Evidence of repeated Late Holocene rapid subsidence in the SE Cyclades (Greece) deduced from submerged notches

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Evidence of repeated late Holocene rapid subsidence in the SE Cyclades (Greece) deduced from submerged notches

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Abstract An underwater geomorphological survey along the coasts of six Cycladic islands (Sifnos, Antiparos, Paros, Naxos, Iraklia and Keros) revealed widespread evidence of seven submerged tidal notches. At least seven former shorelines were identified at depths between 280 ± 20 and 30 ± 5 cm below modern sea level. The vertical succession of several submerged notches suggests the occurrence of rapid subsidence events, potentially of seismic origin. Comparison with other sea-level indicators from Naxos and Delos islands indicates that these relative sea-level changes took place after 3300 BP and provides a rough estimate of the time of development of several submerged shorelines. The submergence of the uppermost notch at −30 ± 5 cm is ascribed to effects of the recent global sea-level rise occurred during the last two centuries and, at least in part, to effects of recent earthquakes. Potential effects of the 1956 Amorgos earthquake with regard to coseismic and post-seismic vertical displacement have been recently investigated using a modellistic approach. According to the above, the lower shorelines should result from repetitive subsidence events and not from gradual subsidence.

Keywords Co-seismic · Post-seismic effect · Tidal notch · Sea-level change · Bioerosion · Crustal thinning

Introduction

In the midlittoral zone (which corresponds to the tidal zone plus the average wave height range), which is very narrow in the Mediterranean, various parallel belts of endolithic microflora are more developed. Limpets and chitons eroding cyanobacteria are more abundant (Laborel and Laborel-Deguen 2005). They all contribute, by eating the belts of endolithic microorganisms, to the erosion of the underlying rock and enable the development (in sites sheltered from strong wave action) of a reclined *U*-shaped or *V*-shaped intertidal notch. This notch shows a vertex located near mean sea level (MSL) (Fairbridge 1952; Hodgkin 1964), the base near the lowest tide level and the top near the highest tide level (Pirazzoli 1986) (Fig. 1).

During the post-glacial relative sea-level rise, a tidal notch could generally not develop until at least the mid-Holocene (about 6–5 ka BP), when the sea-level rise slowed down. Notches also could not develop in areas of rapid tectonic movements exceeding the rates of bioerosion (generally between 0.2 and 1.0 mm/a, see "Results of observations" section) near sea level. Fossil tidal notches can be considered therefore as testifying of periods of relative sea-level stability and their study may provide

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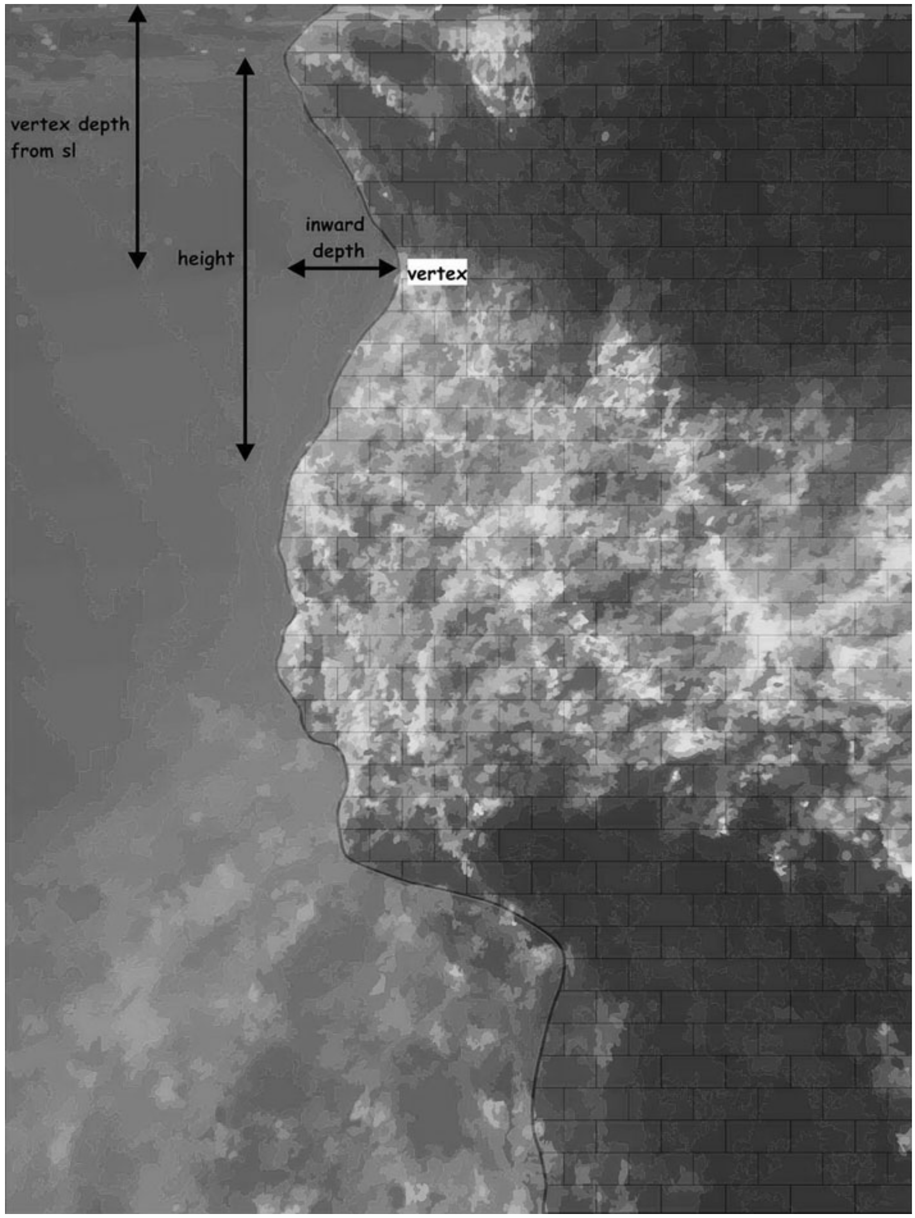

Fig. 1 Schema depicting measurement points on a tidal notch following Pirazzoli (1986)

information on relative vertical movements that affected Mediterranean carbonate coasts during the last millennia.

Many examples on the value of notches for coastal tectonics have been provided, especially in the Eastern Mediterranean (e.g. Pirazzoli 1980, 2005; Pirazzoli et al. 1991; Stiros et al. 2000, 2009; Morhange et al. 2006; Evelpidou et al. 2011). The vertical profile of a tidal notch is an excellent sea-level indicator, especially in tectonic areas (Pirazzoli 2005). If the notch is submerged, the shape of the notch informs on the velocity of the relative subsidence (Fig. 2; Table 1). The inward depth of the profile provides information on the approximate duration during which MSL remained at the level of the notch vertex, under assumptions on the local bioerosion rate. The profile may suggest the occurrence of gradual sea-level movement (at a rate smaller than the rate of bioerosion), during the period of notch development, thus recording not only small eustatic variation, but also possible pre-seismic or post-seismic continuous tectonic displacement. In the case of gradual subsidence, beyond certain subsidence rates, the notch cannot form; thus, when the rate of relative sea-level change is greater than the rate of bioerosion, a tidal notch does not form.

