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Late Holocene shorelines deduced from tidal notches on both sides of the Ionian Thrust (Greece): Fiscardo peninsula (Cephalonia) and Ithaca island

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ABSTRACT

Fossil shorelines produced by recent co-seismic movements were identified through a submarine survey along the coasts of Ithaca and Fiscardo (Greece). In both areas a tidal notch-slightly submerged below present Mean Sea Level (MSL) was observed at various sites. This "modern" notch is known to have been submerged by the global sea-level rise during the 19th and 20th centuries. The depth after tide and air-pressure correction of the vertex of the "modern" notch (that owes its submergence to the current rapid sea level rise) was measured between -20 and -30±5cm at Fiscardo and between -36 and -45±6cm at Ithaca. This "modern" notch at the same depth on east and west sides of the Ionian Thrust suggests that both areas were not affected by the co-seismic vertical movements that occurred in 1953 (in the wider area). On the other hand, a greater depth in Ithaca could be an effect of co-seismic subsidence. Over the long term, the tectonic behavior of Ithaca differs from Fiscardo. At Ithaca no evidence of emergence was found and Holocene vertical movements have been only of subsidence: submerged fossil tidal notches were distinguished below MSL at about -40 (modern), -60, -75, -95, -106, -126, -150 and -220±6cm. On the East coast of Fiscardo peninsula impacts of ancient earthquakes have left some marks of emergence at about +18 and +44±5cm, and of submergence at about -25 (modern), -45, -60, -75, -82, -100 and -230cm, with even some evidence of past uplift and subsidence at the same sites.

KEYWORDS **Tidal notches. Palaeoseismology. Sea level changes. Ionian.**

INTRODUCTION

Significant advances in sea level research have been accomplished through the use of long-term data sets, such as tide gauges, and more recently satellite altimetry. For pre-instrumental times, field observations of palaeoshorelines are a powerful "tool" to reconstruct sea-level changes. Various markers of past sea level, such as geomorphological (*e.g.* Desruelles *et al.*, 2004; Antonioli *et al.*, 2006; 2007; Furlani *et al.*, 2011; Vacchi *et al.*, 2012), sedimentological (*e.g.* Edwards, 2006; Kemp *et al.*, 2011), archaeological (*e.g.* Blackman, 1973, 2005; Flemming and Webb, 1986; Lambeck *et al.*, 2004; Auriemma and Solinas, 2009; Anzidei *et al.*, 2011a, b) or biological (*e.g.* Laborel and Laborel-Deguen, 1994) can be distinguished. They may all provide valuable information in the research on relative sea level changes when their relation to sea level is well established.

However, these markers may represent either rapid or slow sea level changes, depending on whether the fluctuation is due to tectonic activity or ice melting and eustasy (Pirazzoli, 1996). In some areas of the world, such as the Mediterranean, sea level indicators may represent a combination of both causes.

Marine notches are coastal recesses extending along marine cliffs. They owe their development to various chemical, physical, biological or mechanical processes. Many types of marine notches can be distinguished, depending on their shape and origin: structural notches, lithological notches, abrasion (wave-cut) notches, infralittoral, supralittoral and midlittoral notches (Pirazzoli, 1986). Amongst the various notch types, tidal notches, surf notches and solution notches in the midlittoral zone can be useful as sea-level indicators.

In the case of surf notches, when a bioconstructed accretion exists near the notch floor, indications on the former sea-level may be provided by the organic accretion rather than the notch developed above it. Solution notches are frequent in carbonate rocks near the sea level. According to Higgins (1980), solution notches in calcareous rocks occur only in proximity to coastal springs, where surface seawaters are locally diluted by freshwater.

Tidal notches are well known as precise sea level indicators that usually undercut limestone cliffs in the mid-littoral zone (*e.g.* Pirazzoli, 1986). They constitute the most important erosional geomorphological sea-level indicators in microtidal areas, when the wave action is weak. Tidal notches owe their development to the higher rates of bioerosion near the Mean Sea Level (MSL), rather than the upper and lower limits of the intertidal range. The profile of a tidal notch is an excellent sea-level indicator, providing information on the duration in which MSL remained near the level of the notch vertex. In addition if the notch is emerged or submerged, its profile provides information on the speed (slow or rapid) of its emergence or submergence (Pirazzoli, 2005). Tidal notches can provide valuable information on past sea level positions or they can allow the identification of palaeoseismic events (*e.g.* Pirazzoli *et al.*, 1994; Nixon *et al.*, 2009; Stiros *et al.*, 2000, 2009; Evelpidou *et al.*, 2012a, b, c). In microtidal areas sheltered from wave action, elevated or submerged (tidal) notches are used to indicate former sea-level positions, with up to decimeter confidence.

Although the lateral continuity of emerged notches can generally be easily followed in the field, this is usually not the case underwater. It has been shown by Pirazzoli and Evelpidou (2013) that if fossil tidal notches are well marked on certain rocks they may be absent from nearby sites with the same rock and exposure. Raised notches, sometimes associated with marine terraces or reef tracts, have often been used to estimate past changes in sea level and tectonic movements (*e.g.* Pirazzoli *et al.*, 1982; Stiros *et al.*, 2000; Morhange *et al.*, 2006); however, submerged notches, which are more difficult to observe, have been studied only occasionally by a few authors. Such underwater observations have been devoted most of the time to the measurement and interpretation of a single submerged tidal notch (*e.g.* Fouache *et al.*, 2000; Benac *et al.*, 2004; Nixon *et al.*, 2009).

Holocene tectonics may include more than a single episode and it would be useful to extend underwater observations below the first submerged notch. This seems to have been attempted only in very few cases *e.g.* in the Kvarner region, where Benac and Juračič (1998) reported a second submerged tidal notch at a depth of -19m (that they tentatively ascribed to a period of possible temporal sea-level stagnation during the Würm-Holocene transgression).

Evelpidou *et al.* (2011) have shown that two submerged tidal notches can be identified along most of the northern coast of the Corinth Gulf (Evelpidou *et al.*, 2011) and along the coast of Skyros island (Evelpidou *et al.*, 2012a). A similar analysis has revealed that as many as six submerged shorelines can be identified along the coast of the Sporades island (Evelpidou *et al.*, 2013a), while at least seven former shorelines can be identified at depths between 280±20 and 30±5cm below modern sea level in the SE Cyclades (Evelpidou *et al.*, 2013b). In all the studied cases, the vertical succession of submerged notches suggests the occurrence of rapid subsidence events, potentially of seismic origin.

In this paper new evidence is brought to light concerning the modality of subsidence and/or uplift in Ithaca island and

Fiscardo peninsula (Cephalonia) through the study of tidal notches in an attempt to understand the Upper Holocene relative sea level changes.

