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AN OCEANOGRAPHIC INSIGHT IN THE SUBMERGENCE AND RESILIENCE OF THE PAVLOPETRI ARCHAEOLOGICAL SITE

Serafeim E. Poulos[1], Adamantia P. Panagopoulou[2,3] and Vasileios A. Kotinas[1]

[1]Laboratory of Physical Geography, Section of Geography and Climatology, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Panepistimioupoli, 15784 Zografou, Athens, Greece
[2]Department of World Archaeology, Faculty of Archaeology, Leiden University, Einsteinweg 2, 2333 CC Leiden, The Netherlands
[3]National Center for Scientific Research 'Demokritos', Institute of Nanoscience and Nanotechnology, 15341, Aghia Paraskevi, Athens, Greece

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Corresponding author: Poulos S.E. (poulos@geol.uoa.gr)

ABSTRACT

Pavlopetri is one of the oldest submerged cities in the world, established during the Final Neolithic Period (as early as 3500 BC), with its occupation being extended to the post-palatial period (1400-1100 BC) of Minoan chronology, while there is evidence of human presence from the Classical and Hellenistic periods up to the Roman/Byzantine Period. The synthesis of the available archaeological information, morphological, radiocarbon dating and sea level data, makes evident that the Pavlopetri surrounding marine area was about 4 m below present sea level (bpsl) when Pavlopetri was flourishing (2800 - 1180 BC), 1.5-2.0 m bpsl during the Hellenistic period, circa 1.2 m in the Byzantine era and as much as 0.5 m during the Latin period. As the settlement is expected to have been constructed in elevations not less than 2 m above sea level (asl), most of it was partially submerged or flooded during the Hellenistic times, being also subjected to the eroding marine forces and processes. Based on nearshore hydrodynamics, a submerged breakwater built in water depths > 5 m could drastically reduce their impact, while monitoring of the environmental conditions (sea temperature, salinity, biology) can also provide data for the preservation of the monument's building material.

KEYWORDS: sea level, radiocarbon, tectonism, hydrodynamics, deterioration processes, monitoring, underwater museum, sea level, Aegean, shoreline, submerge

1. INTRODUCTION

The submerged Neolithic-Bronze Age town of Pavlopetri (about 5000–3000 BP), lying in water depths of 2.0-5.0 m (Henderson et al., 2011; Pizzaro et al., 2012; Galanidou et al., 2020), is located to the north of the homonymous islet (a rocky outcrop) that is located to the east of the marine channel separating Elafonisos island from the mainland (cape Maleas) – the northeast end of Vatika Bay, and to the southwest of the Punta/Viglafia lagoon (see Fig. 1). The submerged city of Pavlopetri (the ancient city of Voion that was described in the 2nd century AD by Pausanias in his work 'Lakonika') is one of the oldest submerged cities in the world, established during the Final Neolithic Age (as early as 3500 BC), was initially abandoned during the post-palatial period Times (1400 - 1100 BC) of Minoan chronology, possible due to the hypothetical Mycenaean earthquake (Cline, 2014), and was reoccupied during the Classical and Hellenistic periods (indicated by skyphos wine-cups that date from the 4th century BC, and 3rd century BC). Limited Classical to Hellenistic reoccupation is indicated by fourth- and third-century findings (e.g., skyphos and other sherds), whilst archaeological evidence indicate human presence in this area up to the Roman/Byzantine Period (e.g. Pizzaro et al., 2012; Galanidou et al., 2020; Liritzis and Oikonomou, 2021).

Submerged archaeological remains were first identified off the coast of southeastern Laconia, in the west end of the Bay of Vatika, in 1904 by the geologist Fokion Negris but the importance of his discovery was not widely recognized at the time (Negris, 1904; Morgan, 2010). The remains were re-discovered in 1967 by Nicholas Flemming who identified and confirmed the existence of a prehistoric town at the location (Flemming, 1968a, 1968b; Henderson et al., 2011). In 1968 a team from the University of Cambridge surveyed the submerged remains (Harding et al., 1969; Harding, 1970). At least 15 separate building complexes (consisting of a series of rooms), courtyards, streets, two chamber tombs, and 37 cist graves were identified at a depth of no more than 3 m. The remains are indicated by a network of stone walls up to three stones in height, constructed from uncut aeolianite, sandstone and limestone blocks. Farther to the Pavlopetri islet and the eastern rocky ridge of the seabed, no artificial constructions have been traced, i.e.harbor jetties (Henderson et al., 2011). The underwater site continues southward, reaching Pavlopetri island, where the remains of walls and other archaeological material are still visible.

The 1968 project recovered a small amount of surface findings from the seabed (mainly pottery, but also obsidian and chert blades and a bronze figurine), which suggest a date ranging from the Early to the Late Bronze Age (c. 2800–1180 BC) (Harding et al., 1969: 132–137). On the basis of the higher frequency of Late Helladic ceramics, however, the submerged buildings at Pavlopetri are considered to date mainly from the Mycenaean period (1650–1180 BC) (Harding et al., 1969: 139). Around 1200 BC, a period linked to the Trojan War, Pavlopetri was a thriving city of about 2000 inhabitants, as the findings in this area prove. In the heart of the city there was a large plaza of 40 meters by 20 meters, and most of the houses were large, having about 12 rooms. Between the buildings, sometimes constructed inside the walls, there are stone tombs while the main cemetery is located outside the city boundaries. Evidence for the later occupation or use of the site has been provided by the occurrence of a fair quantity of later pottery, namely a fragmentary Hellenistic cooking-pot, black-glazed sherds and fragments of ribbed ware of Roman date, and sherds with wavy grooved decoration of the late 6th or 7th century AD (Harding et al., 1969: 137–138).

After the 1968 survey no further research was carried out and the site was placed under the care and protection of the Greek State. Significant for our understanding of the relations between Pavlopetri and other settlements in the Aegean Sea, is the pottery that shows close links with the Cyclades, western Crete, and northeast Aegean (Henderson et al., 2013). The Late Antique pottery recovered both in 1968 and in 2009 can be associated with the limited re-occupation of the site and the involvement of the local community in the trade of the local poros stone, iron from the nearby ores at Ayios Elissaios, and the exploitation of beds of Murex (marine gastropod Murex trunculus or the banded dye-murex) for the production of purple dye.

