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Multiple Submerged Tidal Notches: A Witness of Sequences of Coseismic Subsidence in the Aegean Sea, Greece

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Abstract: In some islands of the Aegean, there is evidence of the occurrence of repeated rapid subsidences during the Late Holocene. In this paper, the shape of tidal notches that may be well-preserved underwater is recalled in order to reconstruct sequences of coseismic subsidences and other relative sea-level changes, which occurred during, at least, the last few millennia. A reanalysis of the published measurements of submerged tidal notches in several islands reveals that subsidence trends in many areas of the Aegean are not continuous with gradual movement but, also, are the result of repeated coseismic vertical subsidences of some decimetres at each time. The estimated average return times are of the order of approximately some centuries to one millennium. Although the results cannot be used for short-term predictions of earthquakes, they may provide useful indications on the long-term tectonic trends that are active in the Aegean region.

Keywords: bioerosion; subsidence; coseismic; vertical displacements; Holocene; Cyclades; Sporades

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1. Introduction

Tidal notches are well-known sea-level indicators, marking clearly former shorelines, which have often been used to deduce Quaternary tectonic trends and sea-level changes. If raised notches, sometimes associated with marine terraces or reef tracts, have often been used to estimate past changes in sea level and tectonic movements [1–11], submerged notches, which are more difficult to observe, have been studied only occasionally by a few authors. Such underwater observations were, most of the time, devoted to the measurement and interpretation of a single submerged tidal notch [12–20]. Nevertheless, Holocene tectonics may include more than a single episode, and it is 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 Juračić (1998) reported a second submerged tidal notch at the depth of −19 m, which they tentatively ascribed to a period of possible temporal sea-level stagnation during the Würm-Holocene transgression.

In preceding papers [21–23], we found evidence, in some islands of Cyclades and Sporades, of the occurrence of repeated rapid subsidence during the Late Holocene. In this paper, after briefly summarizing what a tidal notch is and how it is developed, we shall recall that the shape of tidal notches may be well-preserved underwater, keeping the main significant characteristics of their profiles almost intact and easily recognizable, thus allowing the reconstruction of sequences of coseismic subsidence and other relative sea-level changes that have occurred during at least the last few millennia. Unfortunately, submerged tidal notches cannot be dated directly, as bioerosion that takes place after the submergence destroys any datable biological remains. Only in a few cases could the dating of submerged tidal notches be estimated with the help of the stratigraphy of nearby coastal cores [17,23,24], of submerged beachrocks, or of archaeological remains [25]. We shall nevertheless provide below several examples showing that the erosion profiles of tidal notches are systematically indicative of the relative sea-level changes that have occurred during their development period and show that approximate estimations of this period of development can be provided by using adequate assumptions on the local rates of intertidal bioerosion.

2. What Is a Tidal Notch?

Erosional processes along coastlines include the direct effects of waves, abrasion, salt weathering, bioerosion and chemical attack [26]. Marine notches on coastal cliffs near sea level may be produced by various processes. According to Trenhaile [27], marine notches formed by tidal wetting and drying and salt weathering have a height dependant on the tidal range, while climate, wave exposure and the development stage (within the cycle of formation and collapse) control their inward depth. The imprecise term "wave-cut", often found in the literature, generally refers to erosion by wave activity slightly above sea level. The effect of waves transporting sand or gravel on the rock is abrasive, forming wave-cut platforms and notches, which are easily recognizable by their polished surfaces. The accuracy of abrasion features as sea-level indicators is often weak, depending mainly on exposure.

Tidal notches [28] should not be confused with "wave-cut" or with abrasional notches. At a sheltered site of a carbonate coast, the most common shape of a tidal notch is a reclined U- or V-shaped profile, with the vertex located near mean sea level (MSL), whereas the floor of the notch appears near the lowest tide and the roof near the highest tide level. The origin of such a profile is generally ascribed to bioerosion effects. In the mid-littoral zone, various parallel vegetational belts are well-developed. In this zone, eroding Cyanobacteria, patellaceous gastropods (limpets) and chitons are abundant [29]; they all contribute, by eating the vegetational belts, to the erosion of the underlying rock, by abrading the surface with their hard teeth and radulas and enable the development of an undercut in limestone cliffs [30–32], with a maximum erosion rate near MSL [33–35].

