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New data on the Holocene sea-level rise in NW Sicily (Central Mediterranean Sea)

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Abstract

The emerged and submerged coastal tracts of selected areas in NW Sicily (San Vito Lo Capo Promontory and **Marettimo Island in the Egadi Archipelago**) have been studied by means of an interdisciplinary approach (geomorphological and neotectonic surveys, palaeontological, depositional and petrographical observations) with the aim to characterize the coastal evolution of the sector over a wide time frame (Late Pleistocene and Holocene) and to recognize the geological indicators of relative sea-level fluctuations. Neotectonic studies performed all along the coastal sector through the check of the present-day height of marine notches and of the inner margin of marine terraces of Eutyrrhenian age allowed to assess the entity of post-Tyrrhenian differential crustal movements in the area. The calculated rates of uplift confirm the relative stability of the area in the last 125 ka and that the relative corrections introduced can be considered negligible in the reconstruction of sea-level rise in the last thousand years. On the base of these considerations, the sea-level rise curve which has been drawn for the Holocene through the radiometric dating (¹⁴C and U/Th) of submerged speleothems and Vermetid reefs is assumed to gain a regional significance and to represent a good reference datum for the Central–Southern Mediterranean Sea. In addition, the sea-level rise data are in good agreement with the predicted sea-level curves based on geophysical models previously applied to the same study areas.

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1. Introduction

The objectives of the EC Project SELF II (Sea-Level Fluctuations in the Mediterranean: Interac-

tions with Climate Processes and Vertical Crustal Movement) included a study of past sea levels in order to provide indications on the long-term sea-level trends in the Mediterranean Sea and to further the understanding of the recent and current processes.

Due to the geodynamical setting of the Mediterranean Basin and to the marked tectonic deformation of its coastal tracts, which frequently exhibit evidence of

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differential vertical movements also during the Holocene, sea-level data regarding the last thousand years are quite scarce, especially the ones limited to the relatively more stable areas (Pirazzoli, 1976; Alessio et al., 1998; Demuro and Orrù, 1998; Laborel, 1986; Laborel et al., 1994; Lambeck and Bard, 2000; Antonioli et al., 2000; Morhange et al., 2001). For the same reasons, any collection of evidences of palaeo-sea levels should be preceded by an accurate exam of the local geology of the relative coastal tract in order to verify the occurrence of crustal motions and to evaluate the reliability of the RSL data. On the Mediterranean coasts, it is used to check the relative vertical stability of a coastal tract since the last 125 ka (i.e. from oxygen isotopic substage 5e) on the base of the recognition of the present-day height of the inner margin of Eutyrrhenian marine terraces or notches having good lateral continuity. These features are assumed to indicate the maximum level reached by the sea at a relative sea-level highstand (Lajoie, 1986), although with different degree of accuracy related to their precise individuation and measurement.

The researches have been carried out in selected coastal areas of NW Sicily (Capo San Vito Promon-

tory and **Marettimo Island in the Egadi Archipelago**, Fig. 1) in order to collect further evidences of sea-level rise and palaeo-climatic variations during the last thousand years for the Central–Southern Mediterranean.

The area has been selected for: (i) its uncommon conservative morphological setting, with well-preserved geomorphological and depositional features connected with Quaternary sea-level fluctuations, such as a succession of marine notches and terraces located both above and below the present m.s.l.; (ii) the presence of accurate and datable indicators of palaeo-sea levels (Vermetid bioconstructions and submerged speleothems), the use of which was subordinate to the knowledge of the vertical crustal movements affecting the coastal sector.

The objectives have been achieved through an interdisciplinary approach, which allowed to support the interpretations on the palaeoenvironmental conditions and the neotectonic behaviour characterizing the coastal evolution of the sector on a wider time frame (Late Pleistocene and Holocene). Moreover, this allowed to verify its suitability for collecting indicators of Holocenic palaeo-sea levels on the base

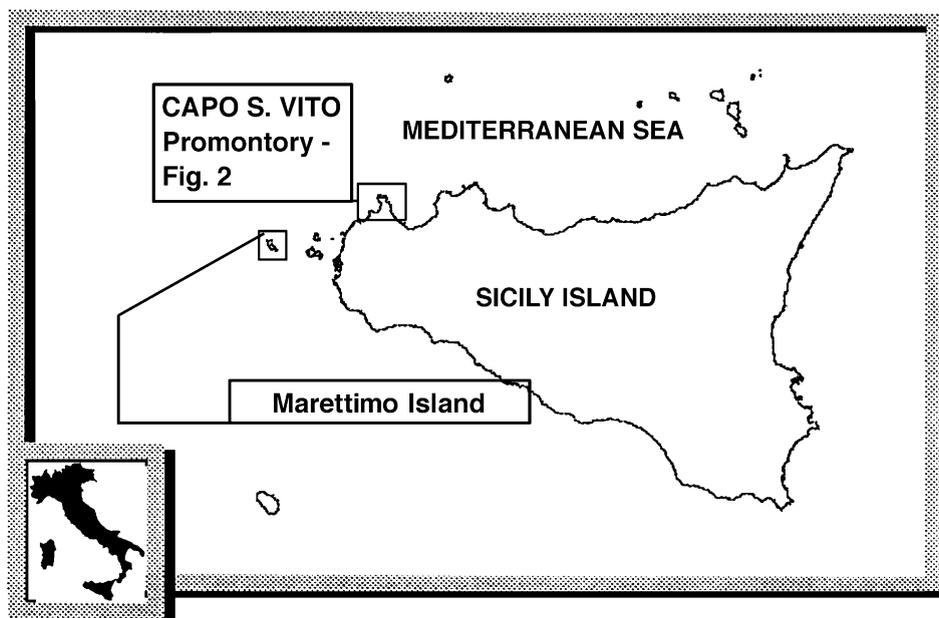


Fig. 1. Location of the study areas.

