, **Vol. 18** pp. 709–721. ISSN 0267-8179.

Received 20 January 2003; Revised 25 September 2003; Accepted 1 October 2003

ABSTRACT: The opening of the north-central Tyrrhenian Sea is the result of the Cretaceous–Paleogene alpine collision, which triggered a series of regional uplift, subsidence and transcurrent tectonic mechanisms along the coastal Tyrrhenian sectors of peninsular Italy. These tectonic processes, in conjunction with the effects of glacio- and hydro-isostasy during the Quaternary, produced substantial crustal responses that, in some cases, reached metres in extent. In the study of coastal neotectonics, geomorphological markers of the last interglacial maximum, corresponding to marine isotope stage 5.5, are generally used to quantify the magnitude of the vertical crustal displacements that have occurred since 125 kyr. Through altimetrical, palaeoenvironmental and chronological reinterpretation of the most significant works published since 1913, combined with an additional set of data reported here, a detailed reconstruction of the shoreline displacements evident along 500 km of coast between northern Tuscany and southern Latium is presented. The reconstruction was carried out by quantifying the vertical movement since the last interglacial period and by identifying the tectonic behaviour of different coastal sectors. This has been done by carefully choosing the eustatic marker, among those available at each study site, in order to minimize the margin of error associated with the measurements. Copyright © 2003 John Wiley & Sons, Ltd.

Journal of Quaternary Science

KEYWORDS: Tyrrhenian coast; coastal deformation; sea-level markers; MIS 5.5; margin of error.

Introduction

The current physiographic and geological setting of the Tyrrhenian–Appennine system has resulted from a complex tectonic evolution which began with the Cretaceous–Paleogene convergence between the Afro-Arabian and the European plates. In Tortonian time, the incomplete collision of the two plates caused an E–W directed opening of a retro-arc basin corresponding with the current Tyrrhenian Sea, connected to the Ionic–Adriatic subduction (Patacca *et al.*, 1990; Faccenna *et al.*, 1996); through time, the extensional processes migrated towards the northeast in accordance with the location of the compressive front (Elter *et al.*, 1975; Sartori *et al.*, 1989; Oldow *et al.*, 1990; Patacca *et al.*, 1990).

The compressional and extensional processes that led to the formation of the Tyrrhenian Basin were followed by transpressional processes that contributed towards the recent evolution of the eastern tectonic margin. This change in the regional geodynamics marks the beginning of a tectonic style dominated by vertical movements (Bordoni and Valensise, 1998; Musacchio, 2000).

This general picture, complicated by recent volcanism (De Rita *et al.*, 1992; Barberi *et al.*, 1994) and by differential rheologic movements of the continental platform induced by glacio- and hydro-isostatic causes (Lambeck and Johnston, 1995; Pirazzoli, 1998; Lambeck and Bard, 2000), has resulted in different types of tectonic evolution in the various coastal segments adjacent to the peri-Tyrrhenian area. Sectors that were active in recent times may in fact be contiguous to areas that were stable by the Middle Pleistocene. The main displacements of the Tyrrhenian coastal areas often seem to be controlled by overlapping mechanisms, which can be summarised as follows:

1 Large-scale regional uplift, subsidence or transcurrent processes, triggered by the evolution of the Tyrrhenian basin.
2 Local uplift and subsidence of '*horst and graben*' type of the continental margins, with substantial throws along normal faults that are responsible for the promontory/coastal plain morphologies.
3 Glacio- and hydro-isostatic rebound, which recurs during every climatic cycle; such phenomena acted in variable ways in the northern and southern Tyrrhenian area, producing crustal responses with differences of up to 7 m in the past 6000 yr.

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Figure 1 Study sites (black line) along the Tyrrhenian coastal line

Displacements since the last interglacial (MIS 5.5, 125 kyr, equivalent to the Tyrrhenian period in the Mediterranean area) are recorded through the use of geomorphological markers that permit inferences to be made about of the position of sea-level at time of deposition. These widely used markers in neotectonic surveys include tidal notches, the inner margins of sea terraces and palaeolagoonal and coastal deposits containing the characteristic Senegalese fauna (see Conato and Dai Pra, 1980; Cosentino and Ghiozzi, 1988; Dai Pra and Hearty, 1988; Carobene and Dai Pra, 1990, 1991; Westaway, 1993; Antonioli and Silenzi, 1998; Zazo *et al.*, 1999). By measuring the bathy/altimetric height of the markers in their modern environmental setting and comparing them with the Tyrrhenian eustatic altitude, it is possible to calculate the degree of vertical displacement from tectonic movements since the last interglacial maximum (125 kyr).

The objective of this study is to reconstruct the degree of vertical displacement of coastal sectors since MIS 5.5 along the coastal Tyrrhenian sector between northern Tuscany and southern Latium (Fig. 1). This aim has been achieved through the synthesis and standardisation of all the data published between 1913 and 2000 related to recorded maximum sea-levels of the last interglacial highstand. Such standardisation (which was also performed in the field) consists of a chrono-altimetric reinterpretation and an evaluation of the error associated with the use of each type of geomorphological marker.

Methods

The term Tyrrhenian indicates the maximum sea transgression during MIS 5.5 (Shackleton *et al.*, 1990), which in the Mediterranean area is related to deposits containing *Strombus bubonius* (Dai Pra and Stearns, 1977; Pisias *et al.*, 1984; Hearty *et al.*,1986; Hearty and Dai Pra, 1992; Cita and Castradori, 1995).

There is no complete agreement on the exact position of the palaeosea-level during MIS 5.5. The estimates, which generally range between 0 m and +10 m with respect to present mean sea-level, also seem to have suffered a substantial revision downwards. For example, according to Ku *et al.* (1974, 1990), Harmon *et al.* (1983) and Bard *et al.* (1990), the MIS 5.5 palaeosea-level ranges between +6 and +8 m. Chappell and Shackelton (1986) state that it should not be higher than +6 m. For Esat *et al.* (1999) it ranges between +3 and +5 m, whereas for McCulloch and Esat (2000) it is between +2 and +4 m. Hearty (2002), in a revised sea-level curve for Bermuda during MIS 5, reports on two different highstands: one in early MIS 5.5 at +2.5 m, and another in the late MIS 5.5 between +6 and +9 m; the latter may correspond to the maximum highstand that occurred at the end of the interglacial (Land *et al.*, 1967). It is also important to bear in mind that the effects of the glacio- and hydro-isostatic rebound on the eustatic fluctuations that took place during the last interglacial may have affected maximum sea transgression elevations of only a few metres. (Lambeck and Nakada, 1992). Of all areas in the central Mediterranean, Sardinia is known to be characterised by tectonic stability, and '*The Tyrrhenian*' was officially instituted in Sardinia at Cala Mosca (Cagliari) by Gignoux in 1913, at an altitude of +5 m. Furthermore, along its eastern coast, a Tyrrhenian tidal notch stretches for about 70 km at a height ranging between +7.7 and +10.4 m (Antonioli *et al.*, 1999c). As the coasts considered in this work are relatively close to Sardinia, we adopt the traditional value of $+7 \pm 1$ m as the eustatic height of MIS 5.5. This altimetric attribution has been utilised previously by Bard *et al.* (2002) to confirm the tectonic stability of Argentarola Cave (very close to Argentario Promontory) during the last glacial cycle.

