



SUPPORTING MARITIME  
ARCHAEOLOGY IN THE  
EASTERN MEDITERRANEAN



*Maritime Archaeology Graduate Symposium 2020*

22<sup>nd</sup> – 23<sup>rd</sup> February 2020. Short Report Series.

doi: <https://doi.org/10.33583/mags2020.10>

© 2020 The Author

## **The Impact of Environmental Changes on Coastal Archaeological Sites in the Mediterranean**

**Mirette Abdelnour**

Alexandria Centre for Maritime Archaeology and Underwater Cultural Heritage, Egypt.

[Mirette\\_Magdi@yahoo.com](mailto:Mirette_Magdi@yahoo.com)

### **Abstract**

This paper is part of an ongoing MA research project that focuses on the influences of environmental changes on coastal archaeological sites in the Mediterranean, threatening the *in situ* protection of coastal, near coastal and underwater cultural heritage (UCH). To effectively address this, I provide a summary of the main environmental factors that have affected different sites in the Mediterranean Sea by examining four specific case studies: Alexandria, Egypt; Pavlopetri, Greece; Baia, Italy; and Apollonia, Libya. The aim of this study is to develop appropriate strategies to mitigate these threats in the future.

### **Key words**

*Coastlines, sea level change, earthquakes, tsunamis, sedimentation.*

---

### **Introductions**

Approximately 3% of the Earth's surface, around 4 million square kilometres of dry land, has been flooded between 20,000 and 5000 years Before Present (BP). During this period the global

environment underwent a series of rapid climatic changes, permanently reshaping our planet (Fairbanks, 1989; Coleman, 2008: 178). The environmental changes presented here include the following:

- sea level change;
- tsunamis;
- earthquakes;
- ocean sedimentation processes;
- and land subsidence.

UNSECO (2021) has estimated that around 53 cultural and natural heritage sites have already been affected by environmentally related factors. According to the Intergovernmental Panel on Climate Change (IPCC), this will intensify in the coming decades if global temperatures increase by 1.5°C by 2040 and 2°C by 2065. Predictions suggest that this will lead to catastrophic events for natural and cultural heritage, with the IPCC suggesting that substantially more sites will be affected in the future ( Reimann *et al.*, 2018; ICOMOS, 2019: 2).

### **Sea level change**

Sea level change is defined as the increasing or decreasing of the seawater volume, caused primarily by the melting of ice sheets and glaciers, and controlled by factors that are related to thermal expansion and plate tectonic movements (Coe *et al.*, 2002: 43). Sea levels are constantly fluctuating at various scales; some of which are very slow whilst others occur more rapidly. These changes are classified as local or global, and are linked to four related processes: eustatic, isotactic, tectonic movements, and ocean tides (Pugh, 2008: 1).

During the Last Glacial Maximum (LGM), *c.*25,000–18,000 BP, global sea level was around 120 m lower than today (Fig. 1), with scholars arguing that sea level continued to rise until approximately 5500 BP, when it reached its approximate present-day level (Fairbanks, 1989; Lambeck and Purcell, 2005; Ren *et al.*, 2017). Geoarchaeological data obtained from the Mediterranean Sea further reveal that sea level has remained more-or-less stable, estimating an approximate rise of 0.5 m during the past 2000 years (Flemming, 1972; Pirazzoli, 2005: 1994).

At the height of the LGM, eustatic sea level was much lower than today because large volumes of water were contained in ice sheets and glaciers. When the ice rapidly melted during the subsequent warmer temperatures of the Bølling-Allerød interstadial (*c.*15,000–13,000 BP), substantial amounts of meltwater poured into the oceans, thus causing sea level rise and a rapid redistribution of weight on

the Earth's crust. The result of this was post-glacial rebound, the creation of new coastlines and landmasses as the retreating ice sheets caused isostatic uplift (Colman, 2008: 184).

The aforementioned process is considered by scholars who have attempted to predict global sea level change in the future, arguing that sea level during the past two decades has increased by 3 cm per decade. Studies also suggest that between 1945 and 2000, sea level has risen between  $0.7 \pm 0.2$  mm  $\text{yr}^{-1}$  (Calafat and Gomis, 2009), with other scholars predicting a more substantial rise of 1.1 mm per  $\text{yr}^{-1}$  (Cramer *et al.*, 2018: 972). More recently, the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report suggested a range of 0.18–0.59 m of sea level rise had occurred between 1980 and 1999, with additional studies postulating an increase of 1 m by the end of 20<sup>th</sup> century (Solomon *et al.*, 2007; Milne *et al.*, 2009).

The numbers presented here are alarming, highlighting the fact that radical changes have been taking place and will continue to do so in the immediate future. In the light of these stark predictions, UNESCO has estimated that at least 136 cultural and historical sites will be submerged by 2100 due to sea level rise (Alvaro, 2016: 842), rendering the development of a strategic management plan to preserve them an absolute necessity.

### **Tsunamis**

The term tsunami is defined as a series of considerably high ocean waves produced when a large volume of ocean water is rapidly displaced, often following a strong earthquake (Stratton, 2016: 578). According to the Global Historical Tsunami Database, since 1900, roughly 80% of tsunamis have been generated by earthquakes. In the Mediterranean, tsunamis have been recorded in areas where subsidence of oceanic crust or plate collision occur. For the entire Mediterranean region, geologists have recorded four main plates: the Gibraltar Arc, the Calabrian Arc, the Hellenic Arc, and the Cyprean Arc. Scholars argue that plate activity is causing the active subduction of the African and Eurasian plates, around 4 to 5 mm per year in the western Mediterranean and around 30 to 50 mm per year in the eastern Mediterranean (Demets *et al.*, 2010).

In the southern Aegean, the Hellenic Arc and Trench have been identified as the main areas where earthquakes, tsunamis, and volcanic activities occur. Archaeological and geological data obtained for the Hellenistic and Roman periods suggest that such processes affected the harbour of Phalasarna in northwest Crete in 66 CE. Geoarchaeological studies have further suggested that a massive tsunami was generated in the area as a by-product of a strong earthquake, with ancient sources postulating that the largest tsunami wave in the entire Mediterranean occurred in 365 BCE (England *et al.*, 2015: 7). It is said that this tsunami affected primarily the south-western Peloponnese, causing significant damage along a substantial length of coastline. Other sources give accounts of a tsunamigenic

earthquake that took place on 8th August 1303 CE, when a large tsunami was generated somewhere between Crete and Rhodes affecting several coastal sites (Evelpidou et al., 2019: 19). On this event, it is reported that the port facilities, including those of Alexandria, Heraclieon in Egypt and Acre in Israel, were also affected (Antonopoulos, 1979: 121). For additional information pertaining to other tsunami events documented in the Mediterranean, see Table 1 at the end of the article (Papageorgiou *et al.*, 2014: 255).

### **Earthquakes**

An earthquake is a massive shaking of the Earth's crust due to the sudden movement of a tectonic plate. There are a number of documented historical earthquakes that affected coastal sites, including one that occurred in 365 BCE off the coast of Crete (Shaw, 2008: 268). Ancient sources state that a strong earthquake dramatically altered Crete's landscape causing half of the island to uplift and the other half to downlift, with scholars estimating a magnitude of 7.7 on the Richter scale (Abdelnaby and Elnashai, 2013). It is reported that this earthquake destroyed sixty out of a hundred towns of the island, with literary sources arguing that Rhodes was also affected by another destructive earthquake more than a century later around 229 and 225 BCE. The result of this earthquake was the destruction of the famous Colossus of Helios (Ambraseys, 2009).