STUDY AREA

The study area, Fiscardo peninsula (Cephalonia island) and Ithaca island, is located in the western Hellenic arc (Ionian Sea, Greece), one of the most active seismic regions worldwide. Seismic events are frequent with magnitudes reaching Mw=7.2, with those of 1867 and 1953 being two of the most destructive. Other large historical events, according to historical macroseismic descriptions, are those of 1469, 1636, and 1767 (Papagiannopoulos *et al.*, 2012).

The study area consists mainly of carbonate rocks. Both Ithaca and Cephalonia are characterized by the presence of alpine as well as Plio-Quaternary formations (Georgiadou-Dikaioulia, 1965; British Petroleum Co. *et al.*, 1985; Stavropoulos, 1991). Alpine formations belong to the external units of the Hellenides; the Paxoi Unit, which forms most of Cephalonia and the Ionian Unit, which forms all of Ithaca (Lekkas *et al.*, 2001). Cephalonia island is composed mainly of limestones, while Neogene deposits are mainly found in the southern part of the island. Ithaca island is composed exclusively of limestones. In the northern part of Cephalonia, around Fiscardo peninsula, the carbonate rocks are mainly thin bedded pelagic, while in Ithaca island limestones thick-bedded clastic, medium-bedded and limestones thin bedded with silex exist.

A previous survey in the 1990s has shown that no evidence of continuous, submerged tidal notches existed around Ithaca. Therefore, we tried to identify isolated sections of tidal-notch profiles along the coasts of Ithaca and Fiscardo, which could subsequently be correlated at certain depths and we measured and mapped only when there was geographical continuity.

In Cephalonia island, vertical displacements, including evidence of coastal uplift, have been reported by Pirazzoli *et al.* (1994) and Stiros *et al.* (1994). According to Stiros *et al.* (1994), an uplift of 30–70cm in the central part of the island is associated with the 1953 earthquake, while evidence of an older shoreline uplifted at +1.2m was noted in the southern part of the island, corresponding to a vertical displacement between AD 350 and 710 (Pirazzoli *et al.*, 1994). However, no uplifted shorelines, associated with the 1953 earthquake, were noted on Fiscardo peninsula in the northern part of the island.

Ithaca island was also affected by the event of 1953 (Grandazzi, 1954; Stiros *et al.*, 1994; Pirazzoli *et al.*, 1994), however no evidence of uplift was reported. Subsidence is considered to predominate around Ithaca (Stiros *et al.*, 1994; Pirazzoli *et al.*, 1994).

METHODS

A detailed survey along the coastal zone of Ithaca island took place during 2012 and along Fiscardo peninsula (Cephalonia) during 2012 and 2013. The sites measured at Cephalonia island were revisited in June 2014 in order to check for possible vertical changes after the earthquakes of early 2014.

All coasts (Fig. 1) were systematically surveyed in detail by snorkeling and diving, using a boat in order to access all sites and establish the continuity of observations. Former sea-level positions were deduced from sea-level indicators, such as emerged and submerged tidal notches. Elements of notch geometry *e.g.* height, inward depth and vertex depth from sea level (Fig. 2) were measured according to Pirazzoli (1986) and Evelpidou *et al.* (2012b). Several measurements were performed at each location to improve their accuracy.

An interpretation of the way the relative sea level has changed was attempted based on the profiles of the notches.

FIGURE 1. Surveyed area. Dots represent the sites discussed in the text and listed in Tables II and III. Site names are also shown in this map, while the measurements and characteristics of each of these are listed in Tables II and III. Different lines depicted in this map correspond to the main faults in the study area, based on Sorel (1976) and Stiros *et al.* (1994). Specifically, AEF is the Agia Ephemia Fault and its inferred extension offshore, a major active reverse fault, KAF is the Kalon Anticline Fault, satellite fault in the hanging wall of the main fault and IT is the Ionian Trust.

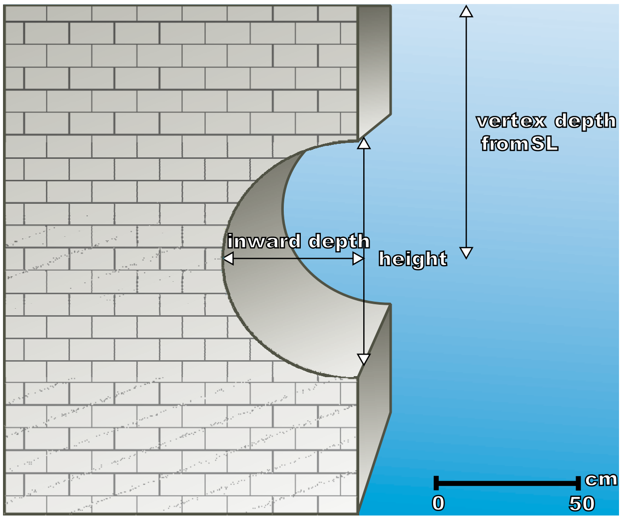

FIGURE 2. Notch geometries measured during fieldwork.

Figure 3 depicts the different types of tidal-notch profiles located in the study area. The maximum bioerosion rate is assumed to be 0.5mm/yr and the tidal range 20cm. A period of 2000 years was considered with the relative sea level stable or rising at a rate smaller than the bioerosion rate, followed by a recent short period of sea-level rise at a rate faster than the bioerosion rate. The most recent continuous sea level rise has resulted to the absence of a present-day notch. Type a: a reclined U-shaped notch profile, of approximately 1m inward depth, which was preserved after a rapid uplift movement greater than the tidal range. Type a': a reclined U-shaped notch profile, of approximately 1m inward depth, which was preserved underwater after a rapid subsidence movement greater than the tidal range. Type b': two submerged former notches, which were preserved after two rapid subsidence movements greater than the tidal range. Type d': a notch higher than the tidal range, of limited inward depth, due to a gradual sea-level rise, at a rate smaller than the bioerosion. Type e': a notch with Hr<Hf and a height greater than the tidal range, corresponding to a gradual sea-level rise of 0.3mm/yr during one millennium, followed by relative sea-level stability. Type e'': a notch with Hr>Hf, and a height greater than the tidal range, corresponding to a relative sea-level stability, followed by a gradual relative sea-level rise.

Based on the measurements of the inward depth, a possible duration of development for the tidal notches was calculated. The time required for tidal-notch profiles to develop depends mainly on the local bioerosion rate, which varies with the rock type and the local climate. Laborel *et al.* (1999) have roughly estimated rates of the order of 1mm/a, however this is only a first order value. Lower rates are generally observed in hard limestones, especially in non-tropical areas. Other detailed estimations provide a range varying from 0.2 to 5mm/a, depending on lithology, location, and probably duration of bioerosion (for references, see Pirazzoli, 1986, table I; Laborel *et al.*, 1999, table 1; Evelpidou *et al.*, 2011). In order to estimate the possible duration of development for the observed tidal notches we considered a minimum and a maximum value of bioerosion, of 0.2mm/a and 1mm/a respectively (see also Evelpidou *et al.*, 2011). Recently, when measuring the inward depth of a well dated tidal notch in Cephalonia developed between the 4th–6th century AD and 1953 AD, it was found that the average intertidal bioerosion rate had been 0.64mm/a during this period.

