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Late Holocene shorelines in east Attica (Greece)

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ABSTRACT

A coastal and submarine geomorphological investigation took place in the coasts of eastern Attica, aiming to identify palaeoshorelines. Former sea-level positions were deduced from emerged and submerged tidal notches. Eight fossil shorelines were deduced in the study area; two emerged ones at about +24 ± 30 and +40 ± 30 cm, and six submerged ones at about −22 ± 30 (modern), −40 ± 30, −60 ± 30, −80 ± 30, −130 ± 30 and −460 ± 30 cm. It is worth mentioning that a rather different tectonic behavior may be distinguished between the south (AT1-AT5) and the north (AT10-AT28) part of the study area.

1. Introduction

Remains of past sea levels, such as tidal notches, benches, beachrocks, etc. may provide valuable information for the investigation of relative sea level changes of eustatic and/or tectonic origin. Tidal notches are usually formed in limestone cliffs in the mid-littoral zone, are well known as precise sea-level indicators (Pirazzoli, 1986, 1996, 2005) and they can attest to the modality of sea level change (rapid or slow) allowing to identify palaeoseismic events (e.g. Benac et al., 2004, 2008; Nixon et al., 2009; Evelpidou et al., 2011a, 2012a; Stiros and Blackman, 2014; Trenhaile, 2015; Boulton and Stewart, 2015; Mourtzas et al., 2016).

Tidal notches owe their formation mainly on bioerosion, which is higher near the mean sea level rather than on the upper and lower limits of the tidal range. Recently, Trenhaile (2014) modelled the development of marine notches, formed by tidal wetting and drying and salt weathering and concluded, among others, that the height of notches is controlled by the tidal range while their inward depth depends on the climate, the rock type, wave exposure and the development stage within a cycle the cycle of formation and collapse.

Tidal notches may present some difficulties in obtaining an age for palaeoshorelines, especially for the submerged notches that cannot be directly dated because bioerosion rapidly destroys submerged fossils, making the collection of samples to be dated almost impossible. In the cases of the slightly uplifted notches there are also difficulties in finding dating material also because of the wave activity. Information can only derive from assumptions on the rates of intertidal undercutting (Evelpidou et al., 2012b). However, tidal notches may be relatively dated from nearby coastal drillings (Evelpidou and Pirazzoli, 2015); for example Nixon et al. (2009) identified and dated transgression events by correlating salt-marsh cores with tidal notches in the area of Korphos. Marriner et al. (2014) also correlated salt-marsh cores with a tidal notch in the Adriatic Sea.

It is also worth noting that Evelpidou et al. (2012b) and Pirazzoli and Evelpidou (2013) suggested that tidal notches are no longer forming in the intertidal zone due to the fact that rate of global sea level rise is larger than the rate of bioerosion. Notches submerged by 20–30 cm are called "modern", due to the fact that at least part of their submergence can be ascribed to the global sea-level rise of about 20 cm that occurred during the 19th and the 20th century (Evelpidou et al., 2012b; Pirazzoli and Evelpidou, 2013). Their theory has been contested by Antonioli et al. (2015) and there is still an ongoing debate (see discussion; Evelpidou and Pirazzoli, 2015; Antonioli et al., 2016).

1.1. Study area

Our study area is situated in the eastern coasts of the Attica Peninsula (eastern Greece) extending from Porto Rafti to Oropos area (Fig. 1). According to Papanikolaou and Papanikolaou (2007)