The walls of the town are made of uncut aeolianite, sandstone and limestone blocks, and were built without mortar. They survive up to three stones in height but the vast majority are only one course high or are completely flush with the seabed. The existence of the eastern rocky ridge has protected the remains from the full force of wave action over the years. The cleaner appearance of the stonework that is observed in the 'new' parts of the town, in comparison to the 'old' parts, which feature well-established marine algal species and encrusting marine organisms, suggests that these buildings were submerged at a later time. Changes in the nearshore sand cover could be related to changes in the position and shape of the shoreline over time causing variability in wave action. Given the lack of rubble from the site, it is likely that the surviving walls represent the ground floor of the buildings, having stone foundations built to around a meter in height, while the upper sections were constructed using mud bricks and/or timber frames covered in plaster. Thus, only the very base of the wall was stone, probably to prevent the foundations from being eroded away by rain and water running down the streets (Henderson et al., 2011). More recently, Papatheodorou et al. (2014) investigating a submerged settlement around Cape Sounio, have also concluded that sea level change was at least 2.5-3.0 m, for the last 2500 years, based on their marine geophysical survey results.

The present contribution considering geological, oceanographic, archaeological and historical information of past disasters (cf., Liritzis et al., 2019), investigates the natural processes involved in the submergence of the Pavlopetri archaeological site, which include: (i) the role of tectonism, associated mainly with sudden tectonic movements (e.g. seismic events of +64 AD and +365 AD), ii) the tsunami events (Stefanakis, 2006; Scheffers et al., 2008) which are caused by fault displacement and/or volcanic activity (e.g., the case of Thera eruption); and (iii) the role of eustatism, i.e. sea level rise of about 6 m during the past 6000 years (Lambeck, 1996; Lambeck and Purcell, 2005).

Furthermore, the impact of nearshore hydrodynamics, upon the state of the monument is investigated, in terms of the interaction between the incoming waves and seabed bathymetry, on the basis of which some thoughts concerning the protection and exploitation of the monument are presented, as well.

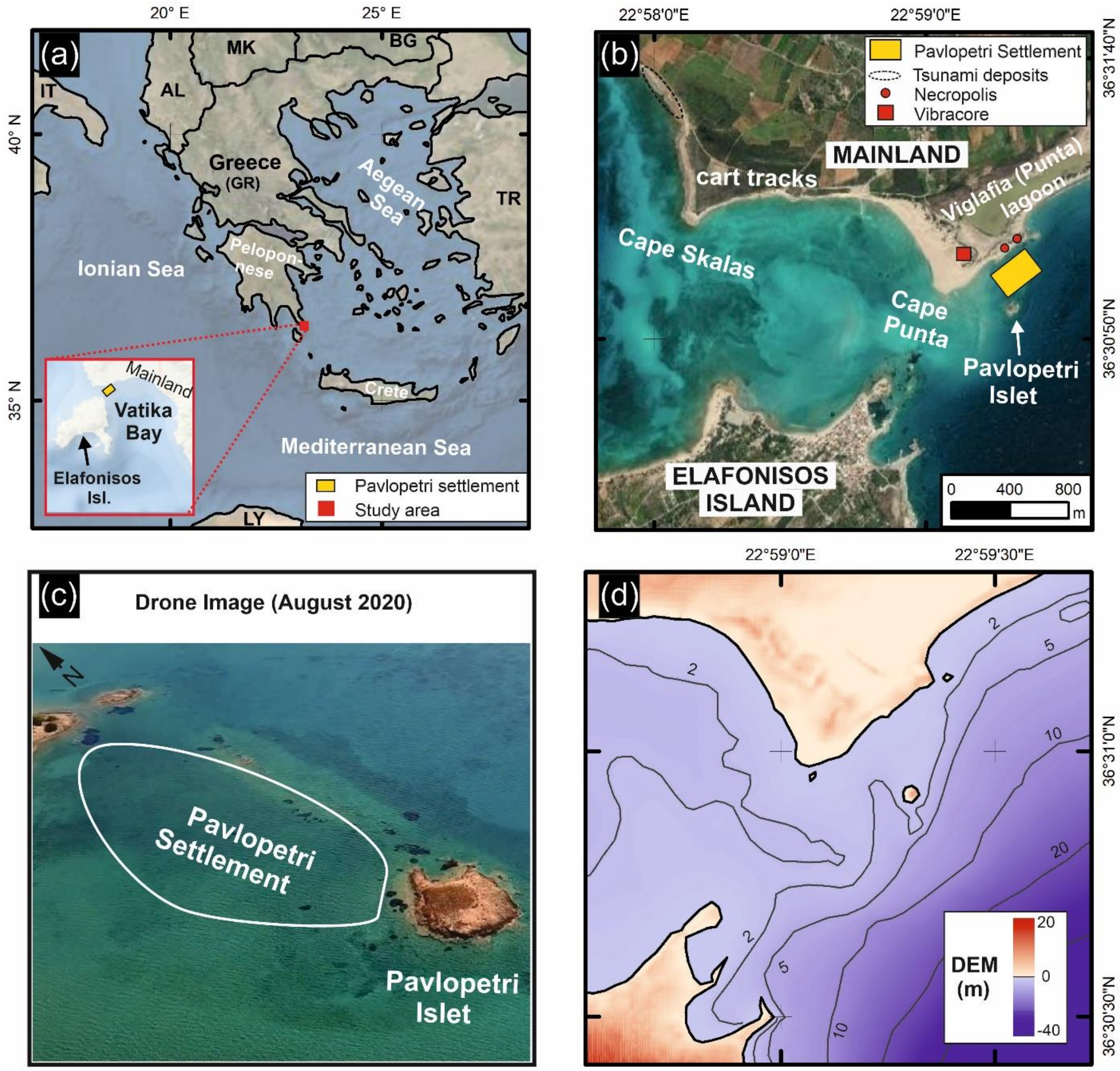

Figure 1: (a)Location of the study area; (b) satellite image of the Pavlopetri settlement and its surrounding area; (c) drone image showing the location of the submerged settlement and (d) bathymetric map of the area.