A tidal notch is preferentially formed in limestone, while gneisses, schists, amphibolites, terrestrial deposits and volcanic rocks are less affected by bioerosion. Most favorable conditions for notch formation occur where the cliff is vertical and smooth on its surface, while oblique cliff and irregularities in the rock surface could retard or even prevent the development of a clear notch profile. It

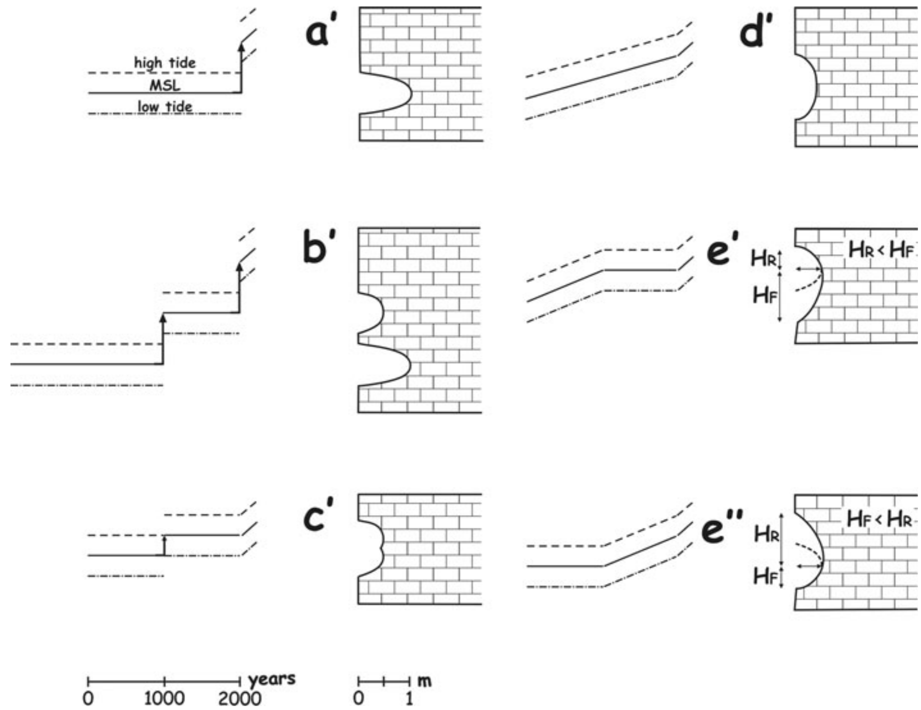

Fig. 2 Schema with theoretical notch geometries on carbonate rock; (a′–e″): submerged tidal notch profiles resulting under different conditions. For the *vertical scale*, it is assumed that the height of the midlittoral zone is about 30 cm, the bioerosion rate may vary between 0.2 and 1 mm/a and that for notch types d′, e′ and e″, the rates of relative sea-level rise remains less than the bioerosion rate. The present-day tidal notch is absent because it could not form during the last 150 years, when the rate of the global sea-level rise has unquestionably exceeded the bioerosion rate. For more details on the characteristics of notch types, see Table 1

Table 1 Different tidal notch types referred in this paper

Notch type	Characteristics	Interpretation
a′	Reclined *U*-shaped notch profile with the height of the notch roof (Hr) very similar to the height of the notch floor	This fossil notch has been preserved underwater after a relative sea-level rise (eustatic or tectonic, eventually coseismic), exceeding the midlittoral zone range, which occurred at a rate greater than the bioerosion rate and followed by a former relative sea-level stability during which the notch could develop
b′	Two submerged fossil notches	The two fossil notches are preserved underwater after two rapid relative sea-level rises, greater than the midlittoral zone
c′	Fossil notch higher than the midlittoral zone with two vertices, separated by an undulation in the notch profile	The notch sunk because of a rapid relative sea-level rise, smaller than the midlittoral zone range, preceded and followed by a relative sea-level stability. Thus, the two vertices indicate the former and the following MSL positions.
d′	Fossil notch higher than the midlittoral range and of limited horizontal depth	It has been derived from a gradual relative sea-level rise at a rate smaller than the bioerosion rate
e′	Fossil notch with a height greater than the midlittoral zone and Hr < Hf	This type derives from a gradual relative sea-level rise, at a rate smaller than the bioerosion rate, followed by relative sea-level stability
e″	Fossil notch with a height greater than the midlittoral zone range and Hr > Hf	This type derives from a relative sea-level stability, followed by a gradual relative sea-level rise at a rate smaller than the bioerosion rate

For the graphic schemes of their profiles, see Fig. 2

has also been noted that tidal notches may occur at some locations, but not on the same rock at some nearby sites, indicating that hydrodynamics or changes in salinity, climate and sedimentation could have a strong influence on epilithic or endolithic flora and on grazing organisms (Pirazzoli and Evelpidou 2013).

The study area is situated in the central Cycladic islands (Aegean Sea, Greece) (Fig. 3). Its geology consists mainly of metamorphic rocks such as mica schists, marbles, gneisses, amphibolites, glaucophane schists and plutonic rocks (Papanikolaou et al. 1981; Papanikolaou 1987). Our case study includes those Cycladic islands in which an important part of the coastal zone consists of carbonate rocks, and of course our field analysis was concentrated at sites described as carbonate rock in detailed geologic maps. Studied area was also selected in order to be close enough to Naxos island in order to make feasible the correlation with archaeological and stratigraphical data and radiocarbon dating.

In the surveyed area, we observed that a tidal notch was absent from the present midlittoral zone, but that submerged notches exist at various depths. After a description of the observed geomorphological remains of the submerged notches, we discuss their implication for the recent tectonic history in the area and the possibility that at least part of the observed submergence is a consequence of seismic activities during the last few thousand years.

The present work is aimed at showing an example of the potential usefulness, in continental shelf research, of submerged tidal notches, which are seldom used for the interpretation of vertical deformation, especially in tectonic and seismic areas. The distribution and size of the various submerged shorelines observed are summarized in Table 2 and, for some significant sites, in Figs. 4, 5, 6, 7, 8, 9.

"Summary of the geodynamic context" section briefly summarizes the geodynamic context derived from a previous study (Evelpidou et al. 2012a). After some information on the methods used in "Methods" section, results of our recent field work are presented in "Results of observations" section. Tentative correlation and dating of the notches is discussed in "Tentative correlation and dating of the submerged notches" section. Finally, a tentative interpretation taking into account the effects of recent earthquakes is outlined in "Discussion" section.

Summary of the geodynamic context

The study area is presumably experiencing an extensional tectonic regime behind the modern volcanic arc at the center of the Aegean plate and characterized by a relatively thin continental crust of about 28–30 km (Tirel et al. 2004; Gaki-Papanastassiou et al. 2010). The Aegean crust is gravitationally collapsing due to the southward displacement of the Cenozoic subduction front and the westwards extrusion of the Anatolian block in the Aegean during the Neogene (McKenzie 1978; Le Pichon et al. 1995; Gautier et al. 1999; Armijo et al. 2003; Tirel et al. 2004).

The general direction of the major submarine faults is east–west, exhibiting a curved shape and coinciding spatially with the volcanic and back arc Cycladic area. Main active faults of the studied area are depicted in Fig. 3. In recent years, several of these major offshore faults have been identified, suggesting the presence of tectonic depressions with horsts. It is generally accepted that the tectonic regime affecting the Aegean is broadly extensional and is dominated by normal faulting (e.g. McKenzie 1978; Mercier et al. 1989; Papazachos 1990).

The Aegean region is characterized by intense seismic activity. However, although the records of historical seismicity are one of the longest and densest in the world, knowledge about co-seismic surface ruptures in the region remains limited, in particular for offshore faults, because many of the epicenters are located at sea and because instrumental data cover less than a century (Pavlidis and Caputo 2004). Where earthquake recurrence rates are <100–200 years, such information might be available. However, the average recurrence interval of specific active faults is often longer than 500 years or even some millennia. This means that several other earthquakes could have occurred in the area but have not been recorded.