Hourly tidal records from a nearby tidal device were provided by the Hellenic Navy Hydrographic Service (HNHS) with a proposed MSL= 0.42m. This hourly record was used to deduce tide corrections for Ithaca measurements. Verification of the meteorological conditions in the area at the time of measurements have shown that the air pressure was relatively high (implying a sea-level correction of about 5cm) without significant wind (and waves), based on the records of the nearby Andravida airport, by Russian site "Russia's weather Server". This permitted an accuracy of ±5cm in depth measurements below the apparent sea level. Most of the corrections suggest that the depth measurements in Ithaca should be slightly increased.

The tidal station of Lefkas (Station ID 1239) was active during the period of measurements in Cephalonia. Tide corrections were computed (including the effects of air pressure) for all our measurements in relation to the apparent sea level by using a value of 0.52m for the MSL, which corresponds to the average hourly sea level during a sufficiently long period of average "normal" air pressure (*i.e.* close to 1013 millibars). This allowed estimating the depth or elevation in relation to MSL of the vertices of all the fossil notches observed around Fiscardo peninsula, with an accuracy of ±5cm.

RESULTS AND DISCUSSION

Eight fossil shorelines were identified on Ithaca island (Tables I; II). Holocene vertical movements seem to have been only of subsidence, with no evidence of emergence found. Shoreline A is at about -60±6cm (Fig. 4A), shoreline B at about -75±6cm, shoreline C at about -95±6cm, shoreline D at about -106±6cm (Fig. 4), shoreline E at about -126±6cm, shoreline F at about -150±6cm and shoreline G at about -220±6cm (Table II).

Tables II and III show the notch measurements at each site, the possible duration of development extracted from the inward depth, a possible genesis interpreted by the

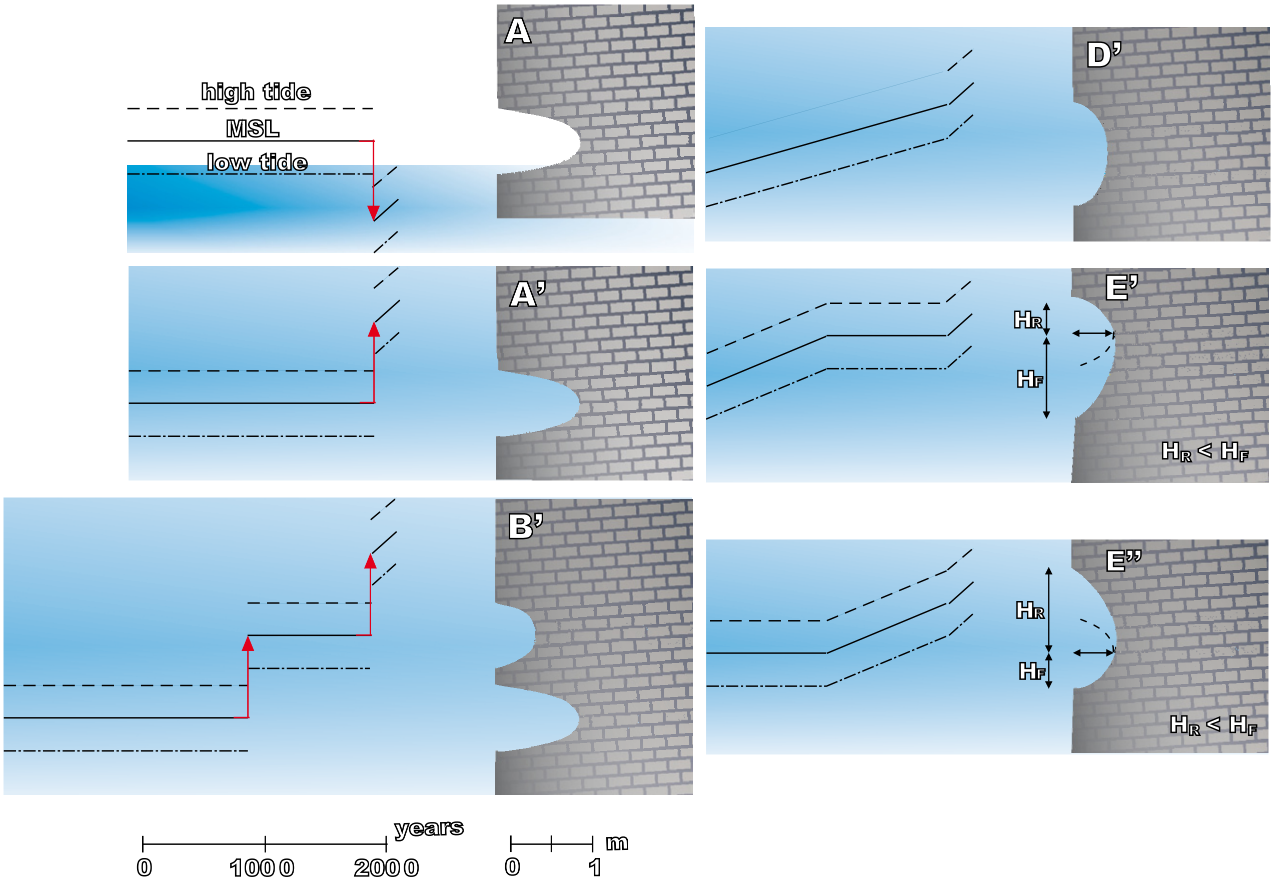

FIGURE 3. Different types of tidal-notch profiles located in the studied area.

notch profile and a tentative regional sea level correlation for Ithaca island and Fiscardo peninsula, respectively.

In Table III, it can be observed that submerged "modern" notches at a depth of -20 to -30cm occur in at least four sites (-30cm at KE5.1, -20cm at KE37.1, -23cm at KE40.2 and -25cm at KE41.1). In Fiscardo peninsula, two emerged shorelines have been identified, at about +18cm (Fig. 4B) and +44±5cm, and seven submerged ones at about -25±5 (modern), -100±5 (Fig. 5C), -45±5, -60±5, -75±5, -82±5 (Figs. 6; 7; 8) and -230±5cm.