The process of intertidal bioerosion is often not gradual and continuous, and the rates may present a wide range of variability, even at the same sites, depending on the local climate and lithology [36]. In the Mediterranean area, in areas with no dissolution effects caused by freshwater springs, bioerosion rates between 0.2 and 1.0 mm/a are often adopted as the minimum and maximum possible normal values for the inward deepening of the tidal notch profile (Table 1). Faivre and Butorac [20] estimated a bioerosion rate of approximately 0.7 mm/a for a recently submerged tidal notch with a mean inward depth of 35 cm, assuming a stability period of 500 years, from the Central Adriatic. For Greece, a recent estimation at 0.64 mm/a for the average rate of intertidal bioerosion has been proposed from the Island of Cephalonia in the Ionian Sea [37], based on a recently uplifted tidal notch with a mean inward depth of 93 cm and considering a stability period of 1450 years.

Table 1. Measured erosion rates on carbonate coastal rocks at Mediterranean sites (MEM is for micro-erosion metre and TMEM for traversing micro-erosion metre).

Locality	Measurement Method	Duration of Measurement or Geological Estimation	Erosion Rate (mm/a)	Reference
Cassis (Marseille)	Notch 0.5 m deep	500 to 2000 years BP	0.25 to 1.0	[38]
Gulf of Trieste	MEM and TMEM	5 years	0.01 to 0.32	[39]
Near Rovinj (Istria)	Supratidal rock pools	<2 years	0.25 to1.0	[30]
Istria N coast	6 intertidal MEM stations	2.5 years	0.46 to1.11	[31]
Istria W coast	10 intertidal MEM stations	2.3 years	0.023 to 0.093	[40]
Makarska, Central Adriatic	Notch 35 cm deep	500 years	0.7	[20]
Antikythira, Greece	Fossil tidal notches 3–7 cm deep	200–250 years	0.2 to 0.3	[1]
Skyros, Greece	2 fossil tidal notches	Less than 710 years	Average: 0.8	[21]
Cephalonia, Greece	Notch 0.93 cm deep	1453 ± 100 years	0.64	[37]

The main characteristics of a tidal notch profile have been described by Pirazzoli [28] for emerged features and by Evelpidou et al. [23] for submerged ones. A change in the relative sea level (RSL) will modify the erosion profile. Various tidal notch profiles for submerged notches have been graphically summarized in various papers [41,42], and six main theoretical schemes of tidal notch profiles on a vertical carbonate cliff have been distinguished, allowing to qualitatively distinguish the mode of subsidence, i.e., co-seismically or through a gradual relative sea-level rise, as follows:

- Type a′ corresponds to a reclined U-shaped notch profile, with the roof height (H_R) being very similar to the height of the floor (H_F). The underwater preserved fossil notch owes its current position to a rapid subsidence, larger than the tidal range.
- Type b′ corresponds to two submerged fossil notches, owing their present location to two rapid subsidence events, larger than the tidal range.
- Type c′ corresponds to a rapid subsidence smaller than the tidal range. When the subsidence is preceded and followed by a relative sea-level stability, it results in a notch profile with a height greater than the tidal range and two vertices separated by an undulation, indicating the former and the following MSL positions.
- Type d′ corresponds to a notch profile much higher than the tidal range but with limited inward depth, which is owed to a gradual RSL rise, at a rate smaller than the bioerosion rate.
- Type e′ corresponds to a notch profile with the floor height (H_F) larger than the roof height (H_R), owing its formation to a gradual RSL rise, followed by relative sea-level stability.
- Type e″ corresponds to a notch profile with the roof height (H_R) larger than the floor height (H_F), owing its formation to a RSL stability followed by a gradual RSL rise.

3. Case Studies

The Greek region is characterized by active geodynamics, continuing geological processes and dynamically changing landscapes [43]. Due to the convergence of the tectonic plates of Africa, Europe and Anatolia, the region is characterized by intense earthquake activity and volcanism, with uplift or subsidence, on both the local and regional scale. These ongoing processes have moderated the effects of eustatic sea-level change associated with the growth and melting of the continental ice sheets, with implications for palaeogeographic reconstructions and the position of prehistoric coastlines [44–48]. In a number of researches, comparisons of models of Glacial Isostatic Adjustment (GIA) with local observations of sea-level change have been used to estimate rates of vertical movements to be estimated for the Late Holocene time [49–51].