The seismicity is of intermediate depth in the South Aegean and shallow almost everywhere else in the Aegean and in adjacent regions (Beuzart 1972; Le Pichon and Angelier 1979).

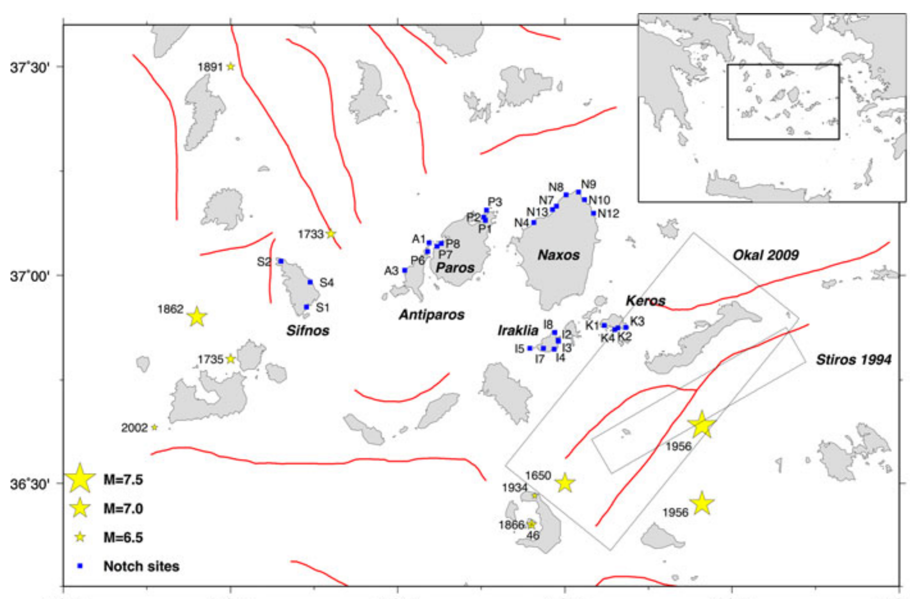

Fig. 3 Map of the tidal notch sites considered in this study. Stars mark the epicentral locations of historical earthquakes occurred in the region. *Red lines* depict the known active faults. The two boxes mark the surface projection of the rupture fault for the 1956 Amorgos earthquake proposed by Stiros et al. (1994) and by Okal et al. (2009)

Table 2 Location and significant sizes of submerged tidal notches in the S-E Cycladic islands

Locality				Submerged tidal notches									
Island	Site	Long. E	Lat. N	Notch name	Roof depth from SL (cm)	Mid-notch depth from SL (cm)	Floor depth from SL (cm)	Inward depth (cm)	Possible duration of development (centuries)	Genesis (Fig. 2)	Shoreline	Photos	Regional sea-level correlation (cm below present SL)
Naxos	N4	25.407	37.127	NA1	23					b′	G		35 ± 5
				NA5	121					e′			
				NA6	230					e″	A		280?
	N7	25.475	37.166	NA2	34	75	115	39	4–19	e′	F		75 ± 10?
	N8	25.504	37.193	NA3	67	103	138	19	2–9	a′?	E		100 ± 10
	N9	25.541	37.200	NA1	0	36	71	24	2.5–12	d′	G	Fig. 4	35 ± 5
				NA4	93	131	169	35	3.5–17	e′	D	Fig. 4	120 ± 10
	N10	25.559	37.182	NA1	0	20	40	32	3–16	c′	G		35 ± 5
				NA3	74	103	132	47	5–23	e′	E		100 ± 10
	N12	25.586	37.149	NA1	0		nm	15	1.5–7	e′	G		35 ± 5
				NA4	90	125	160			e′	D		120 ± 10
	N13	25.463	37.158	NA1	10	43	75	20	2–10	c′	G	Fig. 5	35 ± 5
				NA2?							F?	Fig. 5	nm
				NA6	220	280	340	60	6–30	e′	A	Fig. 5	280 ± 20
Keros	K1	25.618	36.881	KE1	20	35	50	15	1.5–7	b′	G		35 ± 5
				KE3	141	173	205	40	4–20	e′	C		170 ± 10
	K2	25.659	36.875	KE1	20	35	50	15	1.5–7	b′	G		35 ± 5
				KE2	90	105	120	15	1.5–7	d′?	E		100 ± 10
	K3	25.682	36.876	KE1	20	43	65	15	1.5–7	b′	G	Fig. 6	35 ± 5
				KE2	slight erosion marks only						E?	Fig. 6	100 ± 10?
				KE4	190	225	260	nm		e′	B	Fig. 6	220 ± 20
	K4	25.649	36.871	KE1	20	35	49	15	1.5–7	b′	G		35 ± 5
				KE3	129	159	189	nm		e′?	C		170 ± 20?
Iraklia	I2	25.48	36.845	IR1	20	28	35	5	0.5–2.5	b′	G	Fig. 7	35 ± 5
				IR2	90	105	120	15	1.5–7	e′	E	Fig. 7	100 ± 10
	I3	25.481	36.843	IR1	25	45	65	14	1.5–7	b′	G		35 ± 5
				IR4	175	223	270	23	2.5–11	e′	B		220 ± 10
	I4	25.468	36.824	IR3	160		250	27	2.5–12	Structural	C		180 ± 10
	I5	25.395	36.826	IR1	35		78	35	?	Structural	G		35 ± 5
	I7	25.436	36.826	IR3	157		247	nm		e′	C		180 ± 10
	I8	25.470	36.864	IR1	20	38	55	20	2–10	b′	G		35 ± 5
				IR3	157	182	225	25	2.5–12.5	e′	C		180 ± 10
Paros	P1	25.262	37.132	PA1	20	36	52	20	2–10	b′	G		35 ± 5
				PA2	130	152	173	20	2–10	c′	C		150 ± 10
	P2	25.257	37.140	PA1	20	41	61	28	3–14	b′	G		35 ± 5
				PA3	150	181	211	35	3.5–17	e′	C		180 ± 10
	P3	25.266	37.157	PA1	20	31	60	22	2.5–11	b′	G	Fig. 8	35 ± 5
				PA3	130	178	225	47	4.5–23	e′	C	Fig. 8	170 ± 20
	P6	25.090	37.057	PA1	20	30	40	20	2–10	b′	G		35 ± 5
				PA4	200	230	260	nm		b′	B		230 ± 10
	P7	25.118	37.070	PA1	20	40	60	22	2.5–11	c′	G		35 ± 5
				PA3	130	178	225	47	4.5–23	e′	C		170 ± 20
	P8	25.130	37.077	PA1	20	42	63	20	2–10	a′	G		35 ± 5

Table 2 continued

Locality				Submerged tidal notches									
Island	Site	Long. E	Lat. N	Notch name	Roof depth from SL (cm)	Mid-notch depth from SL (cm)	Floor depth from SL (cm)	Inward depth (cm)	Possible duration of development (centuries)	Genesis (Fig. 2)	Shoreline	Photos	Regional sea-level correlation (cm below present SL)
Antiparos	A1	25.094	37.078	AN1	20	33	45	15	1.5–7	a′	G		35 ± 5
	A3	25.021	36.012	AN1	20	37	54	13	1.5–6	a′	G		35 ± 5
Sifnos	S1	24.727	36.924	SI1	22	36	50	20	2–10	a′	G		35 ± 5
	S2	24.651	37.034	SI1	26	37	48	20	2–10	a′	G		35 ± 5
	S4	24.738	36.984	SI1	22	37	52	10	1–5	a′	G		35 ± 5

nm not measured

According to Lykousis (2009), a continuous subsidence rate prevailed during the last 400 ka, with values of 0.34–0.60 mm/a for the Cycladic plateau, with a gradual decrease in the magnitude of the extensional tectonic regime. The relative motion of the Cyclades during the Quaternary is toward the south and south-west with a rate of about 3 cm per year (Peterek and Schwarze 2004).

