Shipworms (*Teredinidae*) and ancient Mediterranean harbours

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Introduction

Shipworms (*Teredinidae*)[1] are bivalve wood-boring molluscs that live in warm seawaters at temperate and tropical latitudes. In the modern world of metal and fiberglass vessels, shipworms have been reduced to a curiosity, but in antiquity with its wooden vessels they were a serious and constant problem for ships and trade. Shipworms and other wood-boring organisms are capable of rapid, high-level degradation of wooden objects. They attack the wooden hulls of ships with such intensity that the weakened bottom planks may disintegrate after even a minor impact caused by hitting a rock or any floating object.[2] Shipworms can also be a problem for contemporary archaeological projects. The best current example of the devastating effect of shipworms is the trireme *Olympias* project, where the replica of a wooden Greek trireme was rapidly destroyed by shipworms.[3] Similarly, a replica of the shipwreck Uluburum III was quickly destroyed by shipworms.[4]

As well as for wooden ships, shipworms and other wood-boring organisms were also a serious problem for harbours and piers during antiquity (and to this day), as wooden material immersed in seawater is quickly degraded by shipworms, while wood above the water is attacked by many kinds of wood-boring insects and decaying fungi. The potential of shipworms and other wood-boring organisms to destroy wood, especially archaeological wood and harbour architecture, is often underestimated.[5]

In this paper we first examine the biology of shipworms and the factors limiting their growth, survival and distribution. We then evaluate ancient protective methods used to prevent damage by shipworms. Finally, we examine and consider what role shipworms and other wood-boring organisms may have played in the establishment of harbours and shipyards around the Mediterranean basin during antiquity. Over the last 20 years, the geoarchaeology of ancient harbours has been a very active area of research around the Mediterranean basin and has generated many palaeoenvironmental data from many harbour sites.[6] Our specific aim is to utilize these novel data in order to explain the role of shipworms in harbour structures and architecture. We also consider how an understanding of the biology and ecology of shipworms may have been used in antiquity to prevent damage to ships and harbours. The key eco-physiological factor in this context is that

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1 About 75 shipworm species have hitherto been described worldwide (Palma – Santhakumaran 2014, 21).

2 Palma – Santhakumaran 2014.

3 Lipke 2012.

4 Müller 2010.

5 For example, see Steinmeyer – Macintosh Turfa 1996, 3.

6 Salomon et al. 2016, 1.

shipworms cannot develop or survive in fresh or brackish water. We feel that the role of water salinity in the management of shipworm damage in antiquity is largely overlooked in modern marine archaeology.

Biology of shipworms

Taxonomically shipworms belong to the bivalve molluscs (*Mollusca*: *Bivalvia*: *Teredinidae*).[7] Shipworms are related to oysters and clams but during their long evolutionary history they have specialized to consume many kinds of wood in coastal habitats worldwide. During their evolution they have also undergone several morphological adaptations. Shipworms have an elongated worm-like body, and the original two shell valves with which clams protect their body have become specialized to bore through wood. The worm-like body has a cephalic hood at the anterior end and siphons at the posterior end. The two valves have denticular ridges used in a grinding action while the siphons serve to connect the shipworm to the outside water. The wooden material is digested with the aid of bacterial endosymbionts which produce cellulolytic enzymes and provide fixed nitrogen.[8] The interior of the tunnels within the wood is coated with a calcareous substance secreted by the organism itself.[9]