With this preliminary assumption, it is possible to calculate the magnitude of vertical displacement of the coastal sectors by subtracting the average eustatic height of +7 m from the current bathy/altimetric heights of the markers indicating the Tyrrhenian palaeosea-level (Z; expressed in mm); assuming that the movements have been constant and homogeneous since 125 kyr, it is thus possible to quantify the uplift and/or subsidence rates according to the relationship

$$(Z - 7 \times 10^3)/(125 \times 10^3) \text{ (mm/year)} \qquad (1)$$

A similar approach for the Italian south-central coasts has been performed by Cosentino and Ghiozzi (1988) and Bordoni and Valensise (1998). The latter presents a complete review of previously published work in Italy (excluding Sardinia). However, it does not consider the margin of error associated with the altimetric reliability of the palaeosea-level markers. For instance, Cosentino and Gliozzi (1988) estimate the current maximum elevation during MIS 5.5 by adding 25 m to any Tyrrhenian deposit characterized by typical fauna, assuming that the habitat of this fauna is centred at 25 m water depth. Bordoni and Valensise (1998) use instead the maximum height of the Tyrrhenian deposits found on the accretion surface where the inner margin of the sea terraces is not visible. Although these approaches are certainly interesting and useful, such methods may lead to either underestimation or overestimation of the actual elevation of the Tyrrhenian shoreline.

Until a few years ago, finds of Senegalese fauna were often used to indicate the maximum sea transgression height as that point. It is known, however, that, for example, *Glycymeris* sp. is commonly found in the *Sables Grossiers et Fins Graviers* (SGCF) biocenosis (Peres and Picard, 1964) and it seems to be commonly found at depths of around 50 m, and that *Strombus bubonius* currently lives at depths of up to 35–40 m. It is therefore clear that the use of non-precise markers may lead to considerable errors (of up to tens of metres) concerning the maximum transgression height.

The method used in the present study is based on the reinterpretation of the most significant geomorphological markers

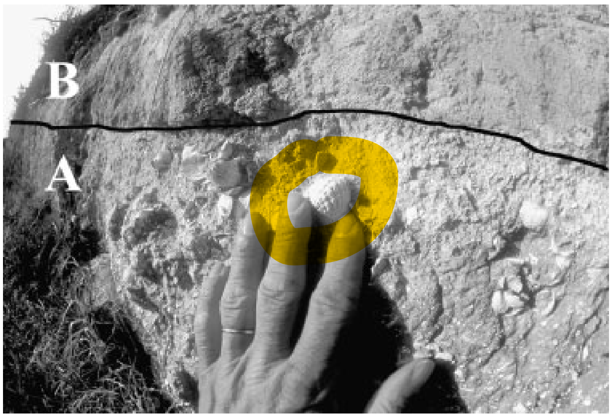

Figure 2 Lagoon deposits with *Cerastoderma glaucum* (A) covered by regressive aeolian sediments (B) in Selva Nera, southern Tuscany. In addition to representing an easily datable material (both with aminostratigraphy and with radiocarbon), *C. glaucum* allows the identification of the shoreline with a very limited margin of error (±1.5 m in lagoonal deposits)

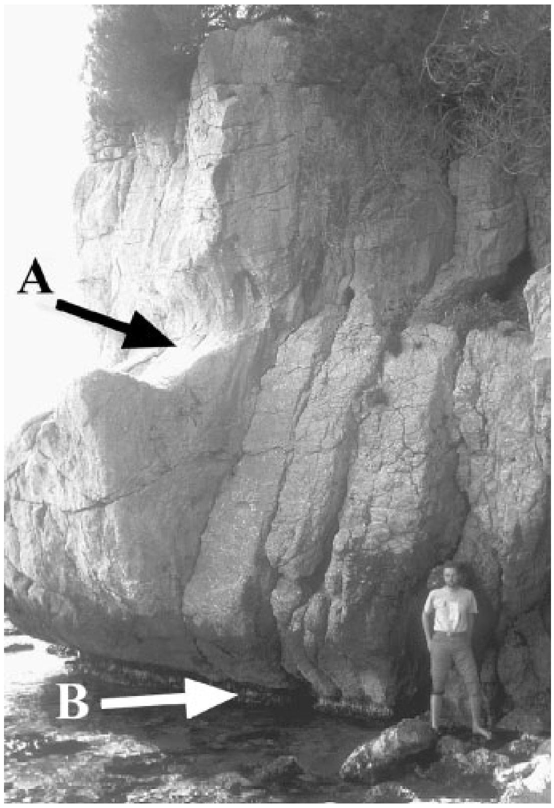

Figure 4 Fossil (A) and present (B) tidal notch on the carbonate cliff of the Talamonaccio Promontory (southern Tuscany). Tidal notches represent the most significant marine erosion landform for neotectonic coastal analyses (Pirazzoli, 1986; Agnesi *et al.*, 1993; Antonioli *et al.*, 1999a). The margin of error for tidal notches as mean sea-level, markers is un greater than ±0.5 m (Antonioli *et al.*,1999a)

described in past studies. This reinterpretation was in many cases performed directly in the field or rechecked with the authors themselves.

Among the available markers, those dated with U/Th, aminostratigraphy, morphostratigraphical and Chronostratigraphical correlations were selected initially. In order to minimise the altimetric error and to obtain a quantitative estimate of the margin of error, it was necessary to concentrate on sections linked with more precise indicators: (i) *Cerastoderma glaucum* layers, (ii) inner margins of the Tyrrhenian marine terrace and (iii) tidal notches (Figs 2–4).

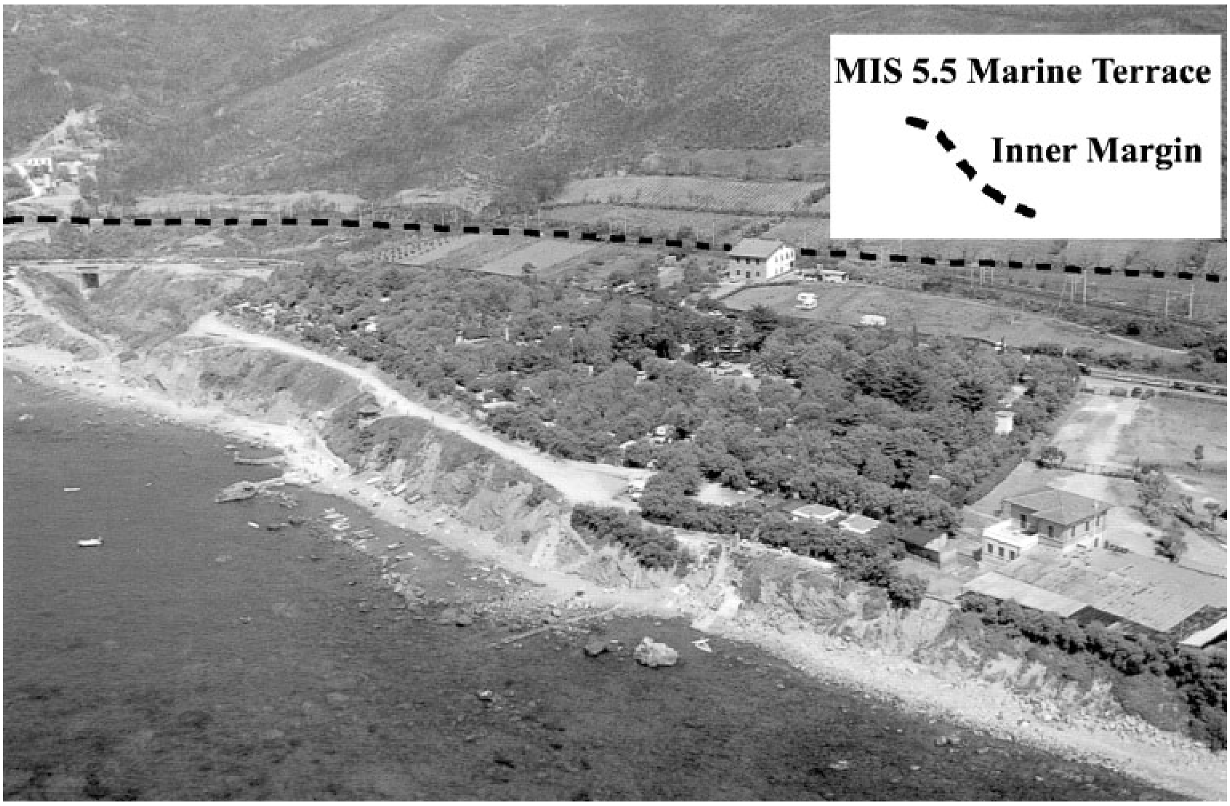

Figure 3 Aerial view of the marine terrace near Antignano (Livorno, Tuscany). The inner margin (dashed line) of the terrace is located above the railway. The inner margin of a marine terrace indicates the relative sea-level with a margin of error of ±1.5 m (Antonioli *et al.*, 1999a)