In a reanalysis of multiple submerged tidal notches studied in several Aegean islands (Figure 1) already reported in previous publications [21–23], we provide evidence below that, far from being gradual and continuous, subsidence in the Aegean occurs rather at the time of repeated sudden coseismic jerks generally caused by earthquakes with magnitudes greater than 6.0 [52], during which observable vertical displacements can be expected. The traces of these coseismic jerks can be deduced from tidal notch profiles that, despite the absence of precise dating of the events, allow a rough estimation of their return time with the help of assumptions on the local intertidal bioerosion rate.

For all case studies, the islands' coastline was surveyed in detail, using a boat, to access all the sites and establish a continuity of the observations. The profiles of the submerged tidal notches were recorded in detail during the fieldwork, and their morphological characteristics, i.e., height, inward depth and vertex depth from sea level, were measured based on references [25,28]. At each site, multiple measurements were taken to improve the accuracy of observations, using a folding meter of rigid parts for the shallower notches and a wrist depth gauge for the deeper ones. All measurements reported were corrected based on hourly tidal records from the nearest station, provided by the Hellenic Hydrographic Service (for details, see references [21–23]). For the estimation of the relative sea level stability during the development of tidal notches, we adopt the bioerosion rate of 0.64 mm/a proposed by Evelpidou and Pirazzoli [37] from the Ionian Sea, as the one geographically nearest.

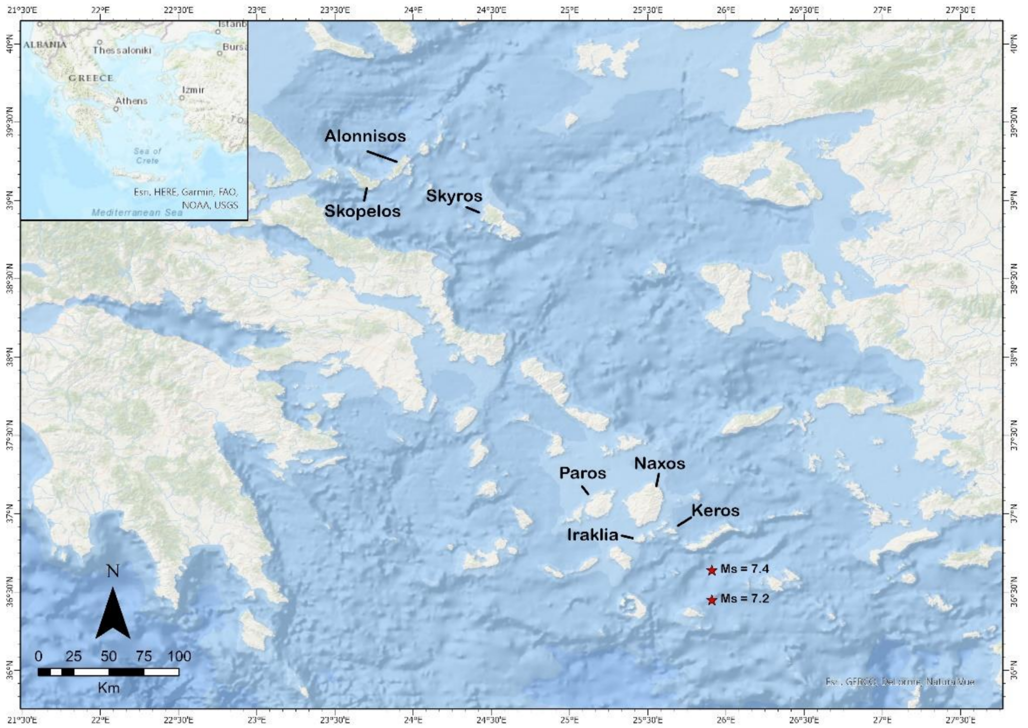


Figure 1. Location map with the studied sites in the Cyclades and Sporades islands. The red stars show the location and magnitude of the 1956 earthquakes, discussed in the text.

4. Results and Discussion

The results published for several Aegean islands (Figure 1) are reanalyzed and summarized in Table 2 for each studied shoreline. None of the notches discussed are parallel with the bedding of the carbonate formations, and in fact, only sites with continuity and no irregularities in the rocks are considered here, as well as the previously published work.