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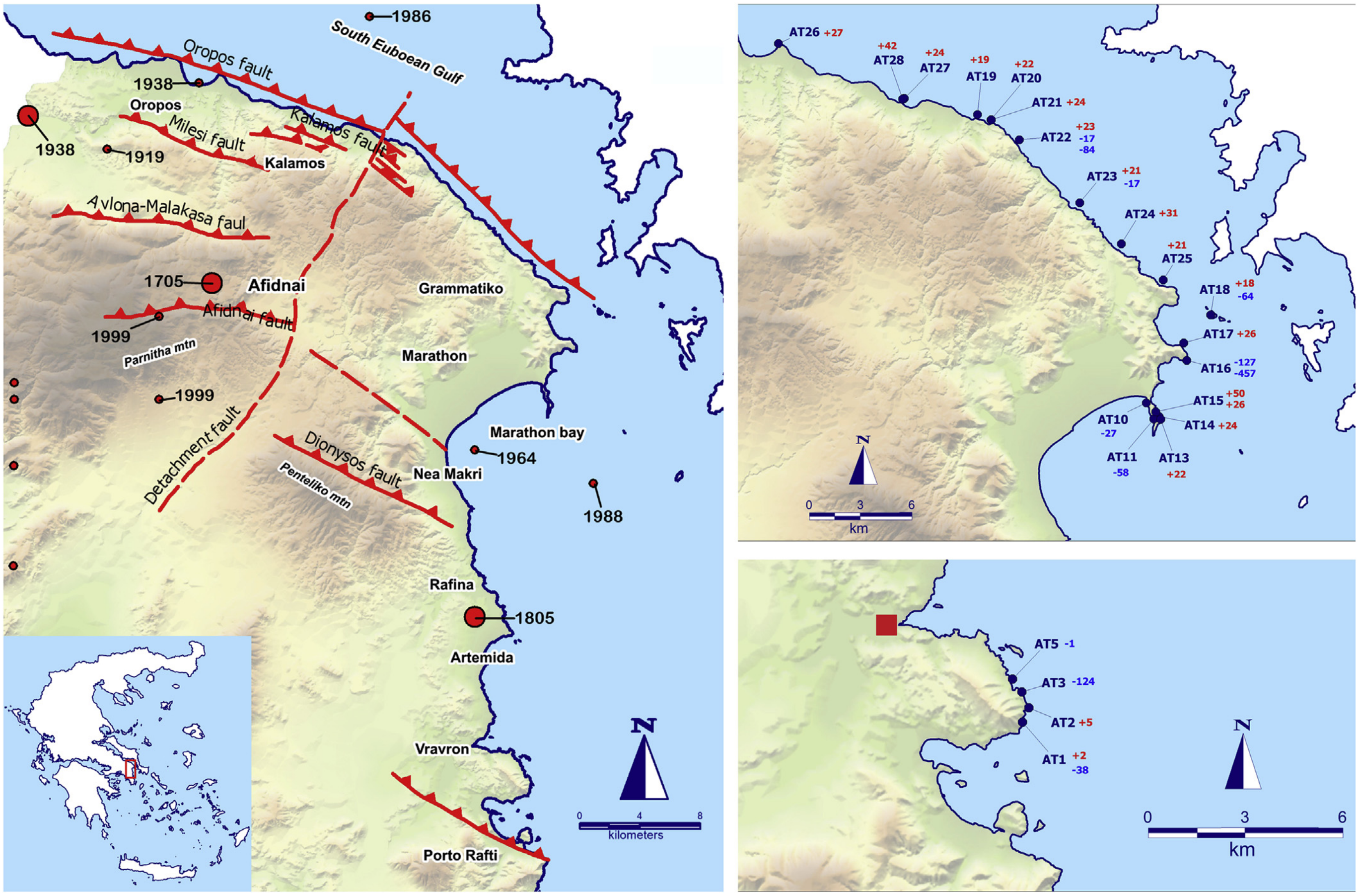

Fig. 1. Surveyed area. Measurements and characteristics of the sites depicted in this map are listed in Tables 1 and 2. Drillings location is indicated by a red square. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the region of NE Attica forms a tilted tectonic block rotating to the S–SW, bounded by the Afidnai fault to the south and the Oropos fault to the north.

According to Ambraseys and Jackson (1998), the wider area shows no indications of major earthquakes during the last 2500 years. Both historical and instrumental data give no evidence for large earthquakes for the period 1700–2000, with the exception of two events, in 1705 and 1938 (Ganas et al., 2005; Papanikolaou and Papanikolaou, 2007). The epicenter of the 1705 event (M 6.5) was located in the northeastern foothills of Parnitha Mountain (Ambraseys and Jackson, 1997; Goldsworthy et al., 2002) and caused minor damages to Athens and Chalkis (Papanikolaou and Papanikolaou, 2007). According to Papanikolaou and Papanikolaou (2007), the Afidnai fault could have ruptured during the 1705 but the availability of data is limited to bring light. The event of 1938 occurred in Oropos area, having a magnitude of ~6, probably ruptured part of the Oropos offshore fault (Ambraseys and Jackson, 1997; Papanikolaou and Papanikolaou, 2007). Ground cracks were reported along the Oropos and the coastal faults, accompanied by slumping in the hanging wall of the coastal fault, and coastline emergence near Kalamos (Goldsworthy et al., 2002). In the study area, evidence of vertical displacements has also been reported by Smith (1994), through uplifted lithophaga and beachrocks in the south Euboean Gulf.