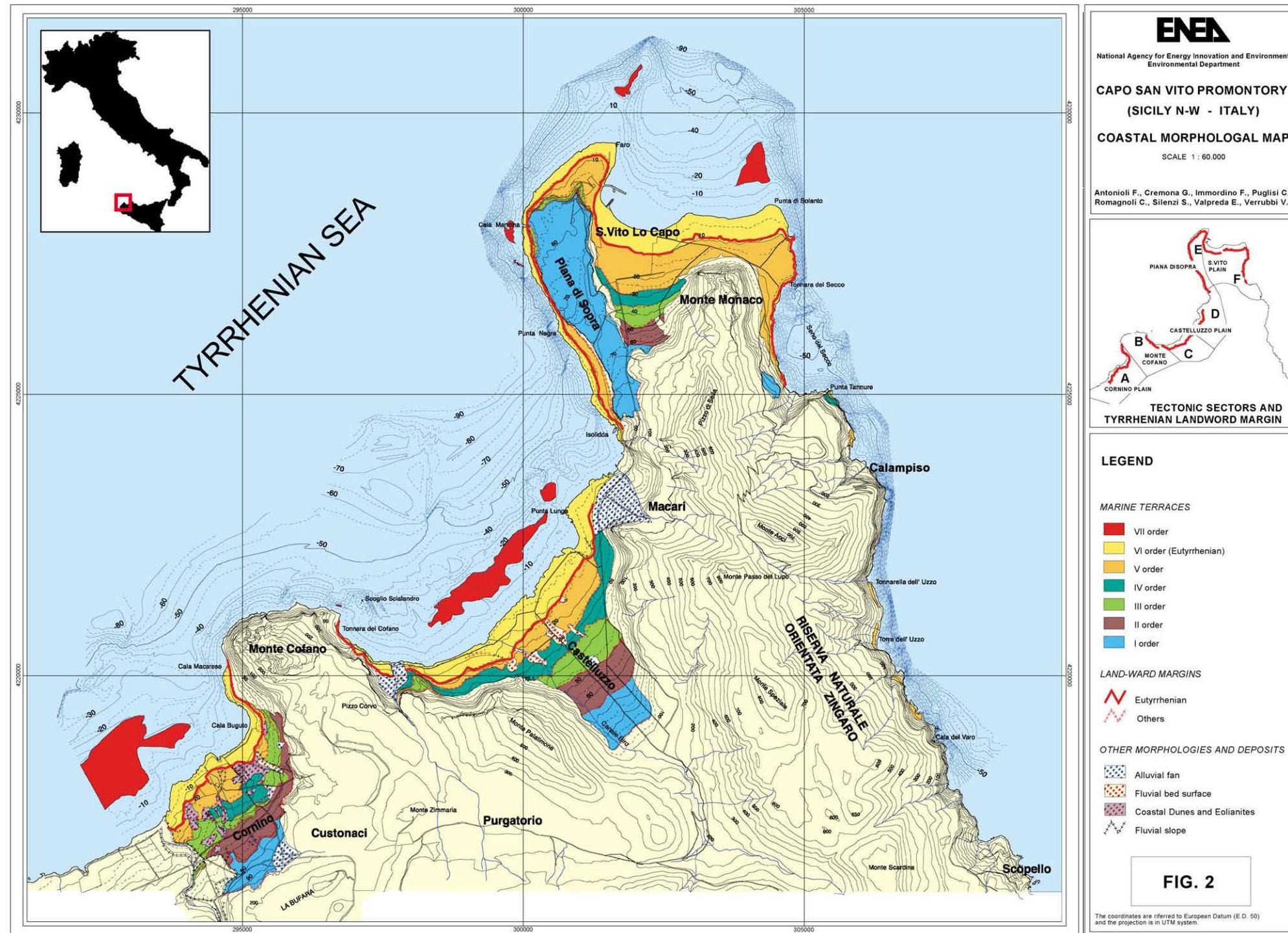


Fig. 2. Coastal geomorphological map of the Capo S. Vito Promontory.

of the assessment of post-Tyrrhenian vertical mobility. By studying the present vertical distribution and by sampling and dating, with absolute-age techniques, Vermetid reefs and a submerged speleothem, sea-level rise data were obtained for San Vito Lo Capo (last 500 years BP) and for **Marettimo Island** (last 9 ka BP). These results have been compared with similar data from the Tyrrhenian Sea (Alessio et al., 1998) and from extra-Mediterranean areas (Bard et al., 1996). The new data have also been compared with predicted sea-level curve based on glacial–isostatic models applied to the same coastal areas (Kurt Lambeck, unpublished data).

2. Geological framework of NW Sicily

The NW sector of Sicily and the Egadi Archipelago represent the emerged western edge of the Sicilian–Maghreb Chain, which originated from the deformation of the Meso-Cenozoic Northern African continental margin. The geological setting of the area is characterized by the overthrusting of tectonic units referable to the Panormid carbonatic platform and its margins on units belonging to other palaeogeographic domains (such as the Trapanese basin; Giunta and Liguori, 1972; Abate et al., 1991, 1993; Catalano and D’Argenio, 1982); the piling up of SE-verging thrust sheets in the Middle–Upper Miocene and in the Middle Pliocene tectonic phases determined the overlying of brittle rocks over more ductile rocks. Further (Pleistocenic) disjunctive and strike-slip tectonics, occurred mainly along NW–SE, NE–SO, N–S and E–W oriented normal fault systems, caused the splintering up into blocks with differential raising and the formation of structural highs alternated to basins (D’Angelo et al., 1997). In the Capo San Vito Promontory, this is reflected by the occurrence of lowered sectors, presently occupied by coastal plains (Castelluzzo and Cornino Plains; Abate et al., 1991). Moreover, the recent tectonics created favorable conditions for the onset of both deep-seated and surficial gravitational slope deformations, which are particularly widespread along the eastern flank of the peninsula (Agnesi et al., 1995).

The Capo San Vito Promontory and the Island of **Marettimo** are characterized by Mesozoic–Tertiary units composed of carbonatic, evaporitic and silico-

clastic deposits, overlain in discordance by late orogenic clastic deposits (Abate et al., 1991, 1996b,c).

Several orders of subhorizontal abrasion surfaces, interpreted as raised marine terraces, are present at different heights (up to 160 m) along wide coastal tracts of the W Sicily, including **Marettimo** island and Capo San Vito peninsula. Their formation has been considered to be of Middle–Upper Pleistocenic age, since they cut not only carbonatic rocks and marlstones of Mesozoic age but also terrigenous, evaporitic and calcarenitic formations of Late Miocene to Lower Pleistocenic age (D’Angelo and Vernuccio, 1996).

Extensive outcrops of Quaternary deposits occur in the coastal plains and along the coastal belt; they are represented by bioclastic calcarenites, conglomerates with sandy matrix, lacustrine sands and gravels and aeolian calcarenites. Particularly, littoral calcarenites and conglomerates, associated with the lowermost marine terrace, outcrop in lenses along the western coastal tract of the Capo San Vito Promontory and on the coasts of **Marettimo**. They have been ascribed to the Eutyrrhenian substage on the base of the presence of a typical warm molluscan fauna (with *Strombus bubonius* and other Senegalese taxon; Malatesta, 1957; Ruggeri et al., 1968; Abate et al., 1993, 1996a; Antonioli et al., 1994b; Mauz et al., 1997). On the base of their present-day height (verified only in one sampling site for the W side of the Capo San Vito Promontory and in three sites for **Marettimo**), previous authors pointed out respectively, for the two areas, a relative stability and a limited, differential uplift during the last 125 ka (Abate et al., 1996a; Mauz et al., 1997).

3. Quaternary marine terraces

A geological survey was performed in a coastal sector including three coastal plains (San Vito, Castelluzzo and Cornino Plains) nearby to San Vito Promontory and the submerged area in front of these, with the aim to study the Upper Quaternary tectonic trends. The morphological evidences of the seven marine terrace (from +90 to about –18 m) surveyed consist in a subhorizontal erosional platforms, with a remarkable lateral continuity (Fig. 2), and locally well-preserved marine deposits lenses. Marine notches (at 2, 6, 15, 45, 60 and 70 m above the

Table 1

Radiometric datings of sampled speleothems, with indications of the correlative marine terrace and sector of provenance (see inset of Fig. 2)

Metres above m.s.l	Sector	Sample no.	Terrace order	Material	Age (year BP)	Dating method
+62	E	ENE1011	II°	speleothem	78,000 ± 1950	Th/U
+42	E	ENE1012	III°	speleothem	>300,000	Th/U
+8	E	ENE1013	VI°	speleothem	19,695 ± 5300	Th/U

present sea level) were also found. The geomorphological mapping of marine erosion surfaces was improved by a spatial elaboration of altimetric data using the Arc/info GIS.

The marine forms were, thus, ascribed to the Middle and Upper Pleistocene, by morphological and stratigraphic criteria. Dating trough U/Th method on speleothems (Table 1), which locally coat marine notches, provide only the upper chronological limit for the Terrace II (linked to the notch at +62 m) modelled in a period before 78,000 ± 1950 years ago and for the lower terrace of the emerged sequence (Terrace VI, lying at 8 m a.s.l.) modelled before 19,695 ± 5300 year BP, which means before the LGM and, as suggested by other observations, in correspondence of the Last Interglacial.

