PALAEOPORTOLOGY

Ancient Coastal settlements, Ports and Harbours

Volume III: Ancient Port Structures

9th edition (2024)

Arthur de Graauw

Cover picture:
Ancient lighthouse of Leptis Magna in 2000
(Photo A. de Graauw)

Contents Volume III

1 INTRODUCTION

1.1 General introduction

This project was started in 2010, aiming at collecting, identifying and locating ancient ports and harbours. It led to an extensive Catalogue including thousands of places. Much attention was also devoted from the onset to structural aspects as described by Vitruvius, and as resulting from modern coastal engineering such as design waves and harbour silting-up. Additional attention was devoted to ancient ships and sailing, as they define the harbour needs.

This work is reported in **4 volumes**, all available in **pdf versions**, and most of it is reproduced on the web site:

Volume I: Catalogue of Ancient Ports gives a list of ancient coastal settlements, ports and harbours with latitudes/longitudes, based on the works of ancient and modern authors.

Volume II: Citations of Ancient Authors gives citations of known ancient authors explicitly mentioning ports and harbours, in French. This work is not available on the web site as it would take too much space.

Volume III: Ancient Port Structures presents:

- Some thoughts on the design of several ancient ports (Actium, Alexandria, Apollonia, the Bosphorus, Caesarea Maritima, Carthage, Centumcellae, Delos, El Hanieh, Leptis Magna, Marius' canal, Narbonne, the Nile Delta, Nirou Khani, Portus, Pisa, Puteoli & Nesis, Charmuthas, Thapsus, Tyre);
- A list of nearly 200 proposed locations for potential ancient harbours;
- Some comments on ancient port structures, like Vitruvius' methods, failure of breakwaters, subsidence and breakwater remains, design waves, reinforced concrete, pilae and arched breakwaters, pierced stones, defensive harbour chains, harbour silting-up, tombolos and salients;
- Some notes on ancient merchant ships and galleys, sailing techniques and Mediterranean sailing routes;
- Some thoughts about ancient trade networks and intermodal hubs;
- Some remarks on ancient maps, on ancient measures and ancient climate, including earthquakes and tsunamis.

Volume IV: Stories of Ancient Sailors provides around twenty stories of ancient sailors … just for the pleasure of reading, in French.

Should the knowledge gathered in this work be given a name, it might be called "**Palaeoportology**" …

The present ninth edition of this work (February 6th, 2024) comes after an eight edition (February 8th, 2022), a seventh edition (March 5th, 2020), a sixth edition (June 21st, 2017), a fifth edition (March 8th, 2016), a fourth edition (January 1st, 2014), a third edition (February 26th, 2013), a second edition (March 29th, 2012) and a first edition (September 19th, 2011).

1.2 Introduction to Volume III

The aim of this project is not only to compile a Catalogue of “all” coastal settlements, ports and harbours, but also to describe a few ancient ports and to better understand how the ancients have been building and using them.

My approach is ‘multidisciplinary’, in the sense that my background being that of a modern coastal engineer, I introduce my own experience into the world of historians, archaeologists, geoarchaeologists, etc. and I believe a different point of view is always useful. However, some dangers exist, as an outsider can easily forget or underestimate some aspects that are obvious to other disciplines, especially when he works in a somewhat lonely way: multidisciplinarity is more powerful in a ‘brainstorming’ approach, when the different disciplines can discuss directly, but that is not always feasible.

My methodology was rather simple: read, read and read. I have of course visited a number of ancient places, and that is how it all began many years ago in Alexandria. I have been talking to archaeologists. I have been sailing to a few places. I have even been diving on some. But the bulk of my knowledge on ancient ports was found in books.

Do not, therefore, expect the traditional ‘introduction-methodology-results-discussion-conclusion’ presentation.

The red line of this Volume III is a study of a few ancient ports, followed by an analysis of some specific structures, such as vertical breakwaters as described by Vitruvius, rubble mound breakwaters, arched breakwaters and more, with an unavoidable stop on coastal morphology, harbour silting-up, tombolos and salients. This quite logically, leads us to a further study of ancient ships, ancient sailing, ancient trade and sailing routes. From there, we move on to ancient maps and ancient measures, to end our presentation with ancient climate, earthquakes and tsunamis.

Nearly one hundred ancient authors have already been listed and quoted in Volumes I and II, while compiling the “Catalogue of ancient coastal settlements, ports and harbours”, and in this Volume III, we shall add hundreds of modern references providing details on ancient ports. Some places have been studied from the point of view of coastal geomorphology (e.g., Portus, Tyre, Narbo, el-Hanieh). Some places have been studied from the point of view of sailing from and to them (e.g., Alexandria, Portus, Narbo). Structures have been investigated in several ports (e.g., Centumcellae, Portus, Puteoli, Delos, Caesarea Maritima, Alexandria, Apollonia, Leptis Magna, Thapsus). Some documents neglected by many archaeologists have been studied and synthetised (e.g., Jondet on Alexandria-Pharos Island). Some places have been re-analysed on the base of Google-Earth picture (e.g., Nirou Khani in Crete, Charmutas in the Red Sea, Portus Pisanus, Marius’ canal in the Rhône delta). Some places have been analysed by means of hydraulic computations (e.g., the Bosphorus, the Actium area). A list of over 200 ‘Potential Ancient Harbours’ was deduced from a comparison of ancient ports listed in Volume I, and ‘excellent shelters’ known by modern yachtsmen.

I felt a strong motivation to explain what I had discovered, not to a few professionals who know all of that, but to other people like me who would appreciate a synthetic explanation. With that aim in mind, I started my own web site in 2011 which has the same content as this Volume III (www.AncientPortsAntiques.com).

Perhaps, a few new points of view popped up during these wanderings, and I hope they will be useful.

You are now ready to begin with “A few ancient ports”, starting with Actium, and others in alphabetical order … Enjoy!

Grenoble, February 6th, 2024

2 A FEW ANCIENT PORTS

2.1 ACTIUM

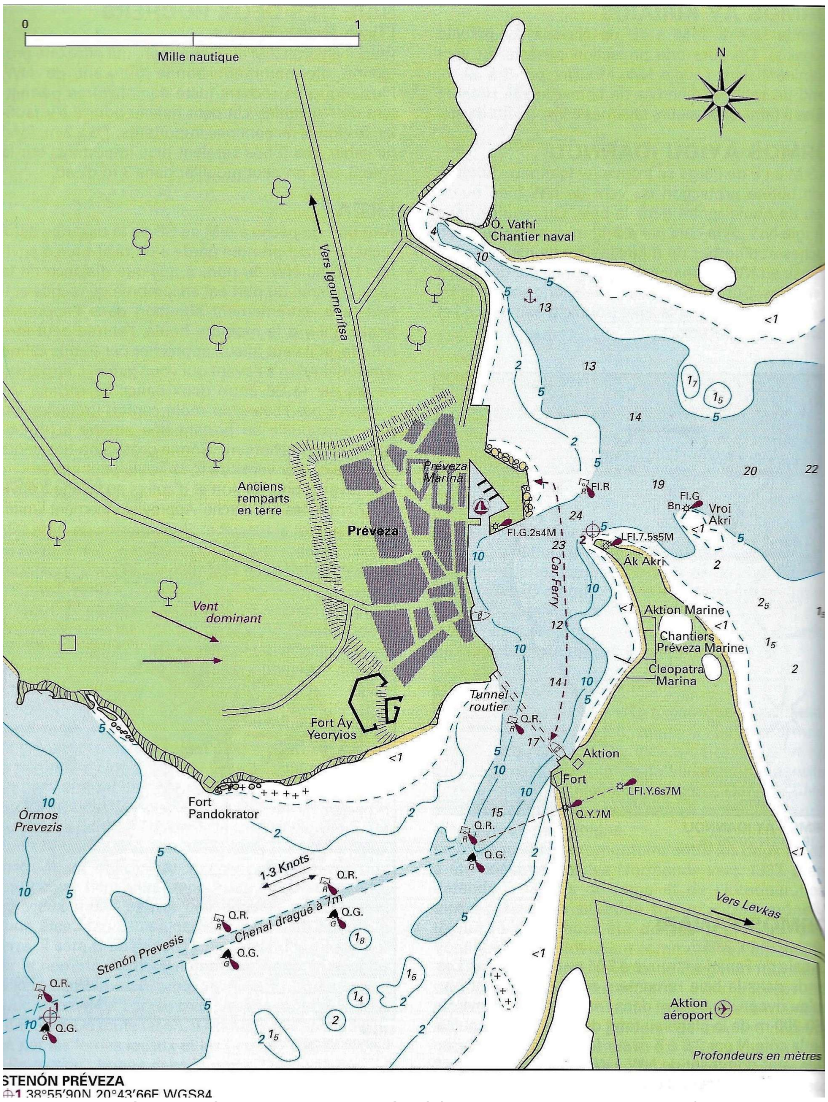
Can we understand why Marcus Antonius, Antony, lost?