The first submerged notch, both in Ithaca and Fiscardo, appears to be of a' type in terms of genesis, suggesting that the recent sea level rise was more rapid than the rates of intertidal bioerosion. The "modern" notch is of d' type at only one site (KE5.1), with a height of 69cm, larger than the tidal range. This suggests that the rate of gradual sea-level rise was smaller than the bioerosion. This site is located on the edge of the KAF fault (see Fig. 1), while a detailed geological map reveals also the possible existence of another fault just offshore, in this area.

In Ithaca, it can be observed from Table II, that most of the tidal notches are of type e', with a few exceptions (ITH1.3, ITH6.1, ITH11.1, 15.3, 16.1). This suggests that the observed notches have a floor height larger that the roof height and a height greater that the tidal range, corresponding to a gradual sea-level rise, followed by relative sea-level stability. In addition, the average inward depth of the aforementioned notches is about 15cm and their average height is about 45cm.

In Fiscardo, shorelines A, B and C are mainly of type d', indicating a gradual sea-level rise, at a rate smaller than the bioerosion during their formation. The notches of d'type have an average height of about 60cm, while their average inward depth is about 20cm. Shoreline D is of type d', e' or e'' and has been mapped throughout all Fiscardo peninsula. Shoreline E, at about -100±5cm, is probably of type a' and is located only on the East part of Fiscardo peninsula. The deepest shoreline, F, is only traceable on the North tip of Fiscardo peninsula.

The shallower shoreline was found at about -40±6cm in Ithaca and it could possibly be considered as "modern". This term is based on Evelpidou *et al.* (2012c) and Evelpidou *et al.* (2013a), meaning that the notch was forming until the beginning of the 20th century, owing at

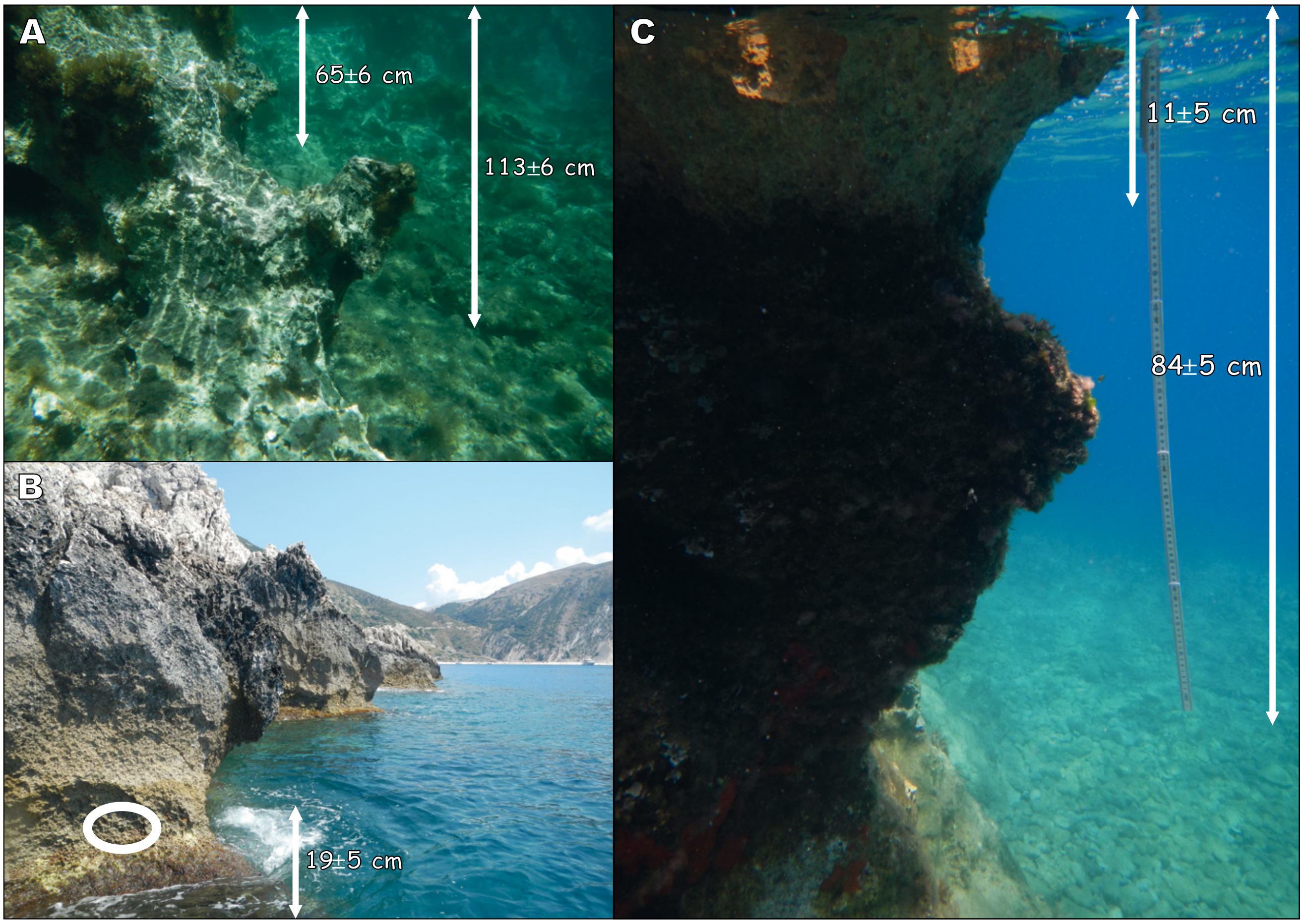

FIGURE 4. A) Shoreline E at Ithaca island at about -113±6cm located at site ITH11.2. Shoreline Ais also visible above shoreline E at about -65±6cm. The upper part of the arrow starts from Sea Level (SL). B) Emerged shoreline at about +19±5cm located at site KE39.2. C) Submerged shoreline at about -11±5cm at Fiscardo peninsula at KE4.2, while below another shoreline at about -84±5 is also visible (KE4.3). The upper part of the arrow starts from SL.

least part of its submergence to the recent rapid sea level rise. The fact that during the last two centuries the rate of global sea-level rise has become greater than the rate of marine intertidal bioerosion, which in the Mediterranean is generally reported between 0.2 and about 1.0mm/a (Pirazzoli, 1986; Laborel *et al.*, 1999; Evelpidou *et al.*, 2011), has prevented the formation of new tidal notches near present sea level (Evelpidou *et al.*, 2012c). Can the shallowest submerged tidal notches observed in Ithaca be considered as "modern"? Such a name is usually given to tidal notches that were submerged by 20 to 30cm due to the global sea-level rise during the 19th and 20th centuries at a rate exceeding the rate of intertidal bioerosion (Evelpidou *et al.*, 2012c; Pirazzoli and Evelpidou, 2013). Greater submergence can be ascribed to recent tectonic events.