Only the shallowest of presently submerged terraces (Terrace VII) shows a good lateral continuity and ranges from −15 to −18 m b.s.l. This terrace could

have developed during oxygen isotope stage 3, as already hypothesized for analogous submerged erosional surfaces located at similar depths in the Tyrrhenian sea (Antonioli and Ferranti, 1996; Antonioli et al., 1994a; De Vita and Orsi, 1994) and in extra-Mediterranean regions (Cann et al., 1988; Aharon and Chappel, 1986).

3.1. Eutyrrhenian erosional forms and deposits

Terrace VI and the associated deposits (Fig. 2) were studied to verify their Eutyrrhenian age (see, for example, Abate et al., 1993; Mauz et al., 1997) and their present-day altimetric distribution.

The palaeontological analysis of the marine sediments showed the presence of a “Senegalese” fauna, with mollusks as *S. bubonius* in several bioclastic lenses overlying the VI-order Terrace. Their occurrence characterizes the base of the Eutyrrhenian sub-

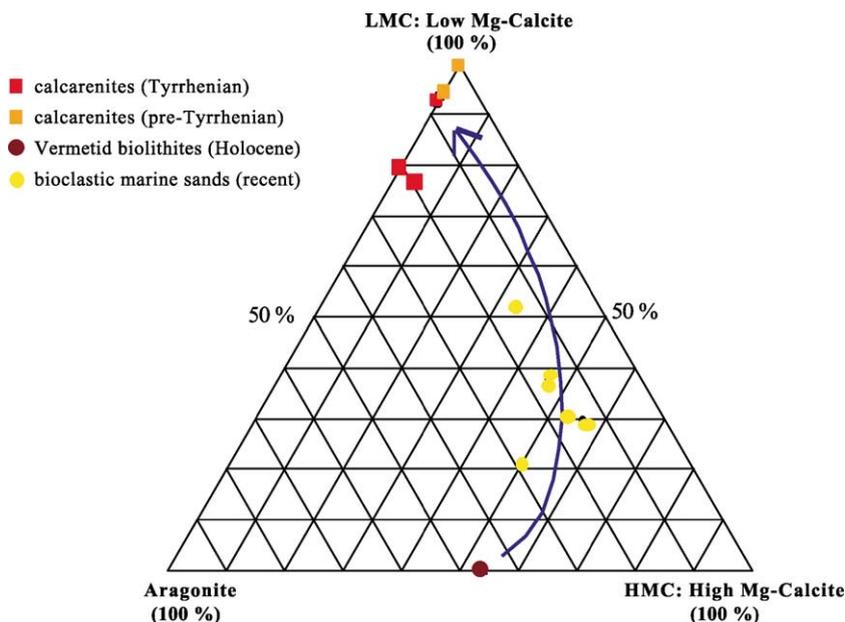


Fig. 3. Triangular plot LMC–HMC–Ar of the sampled carbonatic deposits. The arrow indicates the trend in the mineralogical composition.

stage and, in particular, the oxygen-isotopic sub stage 5e, to which the sampled deposits have been referred.

The mineralogical composition of the calcarenites, outcropping in lenses above the Eutyrrhenian Terrace modeled into the *Calcareniti Siciliane* Formation (Late Pleistocene, Abate et al., 1991, 1993), has been compared with the ones of the older (pre-Tyrrhenian) and recent carbonatic deposits (marine sands and Vermetid reefs); particularly for what regards to their content of the three principal mineralogical phases of CaCO_3 : low Mg-Calcite (LMC), high Mg-Calcite (HMC) and aragonite (Fig. 3). The observed trend

in the mineralogical composition has to be related with the occurrence of a high degree of diagenetic transformations, which, despite the good geomorphological preservation of the Eutyrrhenian forms, are responsible for the marked re-crystallization of both the Eutyrrhenian and older (pre-Tyrrhenian) deposits.

3.2. Neotectonic constraints

Direct measurements by means of a total station (Antonioli et al., 1998a) or indirect measures from the Technical Maps, at 1:10.000 scale, have been carried

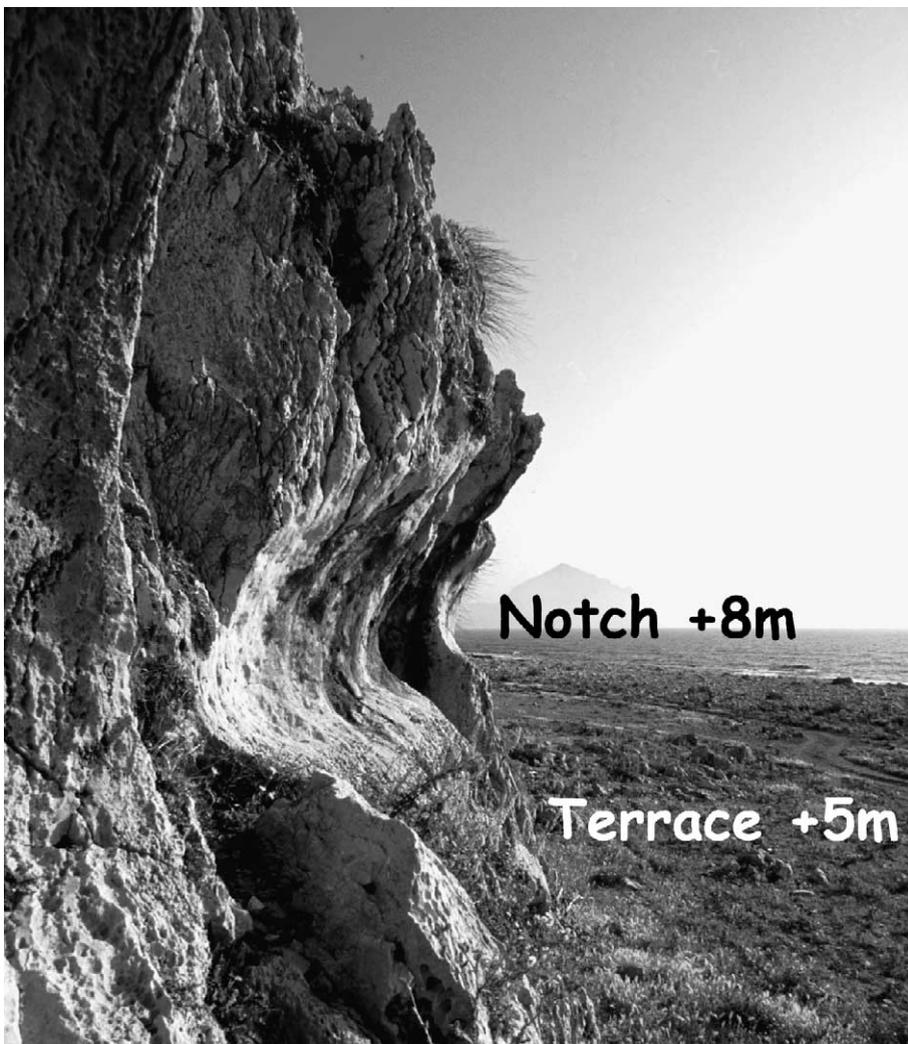


Fig. 4. Marine notch near Cala Mancina (NW edge of the Capo S. Vito Promontory) correlated to substage 5e.