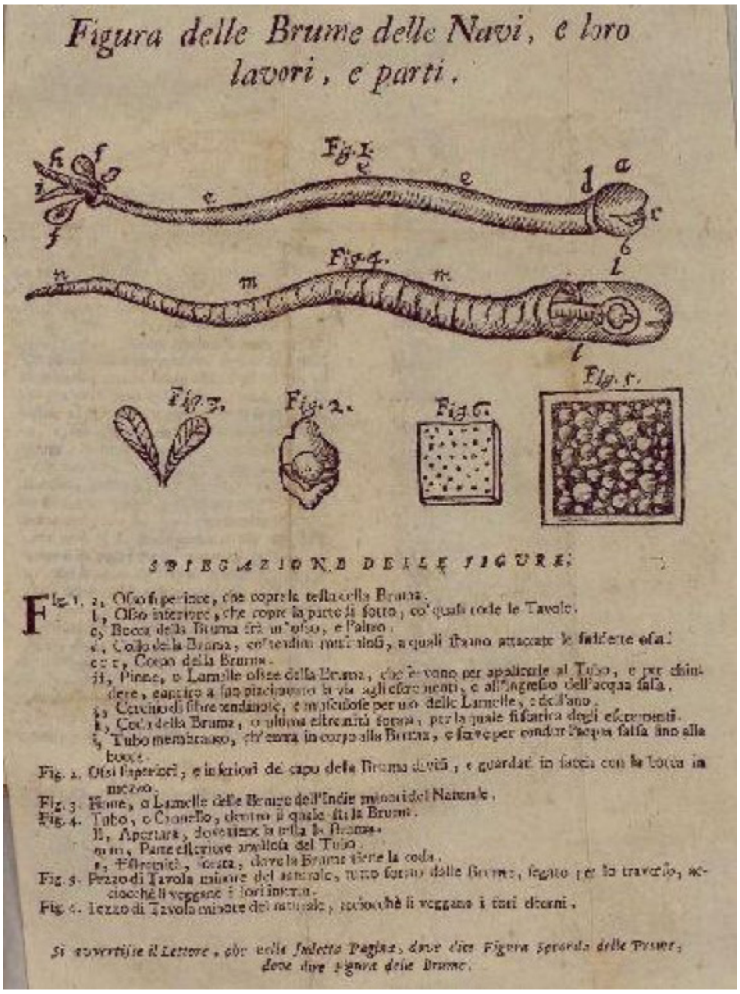

Fig. 1.- Shipworm, in: Antonio Vallisnieri, *Prima raccolta d'osservationi*… Venezia 1710.

The most devastating shipworm species in the Mediterranean area, and probably the best-known to archaeologists, is *Teredo navalis Linnaeus*.[10] Its body can reach a length of up to 45 and a diameter of 1.5 cm. It can penetrate an oak trunk 30 cm in diameter within a year and under certain circumstances can grow 100 mm in a month.[11]

The most crucial eco-physiological characteristic of *Teredo navalis* of relevance to the aims of this article is the salinity of water and its role in shipworm survival and infestations. Shipworms like *Teredo navalis* require a water salt concentration between 7 0/00 and 35 0/00, and water temperatures between 5^{0}C and

7 At least nine shipworm species have been reported in European coastal waters (Lippert et al. 2017, 2).

8 Lippert et al. 2017, 2.

9 Nair – Saraswathy 1971; Palma – Santhakumaran 2014, 15-19. For a closer examination of the biology, life cycle and infestation dynamics of shipworms, see Palma – Santhakumaran 2014, 15-26.

10 Molluscan shipworms belong to two taxonomic families, i.e, *Teredinidae* and *Pholadidae* ("Piddocks"). Four species from the family of *Teredinidae* live in European waters.

11 Palma – Santhakumaran 2014, 22.

27^{0}C for normal development.[12] Ocean water with a minimum salinity of 12 0/00 is necessary for breeding larvae.[13] Consequently, shipworms cannot develop and survive for long in fresh or brackish water. This physiological characteristic is of crucial importance for marine archaeology since in saline water the wooden material of shipwrecks is destroyed within a few years. A good example of the impact of water salinity on the survival of wooden shipwrecks is the Baltic Sea. The water of the Baltic is brackish, with a salinity ranging from 8 0/00 in southern areas to 3 0/00 in the northernmost area of the sea. Consequently, shipworms cannot develop in the low salinity of the Baltic Sea east of the island of Rügen where the salt concentration falls below 8 0/00.[14] This is why wooden shipwrecks in the Baltic Sea have survived well for centuries (a good example is the unique Wasa vessel in Stockholm). For the same reason, wooden material will also survive in freshwater rivers and lakes.