The most detailed description of the famous naval battle of Actium is probably provided by William Murray, 2002, “Age of Titans”, p 232-244). He argues that the maxi-galleys (the “Titans”) are meant for besieging coastal cities more than for naval battle. Antony inherited this tactic from the prestigious Demetrius Poliorcetes who developed it three centuries earlier.

Antony’s ambition was nothing less than the conquest of Italy where Octavian (“Caesar”, future Augustus) was in power. He probably intended to attack cities like Brindisi or Taranto with his maxi-galleys (Murray, 2002, p 243). Antony thus stationed his fleet inside the Ambracian Gulf, rather on the southern banks, near Anactorium. In order to block the way to Italy, Octavian and Agrippa were positioned on the northern coast, near Nicopolis and their fleet was anchored and/or beached on the long Comarus beach (now Mitikas).

The local configuration

Antony had been around for months and he must have known the configuration of the Ambracian Gulf outlet:



Outlet of the Ambracian Gulf (Rod Heikell, 2002, p 68)

- A bar with shallows up to -2 m to -4 m. The distance between the -5 m isobaths on each side of the bar is around 1500 m (a channel is now dredged at -7 m). It may be assumed that sea level rise of nearly 1 m over 2000 years does not interfere as a sandy or silty seabed just follows the seawater level. However, episodic changes may occur due to storms.
- Dominant winds from NW during summer, including September, set in around noon with a force of 2 to 5 on the Beaufort scale (5 to 20 knots), and with a light land wind in the morning (1 to 5 knots), according to Rod Heikell (p 38). This corresponds to a typical breeze regime.
- A semi-diurnal tide of 0.05 m, up to 0.25 m (Ferentinos, 2010) but possibly also some water table tilting due to wind friction inside the gulf.
- Density currents with a salt wedge effect flowing underneath brackish water from two rivers Arachthos and Louros (resp. 63 and 2 m^3/s average annual discharge) inducing an up to 1 knot surface flow velocity in the outlet (Ferentinos, 2010).
- Both latter effects generate currents of 1 to 3 knots, in both directions, in the modern channel outlet, according to Rod Heikell (p 69).

The storm occurring during 4 days before the naval battle on September 2, 31 BC, probably blowed from NW, generating waves running southwards parallel to the coastline and producing an unacceptable rolling of ships, hampering any naval battle. In addition, these waves may have transported much sediment and displaced the shallows of the bar at the gulf outlet.

This storm probably also induced a tilting of the gulf's water table: the large shallow water areas in the north of the gulf may have been emptied to fill the southern part near the outlet of the gulf. Hence, gulf water possibly escaped to sea. Consequently, seawater would have to refill the gulf after the end of the storm.

At dawn of September 2, 31 BC, Antony is perhaps missing a land wind to exit the gulf, he may even have an adverse refilling current occurring after the storm, and rivers may have a reduced discharge in this season not providing him with an outbound fresh water surface current. His largest ships (draught of 2 to 3 m) may experience some difficulty sailing between the shallows which may have been moving around at the outlet of the gulf during the storm. Moreover, some ships may be simply grounded on a shoal … Shame! The gods are against him.

On the other hand, a few hours later, Cleopatra, who stayed somewhat backwards with her fleet during the battle, will use the setting in of the NW wind to escape to the south, saving at least part of the Egyptian treasury (army wages) that Octavian would have loved to take over, according to Dio Cassius (Hist. 50, 34).

The battle

Depending on the various ancient sources, Octavian had between 250 and 400 battle ships and Antony, with his numerous oriental allies, had between 170 and 500 ships, out of which 60 Egyptian ships (Plutarch, Antony, 70). In addition, each had hundreds of supply ships. Octavian's battle ships were mainly triremes (35 x 5 x 1 m) and liburnae of similar size. Antony's ships were larger (quadriremes, up to decaremes) but Murray (2002, p 236) notes that his fleet probably included only about thirty ships larger than a quinquereme, i.e., only 5 to 10% of his fleet. According to Fourdirnoy (2019) a decareme might be twice as large as a trireme (70 x 10 x 2 m).

The modern channel is quite visible with shallows on both sides (Google Earth, 27/4/2017).
Antony's fleet and Octavian's fleet were facing each other near the yellow line over a distance of 3 to 5 km.

Antony's ships were initially anchored inside the Ambracian Gulf, while Octavian's ships were outside. It may therefore be said that Octavian was besieging Antony and that the latter had to attempt an exit manoeuvre. For an escape, Antony positioned his ships outside the gulf in front of Octavian's line of ships (see figure above) in order to cross it as soon as some wind would set in. Antony's decision to remain static, pouring "dense showers of stones and arrows" from his higher and armoured ships on Octavian's smaller ships ressembles an entrenched camp tactic that is rarely winning. This decision can be understood only if he had no other choice: his large ships were short of experienced oarsmen (Plutarch, Antony, 68) therefore not providing him with the required accuracy and speed needed to ram Octavian's lighter ships. His strategy is thus that of an earthling, not that of an admiral.

It is quite clear that Antony was trying to avoid battle against Octavian and Agrippa in order to regroup somewhere on the Peloponnesian coast to prepare new plans to invade Italy. This is the reason why he burnt most of his under-manned Egyptian ships (scorched-earth policy). This is also the reason why he took sails and gear, which was not according to common practise, when going out for a naval battle. Murray (p 238) even suggests that he perhaps subtely rowed northwards in order to prepare to circumvent the Lefkada peninsula when the NW wind would set in.

But, as mentioned above, the gods were not with him on that day.

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Ancient references

The following ancient authors provide details on the Actium battle (in chronological order):

VIRGIL (70-19 BC), AENEID: Book 8, Verse 671 and further

PROPERTIUS (47-14 BC), ELEGIES: Book 4, Elegy 6 (Apollo protector of Octavian)

VELLEIUS PATERCULUS (19 BC – 31 AD), ROMAN HISTORY: Book 2, Chap. 84-85

PLINY THE ELDER (23-79 AD), NATURAL HISTORY: Book 32, Chap. 1 (the remora)

PLUTARCH (46-125 AD), LIVES: Antony, Chap. 67 à 76

TACITUS (55-120 AD), ANNALS: Book 4, Chap. 5

SUETONIUS (70-130 AD), THE TWELVE CESARS: Book 2, Chap 17-18

FLORUS (70-140 AD), ROMAN HISTORY: Book 4 Chap. 11

DIO CASSIUS (155-235 AD), ROMAN HISTORY: Book 50, Chap. 12 & 31-35

VEGETIUS (ca. 400 AD), DE RE MILITARI: Book 5, Chap. 3 & 7

OROSIUS (ca. 400 AD), HISTORY AGAINST THE PAGANS: Book 6, Chap. 19

Dio Cassius's description of the battle

Hist. 50, 31-35, (translation by Earnest Cary, Harvard University Press, 1914-1927, found on Lacus Curtius, with *italics* by me):

" 31, 4. And when they set sail at the sound of the trumpet, and with their ships in dense array *drew up their line a little outside the strait and advanced no further*, Caesar set out as if to engage with them, if they stood their ground, or even to make them retire. But when they neither came out against him on their side nor turned to retire, but remained where they were, and not only that, but also vastly increased the density of their line by their close formation,
5. Caesar checked his course, in doubt what to do. He then ordered his sailors to let their oars rest in the water, and waited for a time; after this he suddenly, at a given signal, led forward both his wings and bent his line in the form of a crescent, hoping if possible *to surround the enemy*, or otherwise to break their formation in any case.
6. Antony, accordingly, fearing this flanking and encircling movement, advanced to meet it as best he could, and thus *reluctantly joined battle* with Caesar.