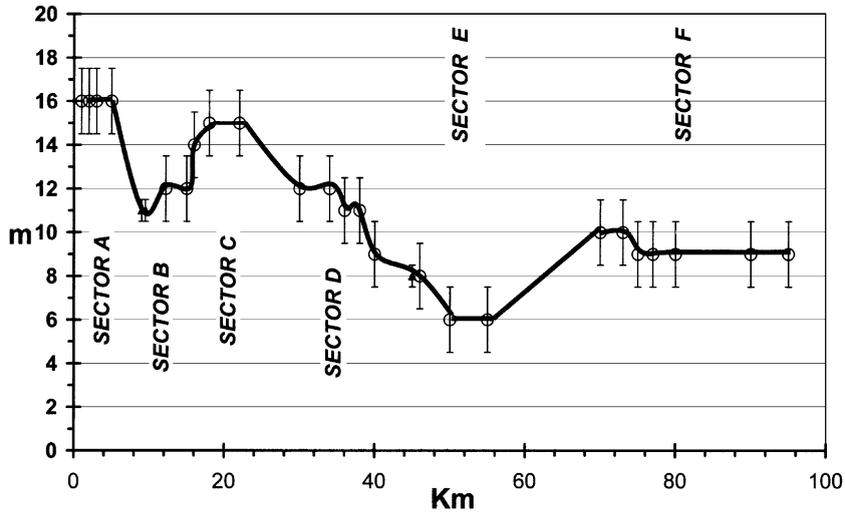


Fig. 5. Heights of geomorphological features attributed to the Eutyrrhenian paleo-sea level. Open circles indicate the inner margin of marine terraces, triangles indicate notches. The bars indicate the error (± 0.5 m for notches and ± 1.5 m for inner margins).

out on marine notches (Fig. 4) and of inner margins of the Eutyrrhenian terraces, to check with accuracy the post-Tyrrhenian vertical crustal movements. These measures provide different degree of accuracy from ± 0.5 m (Carobene and Pasini, 1982; Pirazzoli, 1986) to about ± 1.5 m. Taking into consideration these errors, the vertical distribution of the Eutyrrhenian

forms was analysed with respect to the eustatic maximum reached during the substage 5e.

In order to estimate the maximum sea-level height reached in the Mediterranean during the isotopic stage 5e, we can consider previous studies (Esat et al., 1999; McCulloch and Esat, 2000) on Thyrrhenian forms in other Mediterranean coastal areas having the same

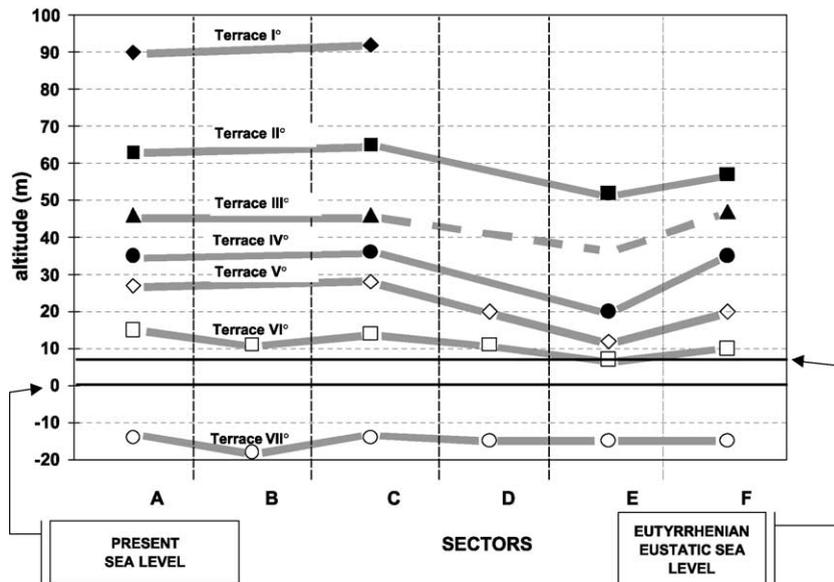


Fig. 6. Outline of the whole succession of marine terraces from Sectors A through F (see inset in Fig. 2 for location).

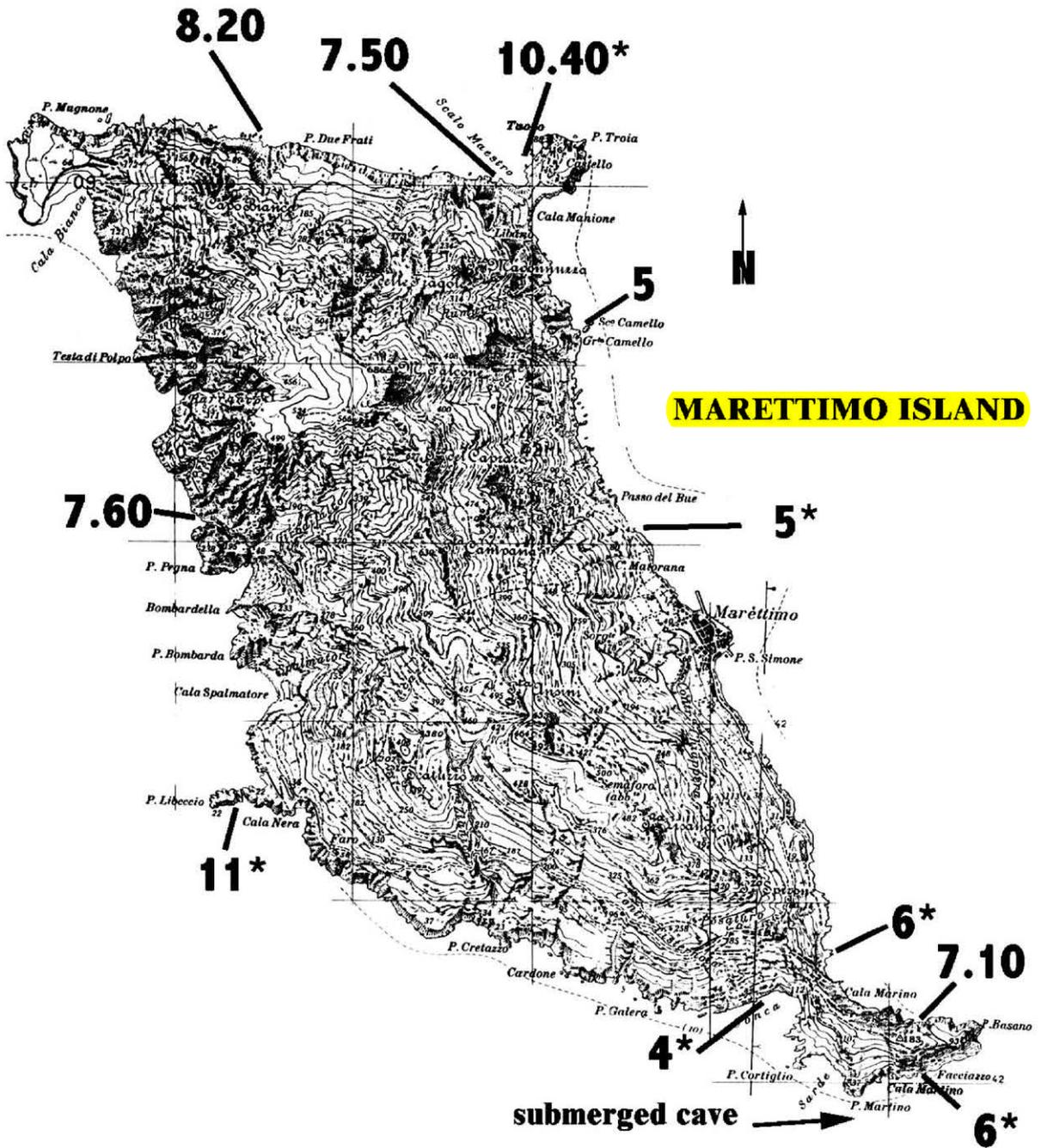


Fig. 7. Map of Marettimo Island, with indication of the present-day height of the Eutyrrhenian notches. The height values marked with asterisk refer to evidences of paleo-shorelines or to *Lithodomus* borings and, therefore, are affected by possible wider error ranges.