Historical evidence

There are several historical sources for the damage caused by shipworms to ships and the role of shipworms and other wood-boring organisms in naval history from antiquity[15] to the end of the wooden ship era in the 19th century.[16]

Theophrastus' book *Historia plantarum* is obviously the first literary source to mention the shipworm (τερηδών). Theophrastus compares the resistance of different tree species to decaying fungi and shipworm. He mentions that "the wood of the fir is more liable to be eaten by the *teredon* than that of the silver fir" (*Hist. Pl.* 5, 4, 4). He also notes that the only tree species resistant to shipworm attack is the olive. Additionally, he gives advice on how to decrease the damage caused by xylophagous bark beetles and longhorn beetles,[17] but regarding shipworm damage he notes "the harm done by *teredon* cannot be undone". Pliny the Elder also references the shipworm: "What teeth, too, has she inserted in the teredo to adapt it for piercing oak even with a sound which fully attests their destructive power! while at the same time she has made wood its principal nutriment." (*nat.* 11, 1). This description most probably derives from Theophrastus.

Protective methods against shipworms

Several indirect and direct methods were used to prevent shipworm damage in antiquity. Beaching the ship was probably the most common indirect method.[18] "It was common throughout antiquity for both merchant vessels and warships to be hauled up onto the beach as an alternative to mooring either overnight or for a more extended period. This would take them out of reach of the *Teredo navalis*, the shipworm which lives in

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12 Steinmeyer – Macintosh Turfa 1996, 105.

13 Müller 2010.

14 Lippert et al. 2017, 4-6

15 For a closer examination of the historical evidence, see Steinmeyer – Turfa 1986, 104-07; Palma – Santhakumaran 2014, 5-12.

16 The ships of Christopher Columbus were very badly damaged by shipworms during his fourth voyage in 1502-1504; Palma – Santhakumaran 2014, 6.

17 Theophrastus uses the terms *scolex* (σκώληξ) and *thrips* (θρίψ*)*. There has been considerable debate about the meaning of these words. Our interpretation is that *scolex* refers to bark beetles (*Scolytidae*) and *Anobiidae* beetles, whilst *thrips* refers to longhorn beetles (*Cerambycidae*).

18 Beaching is even mentioned in the Iliad (1, 485-86): "But when they had come to the wide camp of the Achaeans, they drew the black ship up on the shore, high on the sands, and set in line the long props beneath it…". The black colour obviously refers to the tar treatment of the ship.

salt water and feeds on unprotected wooden hulls".[19] Beaching killed shipworms, and winter maintenance by beaching eliminates that year's infestation of worms and prolongs the ship's life.[20] When possible, ships were run upriver into fresh water, where all marine growth and borers would die within a few days.[21]

With ships of increasingly robust structure and greater weight, classic beaching became impractical.[22] In the Mediterranean, the low tidal range practically precludes the technique of tide beaching and as a consequence various mechanical methods were developed and used to prevent shipworm damage. The wooden planks of merchant ships were lead-sheathed to protect them from *Teredo* attack.[23] For example, the famous Antikythera shipwreck containing valuable Greek sculptures was covered with lead sheaths.[24] Ships belonging to the Emperor Trajan were made of pine and cypress, coated with pitch and sheathed with lead plates fastened with copper nails. Ships' bottoms were also painted with tar or pitch or had their planks smeared with hot tallow, which became stiff and waxy when chilled by seawater.[25]