In this framework, this paper focuses on the coasts of east Attica in order to trace the palaeoshorelines of the Upper Holocene through the use of tidal notches and discuss their implication for the interpretation of the recent tectonic history in the area.

2. Materials and methods

The coastal zone of the study area was surveyed by snorkeling all along the rocky coastline in order to locate Late Holocene sea level indicators and diving where necessary. In order to access all sites, a boat was used. All submarine features were mapped in detail by snorkeling and diving, using a folding ruler to measure their particular characteristics. Palaeoshorelines were identified based on tidal notches.

For each measurement the time and the GPS coordinates were recorded. The sites of tidal notches recorded and measured correspond to the X, Y locations of Table 1. All measurements in relation to sea level were subsequently corrected by comparison with hourly tidal records (provided by the Hellenic Hydrographic Service), taking into account also the real meteorological conditions. In particular, for tide corrections, tidal records from the station of Syros for the time of measurements have been used in order to correct the measurements taken during fieldwork, which were provided by the Hellenic Navy Hydrographical Service (HNHS). Especially for the measurements taken at 16/9/2013 (Sites AT19-AT25), tidal records from the Peiraias station were used, because unfortunately the Syros station was not working.

Notch geometries, namely the height, inward depth and vertex depth from sea level, were measured according to Pirazzoli (1986). The morphological characteristics measured are listed in Table 2 and shown graphically in Fig. 2. Based on the profiles of the notches, an interpretation has been attempted on the mode of relative sea level change.

Table 1
Location of sites in the study area.

Tidal notches		
Site	Long. E	Lat. N
AT1	24° 2′ 31.4412″	37° 53′ 44.0772″
AT2	24° 2′ 39.588″	37° 53′ 58.488″
AT3	24° 2′ 30.7536″	37° 54′ 14.382″
AT5	24° 2′ 18.8628″	37° 54′ 27.072″
AT10	24° 3′ 1.926″	38° 8′ 11.2092″
AT11	24° 3′ 19.9512″	38° 7′ 40.6344″
AT13	24° 3′ 36.9612″	38° 7′ 40.1412″
AT14	24° 3′ 32.7672″	38° 7′ 45.6996″
AT15	24° 3′ 24.8652″	38° 7′ 54.6204″
AT16	24° 4′ 45.3504″	38° 9′ 33.786″
AT17	24° 4′ 31.8864″	38° 10′ 5.0664″
AT18	24° 5′ 33.6804″	38° 10′ 43.0464″
AT19	23° 56′ 15.06″	38° 17′ 18.72″
AT20	23° 56′ 47.82″	38° 17′ 8.64″
AT21	23° 56′ 48.90″	38° 17′ 8.58″
AT22	23° 57′ 56.34″	38° 16′ 30.84″
AT23	24° 0′ 22.20″	38° 14′ 31.32″
AT24	24° 2′ 2.16″	38° 13′ 13.08″
AT25	24° 3′ 42.96″	38° 12′ 4.80″
AT26	23° 48′ 15.2388″	38° 19′ 32.9988″
AT27	23° 53′ 18.988″	38° 17′ 49.0416″
AT28	23° 53′ 14.86″	38° 17′ 47.80″

Submerged tidal notches were correlated and the past sea level positions were nearly dated based on ^{14}C datings from sedimentological data of drillings in nearby locations. Due to the fact that the tidal notches found in the study area were submerged or slightly emerged, fossils were subjected to wave erosion and bioerosion, which is high in this zone, and thus it was not possible to be preserved. Submerged notches cannot be dated directly in the absence of other nearby datable sea-level indicators as bioerosion rapidly destroys submerged fossils, making the collection of samples to be dated almost impossible (Evelpidou and Pirazzoli, 2014). The possible duration of notch development was estimated from the inward depth, assuming that the average intertidal bioerosion rate could have varied between a minimum of 0.2 mm/a and a maximum of 1 mm/a (Evelpidou et al., 2011b). The assumption is based on micro-erosion measurements that have shown that the deepening rate of a tidal notch profile may be very variable in the Mediterranean, ranging from less than 0.1 mm/a to more than 1 mm/a, with averages of the order of 0.2–0.3 mm./a at some sites (Pirazzoli, 1986; Furlani et al., 2011a,b; Evelpidou et al., 2011b).