2. NATURAL SETTING

The coastal morphology of the Pavlopetri broader area is the outcome of the complex interplay between geological (tectonism, isostacy), relative sea level change associated with glacial and inter-glacial periods, current hydrodynamics and nearshore morphodynamics. Historical reports of Thucydides (460 - c. 395 BC) in his "History of the Peloponnesian War (3.89.2) indicate that Elafonisos was connected to the mainland during the Peloponnesian war in the 5th century BC. Portolans of the 16th and 17th century AD mark Elafonisos (Cervus) as an island (Smid, 1970; Antonopoulos, 1992; Mentis, 1993; Papaioannou et al., 2004).

2.1. *Geo-tectonic setting*

Elafonisos and Akra Punta are covered by aeolianite formations, most probably of Pleistocene age, which partly lie under the Holocene dunes of the mainland spit (Cape Punta) located on the opposite side of Elafonisos (Mentis, 2007). Moreover, in these subaerial aeolinite formations, houses and cist graves were excavated by the Helladic people, while a partly submerged necropolis is present (Fig.1).

The Pavlopetri and its surrounding area represents the north end of the western Cretan passage between Peloponnese (Akra Maleas) and NW Crete (Grambousa islet), which is located northwards of the Hellenic Arc-Trench system. The latter, extending from the Ionian islands (to the north-west) through the south-west of Peloponnese, south of Crete, to Karpathos and Rhodes to the south-east. The southeastern part is developed by the subduction of the African Plate under the Aegean Microplate (part of the Eurasian Plate), presenting a relative rate of southeasternwards movement of 3-4 mm/year (Le Pichon and Angelier, 1979; Ten Veen and Kleinspehn, 2002; Sakellariou et al., 2017). Therefore, the broader area belongs to one of the most active geological regions worldwide associated with intensive seismic activity and long-term vertical tectonic movements. In Table 1 the largest earthquake events generated along the Hellenic arc (excluding those affecting the west Greek coast) are listed, some of which have triggered tsunami events in the area.

Vertical tectonic movements along the Hellenic Arc and in other areas of the Aegean Sea have modified significantly the relative coastal effect of Quaternary sea-level fluctuations. A sequence of Pleistocene elevated marine terraces in the area of Neapolis-Elafonisos, located some meters to a few hundred meters above sea level, indicate that the region undergoes tectonic uplift during the Quaternary (Pirazzoli et al., 1982). On the contrary during the Holocene the wider study area (southern Peloponnese) is subjected to tectonic depression, with submersion rates less than 1 meter per millennia (Flemming, 1978; Fig. 2). Moreover, Lambeck (1995) has revealed the role of glacio-isostacy and hydro-isostacy in the relative sea level change. As the ice cover melted, causing the sea level to rise, the surface load decreased, and the earth surface adjusted to this change through a slow uplift of the area. Sea level change in a particular area is the combined effect of the forementioned factors and fluctuates spatially, making the use of local models more accurate; Lambeck (1996) applied his model for the Aegean Sea.

Table 1. Historical earthquake shocks (magnitude M>6 Richter) and tsunamis (T) from the 6th century BC to the 18th century AD of the broader area of the Hellenic arc-trench. (after Papazachos and Papazachou, 2003).

	Year	Location	Magnitude
BC	550	Sparta (36.9N – 22.4E)	6.8
	464	Sparta (36.9N – 22.4E)	6.8
AD	62	Crete (34.8N – 24.1E)	7.5
	365 (T)	Crete (35.2N – 23.4 E)	8.3
	516 (T)	Kos (36.9N - 27.3E)	7.0
	1246	Xania (35.4N - 23.3E)	7.0
	1303 (T)	Rhodes (36.1N - 29.4E)	8.0
	1494	Heraklion (35.5N - 23.3E)	7.5
	1595	Heraklion (35.5N - 23.3E)	6.4
	1604	Heraklion (35.5N - 23.3E)	6.5
	1609 (T)	Rhodes (36.1N - 29.4E)	7.2
	1612	Heraklion (35.0N – 23.8E)	7.2
	1630 (T)	Crete (35.0N - 23.7 E)	7.3
	1646	Rethymno (35.4N - 24.4E)	6.0
	1650 (T)	Thera (36.5N - 25.5E)	6.0
	1665	Heraklion (35.5N - 23.3E)	6.8
	1681	Heraklion (35.5N - 23.3E)	7.0
	1750	Kythira (36.3N - 22.8E)	7.2
	1769	Heraklion (35.6N - 25.5E)	6.8
	1798	Kythira (36.3N - 22.8E)	6.8
	1810	Heraklion (35.5N - 23.3E)	7.5

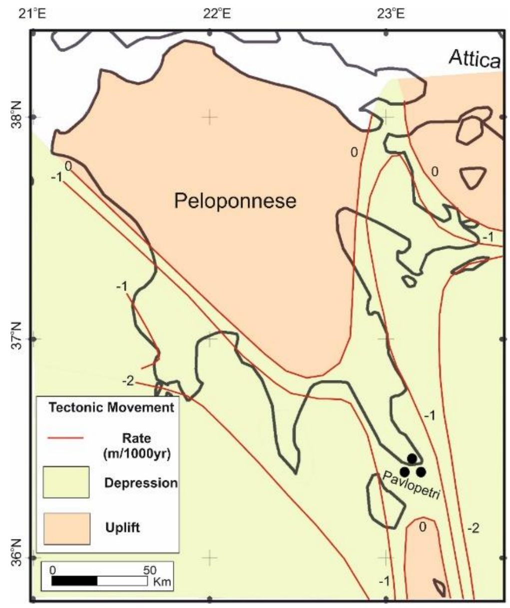

Figure 2. Vertical movements relative to present sea level in the wider study area of Peloponnese (modified after Flemming 1978).