Probably the most vulnerable vessels were the triremes of the Greek states of the Archaic and Classical periods. As trireme warships had to be fast-moving they could not be covered with lead sheaths. Experiments with the modern trireme replica *Olympias* showed that a moderate degree of worm infestation absorbed 8 tons of water, a very significant increase in weight for a 40-ton ship.[26] Fleet commanders used shipworm infestations as part of their naval tactics by preventing enemies from drying out their ships. This tactic was a crucial factor in the outcome of the naval battles of Salamis (480 BC), Syracuse (413 BC) and Drepana (249 BC).[27]

Shipworms and harbours

In addition to attacking wooden ships, shipworms and other wood-boring organisms were also a serious problem for harbours in antiquity. It was not possible to use wooden material for harbours and pier constructions for long periods, because timber submerged in seawater was rapidly damaged by shipworms, and timber above water was attacked by numerous wood-boring insect groups.[28]

Vitruvius gives instructions on how to build embankments around a harbour. Reconstructions indicate that walls surrounding harbours were built of pozzolan mortar, rubble and concrete.[29] Timber was used mainly as a supporting material during the building process. The reason for this might be that wooden material was soon destroyed by shipworms. This is indirectly suggested in the following sentence: "but if the place proves to be soft, the bottom must be staked with piles made of charred alder or olive wood"[30]. As mentioned above,

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19 Rankov 2013, 102.

20 Steinmayer – Turfa 1996, 107-08.

21 Palma – Santhakumaran 2014, 11.

22 Votruba 2017, 7.

23 Palma – Santhakumaran 2014, 10.

24 Kaltsas – Vlachogianni – Bouyia 2012.

25 Palma – Santhakumaran 2014, 10-11.

26 Steinmeyer – Turfa 1996, 112.

27 Steinmeyer – Turfa 1996, 114-66.

28 In addition to shipworms, wooden material in seawater was destroyed by other shipworm species *(Lyrodus pedicellatus, Nototeredo norvatica, Psiloteredo megotara*) and by some crustacean species, like gribbles (*Limnoriidae*) (Palma – Santhakumaran 2014, 21, 26, 27).

29 de Graauw 2017, 142-53.

30 Vitr.5, 12, 6: "Sin autem mollis locus erit, palis ustilatis alneis aut oleagineis configantur".

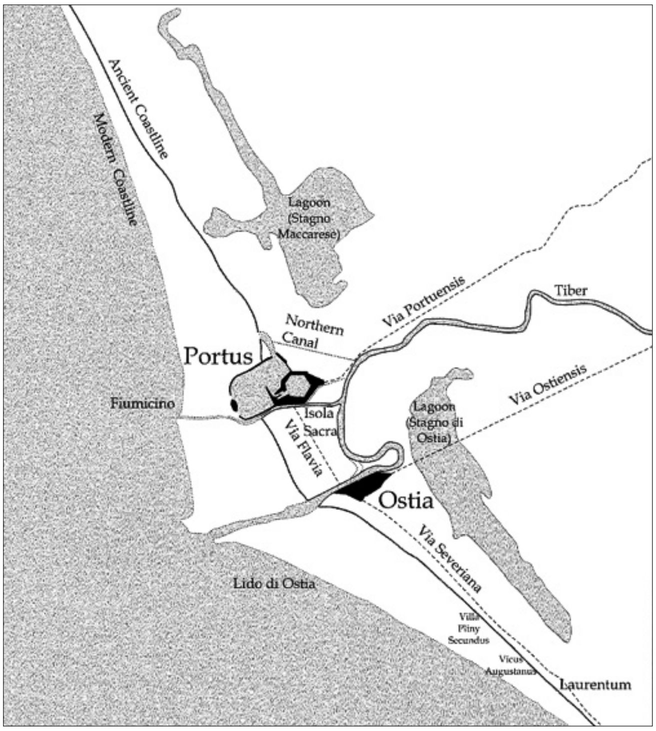

Fig. 2. Portus harbour with connected canals and coastal lagoons (Keay – Paroli 2011).

Theophrastus noted that the olive is the only tree which is resistant against shipworms. Clearly, charred alder has the same property.