Subsidence movements during the late Holocene are confirmed by the frequent evidence of submerged coastal archaeological remains, like a drowned quay at Kea coast (Karthea), submerged walls at Tinos (Klionia) and at Kythnos and Naxos (Gaki-Papanastassiou et al. 2010). Flemming and Webb (1986) mention three submerged sites in Paros, one at a depth of −5 m having an age of 7,000 years and two at depths of −3 m having an age of 2,400 years.

Desruelles et al. (2009) reported three levels of submerged beachrocks in the Mykonos-Delos-Rhenia area submerged to −3.6 ± 0.5 m from about 2000 BC, to −2.5 ± 0.5 m from 400 BC and to −1±0.5 m from around 1000 AD. However, beachrocks are known not to require vertical stability of the shoreline during long time for their formation (Alexandersson 1972).

Methods

Tidal notches can form on carbonate coasts almost anywhere during periods of relative stable sea level, or during which relative sea-level changes occurred at a rate not exceeding the rate of bioerosion. Previous studies in various parts of the world, summarized by Pirazzoli (1986, Table 1), have estimated that intertidal bioerosion rates on calcareous shores may vary between 0.2 and 5 mm/a. These rates depend not only on the type of rock, but also from the local climate, hydrodynamical and biological environment and reach higher rates in tropical areas. If only the Mediterranean region is considered, available data indicate a variability between 0.2 and about 1 mm/a (Torunski 1979; Furlani et al. 2009; Evelpidou et al. 2011). These minimum and maximum values are used below to roughly estimate the duration of relative sea-level stability necessary to the inward deepening the observed notch profiles.

Detailed, accurate and systematic survey along the coastal zone of Sifnos, Antiparos, Paros, Naxos, Iraklia and Keros took place during spring and summer 2010. The coasts of the study area (Fig. 3) were systematically surveyed in detail, by boat, in order to access all sites and to establish lateral continuity of observations. Due to the complete absence of elevated shorelines and even to the surprising lack of clear marks of a tidal notch in the present midlittoral zone, even in rock formations that could be expected to be favorable for its development, our survey was extended underwater along the rock cliffs. During the survey, the local lithology of the Cyclades was taken into account. Forty-three divings were made along the study area in the Cyclades (thirteen in Naxos, four in Koufonissia-Keros, eight in Iraklia, eight in Paros, four in Antiparos and six in Sifnos).

Submerged tidal notches were identified. For each diving site, the time and the GPS coordinates were collected (with an average accuracy of ±5 cm), and in underwater, the observed features were measured in relation to sea level at the time of observation (with a precision that, due to waves, may be estimated to about ±10 cm) and photographed. Notch geometries (e.g. height, vertex depth from sea level and inward depth, Fig. 1) were measured and interpreted following the concept of Fig. 2 and Table 1. On each location, the accuracy was improved by multiple measurements. Comparisons were made with six hourly records of sea-level air pressure at Naxos, (downloaded from the archive of the Russian meteorological site (http://meteo.infospace.ru/wcarch/html) and with hourly tidal

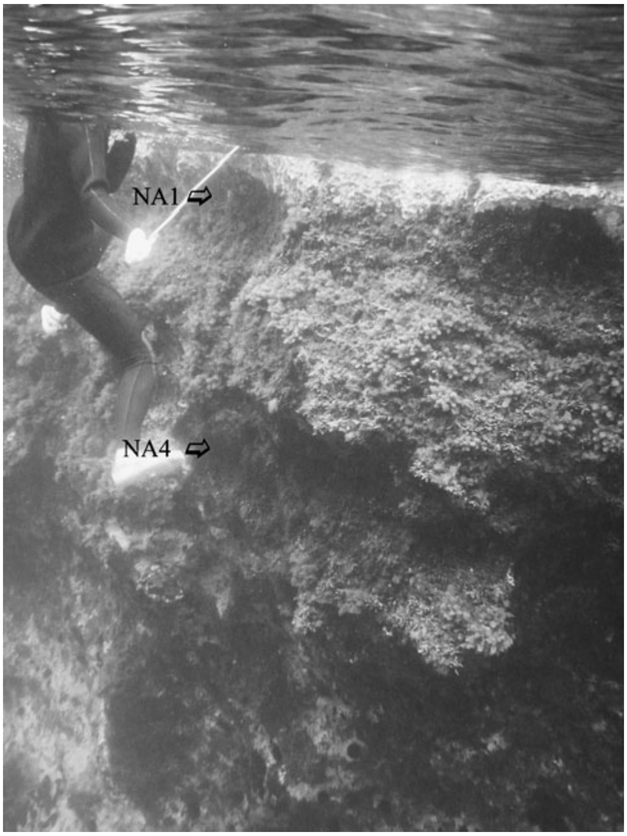

Fig. 4 Naxos: view of notches *NA1* and *NA4* at Site N9 (the first author gives scale)

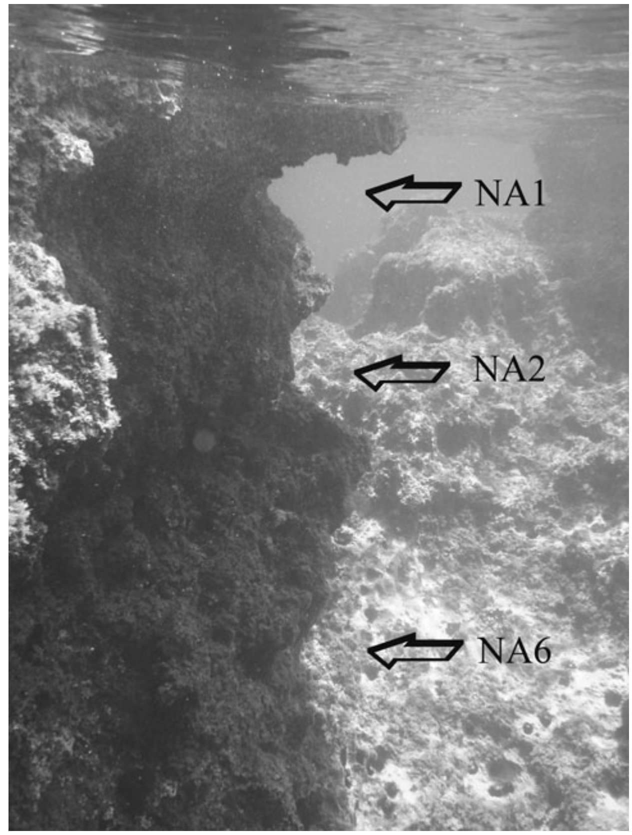

Fig. 5 Naxos: view in the same section of notches *NA1*, *NA2* and *NA6* at Site N13

records at Sifnos (provided by the Hellenic Hydrographic Service), to confirm the validity of the interpretation. The present work is devoted to the distribution and size of the various submerged shorelines observed, which are summarized in Table 2 and, for some significant photographs, in Figs. 4, 5, 6, 7, 8, 9. Other photographs of the upper submerged notch in each island have been shown by Evelpidou et al. (2012a, Fig. 3).

In Table 2, the last column (tentative regional sea-level correlation) has been deduced from a comparison between the notches measured in each island. They do not correspond to measurements, but from the assumption that the various islands have been affected by similar vertical movements.