2.2. *Geomorphological setting*

The coastal geomorphological evolution of the broader area of the south Peloponnese can be distinguished into two geological periods within Quaternary, the first period prior to mid-Pleistocene (e.g. Kleman et al., 2016) and the second one from late Pleistocene to present; the former strongly associated with tectonic uplift, while the latter coinciding to the last interglacial period, where glacio-isostatic and hydro-isostatic processes induce coastal subsidence in this area (Lambeck, 1996; Fig. 3). In southern Peloponnese the calculated relative sea level since the last glacial maximum (20,000 to 18,000 years ago) is estimated to be in total about 127 meters (Fig. 3), while 10,000 years before present (BP) the relative sea level was about 55 meters bpsl, at 6000 BP at about 6 meters and at 2000 BP at about 1.5 m bpsl. Pavlopetri settlement flourished 3000 to 4000 years BP when relative sea level was several meters below present sea level.

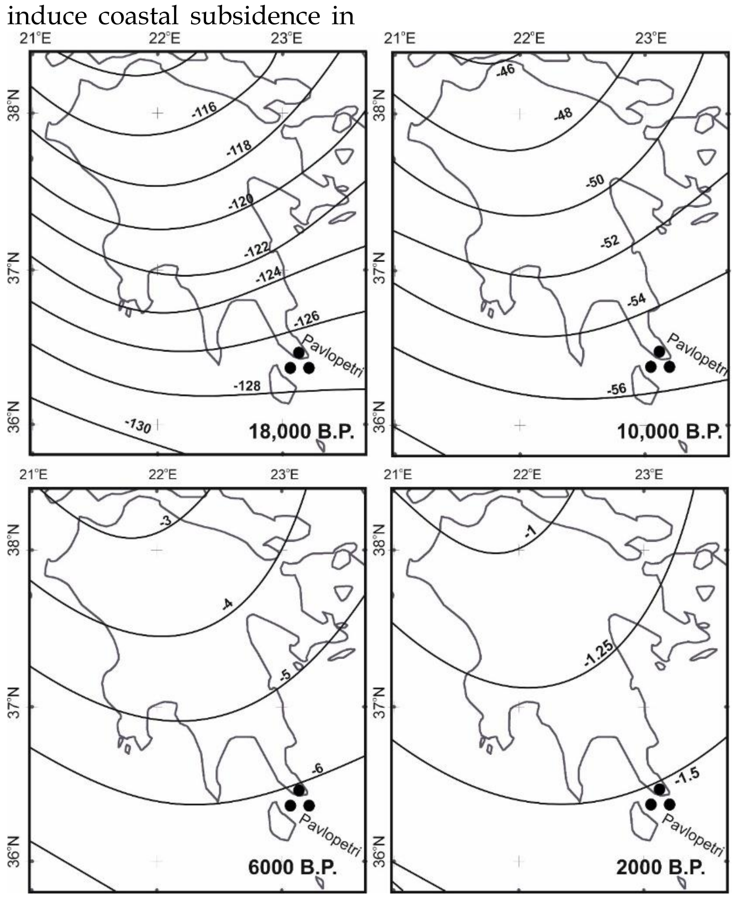

Figure 3. Sea-level stages (in meters) for the broader area at (a) 18,000 BP, (b) 10,000 BP, (c) 6000 BP, (d) 2000 BP (according to Lambeck, 1996).

The Pavlopetri ancient city was built at the north - western end of the Vatika Bay along a shallow valley, whose main axis orientation is NNE-SSW, having at its western side the Elafonisos island, and at its eastern side a western flank of the rocky elongated ridge (outcrop of the basement), connecting the present Pavlopetri island with the small islet to the east of Akra Punta. To the north current water depths are <1 m, whereas at its southern end depths exceed 2.5 m (Scheffers et al., 2008). The eastern flank of the valley was connected to the mainland (Akra Punta); this is justified by the bore hall drilled at the Akra Punta in which the bedrock (aeolinite) was found at an absolute depth of approximately 2 m, when the settlement has been submerged by more than 4 m (the combined effect of relative sea level rise and tectonic activity). Moreover, the radiocarbon dating results in the deposits of the Viglafia lagoon (elevation from -1.92 m to -2.17 m bpsl), showed the existence of the lagoon at 134-380 cal AD; furthermore, this layer overlays a soil layer extending between -2.17 and -2.5 m bpsl, formed under subaerial conditions.

Scheffers et al., (2008) found tsunami indicators west of Cape Skalas, where the mainland coast opens to the west and southwest (i.e., to the Hellenic Trench) and is no longer in the wave shadow of Elafonisos island, which obstructs waves coming from the SW and WSW. Large boulders, some found more than 150 m inland, and up to +14 m asl., provide the most important proof of a tsunami impact along this shallow water coast. The same authors suggest that four tsunami events affected the coasts of southeastern

Lakonia during its recent geological history: (i) the 365 AD event, (ii) the 1303 AD event, (iii) at or after 1467 AD; and (iv) after 1618 cal AD.

Nowadays, depths between Elafonisos and Akra Punta are less than 2 m, with the seabed being covered by sandy deposits of about 2 m, as indicated by the Viglafia lagoon core. Along the crest of the eastern flank of the valley water depths are less than 1.5 m with a small opening to the south of the islet, where depth reaches 3 m. Assuming that the submergence of the ancient settlement was not associated with substantial tilting of the area, the geomorphological setting of the ancient city indicates that the port could be accessed either from its south and/or from its NE end to the south of the islet Punta. Interestingly, there are no findings indicating the existence of artificial harbor constructions or jetties (Henderson et al., 2011).

2.3. *Oceanographic setting*

The settlement is subjected to minor tidal ranges, as the whole easter Mediterranean Sea experiences a minimal tidal range in the order of <20 cm (Tsimplis, 1994), which may increase by meteorological factors (i.e., S, SE winds) to about 0.5 m (Mamoutos et al., 2014). Thus, nearshore hydrodynamics are governed by wave activity, which is also restricted due to the coastal configuration and the limited fetches (distance between Pavlopetri and Crete) which is less than 110 km. On the basis of WHAM model (Korres et al., 2019) the incoming waves from the southern sector, i.e. with a direction of 125-160 degrees (for a 25 year period, i.e. 1991-2015), have an annual frequency of 3.1% and the largest wave height is no more than 1.5 m (see Table 2).