But how well did ancient harbour builders follow Vitruvius' instructions? The extensive RoMP Portuslimen project has studied the development and characteristics of ancient harbours in the Mediterranean using the Palaeoenvironmental Age-Depth Model (PADM). This method offers an opportunity to follow the development of the salinity of ancient harbour waters. A recent study confirms that the harbour of Ostia was a freshwater lagoon of the river Tiber throughout its existence.[31] Because shipworms cannot survive in fresh water, the period during which ships stayed in Ostia to unload their cargo also provided an opportunity to kill the shipworms or at least decrease the amount of infestation.

Despite attempts at dredging, until the late 1st cent. BC to early 1st cent. AD, the water column in the harbour basin of Ostia was restricted to c. 1 m – a depth that rendered it impassable to large ships.[32] Obviously, this development led to a decision to build a larger new harbour, Portus, to meet the expanding supply needs of the growing Rome. Interestingly, the harbour of Portus was connected to the Tiber by two canals (**Fig. 1**) and consequently the water in the harbour lagoon was brackish with fluvial and marine inputs.[33] We do not know the exact salinity content of the water in the harbour, but if it was 7-8 $_{0/00}$ or below it would kill shipworms when ships were moored here. At Portus, large fully-laden ships with a draught of up to 4.5 m could have passed through the harbour pool until the 3rd – 5th cent. AD, after which time the build-up of sediment restricted passage to smaller ships and boats.[34]

It would be very interesting to extend the type of palaeoenvironmental and geoarchaeological analysis undertaken in Ostia and Portus to other ancient harbours in the Mediterranean area, with an emphasis on their connections to potential sources of fresh water. Interestingly, two major ports of Roman Africa – Lepcis Magna and the Magnus Portus at Alexandria – had good freshwater connections.

The harbour of Lepcis Magna (present-day Khoms on the Libyan coast)[35] is located at the mouth of the Wadi Libda river. Obviously, the fresh water from the river made the salty water of the harbour brackish and may have decreased shipworm and other marine infestations while ships were in the harbour.

31 Salomon et al. 2016, 9, 11, 12.

32 Salomon et al. 2016, 18.

33 Salomon et al. 2016, 5, 13-14.

34 Salomon et al. 2016, 18.

35 Keay 2016.

The Portus Magnus in Alexandria was probably the most important Mediterranean harbour. During the Roman era it was the main port from which grain was exported from Egypt to Rome. The old harbour was divided into two ports by a 1200 meter bridge to the island of Pharos. The north-eastern basin (Portus Magnus) was used by military vessels and the southwestern basin (Portus Eunostos) by commercial vessels. The harbour was connected to Lake Mareotis and to the Nile by canals bringing fresh water to the harbour basins.

Obviously, freshwater rivers and channels also served other important purposes such as transportation and the provision of drinking water. But fresh or brackish water also offered an opportunity to kill shipworms and other marine pests and thus this type of architecture helped to "kill two birds with one stone".