Late Quaternary tectonic stability (i.e. Eastern coast of Sardinia). In these areas the Eutyrrhenian notch (Antonioli et al., 1999a) is extended for tens of kilometers, at a level ranging from 7.1 to 8.2 m a.s.l. (maximum semidiurnal tide 12 cm). We can consider this height (about 7 ± 1 m a.s.l.) as a reference level for the quite-stable West Mediterranean coastal zones.

In the Capo San Vito Promontory, we identified six sectors, characterized by different post-Eutyrrhenian neotectonic deformation and uplift (Fig. 2, inset): sector A (Cornino Plain), where the inner margins of Eutyrrhenian terraces and notches lie at about 16 m a.s.l.; sector B (Monte Cofano), where the notches occur at 11 m a.s.l. and the inner margins at 12 m a.s.l.; sector C (southern Castelluzzo Plain), where these features are at heights between 14 and 15 m a.s.l.; sector D (northern Castelluzzo Plain), where the Eutyrrhenian inner margins range from 11 to 12 m a.s.l.; sector E (Piana di Sopra), where the Eutyrrhenian inner margin is decreasing from south to north (ranging from 9 to 6 m a.s.l.); sector F (San Vito Plain), where the Eutyrrhenian morphological features occur at a height between 9 and 10 m a.s.l. (Fig. 5). The vertical dislocation of these sectors from 125 ka to the present day highlights the presence of a differential neotectonic component that displaced sector A of about 8 m, sectors B and D of about 4 m, sector C of over 6 m and sector F of about 2–4 m. On the contrary, the data suggest relatively stable conditions for the sector E or a slight lowering in the northernmost area of the San Vito Promontory. Considering these data, the gathered average magnitude of post-Tyrrhenian differential vertical movement is of about 0.064 mm/year (sector A), of about 0.032 mm/year (sectors B e D), of about 0.048 mm/year (sector C)

and of about 0.024 mm/year (sector F). From the consideration that the submerged shallower marine terrace (VII order) shows a vertical distribution pattern very similar to the one derived for the Eutyrrhenian forms (VI order; Fig. 6), it seems that a rather constant tectonic behavior might have occurred in each sector since the Upper Pleistocene. Moreover, it is interesting to note that in all the sectors the whole uplifted sequence of marine terraces shows a tectonic deformation which is coherent with the gathered uplift rates for the last 125 ka (Fig. 6). Differential behavior between contiguous sectors seems to be in strong relation with the N–S and NE–SW aligned regional tectonic lineaments.

A similar geological survey has been performed also on Marettimo Island to verify the vertical tectonic mobility of the area in recent times and to evaluate the consistency of the indicators of palaeo-sea level. In Marettimo the Eutyrrhenian deposits (represented by calcarenites, breccias and conglomerates with a reddish sandy matrix, overlaid by aeolic and continental sediments, Abate et al., 1996a,c) are present, along some coastal tracts, in limited patches at heights between 2 and 10 m a.s.l. The present-day vertical distribution of the Eutyrrhenian notches along the coasts of Marettimo shows a height range from 5 to 8.20 m (Fig. 7); these values are affected by a degree of accuracy of ± 25 cm in the height estimation. A speleothem was observed at depth of $-23/24$ m b.s.l. during the scuba diving exploration of the “Punta Martini Cape” submerged cave (Fig. 8). It has been sampled and dated with absolute age techniques (^{14}C and U/Th, Table 2).

The notches found at Capo San Vito (Fig. 4) and Marettimo present structural and morphological traits

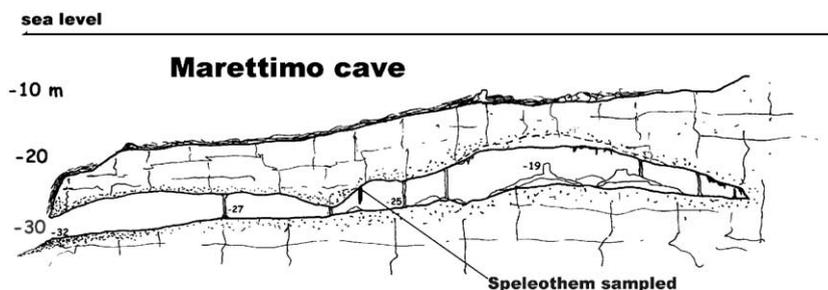


Fig. 8. Section of the submerged cave of Punta Martini Cape in the SE coast of Marettimo (see location in Fig. 7). The entrance to the cave lies at 27 m of depth; the dated speleothem has been sampled around the middle of the cave at -24 m.

Table 2

Results of the U/Th and ^{14}C datings (AMS and conventional) performed on the collected samples

Metres b.s.l	Sector	Material	Age (year BP)	Dating method	Laboratory sample no.
–0.3	F	speleothem	7912–7720	^{14}C cal 1σ	R-2580 Rome
–1.3	F	speleothem	16,731–16,331	^{14}C cal 1σ	R-2580 Rome
–0.4	D	Vermetid reef	461–400	^{14}C cal 1σ	R-2580 Rome
–0.3	D	Vermetid reef	251–127	^{14}C cal 1σ	R-2764 Rome
–0.3	E	Vermetid reef	232–106	^{14}C cal 1σ	R-2741 Rome
–0.3	E	Vermetid reef	232–94	^{14}C cal 1σ	R-2742 Rome
–24	Marettimo	<i>Lithophaga</i>	10,473–10,339	AMS ^{14}C cal 1σ	6810-Utrecht
–24	Marettimo	<i>Lithophaga</i>	9643–9485	AMS ^{14}C cal 1σ	7211-Utrecht
–24	Marettimo	speleothem	39,280 \pm 1500	Th/U	1007-ENEA Rome
–24	Marettimo	speleothem	24,160 \pm 900	Th/U	1006-ENEA Rome

We calibrated (1σ) all the ^{14}C data by using Stuiver et al. (1998) Intcal 98 radiocarbon age calibration. With respect to calibration, it must be stressed that the regional effect was not taken into account ($\text{DR}=0$).

that are very similar to those of limestone notches in other nearly stable areas of Central–Southern Italy. Notches can be solely observed in coastal zones subjected to uplifts not greater than 0.15 mm/year and with sea-level stillstand that lasted at least about a thousand years. These features are related to the maximum relative sea level, which was probably reached at the beginning of stage 5e. Stage 5e lasted about 10–11 ka and was followed and preceded by an abrupt change in sea level (McCulloch and Esat, 2000). In stable continental margins, such as the

Western Australian and the Central Mediterranean, there is an initial overshoot in relative sea level that decreases exponentially because the coastal margin is readjusting to the increased water load (hydroisostasy, see McCulloch and Esat, 2000). It is likely that the marine terraces were formed during the following 10 ka (Fig. 9). The different glacial–isostatic adjustments in the coastal areas should be taken into account since “the relation between height and age of shoreline formed during last interglacial cannot be related directly to changes in ocean volume because of the effect of isostatic uplift” (Lambeck and Nakada, 1992). At present, there are no rebound models availability for the Mediterranean coasts during the Last Interglacial, therefore, it is not possible to achieve an approximation of maximum sea level better than 7–8 m.