In an attempt to date the uplift, a shell of *Patella* sp. was sampled at 50 cm above SL for ^{14}C dating. The shell was selected at site AT15.2 on the east part of Kynosoura peninsula, in Marathon bay. It was found in an almost vertical carbonate cliff, which was part of a cave, inside a narrow fissure. The patella was cemented by stalagmite material. Part of the cave been recently collapsed and probably that was the reason it was possible to find the Patella. It should be noted that this was the only sample found in the rocky part of the study area for dating.

The sample was analyzed by the CEDAD AMS laboratory of the University of Salento, for ^{14}C dating using AMS radiocarbon method. The conventional radiocarbon age of the sample was converted into calendar years by using the software OxCal Ver. 3.5 based on the last marine dataset (Reimer et al., 2013) and using a ΔR value of 158 ± 40 as measured close to Zante (Reimer and McCormac, 2002).

3. Results

Uplifted and submerged notches were identified in the coastal

Table 2
Significant sizes of tidal notches in East Attica.

Site	Notch name	Roof depth from SL (cm)	measured value vertex depth from apparent SL	Corrected vertex depth from MSL	Height (cm)	Inward depth (cm)	Possible duration of development (centuries)	Illustration	Shoreline Regional sea-level correlation (cm in relation to the MSL)
AT1	AT1.1		+14	+2	27	13	1.3–6.5		
	AT1.2		−25	−38	28	29	2.9–14.5	Fig. 2	−40 ± 30
AT2	AT2.1		+18	+5	73	67	6.7–33.5		
AT3	AT3.1	−102	−111	−124	18	9	0.9–4.5	Fig. 3	−130 ± 30
AT5	AT5.1		+12	−1	30	27	2.7–13.5		
AT10	AT10.1		−31	−27	18	19	1.9–9.5		−22 ± 30 (modern?)
	AT10.2	−22			200	nm			
AT11	AT11.1		−61	−58	22	16	1.6–8		−60 ± 30
AT13	AT13.1		+20	+22	55	40	4–20		+24 ± 30
AT14	AT14.1		+23	+24	36	45	4.5–22.5	Fig. 4	+24 ± 30
AT15	AT15.1		+23	+26	36	45	4.5–22.5		+24 ± 30
	AT15.2		+50 (*Patella* sp.)						+40±??
AT16	AT16.1		−130	−127	32	8	0.8–4		−130 ± 30
	AT16.2		−460	−457	109	17	1.7–8.5		−460 ± 30
AT17	AT17.1		+23	+26	36	45	4.5–22.5		+24 ± 30
AT18	AT18.1	+23	+11.5	+18	23	43	4.3–21.5		+24 ± 30
	AT18.2		−70	−64	39	8	0.8–4		−60 ± 30
AT19	AT19.1		+14	+19	34	30	3–15		+24 ± 30
AT20	AT20.1		+14	+22	39	22	2.2–11		+24 ± 30
AT21	AT21.1		+18	+24	36	26	2.6–13		+24 ± 30
AT22	AT22.1		+15	+23	26	21	2.1–10.5		+24 ± 30
	AT22.2		−25	−17	22	10	1–5		−22 ± 30 (modern?)
	AT22.3		−92	−84	20	10	1–5		−80 ± 30
AT23	AT23.1		+13	+21	21	29	2.9–14.5		+24 ± 20
	AT23.2		−25	−17	18	14	1.4–7		−22 ± 30 (modern?)
AT24	AT24.1		+23	+31	20	81 (visor)			+24 ± 30
AT25	AT25.1		+16	+21	34	26	2.6–13		+24 ± 30
AT26	AT26.1		+30	+27	70	38	3.8–19		+24 ± 30
AT27	AT27.1		+24	+24	46	41	4.1–20.5		+24 ± 30
AT28	AT28.1		+41	+42	39	18	1.8–9		+40 ± 30

nm = not measured.

zone from Porto Rafti up to Oropos (Fig. 1). Table 1 indicates all studied sites, while Table 2 includes information regarding notch measurements at each site, the possible range of duration of its development and a tentative regional sea level correlation. No evidence was detected of a present-day tidal notch, in agreement with Evelpidou et al. (2012b), who have stated that the possibilities of intertidal bioerosion are exceeded by the rate of global sea level rise during the 19th and 20th century exceeds resulting to the absence of development of a present-day notch.