Shoreline A in Ithaca has been identified by three notches, all of a' type, with an inward depth varying between 8 and 25cm; it can be deduced that prior to 1953 the relative sea level remained stable during at least a couple of centuries. However, it is not possible to provide similar deductions from the genesis and inward depth of the other measured notches.

On the East coast of Fiscardo peninsula a "modern" notch, at a depth that can be ascribed to the sea level rise during the 19th and 20th centuries, has been identified at several sites (see Table III). At Ithaca the identification of the shallowest submerged notches as "modern" suggests that vertical tectonic movements have occurred since its formation. This means that the area has been possibly affected by the co-seismic vertical movements (Ms=7.2) that took place in 1953 in the wider region. This event was one of the strongest recent earthquakes that have affected the area. According to Grandazzi's (1954) detailed report, the percentage of buildings damaged in the wider area exceeded 98%, while it was 70% for Ithaca and 90% for Cephalonia. According to his map, the degree of destruction both in Ithaca and Fiscardo peninsula was increased towards the South.

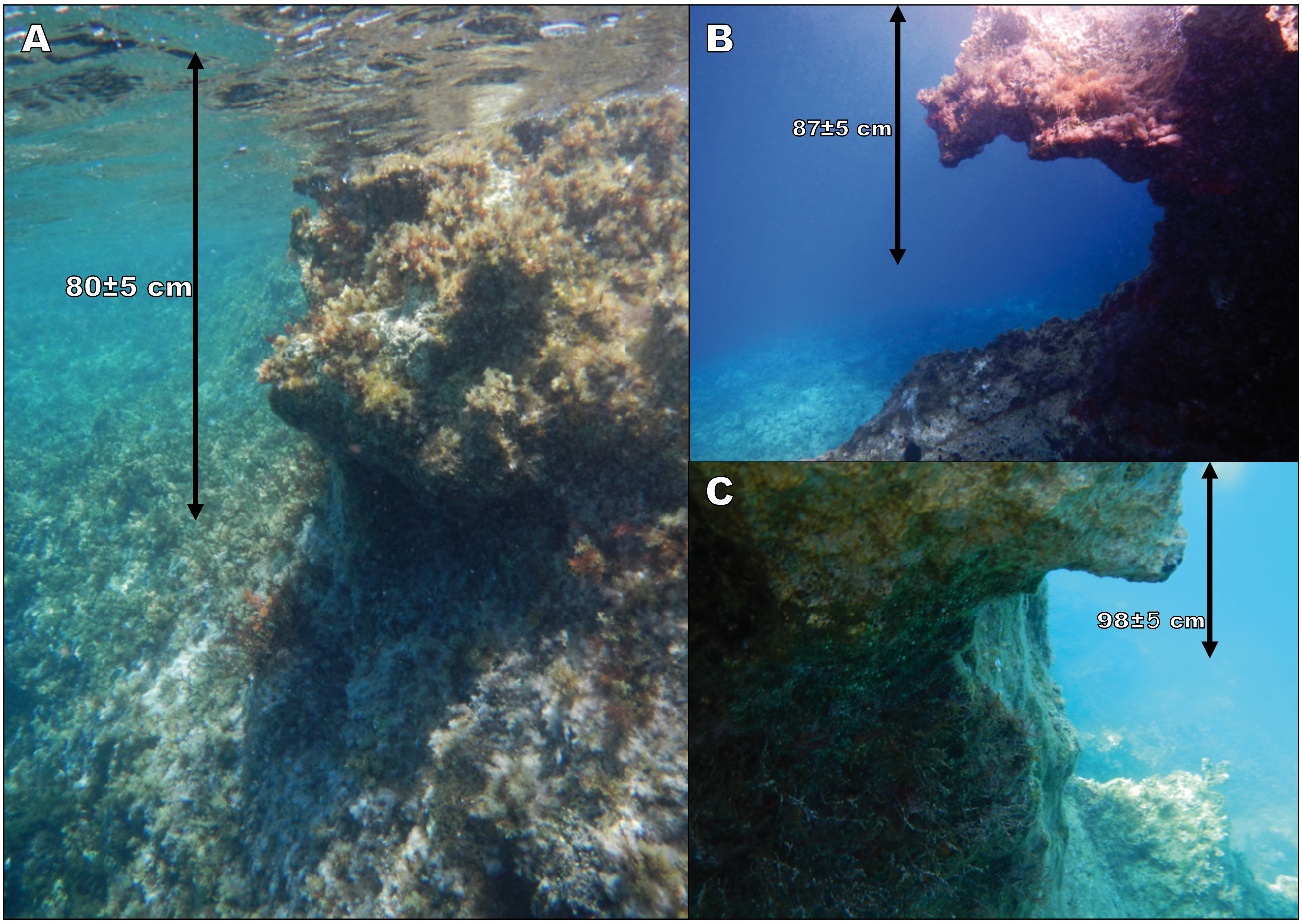

FIGURE 5. A) Submerged shoreline at about -80±5cm at Fiscardo peninsula at site KE36.2. The upper part of the arrow starts from SL. B) Submerged shoreline at about -87±5cm at Fiscardo peninsula at site KE42.2. A living sea urchin is hiding in its own hole just below the notch. C) Submerged shoreline at about -98±5cm at Fiscardo peninsula at site KE41.2. The upper part of the arrow starts from SL.

Measurements of the vertex depth below the apparent sea level of submerged notches at three sites in Ithaca (at -37cm at ITH2.1, at -45cm at ITH.3.1 and at -36cm at ITH15.1) revealed fossil erosion features that could, at first view, be considered as remnants of the "modern" notch, submerged 20 to 30cm by the global sea-level rise that occurred during the 19th and the 20th century (Evelpidou *et al.*, 2012c; Pirazzoli and Evelpidou, 2013), possibly increased from a coseismic subsidence in 1953.

Most of the corrections of measurements (Table II) suggest that the notch depths in Ithaca should be slightly increased. This indicates that the "modern" notch at Ithaca is deeper than its equivalent in Fiscardo, providing some evidence that a co-seismic subsidence has probably occurred at Ithaca since the formation of the modern notch, possibly at the time of the 1953 earthquakes.Furthermore, Holocene vertical movements at Ithaca seem to have been only of subsidence, with no evidence of emergence found. Some shorelines may have resulted from a tilting of the island.

Furthermore, there is evidence of earthquake-induced emergence and submergence on the East coast of Fiscardo peninsula. Alternations of uplift and subsidence have been also reported in the literature in various case studies from Greece, for example in Crete and Antikythira by Pirazzoli *et al.* (1982), in Rhodes by Pirazzoli *et al.* (1989) and in Samos by Stiros and Blackman (2014). In Table III, it can be observed that submerged "modern" notches at depths between -20 and -30cm are found in at least four sites on the Fiscardo peninsula (-30cm at KE5.1, -20cm at KE37.1, -23cm at KE40.2 and -25cm at KE41.1).This suggests, as confirmed by reports on the effects of the 1953 earthquakes, the absence of vertical tectonic movement at that time. No vertical changes have been noted after the recent destructive events in Cephalonia (26 Jan and 3 Feb 2014).