### **Ocean sedimentation processes**

Ocean sedimentation processes are described by geologists as the transportation and deposition of marine sediments and materials, usually carried by water, wind or ice, and deposited anew; the long-term result is the reshaping of the coastal landscapes, for example, causing tombolo effects (Julien, 1995).

Sediments are classified in four types:

- biogenous, which derive from the shells or skeletons of dead organisms;
- cosmogenous, which derive from outer space;
- terrigenous, formed out of pre-existing rocks, shaped from weathering (i.e. shaped by wind, temperature and water), that are usually deposited by wind or rivers leading to the sea;
- and volcanogenous, derived from volcanic eruptions.

These processes can be observed in harbours when silting occurs; a good example being the Heptastadion embankment in Alexandria, Egypt (Goddio and Fabre, 2010; see further discussion below).

## **Land subsidence**

Land subsidence is defined as the gradual lowering of the Earth's surface as a result of the removal or displacement of subsurface materials (Galloway, Jones and Ingebritsen, 1999). Historically, land lowering along the Mediterranean coast has been estimated to be around 1 mm/year since the beginning of the Holocene, c.10,000 BP (Stanley, 1997). Focusing on Alexandria, geologists suggest that the overall coastal geomorphology has undergone land lowering effects due to tectonic settings, ranging 0.5-7.0 mm per year (Frihy, 2003: 123). According to Goddio and Fabre (2010: 54), land level has dropped in Alexandria by 5 to 6 m during the past 2000 years, with other examples in Kekova, Turkey citing a rate of 1.6 mm per year over the past 1400 years (Özdaş and Kızıldağ, 2013: 509-510).

## **Case studies**

The following section will evaluate how the aforementioned processes have affected four historic sites along the Mediterranean coast:

### **Egypt**

Egypt is regularly impacted by a number of environmental threats, including flooding events caused by the Nile, rising sea levels, land subsidence, earthquakes, and severe storms, all of which have contributed to the inundation of coastal archaeological sites., including Thonis-Heraclion, and many other smaller sites along the Nile Delta coastal margin. This section will discuss the impact of these threats on the coast of Alexandria, specifically the eastern harbour, the Ptolemaic Royal Quarter and the Pharos lighthouse.

### **Alexandria**

In 331 BCE, Alexander the Great ordered his town planner Dinocrates to construct the city of Alexandria by linking the island of Pharos to the mainland 'Ra kedet' with a large embankment called the *Heptastadion* (Fig. 2), which means 'seven-stadia', (1 stadium = 186 metres). This construction was around 1260 m in length and divided the area into two harbours: the Eastern Harbour (EH) and the Western Harbour (WH) (Empereur, 2001: 54-55).

The area of the EH was delineated by Cape Lochias to the east and the Heptastadion to the west. Based on the archaeological discoveries in the area, Cape Lochias (or Acra Lochias) was a vibrant part of the Royal Quarter during the Ptolemaic period (305–30 BCE). This is evident due to the excavated royal palaces, the temple of Isis Lochias, the Mausoleum of Cleopatra VII and the Timonium of Marc Antony, as well as the Pharos island and various other subsiding buildings, including the famous lighthouse and temple of Isis Pharia. All of these ruins were excavated underwater as the topography of the coastal zone of Alexandria has changed dramatically over the past two millennia, this is due to three main factors: hydrological changes due to sea level rise and floods; sedimentation processes

related to flooding events of the Nile; and geological changes, such as land subsidence and earthquakes causing tsunamis (see Goddio and Fabre, 2010: 54).

Research on sea level change in relation to Alexandria has noted a significant rise over the last 2000 years, equivalent to approximately 1 to 1.5 m, with land subsidence claiming around 5 to 6 m (Franco and Leopoldo, 1996; Goddio and Fabre, 2010: 54-55). Other scholars have analyzed the sediments in the EH, estimating that sea level has risen nearly 2 m during the last 2400 years (Stanley and Landau, 2010: 45). In sum, these variations in sea level and land subsidence have cooperated fundamentally in the submergence of the EH and its associated facilities.

Alexandria's coastline has also been affected by several massive earthquakes, resulting in the destruction of major sites and monuments, including, most famously, the Pharos lighthouse. The construction of the lighthouse was started in the 3rd century BCE during the reign of Ptolemy I Soter ('Saviour'), designed by the Greek architect Sastrotus of Cnidus to guide the mariners into the city's harbour. It was completed during the reign of his successor, Ptolemy II Philadelphus, constructed out of white marble and reaching a height of 120 m (Riad, 1933: 237). It comprised of three floors, with the lowest being square, the second floor octagonal, and the top cylindrical (Fig. 3) (Empereur, 2004: 26-30).

Since the 4th century CE, the lighthouse was heavily affected by roughly 20 earthquakes (Abdelnaby and Elnashai, 2013: 119). During the Islamic period, in 796 CE, according to Ibn al Athir and Ibn al Bayan al Maghrib the lighthouse presented major structural cracks, which resulted in the total collapse of its upper part. A century and a half later, in 944 CE, El Masudi estimated that the height of the lighthouse was nearly 60 m shorter than its original height. This was confirmed by Abdelatif Albagadadi in 955 CE, when another earthquake destroyed the top 9 m of the remaining tower (Table. 2) (Tzalas, 2000). These earthquakes resulted in the near complete destruction of the lighthouse (see Ambraseys, 2009). A final mention of the lighthouse can be found in Ibn Batutta's book following his visit to Alexandria in 1350 CE. He confirmed the disappearance of the lighthouse, with only a number of blocks visible underwater. The foundations of the lighthouse were subsequently reused in the construction of Qaitbay Fort between 1477 and 1480 CE by the Sultan Qaitbay, part of which remains preserved *in situ* (Dessandier, 2008; Empereur, 1999: 38).

## **Greece**

Greece has a significant number of submerged archaeological sites, including twenty-three studied by oceanographer Nic Flemming as part of a broader study aimed at understanding Regional Sea Levels (RSL) and how environmental changes have impacted on coastal sites. He concluded that there is a

significant peculiarity in the RSL whereby some sites are uplifted while others are displaced, submerged or were simply abandoned (Fig. 4 and Table. 3) (Flemming, 1968: 1031).

Flemming discovered the famous ‘lost city’ of Pavlopetri in the southern Peloponnese, where he proceeded to conduct a partial underwater excavation of the site (Pirazzoli, 1982: 27). He concluded that the settlement was submerged following an ancient earthquake and subsequent tsunamis. He argued that this was most likely due to the tectonically active location of the site near the boundary of the Hellenic Arc, where the African plate is being subducted by the Aegean microplate (Chalkis, 1984: 374; Andreas Vött *et al.*, 2011: 259-260).