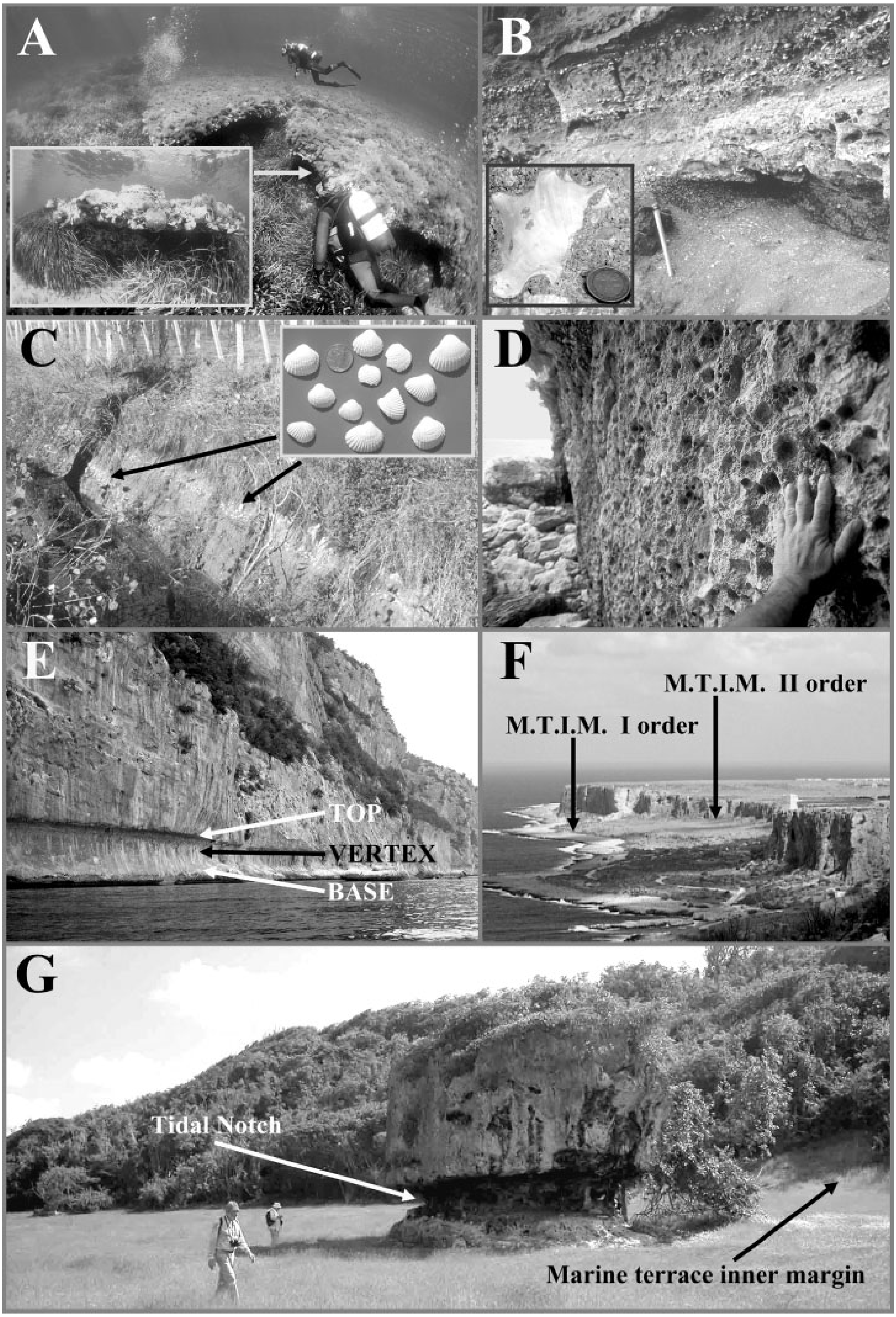

Figure 5 Some representative examples of the main sea-level markers discussed in this work: (A) Holocene beachrock at −3.5 m near Villasimius and Isola dei Cavoli (southeast Sardinia, Italy); (B) MIS 5.5. beach deposits with Senegalese fauna in Buca dei Corvi, southern Tuscany, Italy (in the box, a fossil of *Strombus bubonius*); (C) lagoonal deposits in the Fondi Plain, southern Latium, Italy (in the box, fossils of *Cerastoderma glaucum*); (D) a MIS 5.5 *Lithopaga* holes band in the stable limestone coast of S. Vito Lo Capo, northwest Sicily, Italy (Antonioli *et al.*, 1999a); (E) MIS 5.5 tidal notch (+9.0 m) and the present tidal notch in a very conservative limestone coastal zone (Golfo di Orosei, Est Sardinia, Italy). This morphology is present along more than 50 km of coast; (F) several orders of marine terraces near S. Vito Lo Capo; the first order terrace corresponds to MIS 5.5 (Antonioli *et al.*, 1999a); (G) a tidal notch in a small palaeo-island over the MIS 5.5 marine terrace (Barbados; Schellmann and Radtke, 2002); the relationship between the tidal notch and the terrace inner margin is clearly visible

Table 1 Main markers used in the palaeosea-level altimetric attributions and their error margins

Marker type	Altitude error (+/−)		Mode of formation[a]	Environment
Beachrock	1.0	5.0	2–4	Marine
Beach deposits	1.0	5.0	2–4	
Cerastoderma glaucum	0.5	1.5	2–3	Transitional
Lithophaga holes band	0.5	0.5	1–3	Marine
Marine terrace inner margin	1.5	1.5	1–4	
Tidal notch	0.5	0.5	1–4	
Littoral deposits and aeolian regressive deposits	3.5	3.5	2–4	Continental–marine
Marine terrace inner margin and beachrock	1.5	1.5	1–4	Marine
Tidal notch and *Lithophaga* holes band	0.5	0.5	1–4	

[a]1, erosional; 2, depositional; 3, biological; 4, geomorphological.

In cases where these markers were not available, other markers such as bands of *Litophaga* holes and littoral deposits (with Senegalese fauna, *Glycimeris* sp., *Venus* sp.) were used, sometimes in conjunction with beachrock or tidal notches (Fig. 5). For these markers the related margin of error was also recorded (Table 1).

The methodological approach proposed here allows the standardisation of data for coastal tectonic reconstructions and palaeo-eustatic calibration since MIS 5.5. and should be applicable to the entire Mediterranean basin.

Fifty-two sites have been examined along the Tyrrhenian coastal sector from the Versilia Plain southwards to the Garigliano Plain, over a distance of 481 km (Fig. 6).