While all notches are found around Fiscardo peninsula, the shoreline at -100cm is only in the eastern part of Ithaca island (Site ITH6), opposite shoreline D. If the event that submerged the shoreline at -100cm had affected both Ithaca

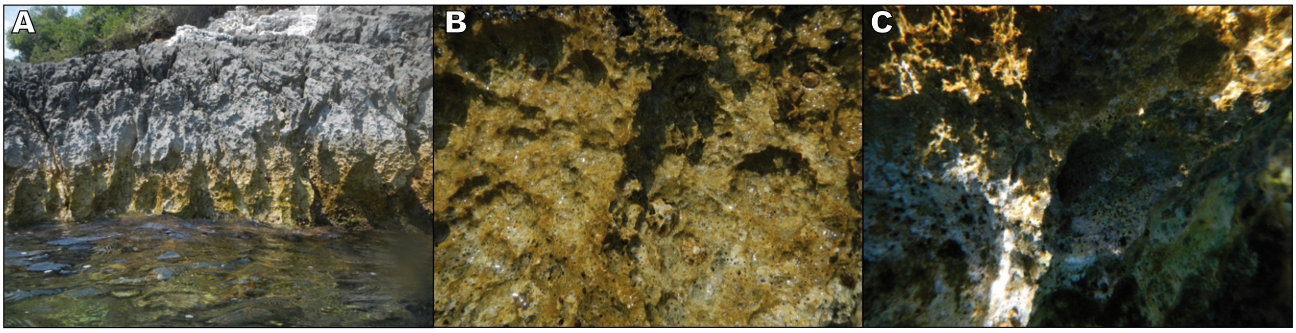

FIGURE 6. Overprinted bioerosion features – evidence of alternating subsidence and uplift events A) holes of subtidal boring bivalves overprinted by supratidal coastal karren; B) subtidal sea urchin boreholes emerged into the supratidal zone, overprinted by coastal karren; C) dark spot: subtidal sea urchin borehole as seen in the roof of uplifted marine notch. For more details see also Table 5.

and Fiscardo peninsula, it would have provoked a tilting towards Ithaca. On the other hand, the deepest shoreline at -230cm has only been recorded in the northern part of the peninsula. It is worth mentioning that some evidence of past uplift and subsidence exists at the same sites (Site KE1, Site KE40).

Assuming that the observed tidal notches are representative of a rigid behavior of the island, rather than of local tilting, the tectonic history of Ithaca before the 19th century (a RSL rise of 120±6cm during a period of 9.6 to 48.5 centuries), suggests an average subsidence rate of between 0.25 and 1.25mm/a (Table IV). By comparison, the average subsidence rate for the Gulf of Patras, calculated for the period 146-18ka BP by Lykousis (2009, Table I) is 0.90mm/a. In addition, the genesis of the notch profiles suggests that subsidence was far from gradual with the occurrence of a small co-seismic subsidence (notch type a' and b') during the late Holocene, before 1953 (Table II). Periods of slow gradual subsidence may also be deduced mainly for notch type d', *e.g.* from submerged shorelines B of Ithaca.

In detail, the average coseismic subsidence has been 15±6cm, with an average return time between 1.6 and 8 centuries (Table IV). Assuming a medium value of 0.6mm/a for the intertidal bioerosion rate, the average return period of subsidence coseismic events would be 2.7 centuries.

Bioerosional features were examined in order to make a preliminary interpretation of the sequence of events. In the absence of age markers, overprinted bioerosion features can describe alternating subsidence and uplift (Fig. 6; Table V) for a few of the very latest events. Overprinting of submerged intertidal notches with traces of sub-tidal boring sea urchins is obvious in Figure 4A, where living sea urchins are hiding in their own holes and empty holes are visible in the lower part of the image (the boring occurred after submergence). Overprinting of emerged notches by supratidal karrenis visible in Figure 4B, where the surface of the emerged notch in indurated limestone is exposed to surf, while the small, rounded, semicircular holes are probably former sea urchin boreholes (encircled), overprinted by surf karren, indicating a former subtidal depth.

Sea urchins live only sub-tidally; they cannot tolerate exposure above sea level, even for a short time. An approximately 20cm wide leafy green algal cover from sea level down to the barren rock surface, where grazing sea urchins keep algae away, indicates that these animals live at depths of -0.3m and more. Although preservation is moderate, the notch in Figure 4B illustrates a complex history of subsidence followed by uplift (Fig. 7): i) the notch was formed in the intertidal zone, ii) subsequent minor subsidence into the sub-tidal zone allowed a population of boring sea urchins to leave their traces. These are the semi-circular holes in the lower part of the notch (see the dark-shadowed hole in the middle Figure 4B), iii) uplift raised the notch above the intertidal zone. The current surface is exposed to surf, producing karren. Following emergence the notch has been shaped by wetting and drying, while

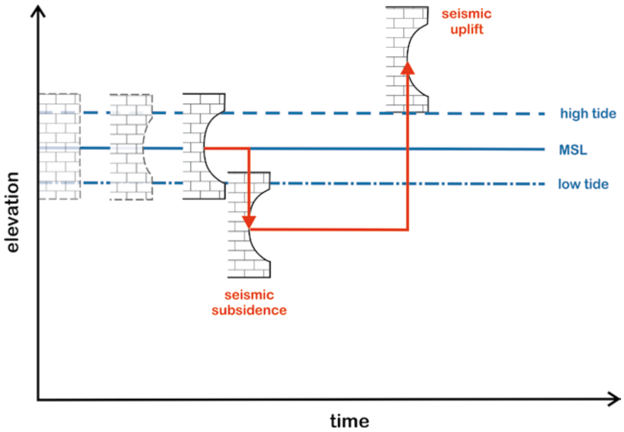

FIGURE 7. Development of tidal notch, followed by subsidence into the subtidal zone and then by uplift into the supratidal zone.

being grazed by numerous small littorinid snails (see Taboroši and Kázmér, 2013).

Regional differences between the notches in the study area have not been observed mainly because the lithology and the structure of the limestones are similar throughout the area.