The notches reported from the Cycladic islands have all exclusively formed on marbles. At the Naxos and Paros Islands, tidal notches were developed on coarsely crystallized white marbles. At Naxos Island (Figure 2), the tidal notch corresponding to shoreline G (at -35 ± 5 cm) was measured in detail at four sites [23] (Table 2). According to the tidal notch profiles, the genesis of shoreline G may not appear the same at certain sites, because its submergence was ascribed, in part, to the global sea-level rise that has occurred since the 19th century [42] but, also, to the coseismic subsidence of an earthquake in 1956 [53]. An average inward depth of 23 cm was computed for the notches of shoreline G. Assuming that the local average intertidal bioerosion rate is about 0.64 mm/a, 3.6 centuries could be estimated for the time of development of this shoreline. In a similar manner, for the four other submerged tidal notches observed at Naxos, which were measured between the present MSL and a depth of about 280 cm, the total duration of the development occurred during periods with an almost stable relative sea level and may be estimated at 29.7 centuries.

Table 3 summarizes some tentative statistics deduced from the values of Table 2. The amount of average coseismic subsidence at Naxos during the period considered was estimated at 56 ± 4 cm. By considering that the local intertidal bioerosion rate was, on average, 0.64 mm/a (in uniform, lithological, biological and climatic conditions), an average coseismic return time of 6.3 centuries is estimated. In the same manner, results for the other studied Cycladic islands (Figure 3a,b) are shown in Tables 2 and 3, suggesting that the average coseismic return time corresponding to an average bioerosion rate of

0.64 mm/a varied from three centuries at Iraklia to about four-and-a-half centuries at Paros. These estimations are consistent with a study by Vamvakaris et al. [54], who suggested very long return periods (> 200 years) for the broader Cyclades plateau for shallow earthquakes with M > 6.0.

Table 2. Depth, number of tidal notches measured for each shoreline and possible duration of development of the submerged tidal notches in the islands of Naxos, Keros, Iraklia, Paros, Skopelos, Alonnisos and Skyros.

Island	Shoreline	Depth below Present MSL (cm)	Number of Notches Measured	Average Inward Depth Notch Profile (cm)	Duration of Development for 0.64-mm/a Bioerosion Rate (Centuries)	Reference
Naxos	G	−35 ± 5	4	23	3.6	[23], Table 2
	F	−75 ± 10	1	39	6.1	[23], Table 2
	E	−100 ± 10	2	33	5.2	[23], Table 2
	D	−120 ± 10	2	35	5.5	[23], Table 2
	A	−280 ± 20	1	60	9.4	[23], Table 2
Total Naxos		**−280 ± 20**			**29.7**	[23], Table 2
Keros	G	−35 ± 5	4	15	2.3	[23], Table 2
	E	−100 ± 10	1	15	2.3	[23], Table 2
	C	−170 ± 10	1	40	6.3	[23], Table 2
Total Keros		**−170 ± 10**			**10.9**	
Iraklia	G	−35 ± 5	3	13	2.0	[23], Table 2
	E	−100 ± 10	1	15	2.3	[23], Table 2
	C	−180 ± 10	1	27	4.2	[23], Table 2
	B	−220 ± 10	1	23	3.6	[23], Table 2
Total Iraklia		**−220 ± 10**			**12.2**	
Paros	G	−35 ± 5	6	22	3.4	[23], Table 2
	C	−170 ± 20	4	35	5.5	[23], Table 2
Total Paros		**−170 ± 20**			**8.9**	
Skopelos	A	−25 ± 11	6	25	3.9	[22], Table 1
	B	−40 ± 11	1	17	2.7	[22], Table 1
	C	−55 ± 11	5	16	2.5	[22], Table 1
	D	−70 ± 11	1	25	3.9	[22], Table 1
	E	−100 ± 11	2	23	3.6	[22], Table 1
	F	−145 ± 11	2	22	3.4	[22], Table 1
	G	−270 ± 11	1	57	8.9	[22], Table 1
Total Skopelos		**−270 ± 11**			**28.9**	
Alonnisos	A	−25 ± 11	6	34	5.3	[22],
	B	−45 ± 11	4	26	4.1	[22],
	C	−85 ± 11	2	16	2.5	[22],
	D	−100 ± 11	2	47	7.3	[22],
	E	−133 ± 11	3	28	4.4	[22],
	F	−150 ± 11		-	-	
	G	−175 ± 11	2	25	3.9	[22],
Total Alonnisos		**−175 ± 11**			**> 27.5**	
Skyros	A	−26 ± 10	11	26	4.1	[21], Table 2
	B	−81 ± 10	6	30	5.0	[21], Table 2
Total Skyros		**−81 ± 10**			**9.1**	