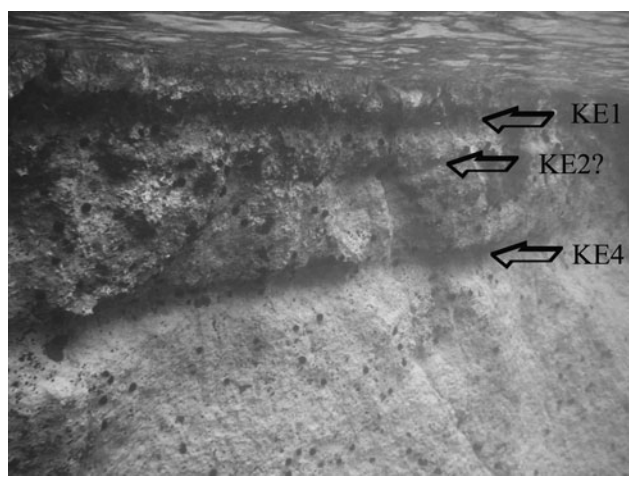

Fig. 6 Keros: view of notches *KE1*, remnants of *KE2* and *KE4* at site K3

Results of observations

In the case of relative sea-level rise at a rate smaller than the bioerosion rate, calculation shows that the inward depth of a tidal notch remains very limited (Table 3), while its height tends to increase.

In Table 2, the column 'Genesis' proposes a tentative interpretation of the genesis of each notch, based on the concept illustrated in Figure 2. This interpretation is based on the comparison of the notch height with the height of the local midlittoral range and has been deduced from the measurements made underwater at each site and from the estimation of the position of the vertex in the notch profile. The vertex position, which may not correspond exactly to

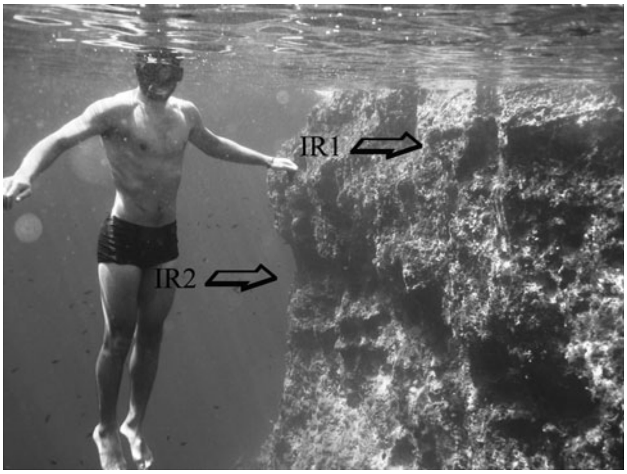

Fig. 7 Iraklia: view of notches *IR1* and *IR2* at SiteI3 (an assistant observer gives scale)

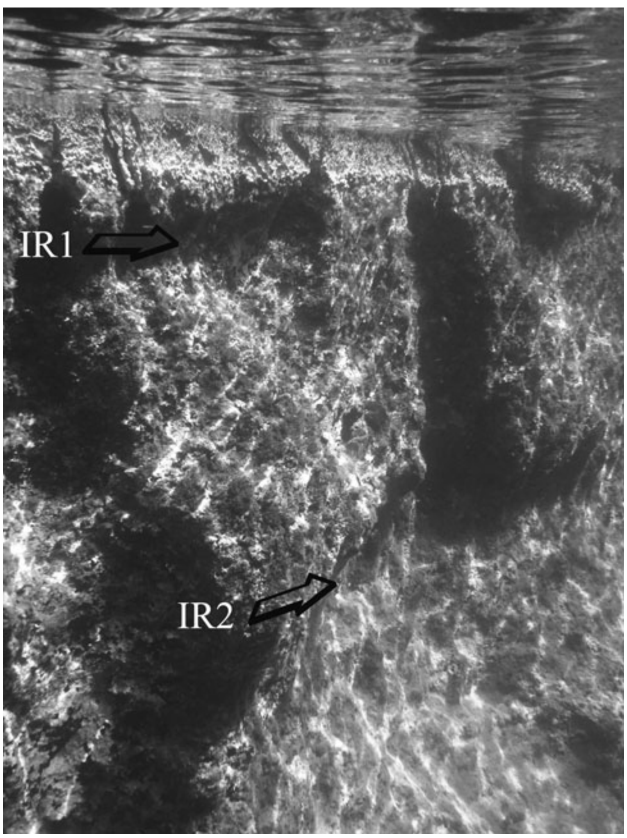

Fig. 8 Iraklia: view of notches *IR1* and *IR2* at Site 12

the mid-notch depth value in Table 2, has been deduced graphically from photographs. However, these measurements being necessarily fragmentary, they do not permit a verification of the lateral continuation of the erosion features all along the coast. This could explain some uncertainties in the interpretation that may sometimes ascribe a variable genesis to the same notch.

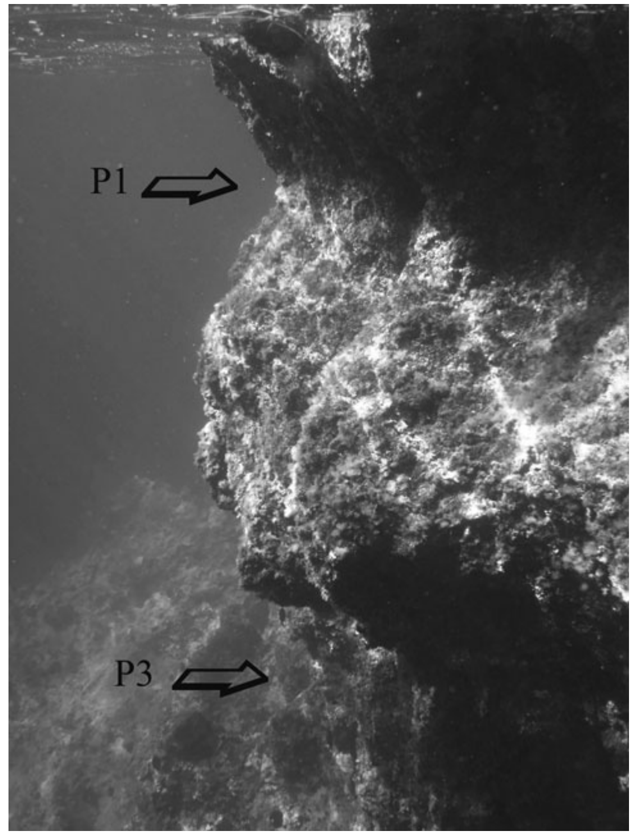

Fig. 9 Paros: view of notches PA1 and PA3 at Site *P3*

Naxos

Only the northern coast that is often exposed to wave action has been investigated underwater. Marks of at least six submerged tidal notches could be distinguished, which we shall call NA1–NA6 (Table 2).

The uppermost tidal notch (NA1) developed between the present sea level and about −70 cm, with a vertex 30–40 cm below the present sea level and an average inward depth of 20–25 cm. Its profile, often of type-b′, suggests a rapid submergence, though some type-d′ or type-e′ profiles, could be consistent also with a slow gradual sea-level rise having preceded the submergence.

A slightly deeper notch (NA2), developed between about -34 ± 10 and -115 ± 10 cm, has been observed mainly at Site N7. The height of this notch, greater than the local midlittoral zone, indicates that it belongs to the type-e′ profile, suggesting that some relative sea-level rise may have occurred during the period of notch formation.

At Site N9, notches NA1 and NA4 are visible together in Fig. 4.

At Site N13 remnants of the notches NA1, NA2 and NA6 may be seen together (Fig. 5). Notch NA2, possibly belonging here to the type-c′ notch profile, may suggest the occurrence of a seismic movement that displaced sea level from NA2 to NA1. In the absence of more detailed measurements, the amount of this displacement cannot, however, be estimated precisely.