### ***Pavlopetri***

The Bronze Age settlement of Pavlopetri is located on the south-eastern coast of Laconia in southern Greece, and is believed to be the oldest submerged city thus far recorded in the Mediterranean (Harding, Cadogan and Howell, 1969: 113; Henderson *et al.*, 2011: 207). Subsequent archaeological studies have confirmed that Pavlopetri was inhabited from the Early Bronze Age *c.*3000 BCE to the end of the Late Bronze Age *c.*1100 BCE (Henderson *et al.*, 2013: 244), and was partially submerged around 1000 BCE. (Mahon *et al.*, 2011: 2315-2316; Gallou and Henderson, 2012). The submerged city contains a courtyard, fifteen buildings, a stone wall-enclosure, a network of interconnected streets, and a large number of tombs, including 37 cist graves. The site was claimed by RSL over the last 5000 years, ultimately covering it under 4-5 m of water (Figs 5&6) (Henderson *et al.*, 2012). Pavlopetri was submerged as a consequence of long-term tectonic movements caused by the subduction of the nearby Cretan Arc and related local and regional faulting (Stiros, 2009). The city’s location in such a tectonically active area had dire consequences, resulting in its gradual inundation following an earthquake in *c.*1000 BCE (Kipreos *et al.*, 2016: 201). Further geological and geoarchaeological studies have concluded that an average rate of 0.8–1.0 m of coastline has been claimed by the sea every 1000 years (Flemming *et al.*, 1986; Marriner and Morhange, 2007).

### **Italy**

The inundation of coastal archaeological sites has also been extensively recorded in Italy, including Bacoli, Baia, Miseno, Nisida, Portus, Pozzuoli and Serapeo. Perhaps the most widely known and intensively studied site is Baia in Napoli (Paoletti *et al.*, 2005: 54). The following section focuses on the analysis of the environmental events that affected the area of Baia, resulting in the submergence and subsequent abandonment of the site.

### ***Baia***

The city of Baia is located in the volcanic area of the Phlegrean Fields west of Napoli, southern Italy. It was established in the 1st century BCE and reached its peak in the 2nd century CE (Bruno *et al.*,



2015: 42). The site was in use until its partial submergence in the 4th century CE but remained occupied until the 6th century CE. According to the ancient authors Cicero, Seneca and Tacitus, the city flourished with luxurious buildings, thermal bathes, villas and inns serving the Roman emperors and other elites (see Bruno *et al.*, 2015: 42). Extensive archaeological studies in the area suggest that the site was heavily affected in the 4th century CE by extensive land subsidence and other land movements caused by the slow uplift and lowering of the ground surface in response to magma infill and degassing (Ricca *et al.*, 2014: 324). These processes caused severe disruption to the site leading to its eventual abandonment between the 4th and 7th centuries CE (Fig. 7). Further geoarchaeological and core data have revealed that by the beginning of the 14th century CE, sections of Baia were submerged under 6.5 m of water, and totally submerged by the 8th century CE under 10 m of water (Paoletti *et al.*, 2005: 54).

## **Libya**

Libya has several submerged cities, including Phycus, El Gabal El Akhdar, Leptis Magna, Sabratha, Tripoli, Villa Selin, Cyrene and Ptolemais. However, the richest site of these is Apollonia, providing a significant deviance to the changes of sea level and land subsidence.

## ***Apollonia***

Apollonia is the largest underwater city dating to the classical Greek period. Located on the coast of Cyrenaica in North Africa, it was established as a colony in 631 BCE by citizens from the Greek island of Thera, functioning initially as a harbour and coastal trading centre. Following its independence as a city state in the 1st century BCE, it started functioning as a city with the name of Apollonia (Flemming, 1971: 95).

Throughout much of its history Apollonia has been influenced by sea level change, land subsidence and earthquakes. Combined, these processes have resulted in the destruction of its lighthouse, two harbours, quarries, the piers, other buildings and fortifications, and fish pools (Fig. 8) (Beltrame *et al.*, 2012: 219). The city and its coastal features can be currently seen submerged at depths ranging from 0 to 5 m, with the far eastern end of the harbour recorded at 8 m depth (Flemming, 1965: 169). Recent studies suggest that during the last 2000 years, relative sea level along the Libyan coast has risen by  $0.24\pm 0.10$  m and  $0.48\pm 0.10$  m, contributing to the overall submergence of the site (Anzidei *et al.*, 2010). According to Flemming (1965: 178), sea level in the area of Apollonia rose nearly 2.8 m during the Roman period, a process that has continued over the past 2000 years. Archaeological evidence from the site has been recorded at depths of 3 m, thus implying that relative sea level rose by about 0.30-0.50 m, in addition to 2.5-2.7 m tectonic subsidence (Flemming, 1965: 178). During the late



Roman period, in 365 CE, a massive earthquake devastated Cyrene, thus contributing to the overall submergence of the city by an average of 3 to 3.5 m (Flemming, 1965: 178).

## **Conclusion**

Sea level change, land subsidence, tsunamis, earthquakes and ocean sedimentation have been affecting the coastal landscape of the Mediterranean Basin for thousands of years. Complex modelling of these processes and predicting their effects remains an issue for academic interpretation and debate; only recently have studies begun to reveal the sheer scale of changing landscapes. Nevertheless, archaeological indicators, including submerged sites, play a crucial role in determining regional sea level curves and act as prime indicators of areas that are likely to be further affected by environmental processes in the near future (see Fig. 9). It is my view that the use of archaeological indicators, as presented here, will become increasingly relevant in the near future as the effects of global warming continue to accelerate. According to the IPCC, in the period from 2080 to 2100, average sea level in the Mediterranean Sea is predicted to rise by 1 m as a result of the melting of the ice sheets and glaciers, with UNESCO estimating the submergence of at least 136 heritage sites by 2100. To that end, UNESCO, specialist academics and heritage managers need to initiate an in-depth study of potential solutions and management plans to safeguard endangered coastal and underwater sites in situ, provide adequate protection from the negative effects of climate change, and ensure that sites are properly recorded prior to being inundated by rising sea levels.

## **Acknowledgements**

I would like to thank my supervisors, Professor Emad Khalil and Dr Ahmed El-shazly, for their endless support. This work would not have been possible without the support of the Honor Frost Foundation, Dr. Lucy Blue and the perfect organisation of the MAGS Symposium committee.

## Bibliography

- Abdelnaby, A. E. and Elnashai, A. S., 2013. Integrity assessment of the Pharos of Alexandria during the AD 1303 earthquake. *Engineering Failure Analysis* 33, 119–138.
- Alvaro, E., 2016. Climate change and underwater cultural heritage: impact and challenges. *Journal of Cultural Heritage* 21, 842–848.
- Ambraseys, N., 2009. Catalogue of earthquakes. In: *Earthquakes in the Mediterranean and Middle East: A Multidisciplinary Study of Seismicity up to 1900*. Cambridge: Cambridge University Press, 60–814.
- Antonopoulos, 1979. Catalogue of tsunamis in the Eastern Mediterranean from antiquity to present times. *Annals of Geophysics*, Volume 32, pp. 113-130.
- Anzidei, M., Antonioli, F., Lambeck, k., Benini, A., Soussi, M., Lakhdar, R., 2010. New insights on the relative sea level change during the Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers. *Quaternary International* 232, 5–12.
- Blackman, D., Rankov, B., Baika, K., Gerding, H., Pakkanen and J., 2013. Apollonia. In: *Ships of the Ancient Mediterranean*: Cambridge University Press, 294–306.
- Bruno, F., Lagudi, A., Muzzupappa, M., Petriaggi, B., Passaro, S., 2015. 3D Documentation of archeological remains in the underwater park of Baiae. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W5, 41–46.
- Calafat, F.-M., Gomis, D., 2009. Reconstruction of Mediterranean Sea level fields for the period 1945–2000. *Global and Planetary Change* 66, 225–234.
- Carter, R. S., 1978. The submerged seaport of Aperlae, Turkey. *International Journal of Nautical Archaeology and Underwater Exploration* 7, 177–185.
- Chalkis, G. P. a. B., 1984. Tsunamis observed in Greece and the surrounding area. *Marine Geology* 56, 309–317.
- Coe, A., Bosence, D., Church, K., Flint, S., Howell, J., and Wilson, R., 2002. *The Sedimentary Record of Sea Level Change*. Cambridge: Cambridge University Press.
- Coleman, D. F., 2008. Archeological Oceanography. In: R. D. Ballard, ed. *Archaeological and Geological Oceanography of Inundated Coastal Landscapes: An Introduction*. Princeton: Princeton University Press, 177–199.

- Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J.-P., Iglesias, A., Lange, M.-A., Lionello, P., Llasat, M.-C., Paz1, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M.-N., and Xoplaki, E., 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change* 8, 972–980.
- De Lange, W. P. and Carter, R.-M., 2014. *Sea-Level Change Living With Uncertainty: The Global Warming Policy Foundation GWPF Report 15*.
- Demets, C., Gordon, R. G. and Argus, D. F., 2010. Geologically current plate motions. *Geophysical Journal International* 181, 1–80.
- Dessandier, D., Akarish, A., Antonelli, F., Lazzarini, L., Leoux, L., Nageh, A., Soheib, A. and Varti-Mataragas, M., 2008. *The Atlas of the Stones of Alexandria Lighthouse*. Orléans: BRGM.
- El-Raey, M., Nasr, S., Frihy, O., Desouki, S. and Dewidar, Kh., 1995. Potential impacts of accelerated sea-level rise on Alexandria Governorate, Egypt. *Journal of Coastal Research* 51, 190–204.
- Emery, K. O., G. Aubrey, D. and Goldsmith, V., 1988. Coastal neo-tectonics of the Mediterranean from tide-gauge records. *Marine Geology* 81(1-4), 41–52.
- Empereur, J.-Y., 1999. Diving on a sunkun city. *Archaeology*, 52, 36-43.
- Empereur, J.-Y., 2001. Alexandria. In: D. B. Redford, ed. *The Oxford Encyclopedia of Ancient Egypt, Vol 1*. New York: Oxford University Press, 54–57.
- Empereur, J.-Y., 2004. *Le Phare d'Alexandrie: La Merveille Retrouvée*. Paris: Gallimard.
- England, F., Howell, A., Jackson, J., Synolakis, C., 2015. Palaeotsunamis and tsunami hazards in the Eastern Mediterranean. *Phil. Trans. R. Soc. A*, Volume 373, 1-22.
- Evelpidou, N., Repapis, C., Zerefos, C., Tzalas, H. and Synolakis, C., 2019. *Geological Phenomena and Alexandria Littoral*. Oxford: Archaeopress Publishing LTD.
- Fairbanks, R. G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342, 637–642.
- Flemming, N.-C., 1973. Archaeological evidence for eustatic and tectonic components of relative sea level change in the south Aegean. In: D. Blackman, ed. *Marine Archaeology*. London: Butterworth, 1–66.
- Flemming, N.-C. and Webb, C.-O., 1986. Tectonic and eustatic coastal changes during the last 10,000 years derived from archaeological data. *Zeitschrift für Geomorphologie* 62, 1–29.

- Flemming, N.-C., 1965. Underwater survey of Apollonia. In: J. d. P. Taylor, ed. *Marine Archaeology*. London: Hutchinson of London, 168–178.
- Flemming, N.-C., 1968. Holocene earth movements and eustatic sea level change in the Peloponnese. *Nature* 217(16), 1031–1032.
- Flemming, N.-C., 1971. *Cities Under the Sea; An Exploration of Ancient Cities Beneath the Mediterranean*. New York: Doubleday & Co.
- Flemming, N.-C., 1972. Eustatic and tectonic factors in the relative vertical displacement of the Aegean coast. In: D. J. Stanley, ed. *The Mediterranean Sea. A Natural Sedimentation Laboratory*. Stroudsburg, Pennsylvania: Dowden, Hutchinson & Ross.
- Foss, C., 1996. *Cities, Fortresses and Villages of Byzantine Asia Minor*. Hampshire: Variorum.
- Franco, L., 1996. Ancient Mediterranean harbours: a heritage to preserve. *Ocean and Coastal Management* 30(2-3), 115–151.
- Frihy, O. E., 2003. The Nile Delta-Alexandria coast: vulnerability to sea-level rise, consequences and adaptation. *Mitigation and Adaptation Strategies for Global Change* 8, 115–138.
- Gallou, C. and Henderson, J., 2012. Pavlopetri, an early Bronze Age harbour town in South-East Laconia Pharos: *Journal of the Netherlands Institute in Athens*. 18(1), 79-104.
- Galloway, D. L., Jones, D. R., and Ingebritsen, S. E., 1999. *Land Subsidence in the United States*. Reston, Virginia: U.S. Geological Survey.
- Goddio, F., and Fabre, D., 2010. *The Development and Operation of the Portus Magnus in Alexandria - An Overview*. Oxford, Oxford Centre for Maritime Archaeology, 53-74.
- Harding, A., Cadogan, G., and Howell, R., 1969. Pavlopetri: an underwater Bronze Age town in Laconia. *The Annual of the British School at Athens* 64, 113–142.
- Henderson, J., Gallou, C., Flemming, N.-C., and Spondylis, E., 2011. The Pavlopetri Underwater Archaeology Project: investigating an ancient submerged town. *Underwater Archaeology and the Submerged Prehistory of Europe*. Oxbow Books, 207-218.
- Henderson, J., Pizarro, O., Johnson-Roberson, M., Mahon, I., 2013. Mapping submerged archaeological sites using stereo-vision photogrammetry. *The International Journal of Nautical Archaeology* 42(2), 243–256.

Hohlfelder, R. L. and Vann, R. L., 1998. Uncovering the secrets of Aperlae: a coastal settlement of Ancient Lycia. *Near Eastern Archaeology* 61, 26–37.

ICOMOS, 2019. *The Future of Our Past: Engaging Cultural Heritage in Climate Action*. Paris, ICOMOS.

Julien, P. Y., 1995. *Erosion and Sedimentation*. Cambridge: Cambridge University Press.

Kipreos, G., Konstantinakos, P., Anagnostopoulou, I., Perrea, A., Kaprinis, S., 2016. Pavlopetri, the world's oldest submerged city: analysis of. *Journal of Investment and Management* 5(6), 199–205.

Lambeck, K., and A. Purcell, 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. *Quaternary Science Reviews* 24: 1969–1988).

Mahon, I., Pizarro, O., Johnson-Roberson, M., Friedman, A., Williams, S.-B. and Henderson, J.-C., 2011, *Reconstructing Pavlopetri: mapping the world's oldest submerged town using stereo-vision photogrammetry*. Shanghai, China: Shanghai International Conference Center, 2315-2321.

Marriner, N. and Morhange, C., 2007. Geoscience of ancient Mediterranean harbours. *Earth-Science Reviews* 80, 137–194.

McKenzie, 2003. Glimpsing Alexandria from archaeological evidence. *Journal of Roman Archaeology*, Volume 16, pp. 35-63.

Millet, B. and Goiran, J.-P., 2007. Impacts of Alexandria's Heptastadion on coastal hydro-sedimentary dynamics during the Hellenistic period: a numerical modelling approach. *The International Journal of Nautical Archaeology* 36(1), 167–176.

Milne, G. A., Gehrels, W.-R., Hughes, C.-W. Tamisiea, M.-E., 2009. Identifying the causes of sea-level change. *Nature Geoscience*, 2, 471–478.