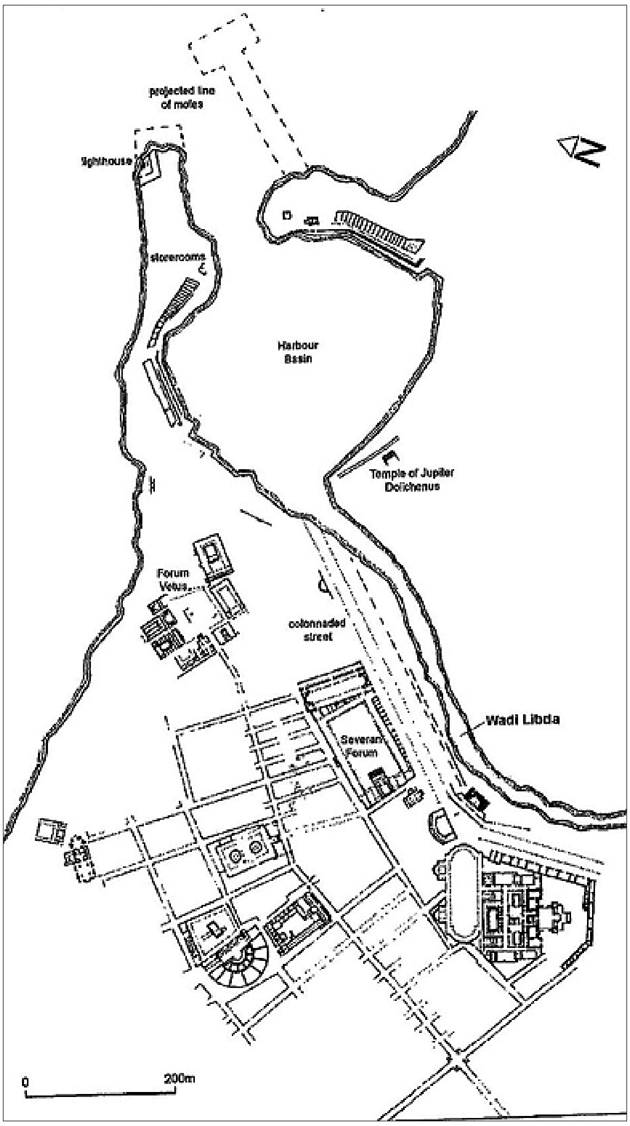

Fig. 3. Map of Lepcis Magna (Keay 2016).

Similarly, the harbour of Ravenna which hosted the second imperial fleet of the Roman Empire was built to be connected through a 25 km man-made canal (Fossa Augusta) to the delta of the River Po for strategic and commercial reasons but perhaps also to guarantee the supply of fresh or brackish water to counter the effect of shipworms.[36] For the same reason, many important harbours like Naroda in Dalmatia37 were located on rivers. In Selinunte both harbours of the Greek city were connected to rivers bringing brackish water.[38]

In autumn and winter, when navigation was difficult, vessels in harbours were often drawn onto land: this is evidenced by numerous ship sheds discovered, for example, in the Aegean harbours,[39] at Naxos in Sicily[40] and – perhaps – also at Trajan's *Portus Romae* where we know of an enormous *navalia*.[41] Might this also have been a precaution to avoid attack by shipworms?

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36 For the harbour of Ravenna see Malmberg 2016 and Buonopane in this volume (p. **XX**).