Poorly preserved remains of notch NA6 have been observed also at Site N4 between about −220 and −340 cm: they seem to correspond to marks of a former sea level about 250 ± 30 below the present one.

Keros

According to their depth, four different notches can be distinguished: KE1, KE2, KE3 and KE4 (Table 2). The uppermost submerged notch (KE1) has developed between −20 and −65 cm and has a vertex at about −40 cm. A second notch (KE2) has been observed between −90 and −120 cm and seems to correspond to a former sea level about one meter below the present one.

The third notch (KE3), between −145 ± 10 and −205 ± 10 cm, would be consistent with a former sea level at about −170 ± 10 cm. Finally, KE4 is well developed between about −190 ± 10 and −260 ± 10 cm, corresponding to a former sea level about 220 ± 20 cm below the present one. It is possible to see KE1 and KE4 and even some marks left by KE2 in Fig. 6.

If notch KE1 that belongs to the b′-type (Fig. 2) suggest a rapid submergence, the profile of the other notches (e′ or d′) is consistent with some gradual relative sea-level rise having occurred during the period of development of their profile.

Iraklia

Four different submerged notches can be distinguished: IR1, IR2, IR3 and IR4.

Notch IR1, developed between −20 and −65 cm, is very similar to KE1.

Notch IR2, between about −90 and −120 cm corresponds to a former sea level about 1 m below the present one, though it can have a structural origin in some cases. Notch IR3, between about −160 ± 10 and −250 ± 10 seems to correspond to a former sea level at about −180 ± 10 cm.

Notch IR4, developed between about −175 ± 10 and 270 ± 10, seems to correspond to a former sea level at about −220 ± 10 cm. Notches IR1 and IR2 can be seen together in Figs. 7 and 8.

Notch IR1 (like KE1) belongs to the b′-type, indicating that its submergence was rapid; whereas the e′-type profile of the other notches suggests the occurrence of some gradual relative sea-level rise at a rate smaller than the bioerosion rate.

Paros

Four different submerged notches have been recognized: PA1, PA2, PA3 and PA4.

PA1 is developed between about −20 and −50 ± 10 cm, with a vertex between −30 ± 10 and −42 ± 10 cm. PA2, observed only at Site P1, extends from −130 ± 10 cm to −173 ± 10 cm, with a vertex at about −150 ± 10 cm. It may often be seen together with P1 (Fig. 9).

Notch PA3, extending between −140 ± 10 and −215 at ± 10 cm, with a vertex near −180 ± 10 cm, is consistent with a former sea level at −170 ± 20 cm.

Finally, notch PA4, extending from −200 ± 10 to −260 ± 10 cm, with a vertex at about −230 ± 10 cm, has been observed only at Site P6.

The height of notches PA1 and of PA2 is of the same order of the local midlittoral range, suggesting that notch development occurred during a period of stable relative sea level preceding their rapid submergence. Notch P3 is different, because the type-e′ of its profile suggests a gradual relative sea-level rise during its development.

Antiparos

Only notch AN1, slightly submerged between −20 ± 10 and −50 ± 10 cm, could be observed.

Table 3 Theoretical profile of tidal notch development in relation to bioerosion/dissolution rates and stable or slightly rising relative sea level, for a height of the midlittoral zone (tide plus regular waves) of 30 cm

Bioerosion/dissolution rate (mm/year)	Time of relative stable sea level				Time of relative sea-level rise of 0.6 mm/year			
	100 years		1,000 years		100 years		1,000 years	
	Notch height (cm)	Inward notch depth (cm)	Notch height (cm)	Inward notch depth (cm)	Notch height (cm)	Inward notch depth (cm)	Notch height (cm)	Inward notch depth (cm)
0.3	30	3	30	30	–	–	–	–
0.5		5		50	–	–	–	–
1.0		10		100	36	4	90	4

Sifnos

Like at Antiparos, only a slightly submerged notch (SI1) has been observed between −22 ± 10 and −55 ± 10 cm, with a vertex at about −36 ± 10 cm.

Tentative correlation and dating of the submerged notches

The lowest shoreline observed that we shall call provisionally A, is indicated by the submerged notches NA6, as indicated by some erosion marks around −280 cm at Sites N4 and N13 of Naxos. Though a e′-type or e″-type profile suggests that some gradual relative sea-level rise occurred during its period of formation, the preserved profile of its roof suggests that after the notch formation period, the relative sea level rose rapidly, probably due to seismic activity.

About 50 cm higher, another former shoreline (B) is identified at about −230 ± 10 cm by PA4 and at −225 ± 20, by KE4 (Table 2). Both notches show a roof which is preserved at some sites, therefore suggesting that sea level was brought to a higher elevation by a seismic event.

At shallow depth, a former shoreline (C) is represented at several sites, by notches PA3 and IR3 at −180 ± 10 cm, KE3 (Site K1) at −160 ± 10 and KE3 (Site K4) and PA3 (Sites P2, P3 and P7) at −180 ± 20 cm (Table 2). They are all of type-e′, suggesting a period of gradual relative sea-level rise during their formation; the roof of this notch is sufficiently well preserved to indicate that a co-seismic subsidence may have contributed to bring the sea level to a higher elevation.

Notch PA2, at −150 ± 10 cm, is different. Typically of the c′-type, its profile does not show any marks of gradual relative sea-level rise during the period of its formation, which according to the limited inward depth must have been relatively short. It can therefore be considered as the final stabilization at about −150 ± 10 cm of shoreline C, before the co-seismic subsidence that brought sea level at a slightly higher elevation.

Marks of the shorelines D, E and F have been observed only along the northern coast of Naxos. At Sites N9 and N12 shoreline, D corresponds to erosional marks of shoreline NA4 at −130 ± 10 cm, with notch profiles that, in spite of the algal vegetation covering the rock, seem to be of type-e′. Similar erosional marks about two decimeters higher, also of type-e′, can be ascribed at Sites N8 and N10 to shoreline E at −100 ± 10 cm. Finally, shoreline F is represented, at Site N7, by N2 at −75 ± 10 cm, also of type-e′.

The uppermost shoreline G, is present at −35 ± 5 cm (NA1, KE1, IR1, AN1, SI1) in all the islands considered and has been already discussed by Evelpidou et al. (2012a).

In Table 2, the last column (tentative regional sea-level correlation) has been deduced from a comparison between the notches measured in each island. They do not correspond to measurements, but from the assumption that the various islands have been affected by similar vertical movements.

Sea level A at −2.9 m may correspond, from the inward depth of notch NA6, to a relatively stable sea level during a period between 6 and 30 centuries. This notch must have been developed at least before 3350–4200 BP, assumption based on Sea level B dating and the duration of sea-level stability necessary to produce the inward depth of this notch. This hypothesis fits with the fact that an earthquake took place around 3300 BP which destroyed House B in Grotta (Naxos). According to Kontoleon (1967) and to Cosmopoulos (1998), there was excessive moisture during this period in Grotta, as shown by the floor construction of the Room A at 0.10 m higher than the earlier floors of House B and Room A of House A. This could be explained by the subsidence of the area caused by the earthquake. The duration of sea level B at −2.3 m can be estimated from the inward depth of notch IR4, assuming that they formed in a uniform lithological, biological and climatic conditions, between 2.5 and 11 centuries. This submergence may be correlated with submerged Grotta settlement ruins existing at the same depth and dated around 3100 BP. This earthquake is probably the reason why the roofs of the LH IIIC chamber tombs in Aplomata collapsed and part of the settlement in Grotta was submerged and subsequently flooded by a tsunami (Kontoleon 1958; Vlachopoulos 2006).