Özdaş, H. and Kızıldağ, N., 2013. Archaeological and geophysical investigation of submerged coastal structures in Kekova, southern coast of Turkey. *Geoarchaeology: An International Journal* 28, 504–516.

Paoletti, V., Secomandi, M., Piromallo, M., Giordano, F., Fedi, M., Rapolla, A.-A., 2005. Magnetic survey at the submerged archaeological site of Baia, Naples, southern Italy. *Archaeological Prospection* 12, 51–59.

Papadopoulos G. A. and Papageorgiou, A., 2014. Large earthquakes and tsunamis in the Mediterranean region and its connected seas. In: *Extreme Natural Hazards, Disaster Risks and Societal Implications*,

*Special Publications of the International Union of Geodesy and Geophysics*. Cambridge: Cambridge University Press, 252–266.

Pizzinato, C., and Beltrame, C., 2012. A project for the creation of an underwater archaeological park at Apollonia, Libya. *International Journal of the Society for Underwater Technology* 30(4), 217–224.

Pirazzoli, P. A., Thommeret, J., Thommeret, Y., Laborel, J. and Montag-Gioni, L.-F., 1982. Crustal block movements from Holocene shorelines: Crete and Antikythira (Greece). *Tectonophysics* 68, 27–43.

Pirazzoli, P.A., 2005, A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. *Quaternary Science Reviews* 24: 1989–2001. Pizzinato, C. and Beltrame, C., 2012. A project for the creation of an underwater park at Apollonia, Libya. *International Journal of the Society for Underwater Technology*, 30(4), 217–224.

Pugh, D. T., 2008. *Changing Sea Level*. Cambridge: Cambridge University Press.

Reimann, L., Vafeidis, A.-T., Brown, S., Hinkel, J., S. J. Tol, R., 2018. Mediterranean UNESCO World Heritage at risk from coastal flooding and erosion due to sea-level rise. *Nature Communications* 9, 1–11.

Riad, M., 1933. Alexandria: Its Town Planning Development. *The Town Planning Review*, Vol. 15, No. 4.

Ricca, M., LA Russa, M.-F., Ruffolo, S.-A., Davidde, B., Barca, D., Crisci, G.-M., 2014. *Mosaic marble tesserae from the underwater archaeological site of Baia (Naples, Italy): determination of the provenance*. Frankfurt and Main, European Mineralogical Conference, 323-331.

Ren, H., Sigman, D.-M., Martínez-García, A., Anderson, R.-F., Chen, M., Ravelo, A.-C., Straub, M., Wong, G.-T.-F., Haug, G.-H., 2017. Impact of glacial/interglacial sea level change on the ocean nitrogen cycle. *Proc Natl Acad Sci U.S.A* 114(33), E6759–E6766.

Shaw, B., Ambraseys, N.-N., England, P.-C., Floyd, M.A., Gorman, G.-J., Higham, T.-F.-G., Jackson, J.-A., Nocquet, J.-M., Nocquet, C.-C. and Piggott, M.-D., 2008. Eastern Mediterranean tectonics and tsunami hazard inferred from the AD 365 earthquake. *Nature Geoscience* 1, 268–276.

Solomon, S.-D., . Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K.-B., Tignor, M. and Miller, H.-L., 2007. The Physical Science Basis. In: *IPCC Climate Change 2007*. Cambridge: Cambridge University Press, 747–845.

- Stanley, J. D., 1997. Mediterranean deltas: In: *Bulletin de L'Institut Océanographique*. Monaco: CIESM - Musée océanographique, 35–62.
- Stanley, J. D., Jorstad, T. F. and Goddio, F., 2006. Human impact on sediment mass movement and submergence in Alexandria. *Norwegian Journal of Geology* 86, 337-350.
- Stanley, J. D. and Landau, E. A., 2010. *Early Human Activity (pre-332) in Alexandria, Egypt: New Findings in Sediment Cores from the Eastern Harbour*. Oxford: Oxford Centre for Maritime Archaeology, 35-52.
- Stiros, S. C., 2009. The 8.5+ magnitude, AD 365 earthquake in Crete: coastal uplift, topography changes, archaeological and historical signature. *Quaternary International* 216, 1–10.
- Stratton, S. J., 2016. Tsunamis. In: Koenig, K.-L. and Schultz, C.-H. eds. *Koenig and Schultz's Disaster Medicine: Comprehensive Principles and Practices 2nd ed.* Cambridge: Cambridge University Press, 661–669.
- Tzalas, H., 2015. The underwater archaeological survey conducted by the Greek Mission in Alexandria. *Societe Archaeologique D'Alexandrie Bulletin* 49 part I, 77–79.
- Tzalas, H. E., 2000. *Underwater Archaeology and Coastal Management Focus on Alexandria*. Paris, UNESCO, 22.
- UNESCO (2021) UNESCO World Heritage List. Available at: <https://whc.unesco.org/en/list/> (Accessed: 24 January 2021).
- Vött, A., Bareth, C., Brückner, H., Lang, F., Sakellariou, D., Hadler, H., Ntageretzis, K., Willershäuser, T., 2011. Olympia's harbour site Pheia (Elis, western Peloponnese, Greece). *DIE ERDE – Journal of the Geographical Society of Berlin* 142, 59–288.



## Figures and Tables

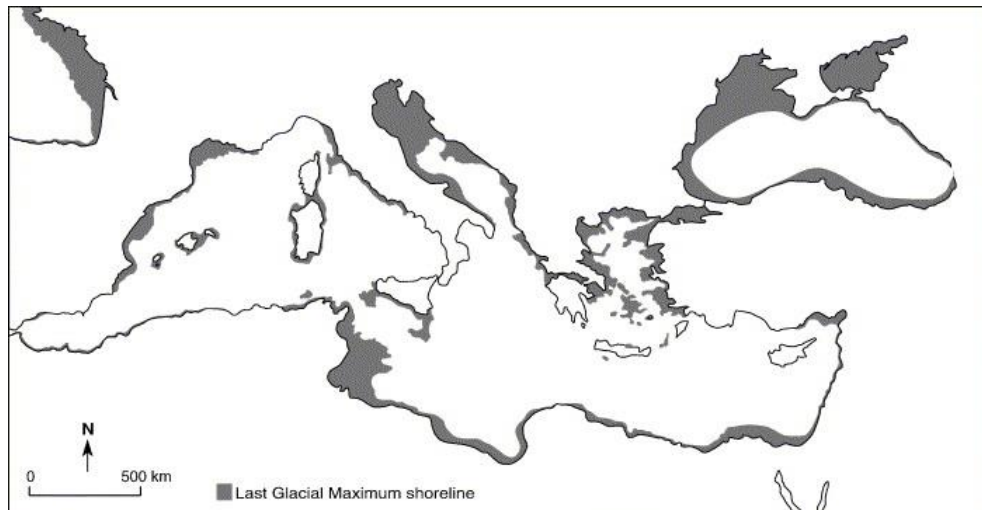


Figure 1: map showing the Mediterranean's coastal margin since 18,000 BP, when sea level was around 120 m below present (Marriner and Morhange, 2007, 148).

