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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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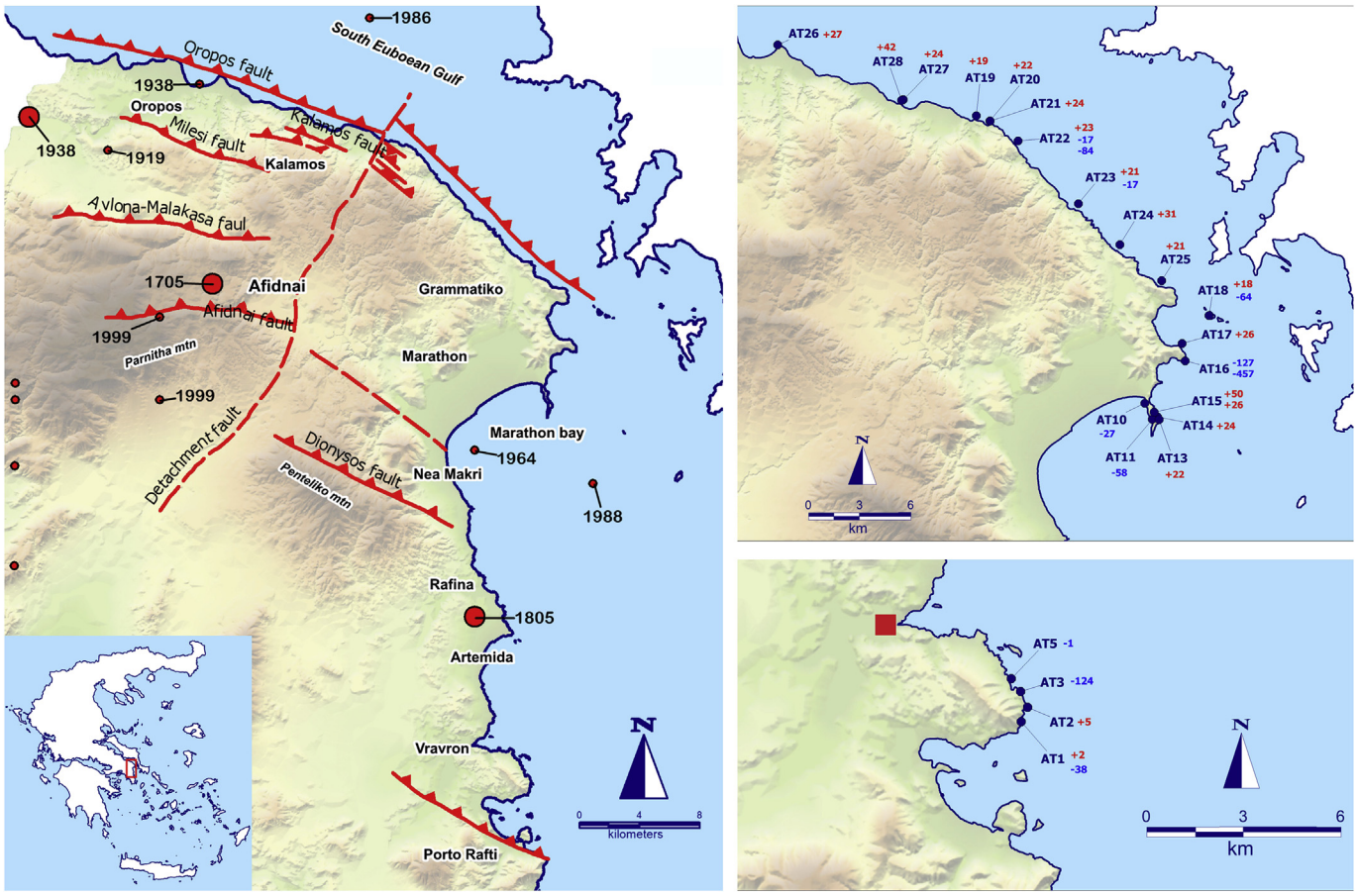


**Fig. 1.** Surveyed area. Measurements and characteristics of the sites depicted in this map are listed in Tables 1 and 2. Drillings location is indicated by a red square. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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.