Sea level C seems consistent with type-e′ fossil notches at about −1.7 m at Paros, Iraklia and Keros. During its existence (at least 4.5 centuries at Site P3), it was affected by a gradual relative sea-level rise of 20 ± 10 cm (at a rate lower than the bioerosion rate) that increased slightly upwards the height of the notch profiles; this can be deduced by comparing the height of the notch with the local midlittoral zone range. Its final stage was characterized by an almost stable sea level during at least 2 centuries, suggested by the development at Site P1 (PA2) of a narrow type-c notch with a vertex at −1.5 m. Marks of sea level C seem completely absent from Naxos, at least from its northern coast. However, it could be correlated with the sample NA2/1.87 cored in the Bay St. Georgios area (Naxos), corresponding to an articulated *Cerastoderma* shell showing that the sea level around 1752 ± 40 years, BP was above −1.78 ± 0.5 m (Evelpidou et al. 2012b). This result is consistent with the presence of an upper beachrock between 0 and −1.7 m in the Vigla area.

Marks of sea level D have been observed only at Naxos.

Sea level E at −1 ± 0.1 m may be tentatively dated at around 941 ± 40 years, BP based on *Cerastoderma* shells of the sample NA2/0.89 cored at −0.89 m again in the

St. Georgios area (Evelpidou et al. 2010; Evelpidou et al. 2012b), also confirmed by the shallower beachrock slabs (−1 m) at Delos island, dated around 1000 AD (Dalongeville et al. 2007).

Shoreline F at −75 ± 10 cm (NA2) is represented by a notch profile that, in spite of the algal vegetation covering the rock, seems to be of type-e′. Sea level F may be dated to about 900 years BP based on *Cerastoderma* shells (Evelpidou et al. 2010; Evelpidou et al. 2012b).

The notches of shoreline G have a mean inward depth of 18.5 cm which may correspond, assuming it formed in a uniform lithological, biological and climatic conditions among the various islands, during a period of relative sea-level stability between 185 and 925 years long. Shoreline G has been dated 232 ± 35 years BP (i.e. at AD 1718 ± 35) by a *Cerastoderma* shell collected at a depth of 63 cm by core NA2 at Naxos near St. Georgios (Evelpidou et al. 2010, 2012b). This brings evidence that the submergence of shoreline G had probably not yet started in the early eighteenth century. The notches of shoreline G have been subsequently submerged by 30–40 cm.

A comparison between the tidal notches left by sea levels A–G on the islands and their correlation with certain geo-archaeological or radiometric ages is summarized graphically in Fig. 10. If the notch related to sea level G is present in all studied islands, the seismic part of its submergence cannot be ascribed everywhere to the Amorgos earthquake. Indeed, as discussed by Evelpidou et al. (2012a), the amplitude of a seismic subsidence should decay with epicentral distance, so that the observed uniform subsidence in the region cannot be ascribed to a single seismic event even if post-seismic contributions are invoked.

In particular at Antiparos and Sifnos, where only the G shoreline is present, coseismic deformation models have proven that only a fraction of submergence can be ascribed, to the Amorgos earthquake, and therefore, these two islands should have been affected by a tectonic history different from that prevailing in the other islands.

Discussion

In Fig. 11, we plot relative sea-level data deduced from the geoarchaeological correlation of palaeo-shorelines discussed in the previous section. The data points show that until about 3300 years BP, a relatively stable sea level has been present in the region, represented by shoreline A at about −2.8 m. Starting at about 3300 years BP, the studied area has been submerged at an average rate of about 1 mm/a, represented by the dotted line in Fig. 11. Compared to the relative sea level during the preceding millennium, this submergence rate is definitely too larger than a fraction of mm/a predicted by isostatic modeling (Lambeck 1995) to be explained in terms of gradual glacio-hydro-isostatic factors. Moreover, features of submerged notches provide evidence that most submergence has occurred as the result of fast, discrete events rather than a gradual subsidence.

The intense seismic activity of the Aegean region may provide a possible alternative explanation of the observed subsidence events. In Table 4, we summarize the historical earthquakes with Ms > 6 having recently occurred in the area studied in the Aegean region. Events with Ms > 6 have been selected because Pavlidis and Caputo (2004) have shown that for earthquakes with a magnitude of less than 5.6–5.7, vertical displacements may be limited to 1–2 cm, i.e., often not distinguishable from other features of ground deformation. Epicentral locations are also shown in Fig. 4. The nearest to the study area, called the 1956 Amorgos earthquake, was not only the strongest event (Ms = 7.4) having occurred in Greece during the last century, but also the best studied. Two models of this Amorgos earthquake, provided by Stiros et al. (1994) and by Okal et al. (2009), have been compared in a previous paper (Evelpidou et al. 2012a), under certain assumptions on lithospheric layer properties and viscoelastic relaxation of ductile mantle layers. It appears that the coseismic and post-seismic effects of that earthquake may have contributed to the observed subsidence in Sifnos, Antiparos, Paros, Naxos, Iraklia and Keros islands, also if the vertical displacements of other islands, more distant from the earthquake fault, seems to have been affected by other seisms.

About two thirds of the 30–40 cm submergence of shoreline G have been ascribed by Evelpidou et al. (2012a) in all the islands considered to the recent global sea-level rise occurred during the last two centuries, while about one decimeter could be ascribed to effects of the Amorgos

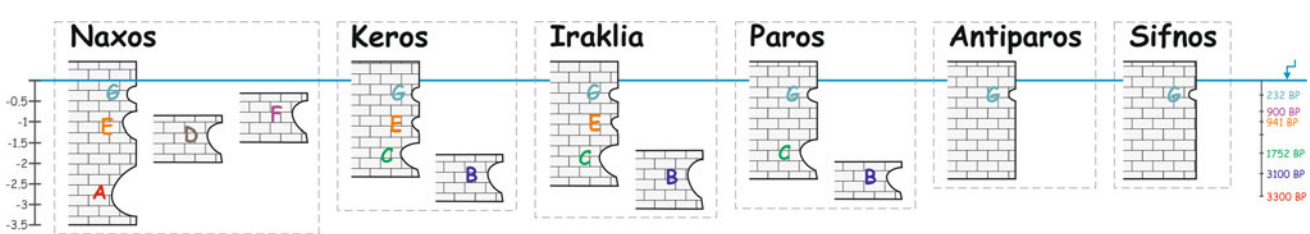

Fig. 10 Correlation between erosional marks of sea levels *A–G* in the various islands studied