| n  | Year | Mo   | Day | $M_w$         | Region                    | Area, $K$             | $h$ (cm) |
|----|------|------|-----|---------------|---------------------------|-----------------------|----------|
| 1  | -426 |      |     | $6.9 \pm 0.3$ | Central Greece            | Maliac Bay, 8         |          |
| 2  | 365  | Jul. | 21  | $8.3 \pm 0.3$ | Crete                     | Alexandria, 10        |          |
| 3  | 544  |      |     | $7.5 \pm 0.5$ | Bulgarian Black Sea       | Odessus, 8-9          |          |
| 4  | 551  | Jul. | 09  | $7.5 \pm 0.3$ | Lebanon                   | Beirut, 8             |          |
| 5  | 1222 | May  | 11  | $6.5 \pm 0.3$ | Southwest Cyprus          | Paphos, 6             |          |
| 6  | 1303 | Aug. | 08  | $8.0 \pm 0.3$ | Crete                     | Heraklion, 10         |          |
| 7  | 1343 | Oct. | 18  | $7.2 \pm 0.3$ | Sea of Marmara            | Constantinople, 8     | 200      |
| 8  | 1365 | Jan. | 02  | $7.3 \pm 0.3$ | North Algeria             | Algiers, 8            |          |
| 9  | 1402 | Jun. |     | $6.8 \pm 0.3$ | Corinth Gulf              | Xylokastro, 8         |          |
| 10 | 1481 | May  | 03  | $7.2 \pm 0.3$ | Rhodes                    | Rhodes, 7             |          |
| 11 | 1755 | Nov. | 01  | $8.3 \pm 0.3$ | Southwest Iberia          | Lisbon, 10            | 1500     |
| 12 | 1908 | Dec. | 28  | $7.2 \pm 0.1$ | Straits of Messina, Italy | Strait of Messina, 10 | 1300     |
| 13 | 1956 | Jul. | 09  | $7.4 \pm 0.2$ | Cyclades                  | Astypalaea, 9         | 1500     |

Table 1: List of Thirteen massive tsunamis along the Mediterranean (Papageorgiou et al., 2014, 257).

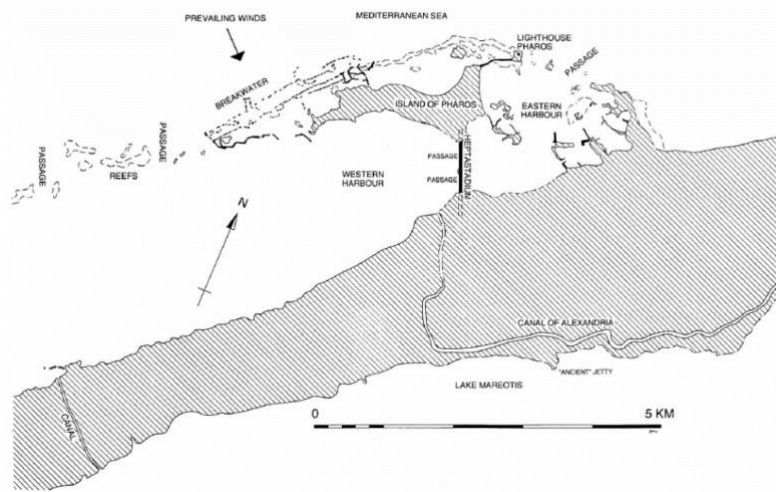


Figure 2: Map showing the city of Alexandria after the construction of the Heptastadion (McKenzie, 2003, p. 37).

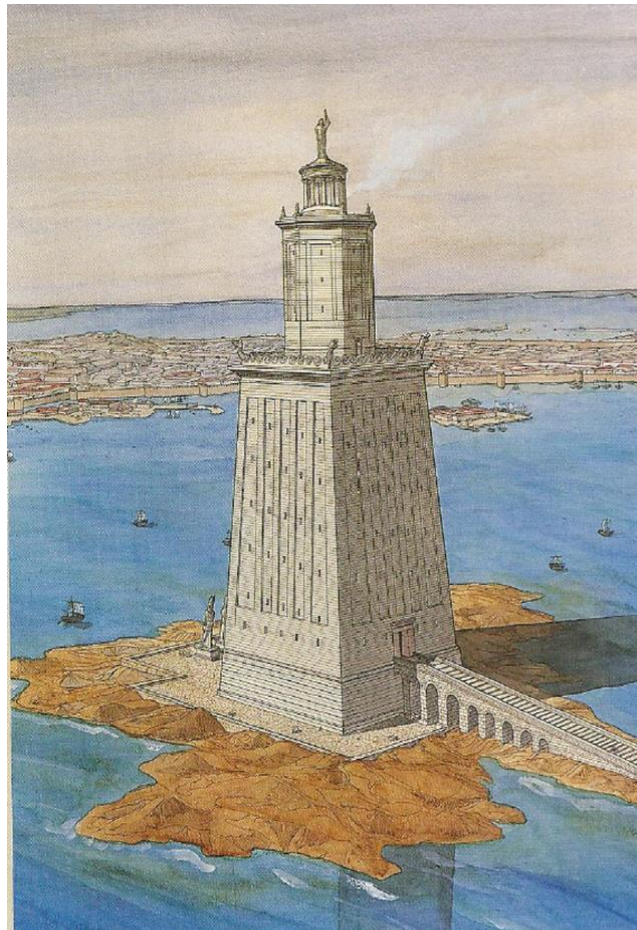


Figure 3: The Lighthouse of Alexandria (Empereur, 2004, 28).

| Event (year) | Intensity | Damage   | Repair  |
|--------------|-----------|--|---|
| 796          | VIII      | Major cracks                                       | Undocumented                                    |
| 951          | VIII-IX   | Failure of some parts of the structure             | Undocumented                                    |
| 956          | VIII-IX   | Collapse of top 20+ meters                         | Topped by an Islamic dome                       |
| 1303         | VIII, SW  | Partial collapse of several parts of the structure | A great deal of effort was dedicated for repair |
| 1375         | VIII      | Near-complete collapse                             | -   |

Table 2: List of major earthquakes fluctuated the lighthouse of Alexandria (Abdelnaby and Elnashai., 2013, 119).

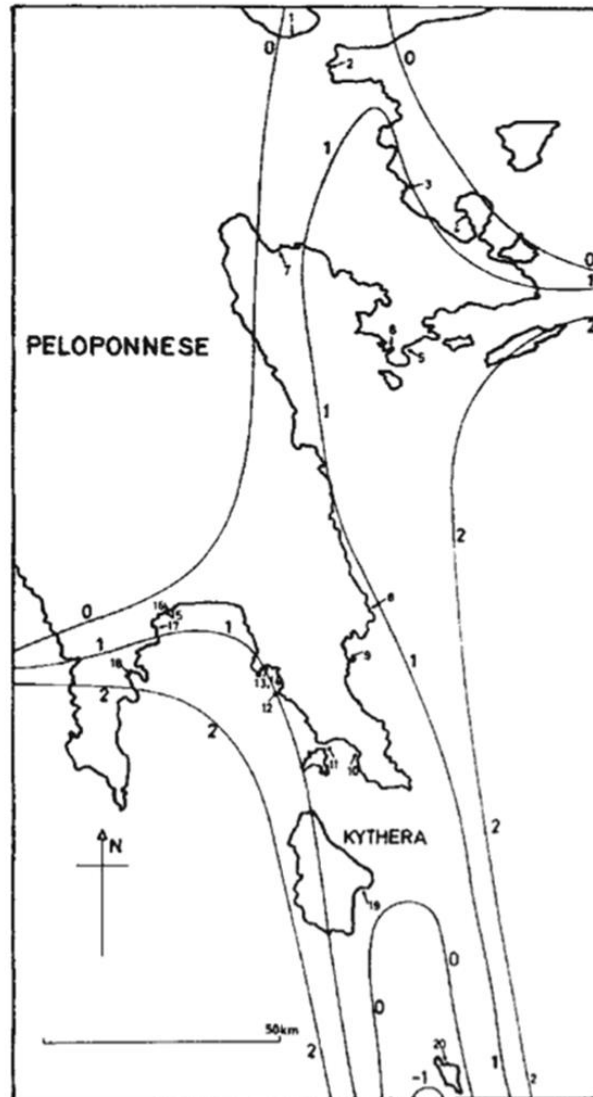


Figure 4: Map of the Eastern Peloponnese, southern Greece described with the submerged sites that were found underneath the sea water (Flemming, 1968. 1031).