32, 1. So they engaged and began the conflict, each side indulging in a great deal of exhortation to its own men in order to call forth the skill and zeal of the fighters, and also hearing many orders shouted out to them from the men on shore.
2. The struggle was not of a similar nature on the two sides, but Caesar's followers, having smaller and swifter ships, would dash forward and ram the enemy, being armoured on all sides to avoid receiving damage. If they sank a vessel, well and good; if not, they would back water before coming to grips,

3. and would either ram the same vessels suddenly again, or would let those go and turn their attention to others; and having done some damage to these also, so far as they could in a brief time, they would proceed against others and then against still others, in order that their assault upon any vessel might be so far as possible unexpected.
4. For since they dreaded the long-range missiles of the enemy no less than their fighting at close quarters, they wasted no time either in the approach or in the encounter, but running up suddenly so as to reach their object before the enemy's archers could get in their work, they would inflict injuries or else cause just enough disturbance to escape being held, and then would retire out of range.
5. The enemy, on the other hand, tried to hit the approaching ships with dense showers of stones and arrows, and to cast iron grapnels upon their assailants.
6. And in case they could reach them they got the better of it, but if they missed, their own boats would be pierced and would sink, or else in their endeavour to avoid this calamity they would waste time and lay themselves more open to attack by other ships; for two or three ships would fall at one time upon the same ship, some doing all the damage they could while the others took the brunt of the injuries.
7. On the one side the pilots and the rowers endured the most hardship and fatigue, and on the other side the marines; and the one side resembled cavalry, now making a charge and now retreating, since it was in their power to attack and back off at will, and the others were like heavy-armed troops guarding against the approach of foes and trying their best to hold them.
8. Consequently each gained advantages over the other; the one party would run in upon the lines of oars projecting from the ships and shatter the blades, and the other party, fighting from the higher level, would sink them with stones and engines. On the other hand, there were also disadvantages on each side: the one party could do no damage to the enemy when it approached, and the other party, if in any case it failed to sink a vessel which it rammed, was hemmed in no longer fought an equal contest.

33, 1. The battle was indecisive for a long time and neither antagonist could get the upper hand anywhere, but the end came in the following way. Cleopatra, riding at anchor behind the combatants, could not endure the long and anxious waiting until a decision could be reached,
2. but true to her nature as a woman and an Egyptian, she was tortured by the agony of the long suspense and by the constant and fearful expectation of either possible outcome, and so she suddenly turned to flight herself and raised the signal for the others, her own subjects.
3. And thus, when they straightway raised their sails and sped out to sea, since *a favouring wind* had by chance arisen, Antony thought they were fleeing, not at the bidding of Cleopatra, but through fear because they felt themselves vanquished, and so he followed them.
4. When this took place the rest of the soldiers became both discouraged and confused, and wishing to make their own escape also in some way or another, they proceeded, some to raise their sails and others to throw the towers and the furnishings into the sea, in order to lighten the vessels and make good their escape.
5. While they were occupied in this way their adversaries fell upon them; they had not pursued the fugitives, because they themselves were *without sails and were prepared only for a naval battle*, and there were many to fight against each ship, both from afar and alongside.
6. Therefore on both sides alike the conflict took on the greatest variety and was waged with the utmost bitterness. For Caesar's men damaged the lower parts of the ships all around, crushed the oars, snapped off the rudders, and climbing on the decks, seized hold of some of the foe and pulled them down, pushed off others, and fought with yet others, since they were now equal to them in numbers;
7. and Antony's men pushed their assailants back with boathooks, cut them down with axes, hurled down upon them stones and heavy missiles made ready for just this purpose, drove back those who tried to climb up, and fought with those who came within reach.
8. An eye-witness of what took place might have compared it, likening small things to great,

to walled towns or else islands, many in number and close together, being besieged from the sea. Thus the *one party strove to scale the boats as they would the dry land or a fortress*, and eagerly brought to bear all the implements that have to do with such an operation, and the others tried to repel them, devising every means that is commonly used in such a case.

34, 1. As the fight continued equal, Caesar, at a loss what he should do, sent for fire from the camp. Previously he had wished to avoid using it, in order *to gain possession of the money*; but now that he saw it was impossible for him to win in any other way, he had recourse to this, as the only thing that would assist him.
2. And now another kind of battle was entered upon. The assailants would approach their victims from many directions at once, shoot blazing missiles at them, hurl with their hands torches fastened to javelins and with the aid of engines would throw from a distance pots full of charcoal and pitch.
3. The defenders tried to ward these missiles off one by one, and when some of them got past them and caught the timbers and at once started a great fire, as must be the case in a ship, they used first the drinking water which they carried on board and extinguished some of the conflagrations, and when that was gone they dipped up the sea-water.
4. And if they used great quantities of it at once, they would somehow stop the fire by main force; but they were unable to do this everywhere, for the buckets they had were not numerous nor large size, and in their confusion they brought them up half full, so that, far from helping the situation at all, they only increased the flames, since salt water poured on a fire in small quantities makes it burn vigorously.
5. So when they found themselves getting the worst of it in this respect also, they heaped on the blaze their thick mantles and the corpses, and for a time these checked the fire and it seemed to abate; but later, especially when the wind raged furiously, the flames flared up more than ever, fed by this very fuel.
6. So long as only a part of the ship was on fire, men would stand by that part and leap into it, hewing away or scattering the timbers; and these detached timbers were hurled by some into the sea and by others against their opponents, in the hope that they, too, might possibly be injured by these missiles.
7. Others would go to the still sound portion of their ship and now more than ever would make use of their grappling-irons and their long spears with the purpose of binding some hostile ship to theirs and crossing over to it, if possible, or, if not, of setting it on fire likewise.

35, 1. But when none of the enemy came near enough, since they were guarding against this very thing, and when the fire spread to the encircling walls and descended into the hold, the most terrible of fates came upon them.
2. Some, and particularly the sailors, perished by the smoke before the flame so much as approached them, while others were roasted in the midst of it as though in ovens. Others were consumed in their armour when it became heated.
3. There were still others, who, before they should suffer such a death, or when they were half-burned, threw off their armour and were wounded by the shots which came from a distance, or again leaped into the sea and were drowned, or were struck by their opponents and sank, or were mangled by sea-monsters.
4. Those alone found a death that was tolerable, considering the sufferings which prevailed, who were killed by their fellows in return for the same service, or else killed themselves, before any such fate could befall them; for they not only had no tortures to endure, but when dead had the burning ships for their funeral pyres.
5. When Caesar’s forces saw the situation, they at first refrained from approaching the enemy, since some of them were still able to defend themselves; but when the fire began to destroy the ships, and the men, far from being able to do any harm to an enemy, could not even help themselves any longer, they eagerly sailed up to them in the hope that they might possibly *gain possession of the money*, and they endeavoured to extinguish the fire which they themselves had caused.
6. Consequently many of these men also fell victims to the flames and to their own rapacity.“

2.2 ALEXANDRIA Magnus Portus

Archaeological investigations carried out in Alexandria Bay by Franck Goddio of the European Institute for Underwater Archaeology have revealed the harbour complex from the time of the first Ptolemies ([16]). These royal ports sheltered the Ptolemies' fleets of warships consisting of several hundred galleys, some of which were extraordinarily large. The complex consists of three ports, probably built between 300 and 250 BC during the Hellenistic period, more than 200 years before the arrival of Julius Caesar in 48 BC They are thus much older than most harbours that have been studied so far, such as Caesarea Maritima (Israel).