Data

The Tyrrhenian sector was subdivided into four main segments according to their geological characteristics and neotectonic behaviour since 125 kyr. For each of the following sectors, the altimetric, geomorphological and chronological characteristics of the surveyed or reinterpreted sections are described (Table 2). The new data presented here concern the inner margin of the Livorno marine terrace and some coastal deposits in the Versilia and Garigliano plains.

Versilia (site 1)

The Versilia Plain represents part of a tectonic subsidence plain, with Appenninic direction, active from the Early Miocene (Della Rocca *et al.*, 1987).

Evidence of Tyrrhenian deposits on the plain is confirmed by stratigraphical analysis (Table 3), thanatocenosis (Table 4) and from datings (^{14}C, ^{230}Th/^{234}U; Table 5) performed on the deposits from a −90 m geognostic (borehole) survey performed by ENEA in 1998 (Antonioli *et al.*, 1999b). The sediments, located between −90.0 m and −68 m, can be dated back to MIS 5.5; in particular, the palaeoshoreline (stratigraphical attribution in the core) can be placed at -64 ± 1 m.

Livorno Plain to Burano Lagoon (sites 2–16)

The southern Tuscan coastal belt is characterised by an alternation of flat areas and morphological highs generated by the development of extensional structures and by intrusive and extrusive magmatic phenomena, which contributed to the development and irregular set up of basins and ridges (Lazzarotto, 1993). Frequent stretches of high coast also characterise the area because of the presence of Upper Pleistocene terrace deposits (Federici and Mazzanti, 1994).

In the area between Casale Vallino (Livorno) and Rosignano we have analysed the inner margins of four terraces, which have for long been known in the literature (Barsotti et al., 1974; Lazzarotto *et al.*, 1990; Federici and Mazzanti, 1994). The presence of *Strombus bubonius* (Barsotti *et al.*, 1974; Lazzarotto *et al.*, 1990; Ottman, 1954) and morpho-chronostratigraphical correlations have established an average terrace height of 15 m for the Tyrrhenian age (MIS 5.5). The development of its inner margin, reconstructed through field surveys and digital photogrammetry (Nisi, 1999), is marked by the presence of beachrock (Barsotti *et al.*, 1974) (sites 2–9), between +11 m at Buca dei Corvi (site 8) and +20 m at both Bagnetti and Antignano (sites 4 and 5).

Moving southwards, the markers of the Tyrrhenian palaeoshoreline of the reinterpreted sections are the ones referring to the beach deposits bearing Senegalese fauna of the Island of Pianosa (site 10), to the tidal notch of Talamonaccio (site 11) and to the lagoonal or coastal facies deposits neighbouring the Monte Argentario (sites 12–16); such markers can be found at heights ranging between +3 and +12 m.

Montalto di Castro Plain to Borgo Sabotino (sites 17–25)

The coastal belt extending from the Argentario Promontory to the northern margin of the Pontina Plain is the segment that mainly suffered the effects of the eruptions of the Vulsini, the Sabatini and the Colli Albani volcanoes, which were active between 600 and 20 kyr (Barberi *et al.*, 1994; De Rita *et al.*, 1992).

From the Fosso Ponte Rotto, a few kilometres south of the Argentario Mountain, a clear increase in the height of the Tyrrhenian deposits can be observed (sites 17–25). The deposits increase from an elevation of +20 m in the lagoon deposits at km 115 of the Aurelia Road (site 17) up to a height of +35 m at the marine terrace, characterised by *S. bubonius* beach facies deposits in Monna Felice (site 22).

To the south, the Tyrrhenian layer can be found again at +35 m by Casale di Statua (site 24). Subsequently, the Tyrrhenian elevation begins to decrease southwards, down to +10 m at Borgo Sabotino (site 25).

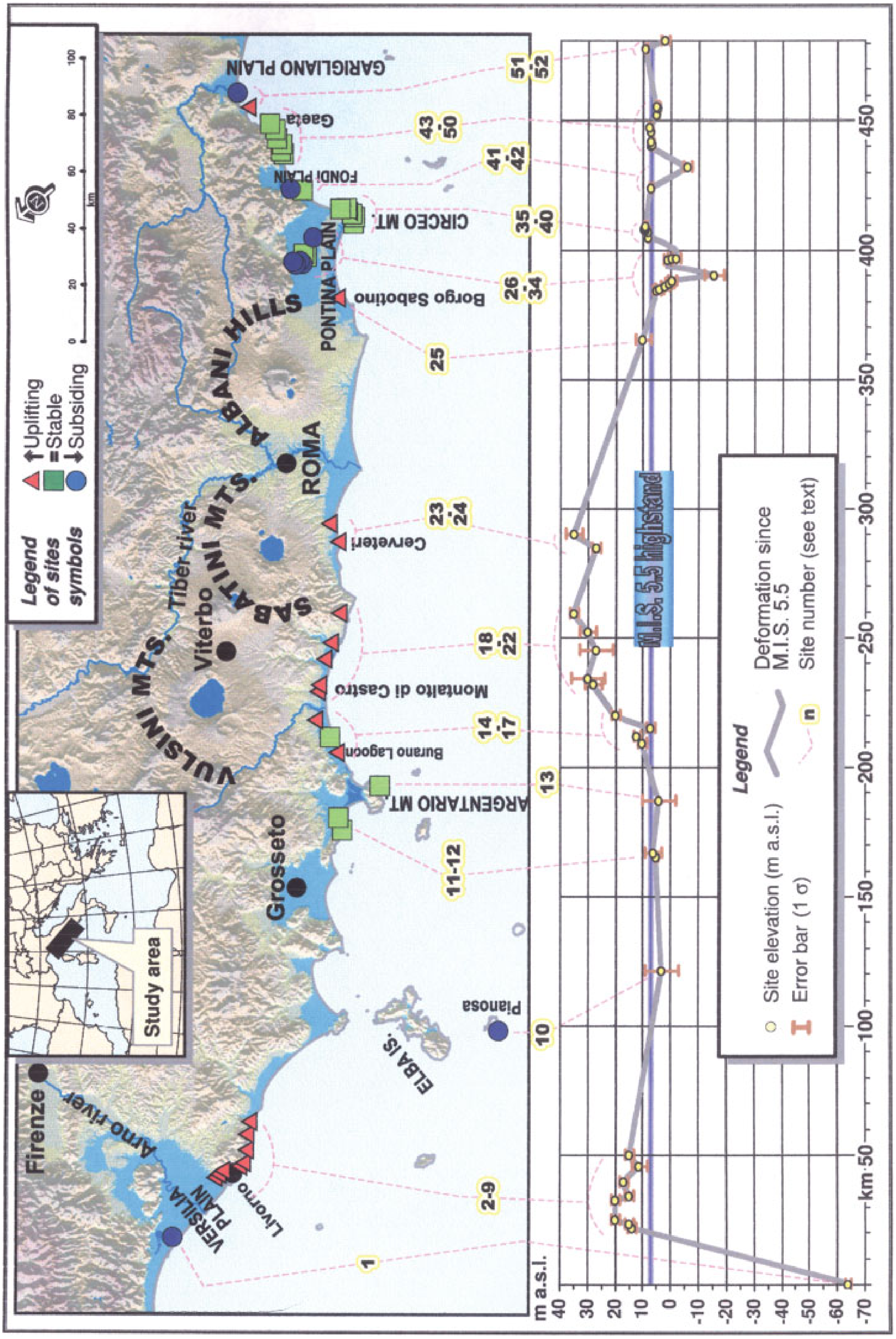

Figure 6 Spatial and altimetric distribution of the Tyrrhenian palaeosea-level markers along the coastal belt examined in this study in relation to the eustatic height of the MIS 5.5 (+7 m). For every site, the respective error bar, which indicates the uncertainty associated with inferred palaeoshoreline on the marker's height in relation to the 125 kyr palaeoshoreline, is shown