Table 2: Southern sector mean annual offshore wave characteristics (H_o: wave height, T_o: mean period, f: mean annual frequency of occurrence) for the waves approaching from south – east directions.

Wave sets	H_o (m)	T_o (s)	Direction (°)	f (%)
Max 1/3	0.5	6.1	141.1	2.38
Max 1/10	0.8	7.0	142.3	0.71
Storm	1.1	7.6	140.8	0.13
Abs. Max	1.5	8.4	146.0	<0.0001

On the basis of the aforementioned data, the ancient city was a naturally protected area from wave activity, being an ideal place for port facilities.

Furthermore, using the data of Table 2 and the equations presented in Table 3, the following parameters have been calculated: (a) the maximum depth of mobilization (closure depth) of the seafloor sediments (d_c) using equations 1 and 2, (b) the breaking depth (d_b) of the incoming offshore waves using equations 3 and 4, (c) the wave runup ($R_{2\%}$) is calculated using equation 5 considering equation 6 and 7. For these calculations the subaqueous slope (m) is considered equal to 2.5%. The output of these calculations is presented in Table 4.

Table 3. Hydrodynamic equations (for the parameters see text)

Author	Equation	
Hallemeyer (1981):	$d_c = 2.28H_0 - 68.5\left(\frac{H_e}{g\,T_e}\right)^2$	(1)
Komar & Gaughan (1972):	$H_b \cong H_0\,(\frac{0.563}{\left(\frac{H_o}{L_o}\right)^{0.2}})$	(2)
Madsen (1976):	$\gamma = 0.72\,(1 + 6.4\,m)$ [m=0.025]	(3)
McCowan (1894):	$d_b = \frac{H_b}{\gamma_b}$	(4)
Stockdon et al. (2006):	$R_{2\%} = 0.043\,(H_o\,L_o)^{1/2}\ for\ \xi_o < 0.3$	(5)
Iribarren & Nogales (1949):	$\xi_o = \frac{m}{\left(\frac{H_o}{d_o}\right)^{0.5}}$	(6)
Komar (1976):	$L_0 = 1.56\,T^2$ (6)	(7)

Note: $H_e$and T_e refer to the extreme wave conditions (height and period)

Table 4: The main wave characteristics (d_c: closure depth, H_b: significant wave height, d_b: breaking depth and R: wave runup) affecting the study area

Wave sets	d_c	H_b	d_b	$R_{2\%}$
Max 1/3		0.75	0.96	0.24
Max 1/10		1.10	1.41	0.33
Storm		1.40	1.89	0.42
Abs. Max	3.20	1.90	2.56	0.55

Nearshore hydrodynamics calculations show that the entire monument is located in water depths shallower than the closure depth (d_c=3.2 m), the largest part of the identified depths are smaller than the breaking depth of the maximum 10% (d_b=1.4 m) and the highest waves (H_b =1.9 m) are associated with the most intensive sediment resuspension and transport. This observation explains also the temporarily and partially covering, by unconsolidated sediment (mostly sand), of the settlement that is located in water depths < 1.5 m.

3. PAVLOPETRI SUBSIDENCE

The Pavlopetri ancient city was established on the 4th millennium BC (as archaeologocial findings suggest; Harding et al., 1969; Henderson et al., 2011), and it flourished during 2800 – 1180 BC, while it seems to be abandoned during the first century BC. Pavlopetri is located in an area that is subjected to subsidence with a mean rate of 1m per millennium (Flemming, 1978). This subsidence is the combined effect of an over hydro-isostatic adjustment of the southern Balkans to the last interglacial period and to local tectonism that is related to the Hellenic subduction zone.

From the glacio- hydro-isostatic model of Lambeck (Lambeck 1996; Lambeck et al. 2005) it is accepted that the relative position of sea level at 2800 BC was c. 4.4 m bpsl, at 1180 BC c. 2.5 m bpsl and during the 1st century BC c. at 1.5 m bpsl. In addition, Pizzaro et al. (2012) have reported three series of beachrocks in between current water depths of 2.5-3.0 m (upper), 2.6-3.5 m (middle) and 3.9-4.8 m (lower), located within a distance of approximately 150 m from shore and about 200 m of the northeastern edge of the submerged city of Pavlopetri; the presence of beachrock formations provide evidence of shoreface displacement (vertical) caused by tectonic activity. The same study demonstrates, through radiocarbon analysis, that the age of the middle and the lower beachrock formations are AD 480-650 and AD 1090-1150, a time when the sea level was -1 m and 0.7 m bpsl, respectively. For the upper beachrock formations, that have an average relative position of c. 0.3 m in respect to the middle formation, the radiocarbon analysis calculated a date older than the lower beachrock formation, which does not comply with their stratigraphic position as they are older than the ages obtained for the deeper formations; the latter could be possibly associated with a tsunami event that took place after the development of the middle formation, carrying and depositing allochthonous older material on the beachface, which is located at the intertidal range (+/- 10 cm), forming the upper beachrock through cementation processes. It has also to be pointed out that the formation of the deepest beachrocks coincides with the beginning of the Medieval warm period (c. 950 AD to c. 1250 AD), whilst the middle and upper formation with the end of the same warm period; the latter period may also be related with a small increase of the sea level. By comparing the dates of the known earthquake events to those referring to beachrock formations, it can be deduced that the lower beachrocks were submerged by earthquake events after the completion of their formation (i.e AD 525±85) and prior to the period of the formation of the middle beachrock formation (AD 1120±30), while the upper layer was subsidized by an earthquake no later than AD 1500, considering its mean difference in elevation (i.e. 30 cm) and the rate of sea level rise (<1 mm/year).