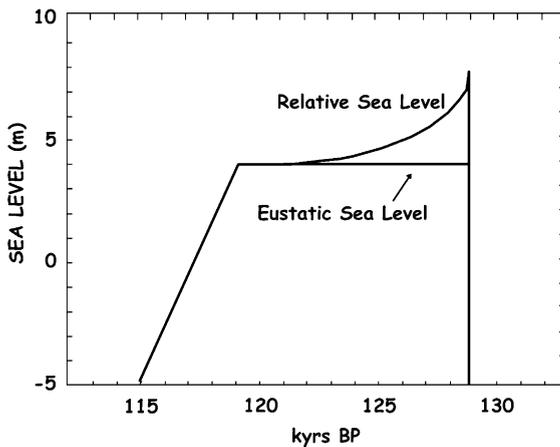


Fig. 9. Diagram showing the effects of hydroisostasy at a far-field ‘stable’ continental margin site such as the Western Australian. For a step-function increase in eustatic sea level, there is an initial overshoot in the relative sea level that decays exponentially due to the coastal margin readjusting to the increased water load (replotted from McCulloch and Esat, 2000).

4. Holocenic sea-level rise curve

Reefs built by Vermetid Gastropods (*Dendropoma petraeum*) and submerged speleothems sampled from the Capo San Vito Promontory and Marettimo coastal zones allowed to reconstruct the sea-level rise through the Holocene. Most carbonatic rocky shores of North-western Sicily are bordered by intertidal reefs, the frame of which results from the coalescence of the tubular shells of the Gastropod Mollusc *D. petraeum*. Midlittoral platforms have the potential to be good environmental and climate indicators because: (1) they are typical of warm-temperate areas, such as the Mediterranean Sea; (2) the vertical growth of the

platforms is restricted to the intertidal zone and, rarely, to the uppermost part of the infralittoral zone; (3) the platforms are easily accessible for sampling; (4) Vermetids can be precisely dated by radiocarbon techniques. The sampled Vermetid reefs have a maximum thickness of 40 cm, and their ^{14}C ages indicate that they started to grow since a few centuries from the Present (Table 2).

Antonioli et al. (1999b) described the biological characteristics and sampling zone of the *Dendropoma* reef of Capo San Vito. The range of the semidiurnal tide at San Vito is 0.12 m; in flat coastal areas, *Dendropoma* platforms, 5–10 m wide, coalesce to form a single, uninterrupted rim stretching for several kilometers. Each platform is 20–40 cm thick, and the upper 8–10 cm consist of living organisms. The upper, living part lies at mean sea level and, consequently, it is exposed during low tide and submerged during high tide. A vertical section of the reef was obtained in order to make morphological observations and sampling for radiocarbon dating feasible. Radiocarbon dating was carried out on the most ancient, fossil part of the reef, which is located at 30–40 cm below present sea level. Two types of sampling were performed: Vermetids were both directly detached from the reef, and collected on the beach 30 to 100 m from the shoreline. The inner margin of the terrace, attributed to the Tyrrhenian transgression, has been measured by a Total Station (Nikon), with the zero being the surface of the reef.

Submerged speleothems have been successfully used to gain information on sea-level fluctuations through time (Lundberg and Ford, 1994). These carbonate deposits are particularly useful to reconstruct sea-level changes when they exhibit both continental and marine layers (sensu Antonioli et al., 1998b). On the coasts of the Capo San Vito Promontory, submerged speleothems do not occur at depths exceeding 5 m below sea level and do not show the association of marine and continental layers. On the contrary, the speleothem sampled at Marettimo, which comes from the submerged cave at “Punta Martini Cape,” exhibits marine organic overgrowth (Fig. 10). Dating was carried out on both continental layers of speleothems and marine deposits, i.e. on shells of *Lithophaga lithophaga*, which are among the first marine organisms that colonize speleothems, and are

always sealed by Serpulids at the time these are reached by the sea, marking in this way the sea-level rise (Antonioli and Oliverio, 1996).

Lithophaga, as all others biological indicators used in sea-level rise analysis (Balanus, Vermetid, Lithophyllum, Serpulid and others), obviously records the age of the arrival and the starting of growth of the shells. The altitude of this retrieval records a sea-level value which is slightly lower than the effective value. This is due to the years necessary to develop the CaCO_3 of the shell. In order to achieve the important results on the raising of the sea level during Holocene, using and dating Tahiti corals, Bard et al., 1996, wrote: “these assemblages are diagnostic of a high water energy reef front at depths less than 6 m below mean sea level.” Cabioch and Montaggioni, 1999, discuss the error margins about habitat and palaeobathymetry on thirty species of corals, coralline algae and vermetid, supplying the bathymetry (with metric and decimetric precision) within which the various species are developed. Antonioli et al., 2001, in reference to *Serpulids* and *Lithophaga* that overgrowth the submerged speleothems in Italian coasts, demonstrate that the error between the sea level and the altitude of the sampled shells should be less than one induced from ^{14}C analysis.

Table 2 shows absolute ages obtained from *Vermetids*, continental portion of speleothems from the Capo San Vito Promontory and from the Marettimo cave and *Lithophaga* shells from the Marettimo submerged speleothem only. The results (which span through hundred years ago for Vermetids, and thousand years BP for speleothems) have been used to reconstruct the Late Holocene sea-level rise curve, the validity of which has been assessed on the base of the verified neotectonic constraints (Section 3.2). From these, the average post-Tyrrhenian uplift rate obtained for the coastal sector D (northern Castelluzzo Plain) is 0.032 mm/year. Since the Vermetid reefs sampled from sector D yielded radiocarbon ages of the order of hundred years, by taking into account the assumed average uplift rate, it can be inferred that neotectonics just slightly contributed to the vertical dislocation of the present-day Vermetid reef height and, thus, affect the palaeo-sea level datum with a quite small error (order of 0.01 m at max.), which is well under the range of about 8 cm introduced on accuracy by the living belt thickness of *Dendropoma*.