Unfortunately, there are no extant documents from the period concerning the design of these ports, and we are now forced to make assumptions on the basis of present knowledge and on the principal ancient text concerning maritime structures, by the Roman author Vitruvius.

The main aspects that are of interest to the harbour design specialist are as follows:

¬ **Choice of site**. A port is not built simply anywhere. It forms an interface between land and sea and its location depends on traffic in these two areas and on certain natural conditions.

¬ **Overall layout**. The layout of a port depends on navigation conditions (winds and waves) and on the types of ship that use it (merchant ships, galleys). The size of the ships defines the acceptable wave-induced disturbance and the possible need to build a breakwater providing protection against storms. The number of ships using the port defines the length of quays and the area of the basins required.

¬ **Harbour structures**. The ships' draught defines the depth at the quayside and thus the height and structure of the quay. Locally available materials (wood, stone and mortar) and construction methods define the specific structures for a region and historical period.

CHOICE OF SITE

In a hurry to conquer the world, Alexander-the-Great cannot have appreciated the fact that the Phoenician city of Tyre resisted for 8 months (January-August 332 BC) before he was able to take it. He had to build a causeway linking the island to the mainland and call on the help of Tyre's rivals to succeed in his enterprise. The similarity between the island of Tyre and the island of Pharos is striking, especially when one adds that Alexander built a causeway between the island and the mainland at both sites, and that they both have a double harbour.

The idea of building a double harbour is motivated by the fact that there are two main wind and offshore wave directions.

In this case, which is quite frequent, it is useful to be able to move ships from one harbour to the other in order to obtain the best protection against wave disturbance in all circumstances. After the construction of the Heptastadium, the island of Pharos became a peninsula that perfectly fulfilled this criterion:

• to the west was built the Port of Eunostos (which became the commercial harbour),
• to the east was built the Magnus Portus (the royal harbour),

and, the ultimate subtlety, ships could be transferred from one to the other without going out to sea, via canals cutting through the Heptastadium. Nevertheless, it should be noted that the western part of Alexandria Bay must have begun to silt up progressively after the construction of the Heptastadium, eventually resulting in the curved shoreline that exists today in this part of the bay.

It is likely that other considerations unrelated to the harbour itself also influenced the choice of site, but it is clear today that the island of Pharos was certainly better than Canopus (present-day Abu Kir), which had been chosen by Alexander's Egyptian predecessors and which is exposed to waves from the N-E sector. These waves are less frequent than those from the W-N sector but are nevertheless very problematic in winter. Moreover, this site has a distinct tendency to silt up owing to its proximity to one of the main mouths of the Nile near Rosetta. Sediment carried down by the Nile is transported along the coast by waves from the N-E sector.

But what were these harbours actually used for?

Alexander was definitely not a sailor. He symbolically burnt his boats on disembarking in Asia after crossing the Hellespont with 300 triremes. He needed the assistance of 400 triremes from Sidon and Cyprus to conquer Tyre, and after founding Alexandria on 20 January 331 BC and remaining in Egypt for only a few months, he subsequently devoted his attention only to mainland countries. He therefore did not choose this site as a base for his fleet of warships, though his successors (in particular Ptolemy II Philadelphus) based their fleets there.

He must nevertheless have learnt the lesson from his master Aristotle, who 11 years earlier had advised him to create an access to the sea so as to be "easily supported on two fronts at once, from the land and from the sea" in the event of an enemy offensive, and also to "import products that are not found in your lands, and export your own surplus produce" ([2], p 9 and 11). The city is indeed located on a strip of land between the sea and lake Mariotis (the present lake Maryut), on which a river port was built. The river port is connected directly with the Nile and the Red Sea by means of a canal built by Ramses II and restored by Ptolemy II.

Three centuries later, at the time Strabo visited Alexandria (around 25 BC), the pirates had disappeared due to the efforts of Pompey's fleets a few decades earlier and trade was booming thanks to the peaceful conditions created by the Romans. Alexandria had almost a million inhabitants of various origins ([1] p 261). It exported wheat to Rome and papyrus throughout the Mediterranean. It imported wood from Lebanon, wine, oil etc. ([1] p 302). At the beginning of the Christian era, the city was exporting up to 150 000 t/year of wheat to Rome ([3] p 297).

Alexandria had thus proved to be in a strategic position from the commercial point of view, as a land-sea interface.

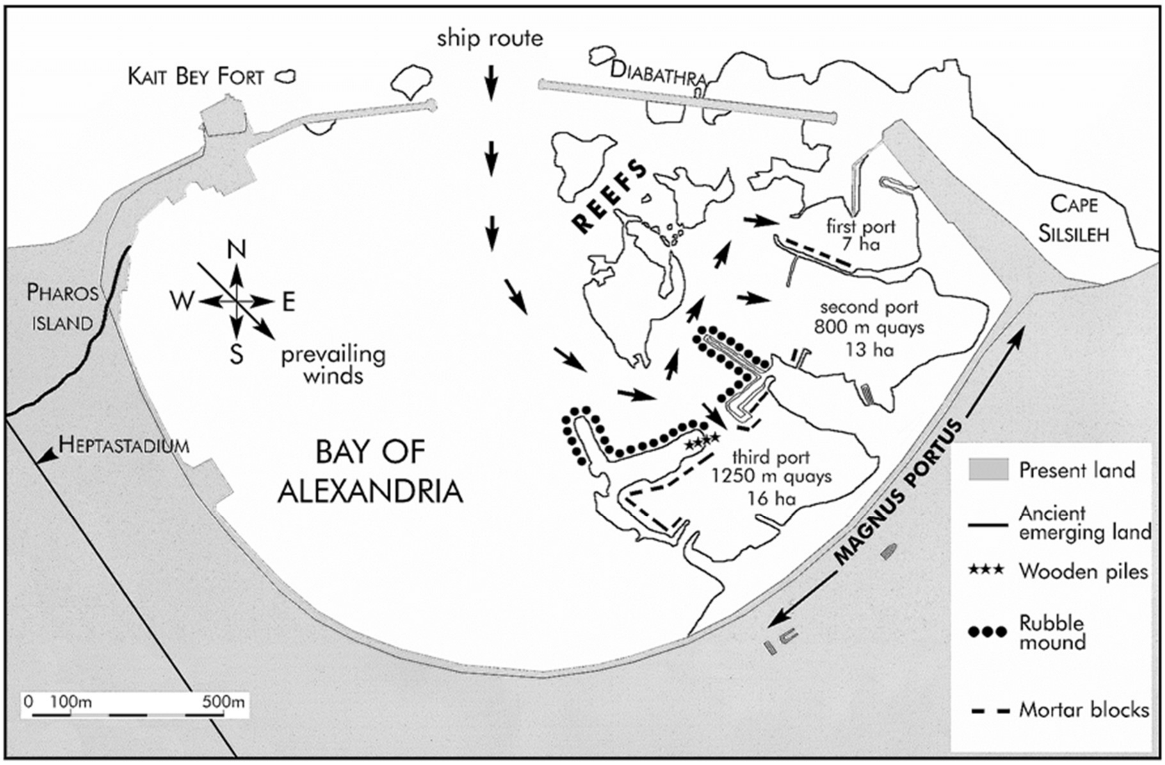
OVERALL LAYOUT

Let us begin with what concerns all shipping, namely wind and waves. It may reasonably be assumed that the wind and wave conditions have hardly altered if at all since ancient times (see section on “Ancient climate”). Present statistics show that winds (and waves) prevailing off Alexandria come from the W-N sector (more than 50% of the time as an annual average and 70-90% of the time during the summer months from June to September). A second important sector is N-E (20-30% of the time during the winter months from October to May). This latter sector has had a considerable importance for the development of the port, as it is the reason for the double harbour arrangement, as pointed out above.