Moreover, intensive tectonic activity with catastrophic consequences is not expected to have taken place during the period of the "flourished" period (2800 -1200? BC) of the Pavlopetri ancient city. Interestingly, during this period the ancient settlement resisted the tsunami initiated by the Thera eruption (1642-1540 BC). However, this may not be the case for the period after 1200 BC and before 550 BC during which no significant earthquakes have been reported, with the exception of the hypothetical Mycenaean earthquake (Cline, 2014). For the period after 550 BC a series of events have been reported (e.g., 550 BC (M=6.8), 464 BC (M=6.8), 413 BC (M<6), AD 62 (Western Crete) (M=7.5), AD 365 W Crete (M=8.3) (Liritzis et al., 1995; Papazachos and Papazachou, 2003). The aforementioned earthquakes caused, most likely, subsidence of the area, contributing to the submergence (at least to some extend) of the Pavlopetri old town.

As demonstrated before, the area of the ancient city of Pavlopetri, was subjected to a sea level rise of c. 4.5 m of which radiocarbon evidence shows that about 3 m occurred AD. The wave runup of the highest waves for the period 1991-2015 is 1.5 m and considering a maximum combined tidal effect of no more than 0.5 m (Tsimplis, 1994), probable the Pavlopetri settlement was built initially at elevations higher than 2 - 3 m (a common practice for the Mediterranean area (e.g. Galilili et al., 2019), when the sea level was c. 4.5 m lower according to Lambeck (1996). At the end of its flourish period (1180 BC) sea level had already increased by c. 2.0 m and the old town of Pavlopetri was located in elevations of no more than 1 - 2 m; the latter means that during southerly waves a part of the town was vulnerably to coastal flooding. Therefore, by the 1st century BC, when sea level was higher by almost another 1 m, the ancient settlement was only ~1 m asl, if not partially submerged; this, in combination with a concurrent tectonic activity, explains the abandonment of the area as stated by Harding et al. (1969). By the years AD 480-650 the sea level was even higher by 0.5 m and the area was downlifted tectonically (according to radiocarbon evidence from beach rock formations) by almost 3 m; thus, at the end of this period most of the settlement was submerged, lying in water depths larger than 1 m. In addition, the Elafonisos and Akra Punta are separated (the Elafonisos-Punta Isthmus is submerged), establishing Elafonisos island. The process of submersion continues till today, as sea level has risen by another 0.5 m to reach its present depth of 2.6-1.5 m bpsl.

More evidence to the above scenario is provided by Thucydides in his "History of the Peloponnesian War (3.89.2), suggesting that during the Peloponnesian war in the 5th century BC, Elafonisos was connected to Akra Punta. Moreover, there are three occurrences of incised cart-tracks cut into the rock on the north shore of the Elafonisos (Fig. 1) whose presence is associated with the transportation of goods through the Elafonisos channel. The westernmost set of tracks nearby cape Skalas is the largest and most heavily incised, and suggests a last-ditch attempt to maintain dryland contact with Elafonisos, where the presence of human activity is dated also from the early Helladic Period (Waterhouse & Simpson, 1961; Gallou & Henderson, 2012; Zavou, 2012). Moreover, a borehole (Fig. 1) drilled within the Punta lagoon, found the bedrock (aeolinite) at a depth of -2.5 m. Therefore, if we assume that the strip of land connecting Elafonisos with the mainland had an elevation of at least 1 m when sea level was 2 m bpsl; thus if we consider a 2 m of sea level rise and a tectonic downlift of 1.6 m we reach the position of the buried crest of the aeolinite (-2.5 m). Therefore, Elafonisos is expected to have been separated since AD 450 when sea level increased by c. 1 m and the tectonic activity downlifted the area by 1.3 m. Later on, Portlands of the 16th and 17th century AD show Elafonisos (Cervus) as an island (Scheffers et al., 2012).

In accordance to the forementioned scenario of geomorphological evolution is the occurrence of a fair quantity of later pottery during the Hellenistic period (323-31 BC), the Roman period (31 BC- AD 324) and some other pottery findings during the late 6th or 7th century AD (Harding et al., 1969), that may be associated with the highest (>3 m) elevation of the settlement, prior to the tectonic downlift after AD 400. It can also be speculated that during this period a 'new' settlement has been established in higher elevations (e.g. at the level of the cemeteries) possible using material from the submerged settlement.

On the basis of the information presented in Table 5, the palaeo-geographic setting of the broader area of the Pavlopetri settlement is visualized in Fig. 4 for the periods 1180 BC, 500 BC, and 500 AD, making the assumption that the Pavlopetri settlement was built at elevations no less than 3 m asl, as discussed before.