Table 3 presents the results of the ^{14}C method which was used in order to date the collected sample. The shell (*patella sp.*) was found at about +50 cm (AT15.2) at Kynosoura Peninsula (Marathon) and was dated at 2755 ± 25 Conv BP.

4. Discussion

Eight fossil shorelines were deduced in the study area (Table 2). Two emerged shorelines were deduced at about +24 ± 30 and +40 ± 30 cm, and six submerged ones at about −22 ± 30 (modern), −40 ± 30 (Fig. 3), −60 ± 30, −80 ± 30, −130 ± 30 (Fig. 4) and −460 ± 30 cm.

The presence of both submerged and uplifted tidal notches testifies to a rather complicated tectonic history for the study area. According to the observed notches, Holocene vertical movements of subsidence have repeatedly affected the area, while evidence of emergence also exists.

Submerged notches that can be considered as “modern” were observed at depths between -17 and -27 cm, in at least three sites (−27 cm at AT10.1, −17 cm at AT22.2 and −17 cm at AT23.2). The “modern” term is used owing to the fact that at least part of its submergence can be ascribed to the global sea-level rise of about 20 cm that occurred during the 19th and the 20th century (Evelpidou et al., 2012b; Pirazzoli and Evelpidou, 2013). It should, however, be noted that the theory of Evelpidou et al. (2012b) has brought about an ongoing debate. In particular it triggered some arguments from Antonioli et al. (2015, 2016) who attempted to evaluate this theory by studying 73 sites in Italy and central Mediterranean and concluded that tidal notches are developed today, challenging the theory. However, Evelpidou and Pirazzoli (2015) commenting on the aforementioned research argued that the sites studied show different genetic backgrounds and in most cases refer to erosional notches rather than tidal notches. Antonioli et al. (2016), replying to Evelpidou and Pirazzoli (2015), stood to their points considering most of the studied notches as tidal notches, concluding also that a lot of work is still needed on tidal notches and their development.

The presence of the modern notch at slightly smaller depths towards the north may suggest that this part of the study area might has been affected by the 1938 event in Oropos, where coastal emergence was reported near Kalamos (Goldsworthy et al., 2002). On the south of the study area, no tidal notch was identified in the aforementioned depths, but at site AT1.2 a tidal notch was found at about −40 ± 30 cm. Considering that the north and south part of the study area demonstrate a rather different tectonic behavior, could the shoreline at about −40 ± 30 cm be considered as remnant of a “modern” tidal notch? Such a case implies that this notch was affected by a recent co-seismic subsidence event.

Uplifted fossil shorelines are mainly detected on the north part of the study area. The uppermost fossil shoreline (AT15.2), identified through a shell (*patella sp.*) collected at +50 cm (AT15), is dated at 2755 ± 25 Conv BP. This fossil shoreline coincides with shoreline AT28.1 at about −40 ± 30 cm. *Patella* is a limpet grazing endolithic microflora, characteristic in the Mediterranean of the inter- and supratidal zones; in sheltered sites it can live between the mean low water level and MSL, while on exposed sections it can live between MSL and the mean high water spring level (Torunski, 1979, Fig.8). According to the exposure of site AT15 and the local tide, it can be considered a good indicator of a former sea-level at about +40 cm, with an accuracy of ±30 cm. The shell of Patella was found cemented by stalagmite material in a narrow fissure of a vertical carbonate cliff, which was part of a collapsed cave. As discussed in Shaw et al. (2010) cementation can alter the age, showing it younger than the real age. In the case of Marathon area, unfortunately it was the only dating material found, so it should be considered that the uplift of the former coastline of +40 ± 30 cm took place earlier of 2755 ± 25 Conv BP.