The first logical reaction would be to locate the port against the Heptastadium, in the shelter of Pharos Island, at the place where today's fishermen shelter their boats from prevailing winds from the W-N sector. Yet this argument does not appear to have carried weight as the three ports discovered to date are located at the opposite end, below Cape Lochias (modern Cape Silsileh), where the royal palace used to be, perhaps because they are located behind reefs that are as many traps for sailors who do not know them precisely. This eastern part of Alexandria Bay is relatively more exposed to offshore NW waves and this meant that it was necessary to build a protective breakwater ("Diabathra") to supplement the natural protection offered by the reefs that emerged above sea level at the time.

Another explanation of why the ports were located on the eastern side of Alexandria Bay could be the siltation that occurred against the Heptastadium and which dissuaded the

Ptolemaic planners, who must have faced the same problem at Canopus. If it is assumed that the construction of the harbour began only during the reign of Ptolemy I Soter at the earliest (he acceded to the throne in 304 BC) then almost 25 years had elapsed since the construction of the Heptastadium. This is quite long enough to reveal siltation against the Heptastadium and incite the planners to locate the ports elsewhere.



Layout of Magnus Portus in the Bay of Alexandria

Access to the ports could therefore only be achieved by skirting the reefs by the west and south. This meant that boats could enter the bay with the wind 3/4 astern before taking in the sail, and then be rowed NE to reach the entrance of one of the three ports.

In terms of the types of ship using the port, even though a few large commercial ships have been identified, the fleets of warships are better known.

At the time the Romans and Carthaginians were battling with triremes and quinqueremes in the western Mediterranean (as at the battle of the Aegates in 241 BC), the Macedonians and Alexandrians were building giant galleys, the likes of which would never be seen again. In particular, it should be noted that these huge ships appeared at the time Ptolemy I was ascending the throne. They seem to have existed for several centuries, as Antony aligned a number of them opposite the Romans at the battle of Actium (31 BC). The most productive was undoubtedly Ptolemy II, who, at his death in 246 BC, left a considerable fleet of warships ([4] p 42):

• 2 "30 " s (i.e., 30 oarsmen on each side, see section on “Ancient ships”),
• 1 "20 " ,
• 4 "13 " s,
• 2 "12 " s,
• 14 "11 " s,
• 67 "9 " s to "7 " s,
• 22 "6 " s & "5 " s (quinqueremes),

• 4 "3 " s (triremes),
• 150 to 200 "2 " s (biremes) and smaller.

making a total of around 10 large ships (from 50 x 10 m to 70 x 20 m), 80 medium ships (45 x 8.5 m) and 175 to 225 small ships (from 20 x 2.5 m to 35 x 5 m), totalling around 300 ships.

This number is of the same order of magnitude as others found at other periods. Pompey's fleet in his war against the pirates (in 67 and 66 BC) consisted of 200 quinqueremes and 30 triremes ([4] p 82) and Antony's fleet at the battle of Actium consisted of 170 to 500 ships (the largest being a "10 "). It is also known that at other periods the Alexandrian fleet was smaller: the fleet burnt by Caesar at the battle of Alexandria in 48 BC consisted of 50 quinqueremes and triremes, 22 other ships and 38 ships hauled up on land in the arsenals ([1] p 311).

As an exercise in defining the overall layout of the harbour, we attempted to find space in the discovered ports for all the ships of Ptolemy II's fleet. The areas of water in the ports are approximately as follows:

• first port: about 7 ha,
• second port: about 13 ha with probably around 800 m of quays,
• third port: about 16 ha with probably around 1250 m of quays,
• Heptastadium bay (between the third port and the island of Pharos): about 100 ha with 1000 to 2000 m of beach.

The first port could comfortably accommodate the 10 large ships mentioned above. The 80 medium ships and 25 small ones could be aligned side by side, stern to quay, in the second port. The remaining 150-200 small ships could be sheltered in the third port, which has quay space for up to 250 quinqueremes.

It should also be noted that the beach in the bay, which was the site for the shipyards ([1] p 283...) must have been covered with slipways for hauling vessels out of the water. Over a distance of 2000 m, it would be possible to accommodate about 200 quinqueremes under construction (with a distance of 5 m between them, which appears to be a minimum for proper working conditions).

As regards commercial ships, the "2000 amphorae" and "10 000 amphorae" must have represented a cargo of the order of 100-500 t. An average ship of 250 t, i.e., 8 000 sacks of one artaba (39 l) weighing ca. 30 kg each (see section on “Ancient measures”). To carry 500 000 t/year of wheat and other imported goods, with two return trips a year, a fleet of around 1000 of these ships would be required. These would sail during the fine season (from May to September) ([3] p 270). However, it is likely that these ships called at the port of Eunostos rather than at the Magnus Portus.

It is clear that Magnus Portus was among the largest ports of the time.

HARBOUR STRUCTURES

Recent archaeological underwater investigations have revealed the existence of the three ports referred to above ([16]). The third port is the largest and uses the island of Antirhodos as a natural protection against wave disturbance. The island was entirely developed as the site for a royal palace and quays consisting of large blocks of concrete cast in situ.

The remains of wooden structures have been used for carbon 14 dating and reveal the existence of an archaic structure in the form of a double row of piles.

One of the ironies of civilisation is that the ancient warship ports are quite similar to modern marinas in terms of the dimensions and the size of the ships using them (modern luxury yachts range in length from 15 to 70 m and more). However, the draught of the ancient galleys was less, of the order of 1 to 1.5 m. The largest ships (the "40"s of Ptolemy IV Philopator, or the Isis) must nevertheless have had a draught of up to 4 m.

The two principal types of harbour structure found in Alexandria are protective breakwaters and quays.

The breakwaters could be rubble mound or vertical-faced structures built of blocks. There is no point in dwelling on this question for Alexandria; the offshore breakwaters have not (yet) been explored, since they are probably located below the modern ones.

The inner breakwaters protecting each of the three ports consist of a sloping mound on the seaward side and in most cases a quay made of mortar blocks on the leeward side.

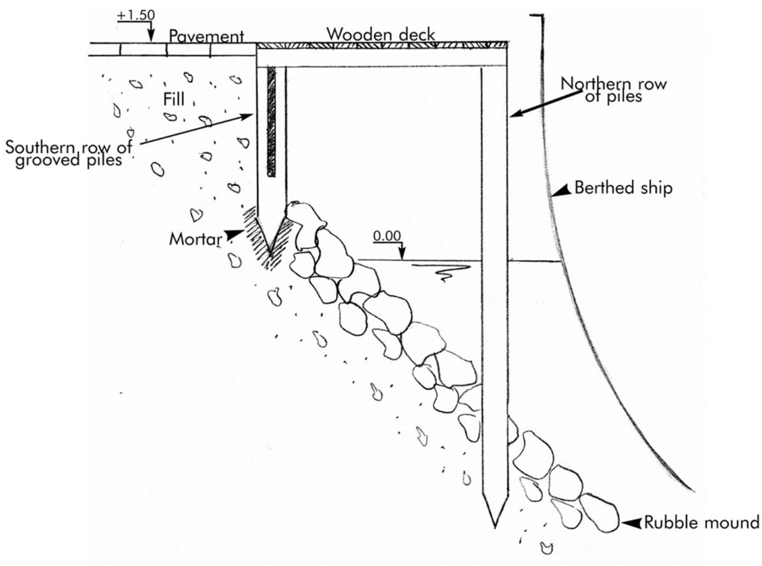
From a general point of view, quay structures may be classified as follows, depending on the material used:

• with wood: wooden platforms on piles or pillars made of blocks of stone,
• without mortar: dressed stone blocks with a possible filling between two facings,
• with mortar, without pozzolana: massive blocks cast in-the-dry in wooden formworks,
• with mortar, with pozzolana: massive blocks cast under water in wooden formworks.