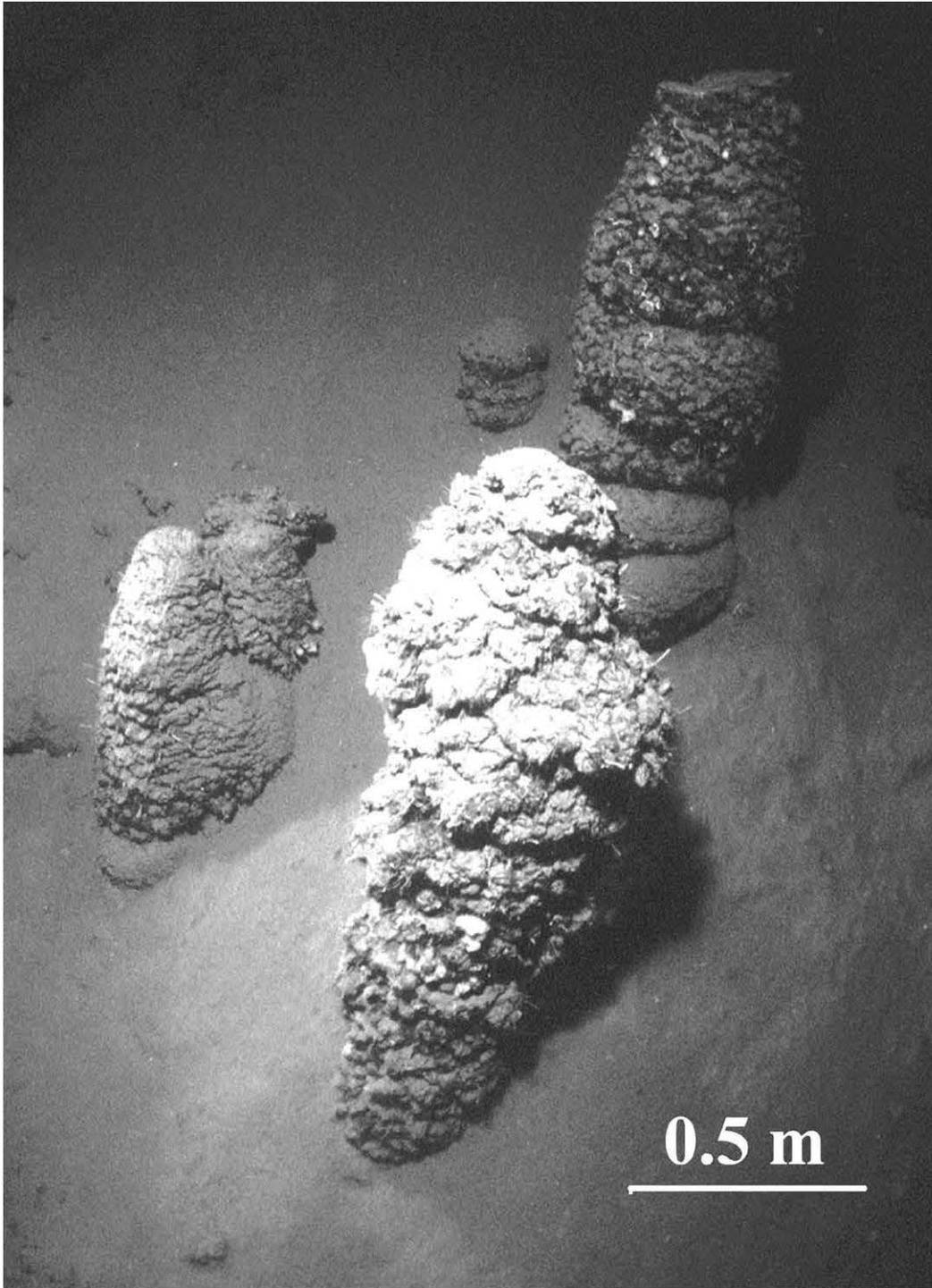


Fig. 10. Marine organic overgrowth (with *Serpulids*) encrusting submerged speleothems in the cave of Punta Martini Cape (Marettimo Island).

In the coastal zone of the Capo San Vito Promontory where submerged speleothems were sampled (sector F), the post-Tyrrhenian average uplift rate obtained on the base of the inner margin of the Eutyrrhenian terrace (0.024 mm/year) is even smaller than that calculated for the northern Castelluzzo Plain. However, considering the age ranges obtained for the speleothems, it introduces an error due to vertical dislocation which is of the order of 0.18–0.40 m, respectively, for the speleothem located at -0.3 and -1.3 m. Since the continental layers of the speleothems just provide indication about the time before the sea level rose (i.e. when it was not present yet) to the level of the speleothems, these errors do not affect the sea-level rise curve.

The limited vertical dislocation shown by the Eutyrrhenian wave-carved notches at **Marettimo** (see Section 3.2) suggests that errors for the neotectonic mobility of the coastal tracts of the island should be lower than the instrumental errors related to the measurement of submerged speleothem depths and than the analytical error related to U/Th radiocarbon dating. The 1-m long speleothem sampled in the Punta Martini Cape submerged cave shows the presence of marine overgrowth of organic material encrusting the continental inner portion of the speleothem, and this makes it particularly suitable for the reconstruction of the Holocenic sea-level rise. Both the marine and continental layers have been radiometrically dated (Table 2) and, following the methodology by Alessio et al. (1992, 1998), the following considerations have been derived. Samples 1007 and 1006 belong to two different inner layers of the stalactitic core. The results suggest that the continental growth of the speleothem began around 40 ka BP and continued undisturbed until about 24 ka ago (i.e. part of the isotopic stage 3), a period during which the sea level was beyond the depth of the speleothem. During the Holocene, the carbonatic continental growth was abruptly interrupted by the arrival of the sea to the speleothem level. This stage is witnessed by the early colonization from *Lithophaga*, which bored into the speleothem soon after the marine submergence. The ^{14}C AMS datings on *Lithophaga* shells collected from the speleothem at about -24 m of depth mark at around 9–10 ka BP the beginning of the marine encrusting deposition, which continued by means of biobuilding organisms (such as *Serpulids*) later on, to the present-day.

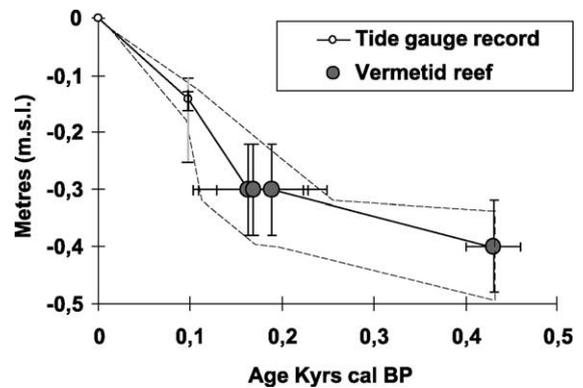


Fig. 11. Sea-level rise curve for the Holocene for Northwestern Sicily. Tide gauge data are from recent IPCC estimations (global data, 10–25 cm, in gray, and Mediterranean data 12–15 cm, in black, from Tsimplis and Baker, 2000).

On the basis of the data obtained from Vermetid reefs and submerged speleothems in Northwestern Sicily, sea-level rise curves for the last 10 ka have been reconstructed (Figs. 11 and 12), considering also sea-level data averaged from tide-gauges for the last century (Tsimplis and Baker, 2000). For the obtained detail and for the very recent (in geological terms) time range involved (last 500 years), especially the younger part of the curve represents an interesting result, although it has been based on a few dated samples and should be supported by further sampling and datings. Relative sea-level data on a similar time range are reported by Laborel et al. (1994), which dated biologically constructed marine rims from the rocky coasts of southwestern France and northern Corsica; but the two sets of data are not exactly comparable (absolute ages reported by Laborel et al. are uncalibrated ^{14}C datings; moreover the data are not supported by a check on the recent neotectonic evolution of the studied coastal tracts).

Fig. 12 compares the sea-level rise data obtained by Alessio et al., 1998 (based on marine overgrowths and *Lithophaga* shells on submerged speleothems from Palinuro and Argentarola, Central Tyrrhenian Sea) with the curve published by Bard et al., 1996 (based on coral reefs from Tahiti) and with the results obtained, in the present work, from the Vermetid reefs sampled at the Capo San Vito Promontory and the speleothem from **Marettimo** cave.