Table 2 Significant characteristics of the 52 sections analysed for the reconstruction of the Tyrrhenian shoreline: place name, location, distance from the Versilian Plain, dating method, types of markers, elevation in relation to the current sea-level, range of error, bibliographic references

Site	Location	Latitude Longitude	Kilometres along road	Dating method[a]	Marker	Elevation (m)	Error (m)	References[b,c]
1	Versilia Plain	43°48′N 10°19′E	0	U/Th	Lagoon deposits *C. coespitosa*	−64	±1	1,2 O
2	C.le Vallino	43°35′N 10°22′E	21.5	Mc	Marine terrace inner margin Beachrock	+14	±1.5	1 O
3	Pian di Rota	43°34′N 10°22′E	23.5	Mc	Marine terrace inner margin Beachrock	+15	±1.5	1 O
4	Bagnetti	43°33′N 10°22′E	25	Mc	Marine terrace inner margin Beachrock	+20	±1.5	1,3 M
5	Antignano	43°30′N 10°20′E	32.5	Mc	Marine terrace inner margin Beachrock	+20	±1.5	1 M
6	Punta Casotto	43°29′N 10°20′E	34	Mc	Marine terrace inner margin Beachrock	+15	±1.5	1 M
7	Quercianella	43°27′N 10°22′E	39.5	Mc	Marine terrace inner margin Senegalese fauna	+17	±1.5	1,3 M
8	Buca dei Corvi	43°25′N 10°25′E	45.5	Am	Beach deposits Senegalese fauna	+11	±3	4,5 6,7
9	Rosignano S.	43°23′N 12°27′E	50	Mc	Marine terrace inner margin Beachrock	+15	±1.5	8
10	Pianosa	42°35′N 10°04′E	121	Mc, Am	Beach deposits *S. bubonius*	+3	±6	6, 30 R
11	Talamonaccio	42°33′N 11°08′E	165	Mc	Tidal Notch *Lithophaga* Holes	+5.3	±0.5	6 M
12	Campo Regio	42°32′N 11°11′E	167	Am	Littoral deposits, aeolian regressive deposits covering the beach	+6	±3.5	6 M
13	Argentario Promontory	42°22′N 11°10′E	187	Cc	Littoral deposits Senegalese fauna	+4	±6	9 M
14	Selva Nera	42°24′N 11°24′E	209	Am	Lagoon deposits *Glycimeris* sp., *C. glaucum*	+10	±1.5	6 M
15	San Angelino	42°23′N 11°28′E	212	Am	Lagoon deposits *C. glaucum*	+12	±1.5	6
16	Lasco del Pozzo	42°23′N 11°28′E	215	Am	Lagoon deposits *Glycimeris* sp., *C. glaucum*	+7	±1.5	6
17	Aurelia km115	42°23′N 11°34′E	220	Am	Lagoon deposits *C. glaucum*	+20	±1.5	6 R
18	Mandrione	42°19′N 11°39′E	232	Cc	Aeolian regressive deposits covering the beach, *S. bubonius*	+28	±3.5	10,11
19	Aurelia km103	42°18′N 11°40′E	234	Am	Littoral deposits *Glycimeris* sp.	+30	±3.5	12
20	Tarquinia Railway Station	42°14′N 11°44′E	245	Cc	Littoral deposits Senegalese fauna	+27	±6	11,13
21	C.le Olivastro	42°11′N 11°46′E	252	Am	Beach deposits *S. bubonius*	+30	±3	6,12
22	Monna Felice	41°58′N 11°52′E	259	Cc	Marine terrace inner margin *S. bubonius*	+35	±1.5	6,14 R
23	Cerveteri	41°57′N 12°04′E	285	Am	Lagoon deposits *C. glaucum, S. bubonius*	+27	±1.5	12,14
24	Casale di Statua	41°56′N 12°09′E	290	Cc, Am	Aeolian regressive deposits covering the beach, *S. bubonius*	+35	±3.5	6,12,14,15 R
25	Borgo Sabotino	41°26′N 12°50′E	365	Am	Regressive deposits covering the beach, *S. bubonius*	+10	±3.5	12,16
26	Pontinia I	41°25′N 13°03′E	384	Am	Lagoon deposits *C. glaucum*	+5.3	±1.5	17
27	Pontinia II	41°25′N 13°04′E	385	Am	Lagoon deposits *C. glaucum*	+4.4	±1.5	17
28	Pontinia III	41°26′N 13°04′E	386	Am	Lagoon deposits *C. glaucum*	+2.3	±1.5	17
29	Pontinia IV	41°26′N 13°05′E	387	Am	Lagoon deposits *C. glaucum*	+0.8	±1.5	17
30	Pontinia V	41°27′N 1305′E	388	Am	Lagoon deposits *C. glaucum*	−0.5	±1.5	17
31	Pontinia VI	41°27′N 13°06′E	390	U/Th, Am	Brackish deposits, *Valvata* sp., *Venus* sp., calcareous concretions	−15.5	±3.5	29 R
32	Borgo Vodige I	41°21′N 13°07′E	396	Am	Lagoon deposits *C. glaucum*	+1.0	±1.5	17

(continued overleaf)

Table 2 *(Continued)*

Site	Location	Latitude Longitude	Kilometres along road	Dating method[a]	Marker	Elevation (m)	Error (m)	References[b,c]
33	Borgo Vodige II	41°21′N 13°07′E	396.5	Am	Lagoon deposits *C. glaucum*	−0.6	±1.5	17
34	Borgo Vodige III	41°21′N 13°07′E	397	Am	Lagoon deposits *C. glaucum*	−1.8	±1.5	17
35	Breuil Cave	41°14′N 13°01′E	405	Mc	*Lithophaga* holes	+8.3	±0.5	18
36	La batteria	41°13′N 13°02′E	407	Mc	*Lithophaga* holes	+8.0	±0.5	19
37	Fossellone Cave	41°13′N 13°03′E	407.5	Mc	Tidal notch	+9.0	±0.5	20,21
38	Capre Cave	41°13′N 13°04′E	408	Mc	Tidal notch	+9.6	±0.5	19,22 23,24
39	Torre del Fico	41°13′N 13°05′E	408.5	Mc	Tidal notch	+9.2	±0.5	19
40	Guattari Cave	41°14′N 13°06′E	409	Mc	Tidal notch	+9.2	±0.5	22,24 25
41	Terracina	41°17′N 13°16′E	424	Mc	Tidal notch	+7.3	±0.5	26
42	Fondi Plain	41°18′N 13°20′E	432	Am	Lagoon deposits *C. glaucum*	−6.0	±1.5	26 R
43	Sperlonga Promontory	41°15′N 13°26′E	440	Mc	Tidal notch	+7.3	±0.5	24
44	Tiberio Cave	41°15′N 13°27′E	441	U/Th, Am	Tidal notch *Glycimeris* sp.	+6.9	±0.5	26,27
45	Torre Capovento	41°14′N 13°28′E	442	Am	*Lithophaga* holes *Glycimeris* sp.	+7.4	±0.5	24,27
46	S. Agostino	41°14′N 13°30′E	445.5	Mc	Tidal notch	+7.0	±0.5	27
47	Arenauta	41°13′N 13°32′E	447.5	Mc	Tidal notch	+7.5	±0.5	24
48	Gaeta I	41°13′N 13°34′E	452	Am	Tidal notch *Glycimeris* sp.	+5.3	±0.5	27
49	Gaeta II	41°13′N 13°34′E	455	Mc	Tidal notch	+4.8	±0.5	27
50	Gaeta III	41°13′N 13°34′E	455.5	Mc	Tidal notch	+5.2	±0.5	27
51	Minturno Promontory	41°14′N 13°41′E	478	Mc	Tidal notch	+9.4	±0.5	28
52	Garigliano Plain	41°13′N 13°47′E	481	Am	Lagoon deposits *C. glaucum*	+2	±1.5	28 O