The early Alexandrians did not have the advantage of pozzolana when they first built Magnus Portus, but the large mortar block discovered in the third port at Alexandria (typically 5-8 m wide, 10-15 m long and 1-3 m high) contains pozzolana and must therefore be of the Roman period[1]. The block consists of alternating layers of mortar and flat pieces of limestone measuring about 0.1 x 0.1 m. The existence of planks of pine wood 3-4 cm thick under the block indicates that it was cast in a watertight floating caisson. This is also confirmed by the existence of vertical and inclined beams held in the mortar, giving the caisson its rigidity during the floating and sinking stages.

The double row of elm piles discovered at the eastern end of the island of Antirhodos ([16]) is older than the large blocks mentioned above (around 400 BC). Moreover, it disappears under more recent fill material and large blocks. The presence of mortar at the lower end of the piles indicates that these rows must have been built in the dry, i.e., that they subsided under the sea after construction.

The following hypothesis could be put forward, whereby this double row of piles could be the remains of an ancient wooden quay.



Archaic quay with wooden deck resting on piles

[1] NB: in a former publication ([16], p 37), this block was believed to contain *no* pozzolana and was dated *250 BC*, but this was amended later on ([17], p 222).

The southern row consists of grooved piles (0.14 x 0.14 m section), spaced 0.4-0.5 m apart, into which pine planks 4 cm thick were introduced to form a small wooden curtain capable of holding quarry run fill. The northern row consists of simple piles spaced 0.2-0.4 m apart. These could have supported wooden planks and have been set in water about a metre deep. The northern row is 1.5-1.8 m from the southern row.

In **conclusion**, it is hoped that these investigations will be just the first in a long series, which will give us further information on ancient port engineering techniques.

It is to be hoped that this part of Alexandria Bay will soon be declared off limits for construction or, even better, transformed into an underwater museum.

OCEANOGRAPHIC CONDITIONS AT ALEXANDRIA

Winds

The following statistics were provided by Alexandria weather station for the period 1973-1992 (expressed as percentages of time per sector):

Month	1	2	3	4	5	6	7	8	9	10	11	12	Year
N to E	19	20	29	30	30	17	5	7	16	30	30	20	21
E to S	15	17	15	15	11	5	2	2	5	12	13	16	11
S to W	35	26	15	9	6	6	5	4	5	10	21	35	15
W to N	31	37	41	46	53	72	88	87	74	48	36	29	53
N (E) S	34	37	44	45	41	22	7	9	21	42	43	36	32
S (W) N	66	63	56	55	59	78	93	91	79	58	57	64	68

Alexandria wind statistics

The first four lines of the table give the frequency of occurrence of winds from the four 90° sectors. The last two lines give the figures for the two 180° sectors that might be referred to as “easterlies” for the N (E) S sector and “westerlies” for the S (W) N sector. The last column gives the annual average.

The following features may be noted:

• as an annual average, westerlies blow for 2/3 of the time and easterlies for 1/3 of the time,
• as an annual average, winds blow from the W-N sector ("from NW") for a little more than half of the time; these are therefore clearly the prevailing winds,
• winds in the summer (June-September) blow from NW for more than 3/4 of the time, and it is only during October and in winter up to May that there are between 35% and 45% of winds from the east.
• the famous "summer winds" in July and August are very clearly shown with over 90% of westerlies.

These figures explain why sailing from Rome to Alexandria was much easier than the reverse. The voyage took between 1 and 2 weeks in the first direction and at least double in the opposite direction. Ships made an average of 2 voyages per year during the fine season from May to September in order to avoid storms ([3] p 270 and 297).

Waves

The following statistics were obtained from observations made on board selected ships in the eastern Mediterranean during the period 1960-1980:

Sector	N285-N325	N325-N5	N5-N35	N35-N65	Calms	Total
H<0.1m	-	-	-	-	56	56
0.1>H>1m	10	6	2	2	-	20
H>1m	13	7	2	2	-	24
Total	23	13	4	4	56	100

Alexandria wave statistics

The first four columns indicate the frequencies of occurrence of offshore waves in percentages of time for the sectors shown. The fifth column gives the percentage of calms (and other sectors that cannot reach Alexandria). The first line shows calms. The second line shows waves below 1 m and the third line those above 1 m (crest-trough height).

The following features may be noted:

• the sea is calm off the coasts of Egypt and Libya for just over half the time,
• waves of more than 1 m, which are problematic for sailing ships, occur for about a quarter of the time,
• waves from the W-N sector (approximately N285 to N5) represent 36% of the time and those from the N-E (approximately N5 to N65) only 8%.

Sea levels
The following levels have been adopted by the Egyptian authorities (with respect to the land datum):

• LLWL (Lowest Low Water Level): -0.43 m
• CD (Chart Datum or hydrographic zero): -0.34 m
• MLWL (Mean Low Water Level): -0.05 m
• MSL (Mean Sea Level): +0.08 m
• MHWL (Mean High Water Level): +0.21 m
• HHWL (Highest High Water Level): +0.74 m

It should be noted that the LLWL is 9 cm below the hydrographic zero and the mean sea level at Alexandria is 8 cm above the Egyptian land datum.

It should be pointed out that mean sea levels have changed over the last 2500 years. Without entering into expert discussions on this subject, it may be estimated that the sea level rise during the period has been about 0.50 m ([19]), i.e., about 2 cm/century. It may be added that the present rate of rise is much greater as it has reached about 18 cm during the past century (1880-1980)([19]) and it is currently estimated that it will be between 50 and 100 cm in the 21st c. (see section on “Sea Level Rise”).

Oscillations in mean sea level nevertheless seem to have occurred over the past two millennia. It is also very difficult to distinguish eustatic movements (those connected with the sea) from tectonic movements (connected with the land). The example of Crete is a good illustration. Over the past 2000 years the sea level has dropped by 4 to 8 m with respect to the land at the western end of the island, whereas at the eastern end it has risen by 1 to 4 m during the same period ([20], p 68).
It is currently admitted that the sea level at Alexandria has risen by 0.5 m and the land level has fallen by 5 to 6 m over the past 2000 years.

It should also be noted that tsunamis have been mentioned on the coasts of the Near East [18] (see section on “Ancient climate”).

Sedimentology
The sediments found on the beaches and seabed near Alexandria Bay consist of sand with a grain size (D_{50}) ranging from 0.20 to 0.50 mm. This sand consists of ancient deposits carried down by the Nile. For the past few decades the beaches at Alexandria have been suffering

from widespread erosion and protective measures have been taken (involving beach nourishment or rockfill structures) with varying degrees of success. This erosion is due mainly to beach sand being carried offshore during storms.

In addition to the offshore transit of sand, there is significant longshore drift to both the east and west. Specialists estimate that the sand transport in each direction amounts to around 100 000 m^3/year, and thus cancels out. It is clear that if an obstacle were to be built perpendicular to the coast, sand would be deposited on either side. This is what must have happened after the construction of the Heptastadium, where at least some of this longshore drift must have been trapped each year.

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2.3 ALEXANDRIA Pharos island

The ancient port on Pharos island may have been one of the largest and oldest ports of the Mediterranean area according to the detailed description provided by Gaston Jondet (1916), followed by Raymond Weill (1916) and Savile (1940). This is confirmed by the modern Google Earth picture of 20/1/2015 that clearly shows the underwater structures. A more recent survey was conducted by the "Centre for Egyptological Studies of the Russian Academy of Sciences" (2003-2015) and reported by Galina Belova (2019)[2].