A marine gastropod (*Murex* sp.) that was found in a core at depth 65 cm below sea level (Triantaphyllou et al., 2010) at Vravron area was dated at approximately 305–516 yr BP (1434–1645 AD). The depth of the sample corresponds to the fossil shoreline at about −60 ± 30 cm (AT11.1, AT18.2), indicated by a tidal notch at Marathon. Since *Murex* sp. may live several meters below the

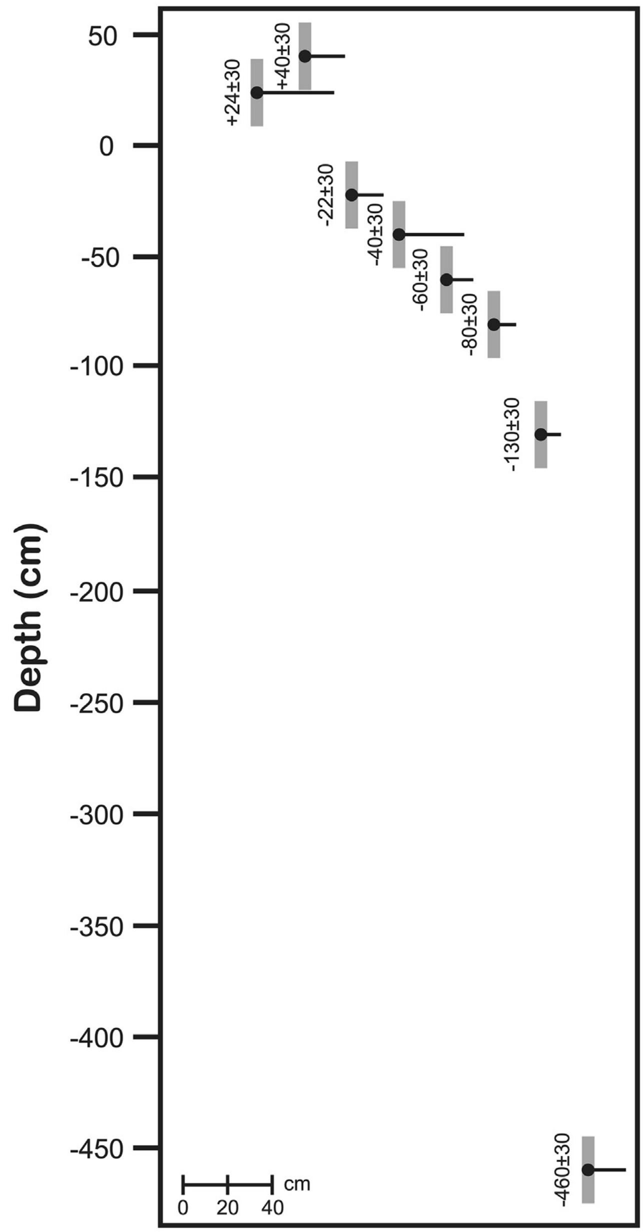

Fig. 2. Paleoshorelines, as deduced from tidal notches. The grey vertical line represents the error and the horizontal line the inward depth.

Table 3
Radiocarbon age for the dated sample, calibrated.

a/a	Lab code	Height above sea level (m)	Material	$\delta^{13}C$ (‰)	Conventional R/C age (yrs BP) ($^{13}C/^{12}C$ corr.)	2σ calibrated age (95.4% probability)
1	LTL13507A	+0.5	Shell	+3.0 ± 0.6	2755 ± 25	440 - 170 Cal BC

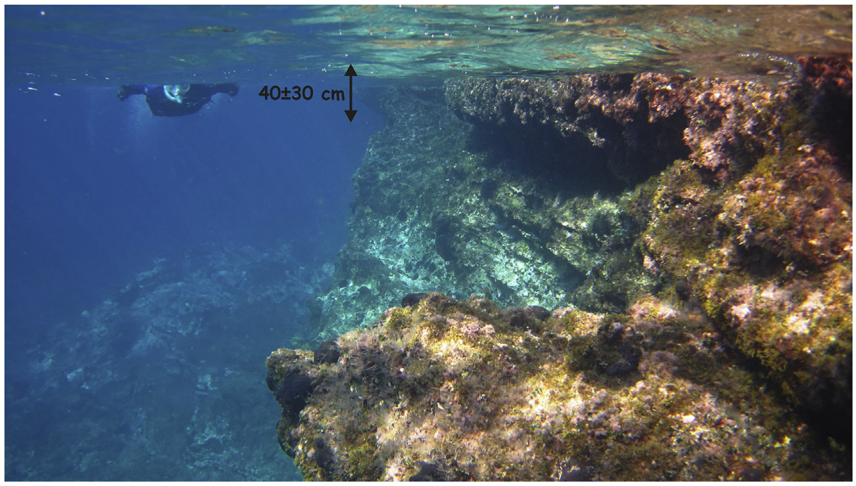

Fig. 3. Submerged shoreline at about -40 ± 30 cm at AT1.2. The upper part of the arrow starts from SL.