[a] Am, aminostratigraphy; Mc, morphostratigraphic correlation; Cc, chronostratigraphic correlation; U/Th, $^{230}Th/^{234}U$ radiometric dating.
[b] 1, Nisi 1999; 2, Antonioli *et al.* 1999b; 3, Lazzarotto *et al.* 1990; 4, Blanc 1953; 5, Hearty *et al.* 1986; 6, Hearty and Dai Pra 1987; 7, Mauz 1999; 8, Galoppini *et al.* 1996; 9, Segre 1959; 10, Bonadonna 1967; 11, Palieri and Sposato 1988; 12, Hearty and Dai Pra 1986; 13, Gignoux 1913; 14, Dai Pra 1978; 15, Blanc 1936; 16, Dai Pra and Arnoldus-Hayzendveld, 1984; 17, Antonioli *et al.* 1999c; 18, Bietti *et al.* 1990; 19, Dai Pra and Ozer 1985; 20, Blanc 1938; 21, Durante 1975; 22, Blanc and Segre 1953; 23, Durante and Settepassi 1974; 24, Ozer *et al.* 1987; 25, Segre 1991; 26, Antonioli *et al.* 1988; 27, Antonioli 1991; 28, Delicato 1999; 29, Barbieri *et al.* 1999; 30, Colantoni and Borsetti 1973.
[c] O, original datum; R, reinterpreted section; M, remeasured section.

Pontina Plain to Garigliano Plain (sites 26–52)

The coastal belt from Borgo Sabotino to the mouth of the Garigliano River is characterised by a series of distinct coastal plains (Pontina Plain, Fondi Plain, Garigliano Plain) that occupy the various structural depressions of which the coastal Tyrrhenian sector is composed (Mariani and Prato, 1992). The plains are separated from one another by the promontories of the Mesozoic carbonate platforms (Ausoni and Aurunci Mountains) and of the platform-to-basin transition reliefs (Mount Circeo). From Borgo Sabotino southwards, the elevations of the Tyrrhenian markers decrease gradually from +5.3 m to −1.8 m. The latter corresponds to the *C. glaucum* palaeolagoon of the south-central portion of the Pontina Plain (sites 26–30 and 32–34). This lagoon, which Segre (1967) correlated with the Holocene, was recently ascribed to the Tyrrhenian transgression by Antonioli *et al.* (1999c). At the eastern margin of the plain (site 31), MIS 5.5 can be found in brackish deposits at about −15.5 m (Barbieri *et al.*, 1999). On the limestone promontories of the Mount Circeo and of the Ausoni Mountains (sites 35–41), a tidal notch and *Lithophaga* holes can be observed at heights ranging between +7.3 and +9.6 m (Figure 7). Moving southwards, in the Fondi Plain (site 42), Tyrrhenian lagoonal deposits can be found at −6 m. Further south, along the coastal mountain side of the Monti Aurunci (sites 43–51), the Tyrrhenian shoreline is indicated by a tidal notch, which often is associated with *Lithophaga* holes and with *Glycimeris* sp. deposits. The heights of these markers fluctuate between +4.8 and +9.4 m. Finally, in the Garigliano Plain (site 52), Delicato (1999) reports a Tyrrhenian palaeolagoon with *Cerastoderma* sp. between 0 and +2 m.

Table 3 Synthetic stratigraphy and chronological attribution deriving from 20 datings ^{14}C and $^{230}Th/^{234}U$ datings (Antonioli *et al.*, 1999b) of the deposits cored by the ENEA survey

Stratigraphy	Marine isotope stage
0–7 m: alternating layers of peat with *C. glaucum*, clay and mud of brackish waters	
7–9 m: muddy sands with bivalves and algal frustules, originating from a lagoon closely connected with the sea	1
9–30 m: marine sands, locally enriched with bivalves and gastropods	
30–34 m: alternating layers of sandy muds, clays and muddy sands with *Cerastoderma* sp.	
34–68 m: silt and clays with brackish water ostracods and gastropods (Pulmonata), intercalated by gravels from flash flood phenomena	4 and/or 2
68–90 m: fine sands and muddy marine sands with *C. caespitosa* and molluscs; malacofauna analysis on samples MV1 (−76 m) MV2 (−72 m) MV3 (−68 m) (see Table 4)	*5*

Table 4 Frequency distribution of the fossiliferous content (referring to malacofauna only) found in the samples MV1, MV2 and MV3: rr = 1 specimen; r = 2/5; f = 6/10; ff = >10. The malacological analysis shows an environmental evolution that, in the context of a lagoon protected offshore by a bar (class III confinement according to Guelorget and Perthuisot, 1983), goes from a meadow of *Posidonia oceanica* (M-V1) to a meadow of *Cymodocea nodosa* in M-V2 and M-V3 with the presence of a hard marine substrate, with a depth probably ranging between 3 and 5 m (Nisi, 1999; R. Chemello, personal communication, 2001)

Malacofauna	Sample code and depth (m)		
	M-V1 (−76.0)	M-V2 (−72.0)	M-V3 (−68.0)
Loripes lacteus	f	f	—
Lucinella divaricata	f	rr	—
Gastrana fragilis	r	—	—
Acanthocardia tuberculata	rr	—	—
Tapes decussatus	r	—	—
Arca noae	—	rr	r
Chama gryphoides	f	—	ff
Ostrea sp.	—	r	f
Clamys varia	—	—	rr
Corbula gibba	r	rr	—
Cerithium vulgatum	ff	f	r
Hinia reticulata mamillata	r	r	r
Hinia incrassata	—	r	r
Bittium reticulatum	ff	ff	ff
Bittium latreillei	ff	ff	ff
Bittium jadertinum	ff	ff	ff
Pusillina radiata	ff	ff	—
Pusillina lineolata	ff	ff	—
Pusillina marginata	ff	ff	r
Rissoa ventricosa	r	—	—
Mangelia sp.	f	—	—
Odostomia conoidea	rr	—	—
Diodora graeca	—	—	rr
Chrysallida excavata	—	—	r
Chrysallida sp.	r	r	—
Alvania cimex	f	r	ff
Clanculus cruciatus	—	—	f
Jujubinus exasperatus	rr	—	r
Mytilastrer lineatus	rr	—	—
Crisilla semistriata	f	—	ff

Discussion

From the comparison between the current elevation of the palaeoshoreline of MIS 5.5 and the relevant eustatic height of +7 m, the uplift or subsidence rates that occurred along the analysed coastal belt in the past 125 kyr have been calculated; these values have confirmed the existence of four main coastal segments (Versilia Plain, Livorno Plain–Burano Lagoon, Montalto di Castro Plain–Borgo Sabotino, Pontina Plain–Garigliano Plain), which include ten sections with distinctly different tectonic histories (Figure 8).

Sector 1, which corresponds to the Pisa–Versilia Plain, seems to have undergone subsidence of about 71 m in 125 000 yr, an average rate of 0.57 mm yr^{-1}. The sinking of the Pisa–Versilia Plain is confirmed by the presence of a system of faults orientated SW–NE (Meloria–Bientina line), which border the southern margin of the Plain. This system has been active since Early Pleistocene times (Cantini *et al.*, 2001). The structure, evidenced by opposing minima and maxima Bouger gravimetric anomalies, has probably caused the subsidence of the coastal area north of Livorno.