Fig. 1: Jondet's map compared to Google Earth's picture (20/1/2015) showing the main north breakwater of the ancient Pharos port.

[2] BELOVA, G., et al., 2019, "Russian underwater archaeological mission to Alexandria, General report (2003-2015)", Egypt and neighbouring countries 3, (p 1-31).

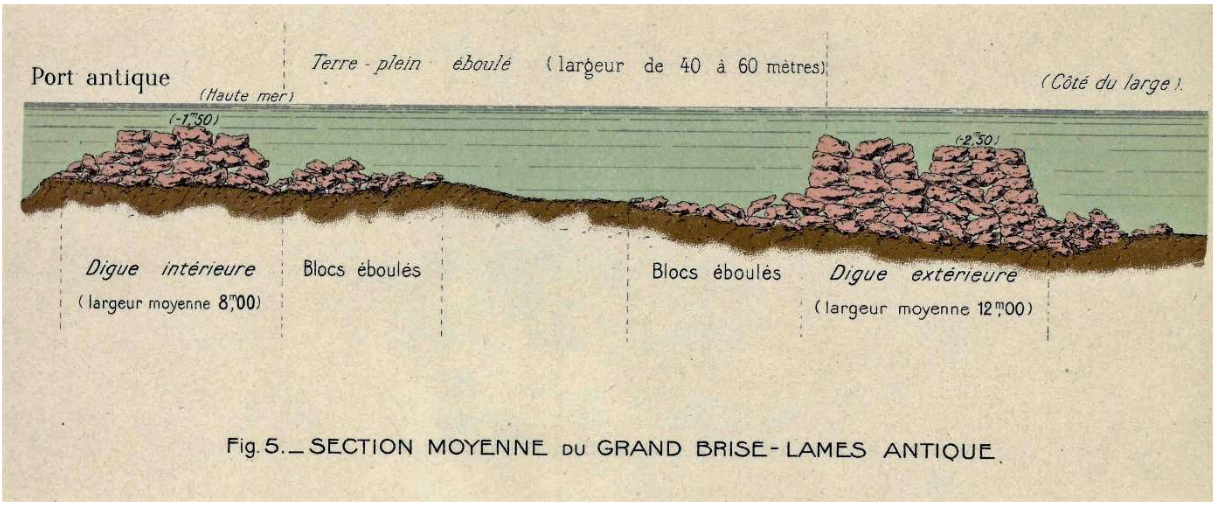

Fig. 2: Jondet's cross-section of the main north breakwater.

According to Jondet and Belova, the main north breakwater, with a total length of more than 2300 m consisted of two submerged mounds on a water depth down to 10 m below present sea level, with 40 to 60 m in-between. The crest is at 1 to 1.5 m below present sea level. The total width of the main north breakwater is therefore 60 to 80 m. Both mounds were made of large quarried blocks (2 x 2 x 1 m 'soft limestone' from local quarries). Many of the blocks have a ca. 10 cm hole near the edge. The area between both rubble mounds was filled with rubble which was found in some places, but in other places, it was washed away over time.

Jondet estimates the total harbour area to around 60 ha. The main entrance was around 200 m wide and 8 m deep on the south side of the Pharos island. It was sheltered by two short breakwaters (called here SW and SE breakwaters). Immediately east of the entrance was an island with what Jondet supposed to be the building of the port authority, with an adjacent small basin protected by two small breakwaters. The main deep-water basin was located west of the entrance and over 500 m long. More basins were located east of the entrance but most were shallow (ca 1 m) and bordered with beaches and very small port structures. A deep-water basin was found on the NE side of the harbour and called "port de commerce" by Jondet. This basin was around 60 x 150 m with its own separate entrance towards north.

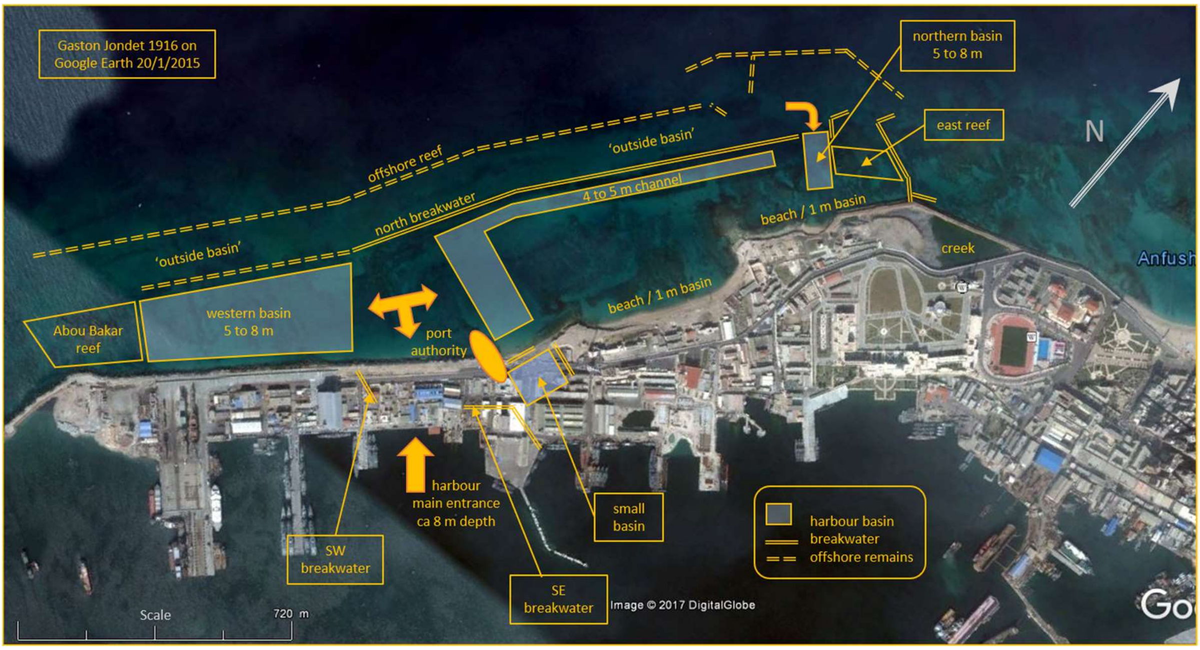

Fig. 3: Jondet's description of the ancient Pharos port.

Additional linear offshore structures were found later on by Jondet's team, but they were identified by Belova (2019) as a natural ridge consisting of broken blocks "recognizable by the exact coincidence of the edges between the fallen 'blocks'.". However, a second line of submerged reefs (ca. 900 m offshore of the modern Ras el-Tin lighthouse) with its crest at 9 to 12 m below present sea level, was surveyed by Belova's team, yielding numerous ancient anchors on its offshore side, possibly indicating an offshore anchorage area.

Jondet paid particular attention to the Abou Bakar reef (now called el-Aramil) on the west side and to the east reef, considering that the structures found there were part of a heavy defence system of the port. However, Belova (2019) did not find firm evidence.

Jondet also mentioned that access from the south was through todays Dikheila area after passing between the reefs in that area.

Dating:

Textual evidence. The port was mentioned by Homer (Odyssey, 4, 353):

"Now there is an isle in the sea-surge off the mouth of the Nile, that men call Pharos, a day's run for a hollow ship with a strong wind astern. There's a good anchorage there, a harbour from which men launch their trim ships into the waves, when they have drawn fresh black water."