A detailed examination of the geological formations of Ithaca reveals that the area is dominated by fine-grained and thin bedded limestones, thin-medium grained dolomitized limestones and limestones, and clastic limestones thick bedded to unbedded; however, these variations do not seem to have an impact in depth variations of the notches. On the other hand, the rock dip and strike may affect the slight depth differences observed in notches of the same "generation"; *e.g.* shoreline B located at about -75±6cm, at sites ITH12.1 (-80cm) and 15.2 (-69cm) is found on thick bedded to unbedded clastic limestones, but the dip is 25°WSW and 30°ENE, respectively. In the case of Fiscardo peninsula, the area is dominated by thin bedded pelagic limestones, with only a few appearances of well-bedded dolomites and limestones. The differences in notch depth and characteristics do not seem to be affected by lithology, but inclination may have an effect to a small degree. Differences in water turbulence, which would affect the bioerosion and chemical solution rate on the two sides of the Ionian Thrust, can be easily excluded.

There is no evidence of notch collapse in the region mainly because the notches are fairly shallow and the rocks are quite resistant and, therefore, have a large bearing capacity.

In Figure 8A, a graph compares the average depths of notch vertices, in relation to MSL, and the average inward depths of the shorelines deduced from tidal notches at Fiscardo (Table III) with those at Ithaca (Table II). Although the average profiles of the notches are not indicated in the graph, it appears that, due to the average height of the notches, their profiles would be superimposed on each other in most cases. In other words, it would not be possible to find marks of all the notches of Fiscardo or of Ithaca on the same rock sections.

Although laterally continuous,single submerged tidal notches have been observed over tens of meters in some cases, individual shorelines could only be distinguished in Fiscardo and Ithaca (as in many other places) through compilation of profiles that could be identified separately at some sites and correlated. Moreover, this is consistent with the conclusions reached by Pirazzoli and Evelpidou (2013) that fossil tidal notches can be well marked on certain rocks but inexplicably absent from nearby sites with the same rock and exposure. In the absence of datings, a correlation could be attempted between two specific shorelines only by taking into account for the two shorelines the cliff orientation and dynamic of the waves (orientation) caused by diffraction and refraction, due to the eventual presence of islets or stacks, that might change the beating of the waves. However we can also observe in Figure 8 that the average inward depth of the notches is generally greater in Fiscardo than in Ithaca. This suggests that a longer time period was necessary for the development of the notches in Fiscardo, *i.e.* that the chronology of vertical movements on Fiscardo may be different (and more ancient) in relation to Ithaca.

CONCLUSIONS

The modern notch at Ithaca is at a greater depth than its equivalent in Fiscardo, providing some evidence that a co-seismic subsidence of the order of about 0.1m has probably occurred in Ithaca since the formation of the notch, possibly at the time of the 1953 earthquakes. Although a subsidence of about one decimeter is near the limit of what can be observed in the field, this magnitude is consistent

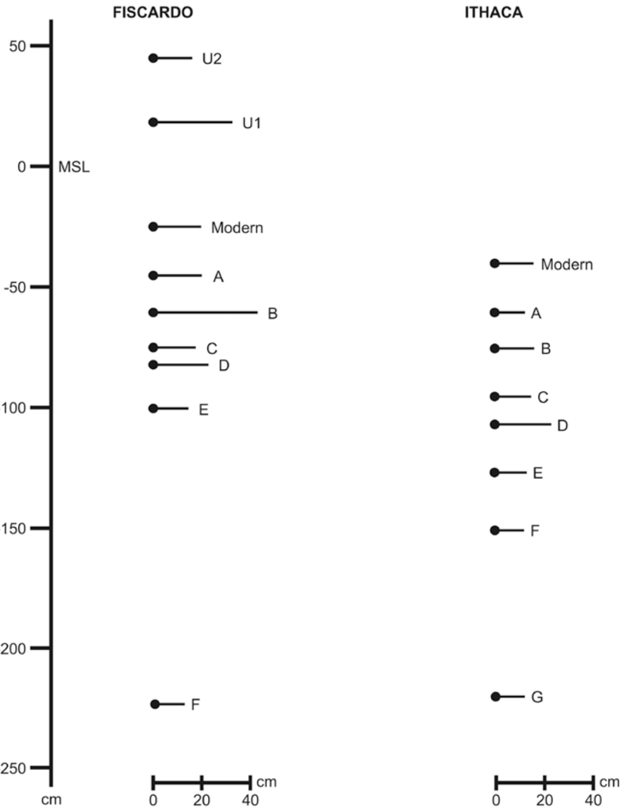

FIGURE 8. The average inward depth of notches is generally greater in Fiscardo than in Ithaca, suggesting that a longer time period was necessary for the development of notches in Fiscardo.

with the series of subsidence events indicated by the other submerged tidal notches of Ithaca.

Former shorelines reveal only repeated subsidence in Ithaca, while Fiscardo bears evidence of similar subsidence alternated with undated occurrences of uplift. Some shorelines in Ithaca may have resulted from a tilting of the island, such as shoreline E, which suggests southward tilting.

Assuming that the observed tidal notches are representative of a rigid behavior of the island, rather than of local tilting, the tectonic history of Ithaca before the 19th century suggests an average subsidence rate of between 0.25 and 1.25mm/a, and an average return time of coseismic subsidence movements of the order of a few centuries (2.7 centuries on average). Such a result, which is still based on a poor knowledge of the real local rates of intertidal bioerosion, cannot be used for short-term predictions of earthquakes. Nevertheless, it may provide useful indications for the long-term tectonic trends at Ithaca.

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APPENDIX I

TABLE I. Location of sites in Ithaca island and Fiscardo peninsula (Cephalonia island) (Pirazzoli, 1986; Laborel *et al.,* 1999)

Location	Site	Long. E	Lat. N	Location	Site	Long. E	Lat. N
Ithaca	ITH1	20° 40.831’	38° 23.236’	Fiscardo (Cephalonia)	KE1	20° 37.376’	38° 21.157’
	ITH2	20° 40.735’	38° 23.110’		KE2	20° 37.436’	38° 20.955’
	ITH3	20° 41.964’	38° 22.540’		KE3	20° 37.438’	38° 20.341’
	ITH5	20° 40.293’	38° 21.268’		KE4	20° 37.447’	38° 20.373’
	ITH6	20° 38.517’	38° 25.179’		KE5	20° 37.685’	38° 19.395’
	ITH9	20° 37.269’	38° 28.676’		KE33	20° 33.762’	38° 28.336’
	ITH11	20° 38.888’	38° 29.613’		KE34	20° 33.490’	38° 28.421’
	ITH12	20° 43.608’	38° 18.283’		KE36	20° 32.167’	38° 26.127’
	ITH14	20° 44.656’	38° 19.795’		KE37	20° 32.321’	38° 24.746’
	ITH15	20° 45.345’	38° 21.868’		KE38	20° 31.564’	38° 23.296’
	ITH16	20° 42.097’	38° 23.060’		KE39	20° 35.145’	38° 26.658’
					KE40	20° 35.145’	38° 26.658’
					KE41	20° 35.462’	38° 25.502’
					KE42	20° 35.900’	38° 24.863’