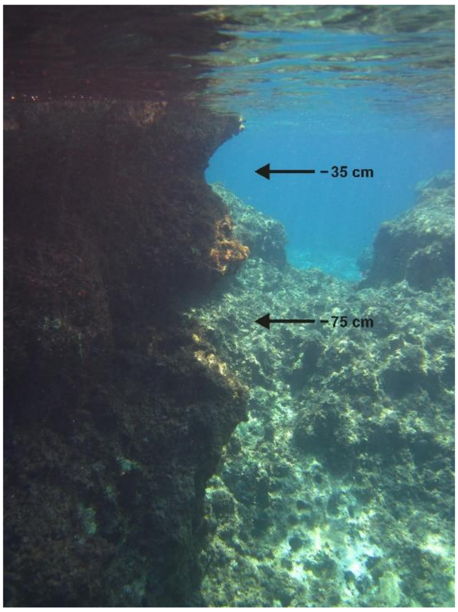
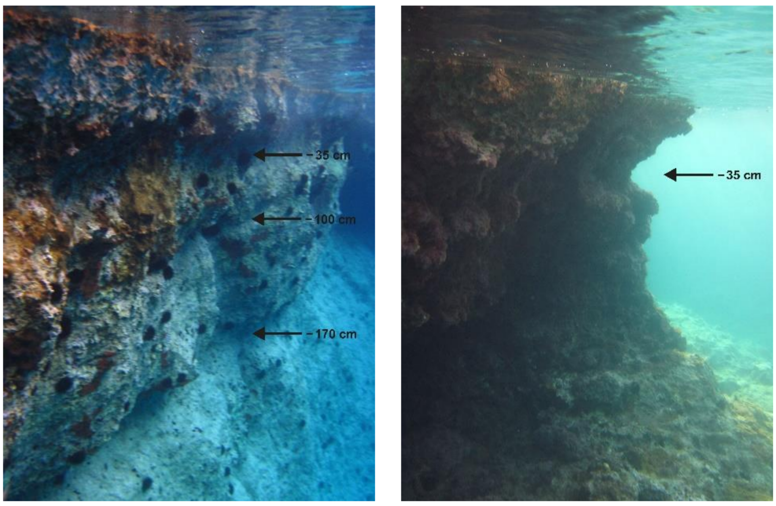


Figure 2. Submerged notch of type c′ at Naxos Island.

Table 3. Number, amount and rough estimation of the possible return times of the late Holocene coseismic subsidence disclosed from submerged tidal notches at the islands of Naxos, Keros, Iraklia, Paros, Skopelos, Alonnisos and Skyros, considering a bioerosion rate of 0.64 mm/a.

Island	Total Observed Subsidence (cm Below Present MSL)	No of Coseismic Subsidence Disclosed by Tidal Notches	Average Coseismic Subsidence (cm)	Average Coseismic Return Time (centuries)	Reference
Naxos	280 ± 20	5	56 ± 4	5.9	[23]
Keros	170 ± 10	3	57 ± 3	3.6	[23]
Iraklia	180 ± 10	3	60 ± 3	3	[23]
Paros	170 ± 20	2	85 ± 10	4.5	[23]
Skopelos	270 ± 11	6	45 ± 2	4.1	[22]
Alonnisos	175 ± 11	6	29 ± 2	3.9	[22]
Skyros	−81 ± 10	2	40 ± 2	4.5	[21]



(**a**) (**b**)

Figure 3. (**a**) Multiple submerged tidal notches at Keros Island at −35 cm, −100 cm and −170 cm. (**b**) The upper tidal notch at Paros Island is about −35 cm.

In Sporades, at Skopelos Island, tidal notches have been developed primarily on Triassic dolomites. The tidal notch corresponding to shoreline A (Figure 4a) was measured in detail at six sites [22] (Table 1). An average inward depth of the profile (generally of the a′ type) of 25 cm was computed. Assuming that the local average intertidal bioerosion rate may be estimated at 0.64 mm/a, the time of development of this shoreline with an almost stable sea level was 3.9 centuries. In a similar manner, for the other six submerged tidal notches of Skopelos, which were measured between the present MSL and −270 ± 11 cm, the total duration of development occurred during periods with an almost stable relative sea level for 28.9 centuries. According to the types of profiles observed, and assuming that no uplift movement has occurred, if shoreline A ('modern') has been submerged mostly by the global sea-level rise that occurred since the 19th century in combination with a (probably a minor coseismic subsidence [22]), then the passages from any submerged tidal notch to the next one at a lower depth occurred at the time of six coseismic subsidences.