We therefore agree with the conclusions of Cantini *et al.* (2001). Our data, however, have the advantage of a high measurement precision in the evaluation of the plain's subsidence.

Sector 2, from Livorno to Rosignano Solvay, shows an uplift ranging between 4 and 13 m in the past 125 kyr, with average rates between 0.03 and 0.10 mm yr^{-1}.

Sector 3, comprising the area between the Island of Pianosa and Lasco del Pozzo and covering a distance of about 100 km, can be considered as substantially stable. Only the narrow area of San Angelino shows a noticeable uplift of about 0.04 mm yr^{-1}. Our observations along this section are also supported by stratigraphical and geodynamic evidence. Mazzini *et al.* (1999) describe subsurface Holocene deposits in the Albinia Plain (dated by AMS ^{14}C analysis) showing a trend that is similar to the sea-level curve for the Tyrrhenian Sea published by Alessio *et al.* (1996). Extensional or compressive seismogenetic areas do not seem to exist in the areas adjacent to the Monte Argentario (Scandone *et al.*, 1990) and there is no historic evidence of earthquakes in this area (INGV, 1998).

Sector 4 stretches from the Fosso Ponte Rotto (km 115 on the Aurelia Road) up to the northern margin of the Pontina Plain (Borgo Sabotino). This area presents the most important uplift, ranging between 13 and 28 m, with average rates ranging between 0.1 and 0.23 mm yr^{-1}.

In this section, and particularly between Montalto di Castro and Civitavecchia, various authors have attributed the deposits located between +20 and +65 m to the Tyrrhenian age (see Gignoux, 1913; Bonadonna, 1967; Dai Pra, 1978; Bosi *et al.*, 1990; De Rita *et al.*, 2002). This area is particularly complex because of the presence of numerous depositional terraces with abundant fossil-bearing outcrops. Many of the interpretational problems caused by the complexity of the area have been solved through the use of aminostratigraphical and radiometric methods (Hearty and Dai Pra 1986, 1987; Radtke, 1986; Palieri and Sposato, 1988). Here we restrict consideration to sites with elevations between +20 and +35 m based on the findings of *S. bubonius* or on aminostratigraphical correlation (Table 2). It is also important to emphasise that beyond the Tiber Valley, near Pomezia, the marine deposits of the last interglacial may be elevated to a height of +45 m in Tacconi quarry (Dai Pra and Arnoldus-Huyzendveld, 1984; Malatesta and Zarlenga, 1986; Milli and Zarlenga, 1991). The latter site has not been considered here because of lack of dating support.

Such conspicuous uplift is evidently linked to the Vulsini, Sabatini and Colli Albani volcanoes (Figure 6), which were

Table 5 Results of the radiometric dating performed with the $^{230}Th/^{234}U$ method and with the accelerator mass spectrometry (AMS) on materials from the ENEA survey (between −72 and −68 m). The age of the sample ACG-C48 has been calibrated according to Stuiver and Reimer (1993)

Species	Sample code	Depth	Dating method	Age (yr BP)
Cladocora coespitosa	ACG-V3	−68.0	$^{230}Th/^{234}U$	129 200 ± 15 000
Cerithium sp.	ACG-C48	−69.2	^{14}C AMS	> 53 500
Cladocora coespitosa	ACG-V2	−72.0	$^{230}Th/^{234}U$	132 800 ± 15 000

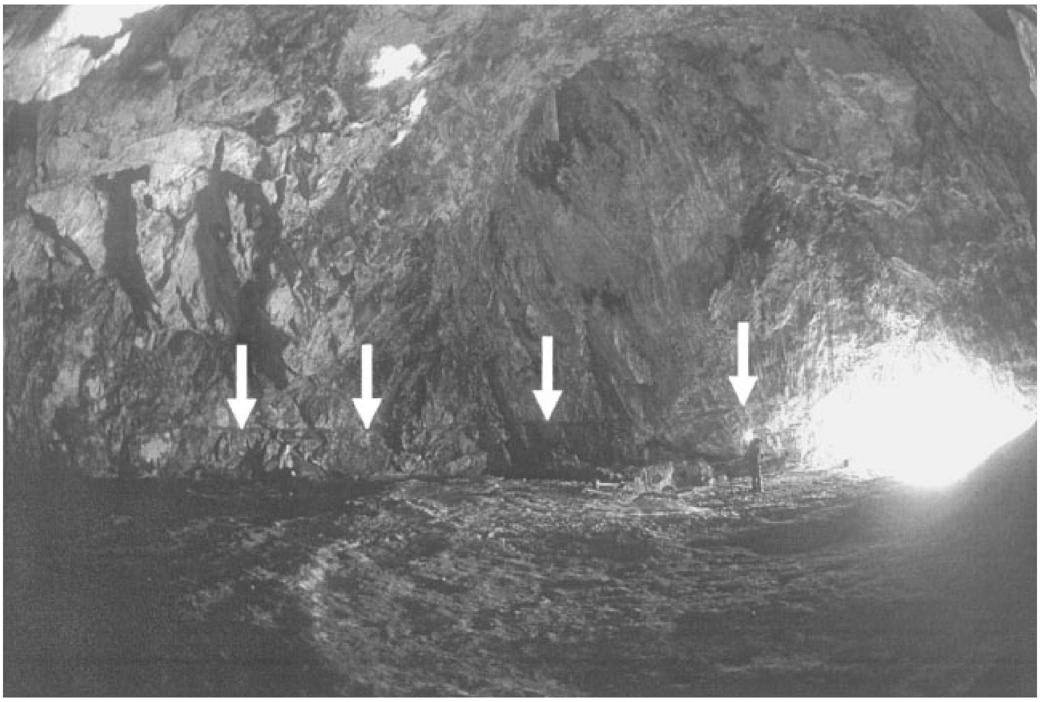

Figure 7 Tyrrhenian tidal notch at +9.6 m in the Capre Cave (Circeo Promontory, southern Latium)

active from the pre-Tyrrhenian until about 20 kyr (De Rita *et al.*, 1992). This area also contains various epicentres of historic earthquakes recorded from 461 BC until AD 1997 (INGV, 1998).

In agreement with the findings of Bordoni and Valensise (1998) and Hearty and Dai Pra (1987), the Tyrrhenian palaeoshoreline in this sector shows a conspicnous flexure that is related to distance from the volcanoes. The deformation seems to be linked to the uplift of the mantle dome and to the related volcanism. Since the Mid-Pliocene there has been regional uplift with a maximum in the Vulsine area (Locardi, 1986; Hearty and Dai Pra, 1987). Given the large amount of lava erupted and the age of volcanic phenomena, the uplift that followed MIS 5.5 can be reasonably attributed to the effects of the weight of the volcanic complex on the mantle and the associated isostatic rebound of the coastal zone (Kurt Lambek, personal communication, 2003).

In sector 5, from Borgo Sabotino to Pontinia, the Tyrrhenian markers are found at slightly lower heights compared with their eustatic level; however, these negative displacement rates are considered negligible, and the whole sector can be considered as stable.

Along sector 6, from Pontinia to Borgo Vodige, the coastal belt shows a clear and progressive subsidence reaching a maximum of 22.5 m since 125 kyr, with a maximum rate of 0.18 mm yr^{-1}. The marker distribution also indicates that the Pontina Plain has suffered a progressive tectonic lowering from west to east.

Sector 7 includes the uplouds of Mount Circeo and of Mount Leano (Breuil Cave–Terracina). This area shows substantial stability, as the elevations of the Tyrrhenian markers are very close to the eustatic level.

Sector 8, represented by the Fondi Plain, shows in contrast, a subsidence with an average rate of about 0.1 mm yr^{-1}.