37 Lindhagen 2012.

38 Albers – Rimböck – Benz – Renners – Schlöffel – Schneider 2018.

39 Bouras 2012, 215.

40 Lentini – Blackman – Pakkanen 2012.

41 See Keay in this volume, p. **XX**.

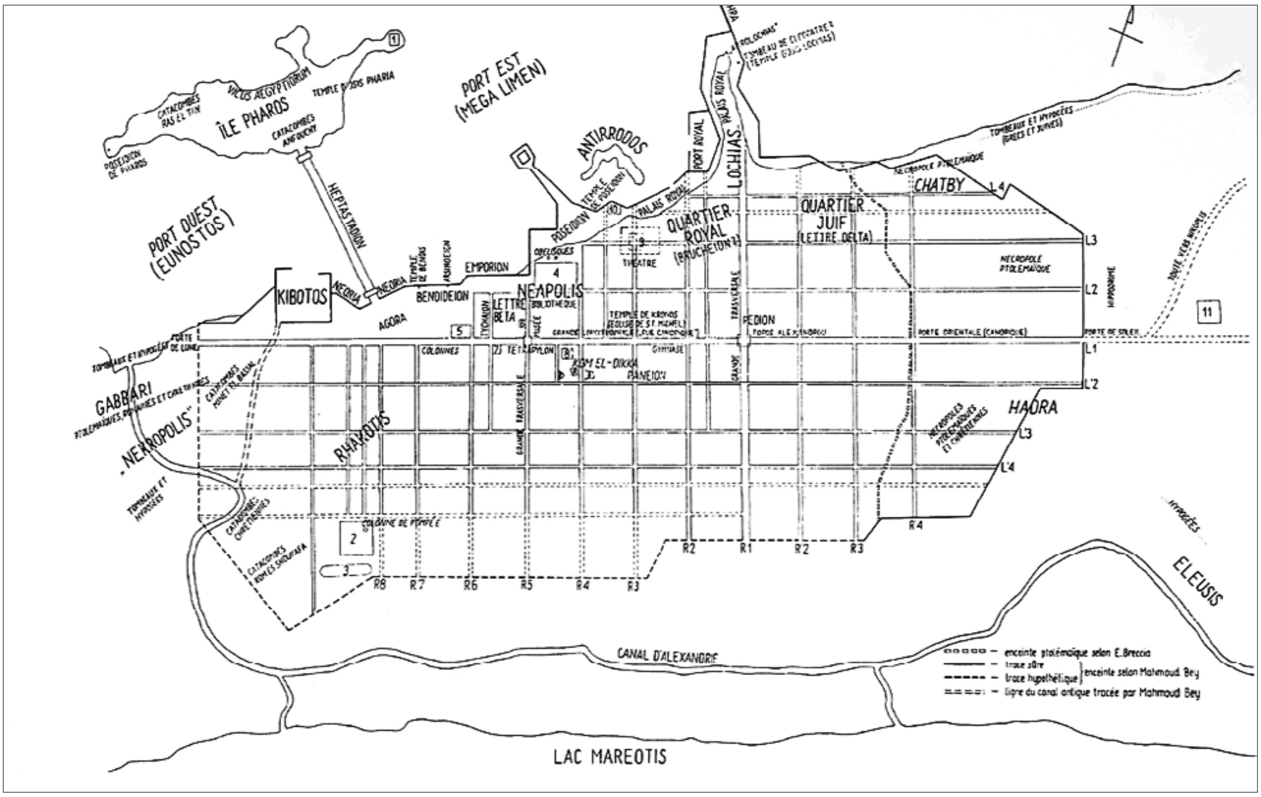

Fig. 4. The port of Alexandria (Tkaczow 1993).

Shipworms and shipyards

Vitruvius also provides instructions for building shipyards near harbours. Shipyards consumed large amounts of timber and obviously large shipyards had substantial stores of timber waiting to be used. Consequently, they attracted numerous kinds of wood-boring organisms and decaying fungi. Any wooden material above water in shipyards and piers was damaged by a variety of xylophagous beetles of the *Scolytidae* and *Anobiidae* families, as well as by longhorn beetles (*Cerambycidae*). Bark and ambrosia beetles which attached to stored timber also carried symbiotic fungi that destroyed timber. Vitruvius was well aware of this threat.

"*His perfectis navaliorum ea erit ratio, ut constituatur spectantia maxime ad septentrionem; nam meridianae regiones propter aestus aestus carem, tineam, teredines reliquaque bestiarum nocentium genera procreant alendoque conservant*".[42]

Vitruvius' text also indicates that ships were hauled up in shipyards, possibly for preparation after damage caused by shipworms and other wood-boring organisms.

"*De magnitudinibus autem finitio nulla debet esse, sed faciunda ad maximum navium modum, uti, etsi maiores naves subductae fuerint, habeant cum laxamentoibi conlocatione* ".[43]

42 Vitr. 5, 12, 7: "Subsequently the shipyards are to be built and with a northern aspect, as a rule. For southern aspects because of their warmth generate dry rot, wood worms and shipworms (*teredines*) with other noxious creatures and feed and maintain them." (transl. Frank Granger, Loeb Classical Library).

43 Vitr. 5, 12, 7: "As to their dimensions no rule should be laid down. They are to be made to take the largest vessels; so that even if such vessels are drawn ashore, they may have roomy berth." (transl. Frank Granger, Loeb Classical Library).

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