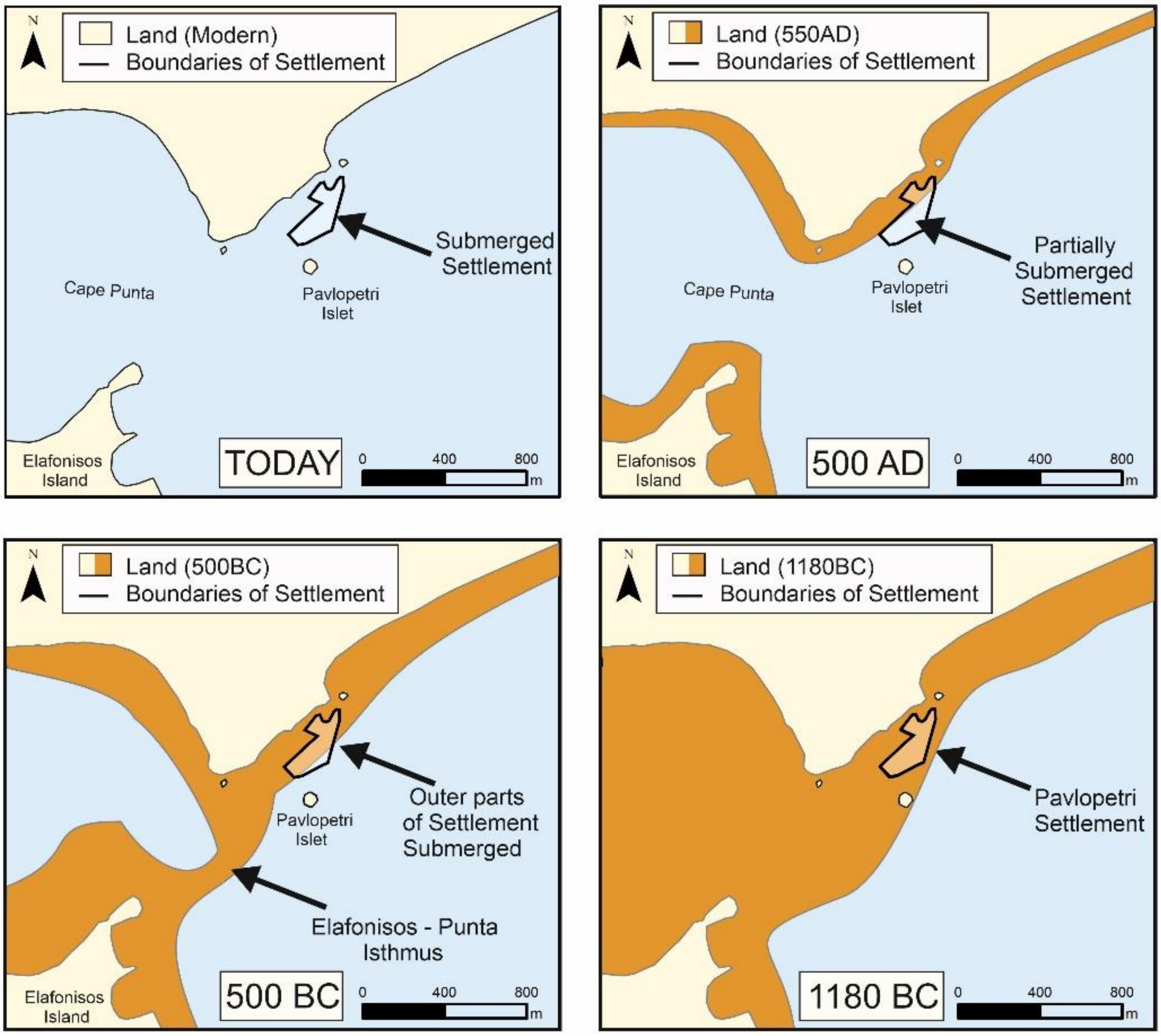

Figure 4. A paleogeographic reconstruction of the broader are of the Pavlopetri settlement at BC 1180, BC 500, AD 500.

Table 5: Geoarchaeological information and radiocarbon data

Sea level below present (Lambeck, 1996)	Historical Periods (see text)	Radiocarbon dating (cal 1950) (Pizarro et al., 2012)	Earthquakes-Tsunamis(T) (Papazachos & Papazachou, 2003)	Historical Information for Elafonisos Evolution (see text)
-	-	-	1650 AD	-
0.3	16th century		-	Elafonisos Island
-	-	-	1494 AD	-
-	-	-	1303 (T)	-
-	-	-	1246 AD	-
		(BR= 2.5-3.5m) Inconsistent dating (probable due to tsunami)	-	-
0.6	AD 1204 Latin		-	-
0.7	-	AD 1120+/-30 (BR= 2.6-3.9m)	-	-
	-	-	516 AD (T)	-
1	-	AD 565 +/- 35 BR (3.9-4.8 m)	-	-
-	-	-	AD 365	-
c. 1.2	AD 324 Byzantine	-	-	-
c. 1.4-1.1	-	AD 207 +/- 123 (Punta Lagoonal deposits)	-	-
-	-	-	AD 62	-
1.5	AD 31 Roman AD/BC 1st century BC	-	-	-
c. 1.9	323 BC Hellenistic period	-	-	-
c. 1.8	-	-	464 BC	-
-	490/80 BC (classical period)	-	-	-
2.0	5th century BC	-	-	Elafonisos-Punta Isthmous
c. 2.1	-	-	550 BC	-
-	-	-	1177 BC**	-
2.5	1180 BC	-	-	-
4.4	2800 BC	-	-	-

*According to sea levels presented in Fig. 3, **Hypothetical earthquake shock after Cline, 2014

4. MONUMENT PRESERVATION AND RESILIENCE

The construction characteristics (as presented in the introduction), the morphological setting and the particular morphodynamic conditions in such a shallow marine environment make the conservation of the Pavlopetri remains an extremely complex task.

The factors considered to be among the leading causes of building stone deterioration include salt crystallization, aqueous dissolution, microbiological growth, original construction and human activity. Specifically, salt crystallization within the pores of stones can generate sufficient stresses to cause the cracking of stone, often into powder fragments. Closely related to the crystallization of salt is damage caused by salt hydration and by differential thermal expansion of salts. The resistance of stone to salt damage is dependent on the pore size distribution and decreases as the proportion of fine pores increases. Furthermore, some types of bacteria, fungi, algae, and lichens produce acids and other chemicals which attack to carbonate and silicate minerals and mainly to these which do not cover by sand. Moreover, the original construction of the walls by mud brick and/or timber frames covered in plaster was very sensitive in dissolution in the water. Finally, human activity such as removal of building elements (e.g. stones) for onshore constructions (maybe this is one of the reasons for monument's present stage, together with anchoring and seabed disturbance through propellers.

Regarding the crystallization pressure, salt weathering has been reported to be the result of crystallization pressure build-up against pore walls, when salt nucleation and growth take place in a confined space (Evans, 1970). Based on the analogy with the theoretical freezing model in porous media developed by Everest (1961), first Wellman and Wilson (1965, 1968) and later Fitzner and Snethlage (1982) developed a thermodynamic model for calculating the crystallization pressure of a salt in a pore. According to Wellman and Wilson (1965) salt crystals grow preferentially in the largest pores and the salt solution is withdrawn from the smaller pores. When a crystal fills a large pore, crystallization can take place in smaller pores connected to it, but the crystal will continue growing and it will generate a pressure P against the pore walls. This suggests that in a smaller sized pore the pressure developed by crystal growth is higher than in larger pores. Thus, when the crystallization pressure exceeds the tensile strength of the stone, fracture of the material takes place. Concerning the seawater contribution to salt solution the most usual method for evaluating this contribution is through the comparison of ionic concentration ratios of measured ions to Na+ with those found in seawater (Schneider 1987).