Sector 9 comprises the coastal belt stretching from Sperlonga to the Minturno Promontory and it presents traces of the Tyrrhenian palaeoshoreline with an elevation that coincides with the eustatic level. This too shows that the sectors characterised by the presence of limestone promontories (Talamonaccio, Mount Circeo, Terracina, Sperlonga, Gaeta, Minturno) seem to have remained substantially stable at least since Tyrrhenian time. Indeed, it would appear to be statistically improbable to find cases in which the sum of positive and negative movements would bring coastal areas back to a height that is very close to +7 m.

Sector 10, corresponding to the Garigliano river plain, shows a negative displacement of 5 m, with an average subsidence rate of 0.04 mm yr^{-1}. In contrast to limestone promontories, it is evident that coastal plain subsidence is dominant (Versilia Plain, Pontina Plain, Fondi Plain, Garigliano Plain).

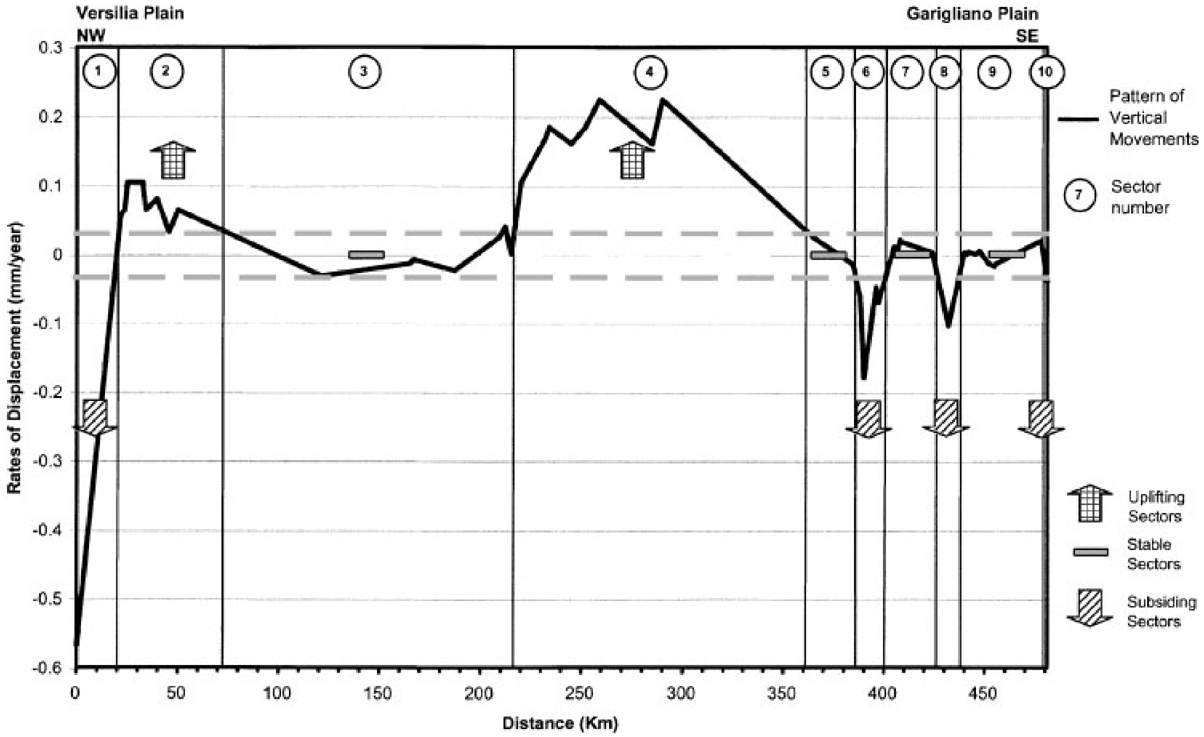

Figure 8 Identified vertical deformation and uplift rates (expressed in mm yr^{-1}) of the Tyrrhenian coastal area in the past 125 kyr. It is assumed that the post-Tyrrhenian vertical movements have been constant and homogeneous throughout time. Coastal areas are considered stable if their vertical movements occurred since MIS 5.5 show variations lower than ±4 m in 125 kyr in relation to the eustatic height of 7 ± 1 m (Antonioli and Silenzi, 1998) and if their displacement rates correspond to ± 0.032 mm yr^{-1} (represented by a dashed line in the figure). Sectors: 1, Versilia Plain (site 1); 2, Livorno–Rosignano (sites 2–9); 3, Pianosa–L. Pozzo (sites 10–16); 4, km 115 on Aurelia Road–B. Sabotino (sites 17–25); 5, B. Sabotino–Pontinia (sites 25–27); 6, Pontinia–B. Vodige (sites 28–34); 7, Breuil Cave–Terracina (sites 35–41); 8, Fondi Plain (site 42); 9, Sperlonga–Minturno (sites 43–51); 10, Garigliano Plain (site 52)

Conclusions

Through the chronological and morphological analysis of coastal facies and deposits, it has been possible to reconstruct the last interglacial shoreline along a Tyrrhenian sector that includes the coastal belts of Tuscany and Latium (Fig. 6).

In order to achieve this result it has been necessary to reinterpret and re-measure the sections described in the literature, implementing the known data with new Tyrrhenian evidence obtained from a borehole survey in Versilia (coastal facies deposits at about −68 m), from the reconstruction of the inner margin of the Tyrrhenian terrace between Livorno and Rosignano Solvay (+11/+20 m) and from a *Cerastoderma glaucum* lagoon in the Garigliano Plain (+2 m). It has been possible to review a total of 52 sections on a stretch of coast of about 500 km, with an average distribution of about one site every 9 km.

The main and most innovative contribution of this study has been provided by the standardisation of the data, obtained through defining, for each of the markers used, the bathymetric significance in relation to the palaeosea-level and ascribing an exact margin of error to every marker and section (Tables 1 and 2). This analytical approach has allowed us to select tidal notches (sometimes also linked to *Lithophaga* holes), *Cerastoderma glaucum* lagoons and the inner margin of marine terraces as indicators of past sea-level for the neotectonic surveys; subordinately, it has been useful to use other markers such as the *Lithophaga* hole bands and Senegalese fauna (e.g. *Strombus bubonius*, *Conus testudinarius*) sometimes linked to beach deposits or to tidal notches. Furthermore, only the markers with reliable dating control were taken into consideration.

The analysis of the spatial and altimetric distribution of the markers selected with these criteria has therefore confirmed, and provided details of, the existence of differential vertical movements occurring since 125 kyr along the whole coastal belt studied (Fig. 8). It is possible to discriminate between four main coastal segments, including ten sectors with demonstrably different tectonic behaviour. The coastal plains of Versilia, Pontina, Fondi and Garigliano are located in structural depressions characterised by subsidence with average rates range between 0.04 and 0.57 mm yr^{-1}. In contrast, the carbonate promontories of Talamonaccio, Mount Circeo, Terracina, Sperlonga, Gaeta, Minturno do not seem to have been significantly affected by post–Tyrrhenian tectonic processes. Finally, the coastal segment that is closer to the Tuscan–Latial eruptive centres shows conspicuous uplift with vertical rates between 0.1 and 0.23 mm yr^{-1}.

The results confirm the effectiveness of geological and geomorphological Tyrrhenian markers for the analysis of late Quaternary tectonics, as well as for evaluation and calibration of eustatic phenomena since MIS 5.5. This approach can be used in other coastal areas to analyse the history of tectonic motion since the last interglacial.

Acknowledgements The authors wish to thank Paul J. Hearty and Colin Murray-Wallace for their valuable suggestions.

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