| Site No. | Name         | Age (millennia) | Depth (m) | Depth/age (m/millennium) | Bouger (mgal) | Gravity gradient (mgals/km) |
|----------|--------------|-----------------|-----------|--------------------------|---------------|-----------------------------|
| 1        | Lechaemum    | 2.0             | 0.7       | 0.3                      | 04            | 1.0                         |
| 2        | Kenchreai    | 2.5             | 2.0       | 0.8                      | 15            | 1.0                         |
| 3        | P. Epidaurus | 2.0             | 2.7       | 1.3                      | 35            | 1.0                         |
| 4        | Methane      | 2.0             | 1.0       | 0.5                      | 60            | 1.3                         |
| 5        | Lorenzon     | 1.0             | 2.0       | 2.0                      | 60            | 4.0                         |
| 6        | Halleis      | 2.4             | 2.7       | 1.1                      | 60            | 4.0                         |
| 7        | Asine        | 3.0             | 2.0       | 0.7                      | 20            | 1.0                         |
| 8        | Xarax        | 2.5             | 3.0       | 1.2                      | 60            | 1.0                         |
| 9        | Monemvasia   | 2.0             | 1.0       | 0.5                      | 60            | 1.0                         |
| 10       | Neapolis     | 1.5             | 0.3       | 0.2                      | 55            | 2.5                         |
| 11       | Elaphonisos  | 3.5             | 3.0       | 0.9                      | 40            | 4.0                         |
| 12       | Arkangelos   | 2.0             | 0.2       | 0.1                      | 05            | 4.0                         |
| 13       | Piltra (1)   | 3.0             | 3.0       | 1.0                      | -05           | 4.0                         |
| 14       | Piltra (2)   | 1.5             | 2.0       | 1.3                      | -05           | 4.0                         |
| 15       | Trinisi (1)  | 1.0             | 1.0       | 1.0                      | -70           | 1.0                         |
| 16       | Trinisi (2)  | 1.0             | 1.0       | 1.0                      | -70           | 1.0                         |
| 17       | Gythion      | 1.5             | 2.5       | 1.5                      | -70           | 1.0                         |
| 18       | Skutari      | 1.5             | 3.5       | 2.2                      | -70           | 1.0                         |
| 19       | Kythera      | 4.0             | 0.0       | 0.0                      | 10            | 2.5                         |
| 20       | Antikythera  | 5.0             | -3.0      | -0.6                     | -30           | 0.0                         |

Table 3: Table of the sites that were found along the coast of the Eastern Peloponnese, southern Greece (Flemming, 1968, 1031).

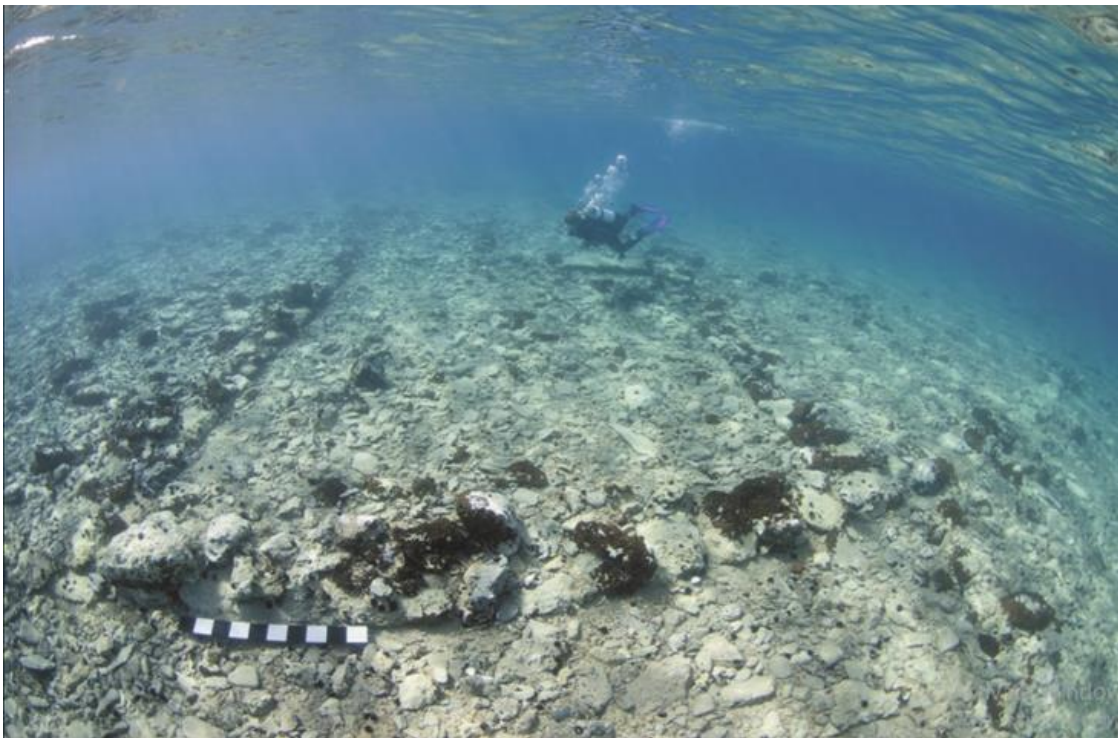


Figure 5: Remains of submerged city of Pavlopetri (Henderson et al., 2012, 212).