(**a**) (**b**)

Figure 4. (**a**) Submerged tidal notch at Skopelos Island at about −25 cm. (**b**) Submerged tidal notch at Alonnisos Island at about −25 cm.

At Skopelos, the average coseismic subsidence during the period considered was 45 ± 2 cm (Figure 5) with possible return times of 4.1 centuries by assuming that the local intertidal bioerosion rate was, on average, 0.64 mm/a.

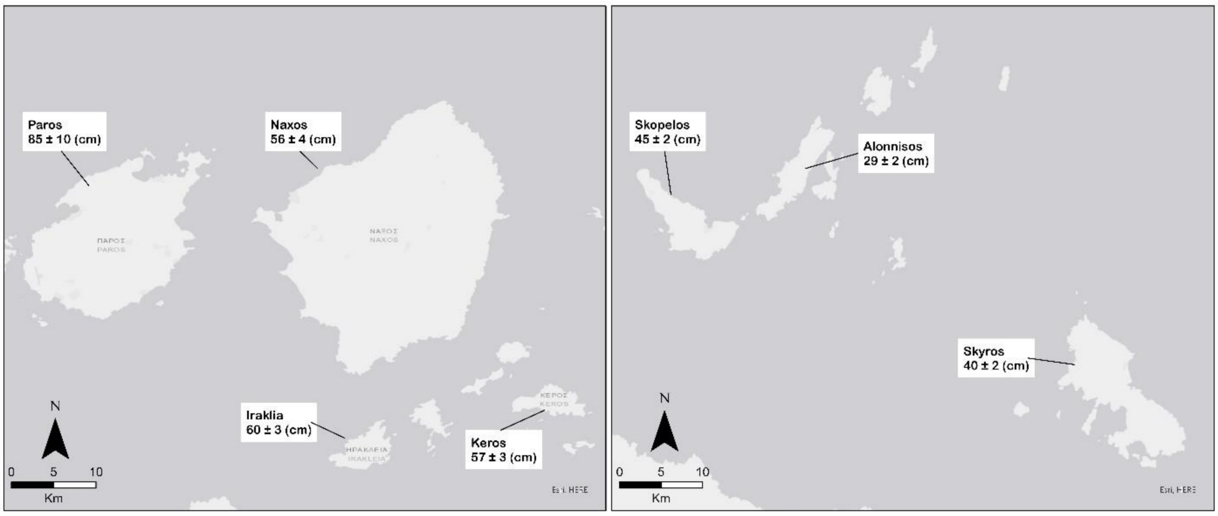


Figure 5. Average coseismic subsidence (cm) based on submerged tidal notches at the islands of Naxos, Keros, Iraklia, Paros, Skopelos, Alonnisos and Skyros.

At Alonnisos Island, the reported submerged tidal notches have all developed on upper Jurassic–Cretaceous grey crystalline, usually medium-bedded limestones. The results for Alonnisos Island (Figure 4b) suggest that the average coseismic subsidence was of the order of 29 ± 2 cm, with possible return times of about 3.9 centuries for an average bioerosion rate of 0.64 mm/a.

At the neighboring island of Skyros, the tidal notches were almost exclusively developed on calcite-dolomite thick-bedded marbles. The tidal notch corresponding to shoreline A was measured in detail at 11 sites [21] (Table 2). The average inward depth of 26 cm for shoreline A suggests a relative sea level stability for 4.1 centuries for its development by considering a local average intertidal bioerosion rate of 0.64 mm/a. According to Evelpidou et al. [21], the submergence of shoreline B at Skyros Island can be correlated with an earthquake that occurred slightly less than 850 years BP, suggesting that shoreline A started developing after that time.

The studied Sporades islands share a common trend, that of tectonic subsidence. Although the evidence from Skopelos and Alonnisos suggests multiple subsidence events, the fossil shorelines at Skyros do not show a similar trend. Our results highlight the significance of underwater geomorphological observations, as they may provide insights into the tectonics of a particular area and on the trend and amount of vertical displacements.

5. Conclusions

The submerged tidal notches of all the studied islands reveal that subsidence was not gradual and uniform but also took place at the time of several coseismic jerks, each with some decimetres of vertical displacement. Although the return times may be variable, they may correspond to at least several centuries at various islands of Sporades and Cyclades. These provisional results are still based on poor knowledge of the real local rates of intertidal bioerosion. However, although they cannot be used for short-term predictions of earthquakes, they may provide useful indications concerning the long-term tectonic trends that are active in the Aegean region.

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