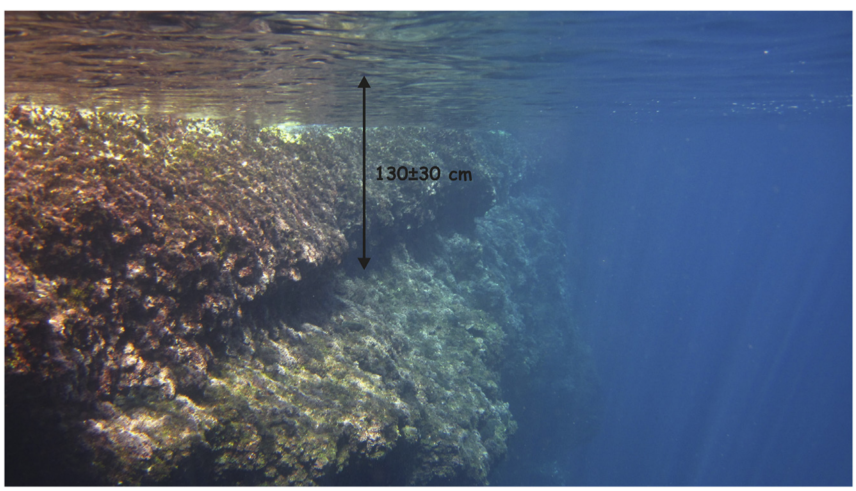

Fig. 4. Submerged shoreline at about -130 ± 30 cm at AT3.1. The upper part of the arrow starts from SL.

shoreline, it can only indicate that the fossil shoreline at about −60 ± 30 cm is younger than 305–516 yr BP (1434–1645 AD).

In addition, the deepest shoreline at about −460 ± 30 cm (AT16.2), deduced from a tidal notch may be tentatively dated less than 4579–4848 yr BP (2899–2630 BCE), based on a marine gastropod (*Murex* sp.) found at 4.78 m below sea level from Triantaphyllou et al. (2010).

The profile of tidal notches observed in the study area suggests that subsidence was not always gradual but that co-seismic events have occurred in the area after 305–516 yr BP and slightly before 4579–4848 BP.

Additionally, one may distinguish a rather different tectonic behavior between the south (AT1-AT5) and north (AT10-AT28) part of the study area. On the north part, clear evidence exists on alternating subsidence and uplift events, as attested by two uplifted notches at +24 cm (Fig. 5) and +40 cm. On the south part, partly emerged tidal notches were identified at maximum heights of +5 cm; this could imply that the area was affected by a subsidence event that brought this formerly uplifted notch to its present elevation. This would also be in agreement with the observations of the notch found at about −40 cm (AT1.2).

Unfortunately, recent earthquakes are not well documented for the study area, and existing data only provide information for the north part near Chalkis area, where two earthquakes have been recorded at 1694 with Ms = 6.2 and at 198 BCE with Ms = 6.6. Following the historical catalogue, no large events (Ms > 6.5) or severe damages have been recorded in NE Attica (Galanopoulos, 1955; Papazachos and Papazachou, 1997). The historical record is considered complete for shallow events (h < 60 km) for Ms > 6.5 since 1845 and for Ms > 7.3 since 1500 (Papazachos et al., 2000). According to Papanikolaou and Papanikolaou (2007), it is possible that an earthquake of Ms = 6.0 to 6.4 could have occurred before the year 1845 and for several reasons has not been recorded.

Fig. 5. Emerged shoreline at about +24 ± 30 cm located at site AT14.1. The lower part of the arrow starts from SL.

5. Conclusions

At least two uplifts and six subsidence events were identified in the area from Porto Rafti to Oropos. The highest uplifted shoreline is found at about +40 ± 30 cm, while the deepest fossil shoreline reaches −460 ± 30 cm. The presence of uplifted and submerged tidal notches at different elevations suggests a rather different tectonic behavior of the south part in relation to the north. Clear evidence of uplift alternating with subsidence exists in the north part, where the uppermost shoreline is dated at about 2755 ± 25 Conv BP, while in the south the evidence of uplift are very slight.

A correlation of the fossil shorelines with coastal drillings in nearby locations suggest that co-seismic events have occurred in the area, at least, around after 305–516 yr BP and slightly before 4579–4848 BP.

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