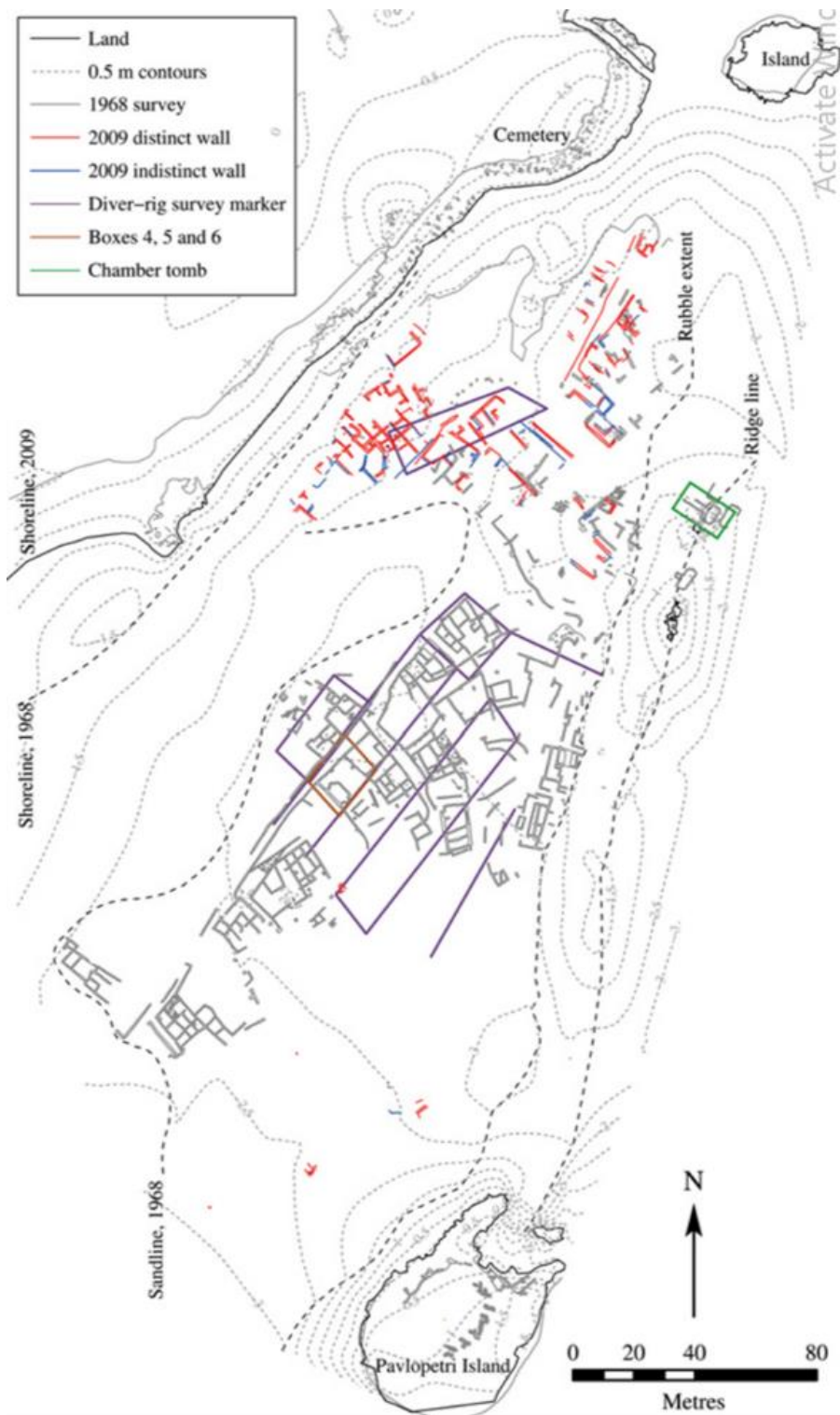


Figure 6: Archaeological remains that found in Pavlopetri (Henderson et al., 2012, 209).

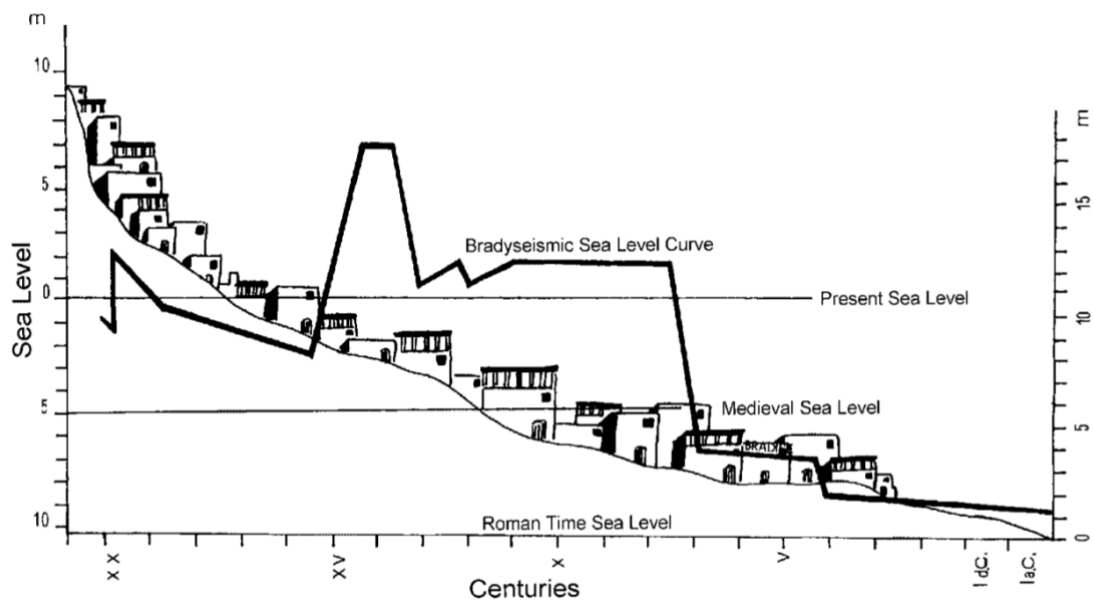


Figure 7: shows the average sea level change in Roman and Medieval periods at Baia (Paoletti et al., 2005, 55).

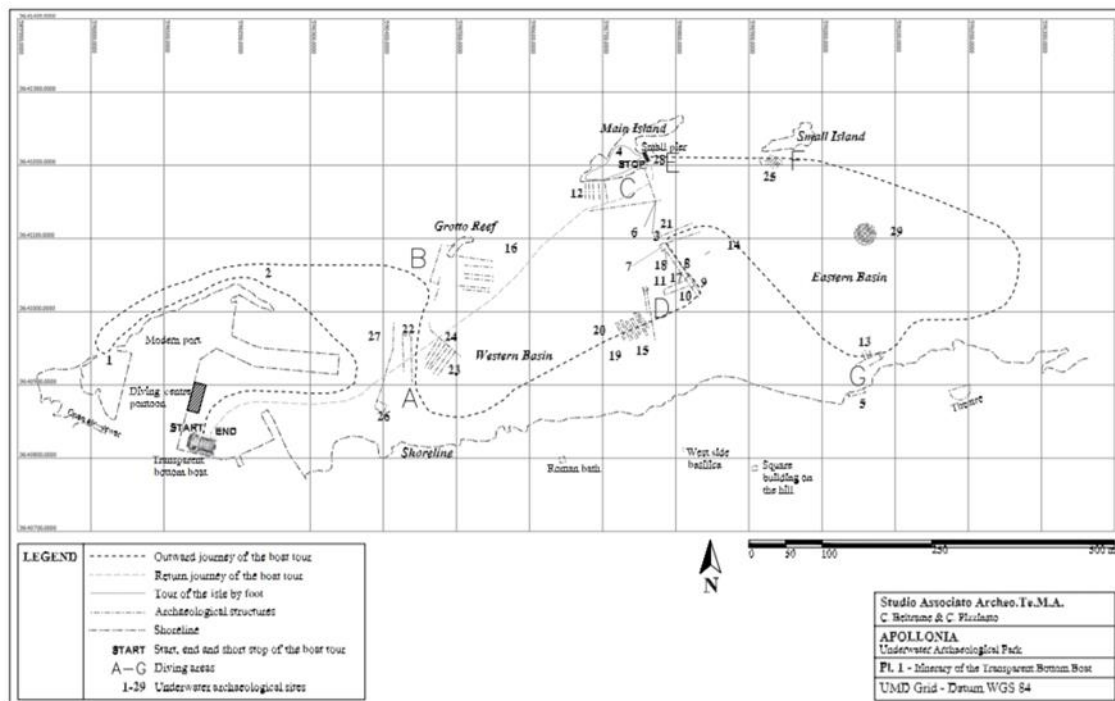


Figure 8: Map of Apollonia published by (Pizzinato and Beltrame, 2012, 221).



Figure 9: map presents submerged harbours along the Mediterranean coast (Marriner and Morhange, 2007, 148).