In addition, the forces related to the wave regime and the associated sediment movement, the tectonic (earthquake) effects and the behaviour of the structure in the case of the occurrence of a tsunami wave have to be taken into account. Most of the Pavlopetri area is under the influence of wave activity as it lies in water depths less than 3 m, which is typically the maximum depth at which waves could initiate sediment movement. In the parts that are shallower than 2.5 m, which is the breaking depth, the maximum dissipation of the incoming highest waves is recorded accompanied by larger movements of the seabed sediment. On the basis of satellite observations (comparing successive Google earth images) changes of the shoreline position at Akra Punta are revealed and also to nearshore bathymetry; making essential the periodical monitoring of the seabed around the monument, with the use of acoustic devices (e.g. multibeam) at least once a year. The changing nearshore bathymetry provides evidence for a temporal siltation (burial) of the shallower part of the submerged part of the settlement. Finally, the construction of submerged breakwaters in water depths larger than the closure depth (e.g. at depths of more than 5 m) could minimize wave energy and the associated changes in seabed relief which affect the site.

To insure the resilience of the monument to natural processes (including climate change), it is obvious that periodical monitoring of the state of preservation is essential, not only to prevent irrecoverable damage but also to plan conservative interventions, and, above all, to conduct maintenance operations; this could be achieved through monitoring of the agents of deterioration (Cardell et al., 2003; Goudie, 1997). Moreover, the nearshore oceanographic conditions need to be monitored, whilst periodical surveys determining accurately the changes of the bathymetry and the position of shoreline in Pavlopetri settlement, and the surrounding area could also provide useful information. These practices are essential for the protection of the antiquities but also of rare or endangered terrestrial and marine species as well as the lagoon that is located next to the cemetery and is protected by the Nature 2000 program.

5. PAVLOPETRI TOURISTIC EXPLOITATION

The Blue Tourism sector (developed on coastal spaces and including heritage resources) has been identified as an area of particular potential within the EU Blue Growth Strategy and is the most important tourism subsector in Europe (European Commission 2021). As part of this strategy the access of public to underwater archaeological sites should be facilitated, with special emphasis on these aspects: knowledge and understanding, citizen involvement and responsible access. Increased awareness and education favour the involvement of communities in the protection of this heritage, not only because it turns them into "guardians of the past" (Maarleveld et al., 2013) but also because it has a direct impact on the local economy, fostering sustainable development and strengthening the idea, that preserving heritage has more advantages than passively witnessing its despoilment.

In Greece, there are hundreds of ancient shipwrecks, ancient ports and remnants of ancient civilizations that were immersed in the sea. Thus, the creation, in these places of underwater museums, can result in a network of marine facilities for the study and promotion of the ancient wealth of the country. There are many reasons why underwater archaeology can make a significant contribution to our knowledge of the past. But underwater sites are inevitably difficult to access, and more hazardous, compared with sites on dry land. In order to access the site directly, diving equipment and diving skills are necessary, as a result, they do not provide good outreach possibilities or access for the general public.

Nowadays, work has been done to bridge this difficulty, through the use of the World Wide Web for webcasting projects, or dedicated virtual reality systems (Corfield, 1996) that allow users to perform a virtual diving into an interactive 3D reconstruction of the underwater archaeological site. On the other hand, virtual or indirect access solutions are very useful, but always through the correct interpretation of the heritage.

A proposed action for the exploitation and protection of the Pavlopetri ancient town could be the construction of an underwater museum (made of glass) that "covers" the location of the old town, which would be accessible from the shore through a fixed tunnel. The feasibility of such a construction, from the engineering point of view has been provided by

Moliviati and Fotiou (2014). Such an underwater museum (likewise the Museo Atlantico Lanzarote in Canary Islands) could address two different thematic units: the first unit will include the archaeological site itself, whereas the second unit refers to the representation of architectural structures with scenes from everyday life, such as ceremonies, cooking, childhood, work, material culture and bourgeois interiors, etc. These moments of everyday life will share with the visitors a real conception about the past. An alternative proposal could be the construction of an inland museum at the nearby area, in which the visitor could see archaeological exhibits and representations of parts of the ancient town.

6. CONCLUSIONS

The Pavlopetri settlement monument and the geomorphological evolution of its surrounding area is the outcome of the interplay between sea level rise (about 4-5 m since the initial establishment of the settlement), tectonic activity related to earthquake socks (subsidence of ~2-3 m) and the impact of marine processes that include the incoming wave energy and tsunami events. Especially for the deterioration of the building materials crystallisation pressure and seawater properties (i.e. dissolved salts) are crucial parameters.

On the basis of the archaeological data the proposed paleogeographic reconstruction shows that at the beginning of the monuments' flourish period (2800 BC) sea level was about 4.5 m bpsl, whilst at 1180 BC (Minoan/Palatian period), sea level was 2.5 m bpsl. At 500 BC Pavlopetri area was about 2 m asl and the dry path connecting Elafonisos with the mainland was still active. In AD 500, when sea level increased by an additional ~1 m, the lower southern part of the Pavlopetri old town would have been flooded, whilst the passage between Elafonisos and the mainland would have been almost submerged, with very shallow depths (0 m +/- 0.5 m).

For the preservation of the monument there is a need of periodical monitoring of the physico-geographical characteristics and the deterioration of its building materials, whilst the construction of a submerged breakwater in water depths larger than 5 m could minimize wave energy and the associated changes in seabed relief.

Finally, for the promotion of Pavlopetri archaeological area, it is proposed to create an underwater museum, in accordance to Blue Tourism sector (developed on coastal spaces and including heritage resources), which has been identified as an area of particular potential within the EU Blue Growth Strategy (European Commission 2021).

AUTHOR CONTRIBUTION

Conceptualization, S.P., A.P. and V.K.; methodology, S.P., A.P. and V.K.; formal analysis, S.P., A.P.; investigation, A.P., S.P. and V.K.; resources, S.P., A.P. and V.K.; data curation, V.K , S.P. and A.P.; writing—original draft preparation, S.P., A.P. and V.K.; writing—review and editing, S.P., V.K. and A.P.; visualization, V.K.; supervision, S.P.; funding acquisition, S.P.; All authors have read and agreed to the published version of the manuscript.

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