TABLE II. Significant sizes of tidal notches in Ithaca island

Site	Notch Name	Measured Vertex depth from apparent SL (cm, ±5 cm) (see Figure 2)	Corrected Vertex Depth from MSL (cm, ±6 cm)	Height (cm) (see Figure 2)	Inward depth (cm) (see Figure 2)	Possible duration of development (centuries)	Genesis	Illustration	Shoreline	
									Local name	Regional sea-level correlation (cm in relation to the MSL)
ITH1	ITH1.1	-101	-106	63	3?		e’		D	-106±6
	ITH1.2	-115	-120	40	10	1-5	e’		E	-126±6
	ITH1.3	-212	-217	50	nm		b’		G	-220±6
ITH2	ITH2.1	-32	-37	36	25	2.5-12.5	a’		Modern	-40±6
ITH3	ITH3.1	-40	-45	40	8	0.8-4	a’		Modern	-40±6
	ITH3.2	-91	-96	32	12	1.2-6	e’’		C	-95±6
ITH5	ITH5.1	-71	-79	25	18	1.8-9	e’ or d’		B	-75±6
ITH6	ITH6.1	-92	-100	84	49	4.9-24	a’		D	-106±6
ITH9	ITH9.1	-118	-125	42	17	1.7-8.5	e’		E	-126±6
	ITH9.2			nm	nm		e’		G	-220±6
ITH11	ITH11.1	-58	-65	28	10	1-5	a’	Figure 4A	A	-60±6
	ITH11.2	-106	-113	61	18	1.8-9	e’	Figure 4A	D	-106±6
ITH12	ITH12.1	-73	-80	34	13	1.3-6.5	e’ or d’		B	-75±6
	ITH12.2	-121	-128	95	13	1.3-6.5	e’		E	-126±6
	ITH12.3	-125	-132	20	nm		e’		E	-126±6
ITH14	ITH14.1	-50	-56	27	15	1.5-7.5	e’		A	-60±6
ITH15	ITH15.1	-30	-36	30	15	1.5-7.5	a’		Modern	-40±6
	ITH15.2	-63	-69	40	18	1.8-9	e’		B	-75±6
	ITH15.3	-144	-150	nm	nm		e’’		F	-150±6
ITH16	ITH16.1	-92	-98	42	18	1.8-9			C	-95±6

nm = not measured

TABLE III. Significant sizes of tidal notches in Fiscardo peninsula (Cephalonia)

Site	Notch Name	Measured Vertex depth or elevation from apparent SL (cm, ±5 cm)	Corrected Vertex Depth or elevation from MSL (cm, ±5 cm)	Height (cm)	Inward depth (cm)	Possible duration of development (centuries)	Genesis	Illustration	Shoreline	
									Local name	Regional sea-level correlation (cm in relation to the present MSL)
KE1	KE1.1	+16	+17	nm	nm	nm	a		U1	+18±5
	KE1.2	-72	-72	77	27	2.7-13.5	d’		C	-75±5
	KE1.3	-102	-102	44	18	1.8-9	a’?		E	-100±5
KE2	KE2.1	+16	+17	37	14	1.4-7	a		U1	+18±5
	KE2.2	-41	-40	77	34	3.4-17	d’		A	-45±5
KE3	KE3.1	-62	-56	145	43	4.3-21.5	e’’		B	-60±5
KE4	KE4.1	+15	+21	24	26	2.6-13	a		U1	+18±5
	KE4.2	-17	-11	27	14	1.4-7	a’	Figure 4C	>	??±5
	KE4.3	-90	-84	62	19	1.9-9.5	e’	Figure 4C	D	-82±5
KE5	KE5.1	-37	-30	69	31	3.1-15.5	d’		Modern	-25±5
	KE5.2	-66	-59	88	23	2.3-11.5	d’		B	-60±5
KE33	KE33.1	-70	-76	37	8	0.8-4	d’		C	-75±5
KE34	KE34.1	-45	-51	33	6	0.6-3	d’		A	-45±5
	KE34.2	-225	-231	38	13	1.3-6.5			F	-230±5
KE36	KE36.1	+17	+13	35	43	4.3-21.5	a		U1	+18±5
	KE36.2	-75	-80	54	32	3.2-16	d’	Figure 5A	D	-82±5
KE37	KE37.1	-17	-20	36	23	2.3-11.5	a’		Modern	-25±5
	KE37.2	-81	-84	36	14	1.4-7	e’		D	-82±5
KE38	KE38.1	+15	+13	68	62	6.2-31	a		U1	+18±5
KE39	KE39.1	+43	+43	56	16	1.6-8	a		U2	+44±5
	KE39.2	+19	+19	73	18	1.8-9	a	Figure 4B	U1	+18±5
KE40	KE40.1	+43	+45	56	16	1.6-8	a		U2	+44±5
	KE40.2	-25	-23	26	8	0.8-4	a’		Modern	-25±5
KE41	KE41.1	-30	-25	26	17	1.7-8.5			Modern	-25±5
	KE41.2	-103	-98	35	11	1.1-5.5		Figure 5C	E	-100±5
KE42	KE42.1	-62	-56	78	63		a’		B	-60±5
	KE42.2	-93	-87	38	26		e’’	Figure 5B	D	-82±5

nm = not measured

TABLE IV. Number, depth below MSL, average inward depth, amount of coseismic submergences and possible duration of development for the submerged tidal notches observed in Ithaca island

Shoreline	Number of tidal notches measured	Depth below the present MSL (cm)	Average inward depth (cm)	Amount of coseismic submergence (cm)	Possible average duration of development assumed for certain bioerosion rates (centuries)		
					1.0 mm/a	0.2 mm/a	0.6 mm/a
A	3	-40±6	16	10±6 ?	1.6	8	2.7
B	2	-60±6	12.5	20±6	1.3	6	2.1
C	2	-75±6	16.3	15±6	1.6	8	2.7
D	2	-90±6	15	15±6	1.5	7.5	2.5
E	3	-100 to 110±6	23.3	10 to 20±6	2.3	12	3.9
F	4	-120±6	13.3	10 to 20±6	1.3	7	2.2
G	1	-150±6	nm	nm			
H	2	-220±6	nm	nm			
Total	16	120±6			9.6	48.5	16.1
Average				15±6	1.6	8	2.7

TABLE V. Traces of active and subfossil bioerosion traces along the coasts of Fiscardo peninsula

Site	Illustration	Bioerosion trace in the wrong place (fossil)	Active overprinting	Interpretation
KE3-4	Figure 6A	eroded hole of boring bivalve	limpet grazing	uplift
KE1	Figure 6B	heavily eroded hole of boring bivalve above sea level	limpet grazing	uplift
KE40	Figure 6C	notch	holes of boring organisms	subsidence