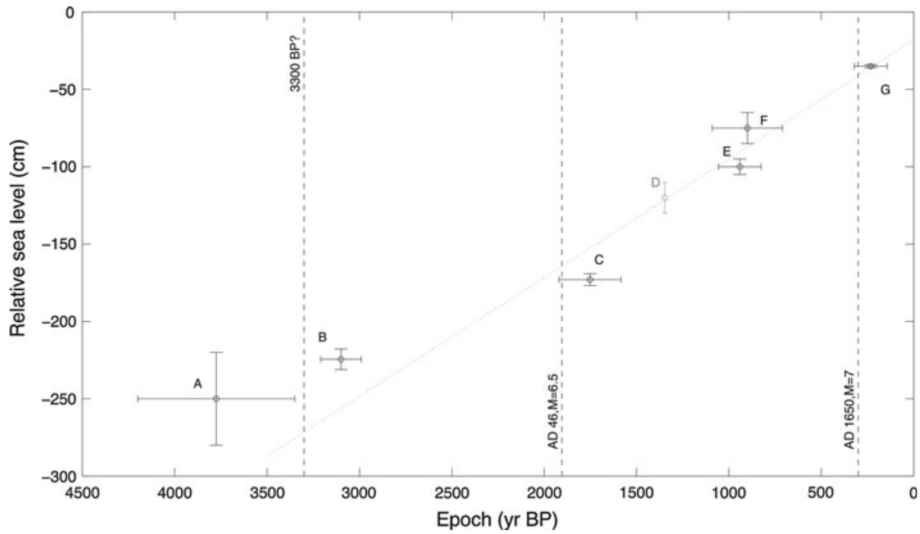

Fig. 11 Relative sea level deduced from notch information. Data points represent weighted averages of all palaeo-sea-level estimates relative to each shoreline. *Vertical error bars* represent associated uncertainties; *horizontal error bars* represent the maximum estimated period of sea-level stability associated to each paleo-shoreline. *Vertical dashed lines* mark the occurrence of the 46 AD, M = 6.5 and 1650 AD, M = 7 earthquakes. The occurrence time of an earthquake occurred in the region about 3300 years BP is also marked. A *dotted line* represents the average sea-level rise, corresponding to about 1 mm/a. For paleo-shoreline *D* (in *gray*), no archaeological correlation is available, so, it has been plotted between sea levels *C* and *E*

Table 4 Historical earthquakes with Ms > 6 having recently occurred in the area studied (Papazachos and Papazachou 2003)

Year AD	Time (mm/dd-hh.min)	Long.	Lat.	Ms	Area
1956	07/09-03.11	25.91	36.64	7.4	Amorgos
1956	07/09-03.24	25.91	36.45	7.2	Amorgos
1650	10/09-	25.5	36.5	7.0	Thera
1862	06/21-05.30	24.4	36.9	7.0	Melos
46		25.4	36.4	6.5	Thera
1733	12/23-15	24.8	37.1	6.5	Sifnos
1735		24.5	36.8	6.5	Melos
1891	05/11-	24.5	37.5	6.4	Kithnos
1934	11/09-13.41	25.41	36.47	6.3	Thera
2002	05/21-20.53	24.273	36.635	6.3	Melos
1866	01/31-	25.4	36.4	6.1	Thera

earthquake, at least at Naxos, Keros, Iraklia and Paros, while about one decimeter of submergence in Antiparos and Sifnos should probably result from a previous seismic event (for possible earthquakes, see Table 4).

The deeper-submerged notches suggest the occurrence during the last few thousand years of differential vertical movements, probably related not only to seismic events, but also to short-lived subsidence trends, sometimes different from island to island.

Assuming that the tidal notches observed are representative of a rigid behavior of the islands, rather than of local tiltings, the tectonic history of Naxos before the nineteenth century, a RSL rise of 280 ± 20 cm during a period of 19.3–93.7 centuries (Table 5) suggests, from the analysis of only the tidal notches, an average subsidence rate between 0.3 and 1.54 mm/a.

In the same manner, the subsidence suggested by the tidal notches can be estimated:

at Keros, of 170 ± 10 cm during a period between 7 and 34 centuries, at an average rate between 0.5 and 2.6 mm/a;
at Iraklia, of 180 ± 10 cm during 5.3–26 centuries, at an average rate between 0.3 and 0.7 mm/a;
at Paros, of 170 ± 20 cm during 5.9–29.2 centuries, at an average rate between 0.51 and 3.2 mm/a.

However, if the archaeological date of 3300 BP can be accepted for a subsidence of 280 ± 20 cm at the House B of Grotta (Naxos), then a more precise subsidence rate of 0.8–0.9 mm/a can be deduced for about the last three millennia at Naxos.

In comparison, the average subsidence rate for the eastern Cycladic margin calculated for the period 146–18 ka BP by Lykousis (2009) is 0.34 mm/a.

Finally, it should be noted that the subsidence observed was far from gradual in the SE Cyclades, because the notch types b′ and c′ observed at Naxos, Keros, Iraklia and Paros suggest coseismic subsidence, while notch types d′ and e′ in the same islands suggest periods of gradual slow subsidence and notch types e′ suggest periods of almost stable MSL interspaced with periods of gradual slow sea-level rise.

A general tectonic explanation can hardly be attempted from the few information available on historical seismicity

Table 5 Comparison of the modalities of late Holocene subsidence in Naxos, Keros, Iraklia and Paros as deduced from Table 2

Island	Local shoreline	Genesis (Fig. 2)	Number of notches observed	Average possible duration of development (centuries)	Depth below present MSL (cm)
Naxos	G	d′, c′, b′	3	2.3–11.7	−35 ± 7
	F	e′	1	4–19	−75 ± 10
	E	a′, e′	2	3.5–16	−100 ± 10
	D	e′	1	3.5–17	−120 ± 10
	A	e′	1	6–30	−280 ± 20
Total			8	19.3–93.7	−280 ± 20
Keros	G	b′	3	1.5–7	−35 ± 5
	E	d′	1	1.5–7	−100 ± 10
	C	e′	1	4–20	−170 ± 10
Total			5	7–34	−170 ± 10
Iraklia	G	b′	3	1.3–6.5	−35 ± 5
	E	e′	1	1.5–7	−100 ± 10
	C	e′	1	2.5–12.5	−180 ± 10
Total			5	5.3–26	−180 ± 10
Paros	G	b′, c′, e′	6	2.3–11	−35 ± 5
	C	c′, e′	4	3.6–18.2	−170 ± 20
Total			10	5.9–29.2	−170 ± 20

in the area. It is generally assumed that most Cycladic islands are affected by a gradual subsidence that is ascribed to the thinning of the local earth crust and to isostatic processes that accompanied the post-glacial rise in sea level. The absence of morphological coastal features indicative of uplift, such as marine terraces or benches, elevated beachrocks, marine notches, or raised Quaternary coastal deposits, are often interpreted as an absence of local uplift tectonism, at least during the Holocene.

The study of submerged beachrocks by Desruelles et al. (2009) mentions some late Holocene sea-level stands, the duration of which could not, however, be estimated. Also, the modalities of sea-level change (gradual, or rapid) that occurred from one stand to the other cannot be specified from the study of beachrocks.

Our study provides evidence that the Cycladic region has undergone a submergence during at least the last 2,000 years. Measurements have proven that the amplitude of submergence is too large to be explained only in terms of glacio-hydro-isostatic effects, so that also vertical crustal movements have contributed to the submergence. Moreover, the layout of observed notches indicate that observed submergence occurred as the cumulative result of discrete events rather than as a gradual, continuous phenomenon. For these reasons, our measurements strongly suggest that the Cycladic region has undergone, during the observation time window, a series of strong seismic events and/or short-timescale tectonic subsidence trends. However, the occurrence of non-volcanic (aseismic) tremors accompanying slow deformation or even the still poorly known "slow slip events" (Vidale and Houston 2012), as well as post-seismic deformation following large seismic events, may also have taken place and may contribute to find an explanation of the vertical displacements that affects the Cycladic region.

Conclusions

Seven submerged notches found in SE Cyclades suggests the occurrence of rapid subsidence events, potentially of seismic origin. Comparisons with other sea-level indicators from Naxos and Delos islands indicates that these relative sea-level changes took place between about 3300 BP and very recent.

The submergence of the uppermost notch is party ascribed to effects of the recent global sea-level rise occurred during the last two centuries and, partly to effects of recent earthquakes. The coseismic and post-seismic effects of that earthquake may have contributed to the observed subsidence in Sifnos, Antiparos, Paros, Naxos, Iraklia and Keros islands, also if the vertical displacements of other islands, more distant from the earthquake fault, seem to have been affected by other seisms.

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