Recently, the glacio-hydroisostatic theories and modelling (Lambeck and Johnston, 1995; Peltier,

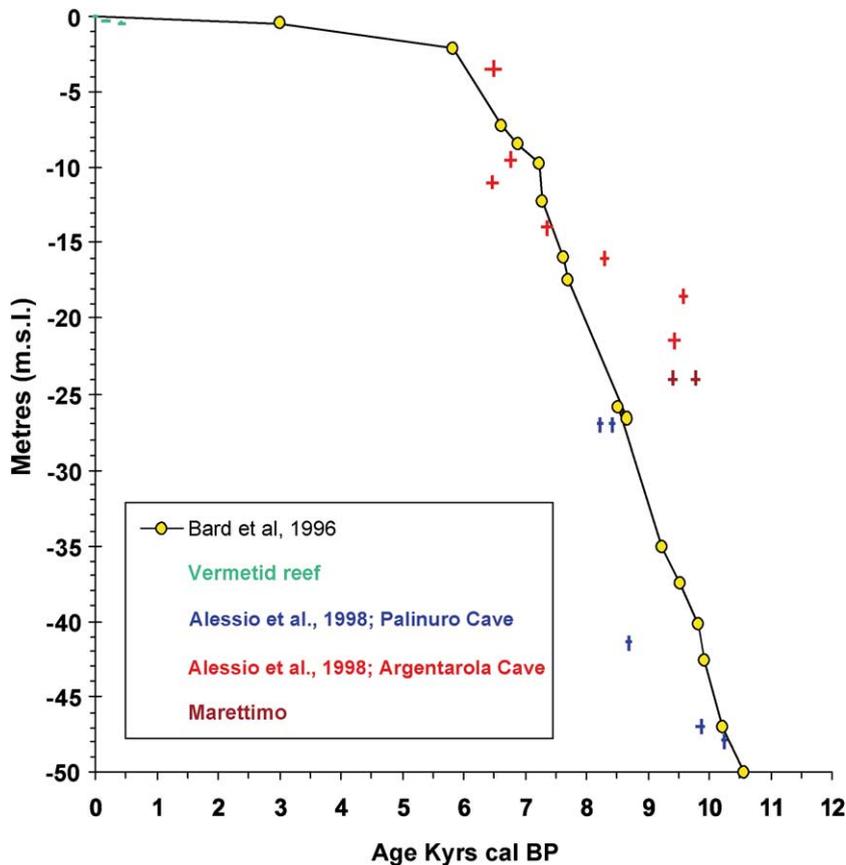


Fig. 12. Sea-level positions reconstructed by Alessio et al. (1998) for the central Tyrrhenian Sea, and by Bard et al. (1996) for the Pacific Ocean. Data obtained from Vermetid reefs and *Lithophaga* from Marettimo have been also reported for comparison. Vertical error for sea level data is assumed ± 50 cm for Argentarola, Palinuro and Marettimo; ± 8 cm for San Vito Vermetids. Maximum analytical error for ^{14}C analysis show a range comprised between ± 21 and ± 285 years cal BP.

1996) have contributed to the many uncertainties affecting the reconstruction of Holocene relative sea-level. Lambeck and Johnston (1995) calculated the hydro- and glacio-isostatic-related uplift (or depression) for the Earth crust which is due, respectively, to the differences in sea-water load on continental platforms, and to the melting (during interglacial periods) of glaciers and ice caps that weighted heavily on the crust. Pirazzoli et al. (1997) reported a first indicative isostatic model calculated for the Italian region by Lambeck and Johnston. These curves show the values of the glacio and hydroisostatic component to relative sea level for the last 2000 and 6000 years BP. For the 2000-year BP time-slice, the differential contribution for hydroisostatic effects along the Tyrrhenian coast is

quite limited, while for the 6000-year BP time interval, the glacio- and hydroisostatic components show horizontal gradients in the relative sea-level fluctuations along the Italian coasts up to some meters. Up to now, these curves have been modeled by the Authors introducing structural data from the Eastern Mediterranean Sea only and, for this reason, they need to be implemented with the introduction of local data from the Central Mediterranean Sea (including Sicily) to model with further detail the glacio- and hydro-isostatic behaviour of this area.

The preliminary results on predicted (based on the ice model prediction 1151, earth model maA4, K. Lambeck, personal communication) and observed sea level positions in the last thousand years for the Capo

San Vito Promontory indicate a mismatch of about 20 cm. If we subtract the 8 cm of living Vermetids, we obtain a difference of about 10 cm, which lies within the uncertainty of ^{14}C datation. For Marettimo Island, the difference between predicted and observed is about 3.5 m. This result certainly needs further studies.

Fig. 12 shows that for different time slices sea level data are different, evidencing that sea-level curves cannot be obtained on a national basis, but only on a regional one. We suppose this is due to differences in crustal rebound, since relevant tectonic movements do not seem to be related to the maximum level of Tyrrhenian ingression (stage 5e), which is easy to determine: Argentarola notch 5.30 m s.l.m., Palinuro notch 2.8 m s.l.m., Marettimo notch 7.8 m s.l.m., San Vito Lo Capo notches and inner margin from 8 to 13.8 m s.l.m. The difference in sea level can be attributed to tectonical or hydroisostatic adjustments (i.e. San Vito Lo Capo), but it seems of little significance when compared to the ages of Spelothems and Vermetids.

5. Conclusions

The results of the researches carried out along coastal tracts of the Capo San Vito Promontory and Marettimo Island underline the positive role of an interdisciplinary approach in characterizing the coastal evolution of the sector during the Quaternary and unravelling the sea level and climate history occurred in its recent and geological past.

Particularly, the aim of our study was to collect original data regarding the sea-level rise during the Holocene. The selection of the site resulted successful for this purpose, because of its notable morphological preservation, quite uncommon for the Mediterranean, although not associated with the conservation of the original depositional and textural characters of the Quaternary deposits, probably due to the alternation of semiarid and semihumid climatic intervals in the area during the last thousand years (Mauz et al., 1997).

The crustal uplifting of the whole area allowed a series of marine terraces and notches of Middle–Upper Pleistocenic age to remain well preserved. The accurate mapping of their present-day height above sea level has been used in order to verify the

differential vertical mobility among different sectors and to evaluate the maximum displacement and, thus, the reliability of datable indicators of palaeo-sea levels.

Vermetid (*D. petraeum*) reefs and submerged speleothems confirmed to be a tool for reconstructing a sea-level rise curve for Northwestern Sicily, particularly for what regards the last five centuries. This represents a new result to be held in consideration and, possibly, to be used as an input for the improvement of geophysical sea-level models of regional significance for the Central Mediterranean Sea.

The palaeo-sea level data obtained for Marettimo Island suggest the presence of a small anomaly with respect to other Mediterranean and extra-Mediterranean sea-level curves, although this does not represent an isolated case for the Central Mediterranean. The complex and interconnected mechanisms of eustatic sea rise, coastal rebound and tectonic movements are still poorly understood and certainly underinvestigated in the Central Mediterranean. It would be of great interest to extend this kind of investigation to the entire coast of Italy, with the additional aim of providing indications on possible future scenarios.

Note added in proof

At the end of cap 3 “Quaternary marine terraces”, we have correlated our terrace VII to the oxygen isotope stage 3. On the basis of very recent publications on timing and altitude of sea level, now we argue that the –18 to –15 m terrace was carved during stage 7. In fact, Bard et al. (2002) recently established that the sea level during stage 7a should be comprised between –18 and –10; moreover, Lambeck et al. (2002) established that sea level of stage 3 was never higher than –50 m.

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