However, no other ancient author did so and this may be a sign that the port disappeared soon after Homer's time (i.e., between the 8th and the 5th c. BC), possibly due to sudden tectonic activity. However, Homer may have been talking about an archaic port long before his time and even before the Trojan war (now dated around 1200 BC).
Gaston Jondet tried to date the port but he had no archaeological clues to do so. He came up with a theory that Rameses II (reign 1279 to 1213 BC) may have ordered its construction after his victory over the Sea Peoples (1277 BC). This theory would be valid also for Merneptah (1208 BC battle) and Rameses III (1175 BC battle) but it is somewhat surprising that none of these kings mentions this port and that all battles have been fought inside the Nile delta and not in open sea. This would leave us with an estimated "around 1200 BC".
It may be mentioned that the Amarna Letters (around 1350 BC) do not mention this port although many other places on the Levantine coast are. However, this is of little help because the port may have been built later, or earlier and already disappeared.
Raymond Weill (1916) suggested that the port was built by Minoan foreigners whose settlement would have been accepted by the pharaoh sometime between 2000 and 1500 BC. But this theory now seems somewhat unlikely if we consider the remains of the 85 Minoan ports identified so far, which are all quite modest, except Phalasarna, perhaps. He also points at the Phoenician Tyrians who lived in very similar conditions and were great builders in the same period. This theory makes more sense.

Archaeological evidence: none published so far (?), except the fact that the breakwater cross-section shown in fig. 2 above could be seen as an ancestor of the typical Phoenician breakwater structure.

Geochemical evidence. Recent investigations on lead (Pb) pollution of sediments taken from the Alexandria Bay (Magnus Portus) show a possible anthropogenic imprint as early as 2300-2650 (±200) BC and, to a lesser extent, 3500-3800 (±170) BC (Véron et al., 2013). Lead pollution is strongly correlated with human activity as it was used for pipes carrying drinking water and for many other things.

Geoarchaeological evidence. According to Homer (8th c. BC) the port was located on an island and this is confirmed by modern geo-archaeological investigations that show that a tombolo developed during the 3rd and 2nd millennia BC between the island and the continent (Goiran et al., 2014). This was due to wave action from NW inducing a littoral drift (sand transport) from west to east. This sand deposited in the lee of the island where wave action was limited. Hence, the insular character of Pharos island gradually diminished and a ford was probably available for crossing from the mainland to the island in the 2nd millennium BC.

These investigations show that this area was inhabited very early, and this is no wonder for such a nice shelter for shipping, but it would be difficult to believe this very large port of Pharos being built before 2000 BC. Hence, our construction date estimate cannot be more accurate than "sometime between 2000 and 1000 BC", possibly by Tyrians.

After that, the story is well-known: Alexander founded Alexandria on the mainland at a place called Rhakotis in 331 BC and his successors, Ptolemy I and/or II, built the Heptastadion and the eastern port, Magnus Portus, around 300 BC.

And what happened in 21st century?! A large land reclamation project was carried out between 2016 and 2018, covering the whole ancient port area …

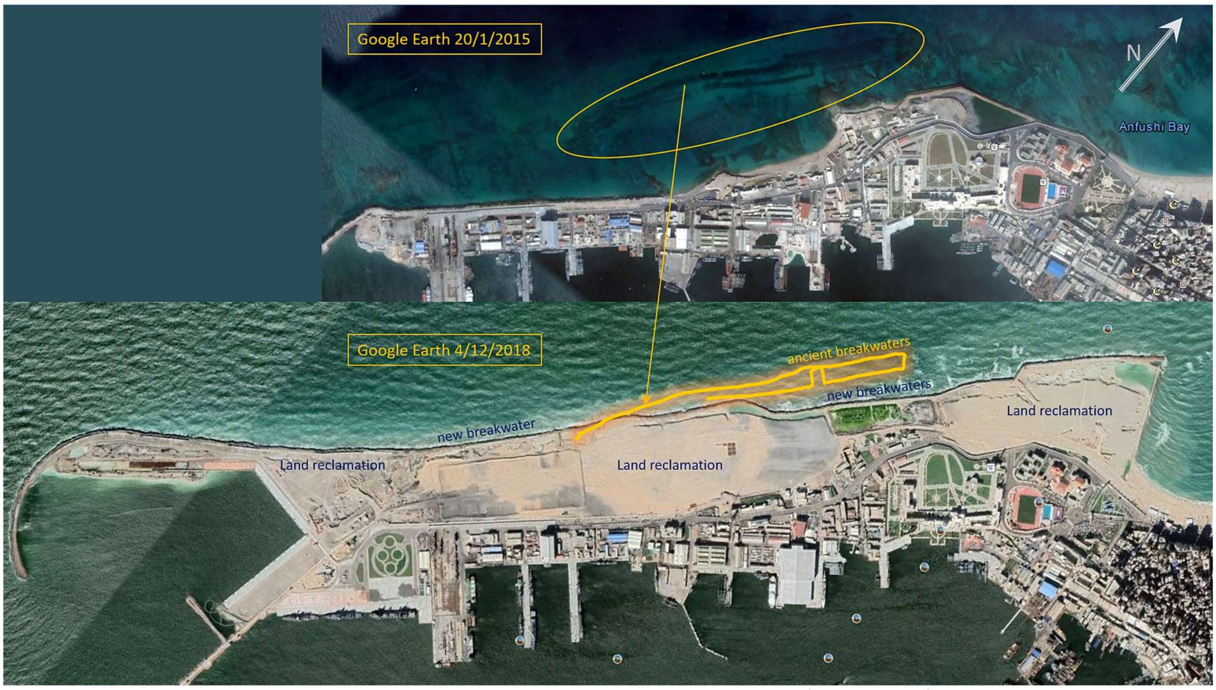

Fig. 4: Land reclamation project on Pharos island (2016-2018).

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2.4 APOLLONIA

Let me put things straight: I have never been to Apollonia (I did not go further than Leptis Magna) but I met some of the most knowledgeable persons (Nic Flemming, André Laronde (†), Jean-Pierre Misson, Claude Sintès) who convinced me that Apollonia hosts the most important ancient port remains, preserved mainly because they are now under water. I would not feel entitled to write anything on this port, were it not that Jean-Pierre Misson showed me some under water pictures made in the sixties and in 2012 that are not yet published elsewhere. He did me great honour to accept publication on this web site.
I therefore rely heavily on quotations from several authors.

In Nic Flemming's words (personal communication, 9/2/2014):
*"I have seen hundreds of other ports. […] **Apollonia is unique**.*
The unique features of Apollonia are:

- *Relatively early date, 6-7th c. BC, and later during the epoch of trireme warfare. No other complete harbour of this date.*
- *Completeness of port area, shore side, and dock structures. It is a complete 'deck of cards' so to speak, with nothing missing. A complete range of different structures and ancient technological functions, some still unexplained.*
- *Completeness (although collapsing) of the original sea defences, sea walls, cut wave traps, rubble breakwaters, as a complete system.*
- *Multiple layers preserved in stratigraphic context of at least 3 generations of structures on the dockside, all submerged, in the period 600 BC to Hellenistic/Roman.*
- *Numerous structures and rock-cuttings which are still unexplained, like the nine 'quays'.*
- *Excellent clear water, easy place to film or work, and layers of sand accumulated which will preserve pottery and other artefacts. Hardly any excavation in the underwater city, so a great deal still to be learned.*
- *Evidence that micro-features such as lead dowels, carvings, statues, pottery and other small items neglected in previous surveys still survive."*

Quoting Kalliopi Baika (2013) on the History of Apollonia:
"The ancient harbour of Apollonia in Cyrenaica was the epineion (out-port) of Cyrene, which lay 18 km inland. It is in a broad open bay, delimited to the east by Cape Naustathmos (Ras el-Hilal) 20 km away, and to the west by Phycus ([near] *Ras Aamer).*
The natural harbour must have been in use since the foundation of Cyrene in 631 BC as a Greek colony from Thera. Apollonia is recorded as established in ca 600 BC as the 'harbour of Cyrene'. Cyrenaica became a dependency of the Ptolemaic kingdom under Ptolemy I Soter in 322-321 BC. The cities of Cyrenaica became independent in 97 BC, after the kingdom passed to Rome. It received the name Apollonia. Mark Antony restored Cyrenaica to the Ptolemaic empire, and after the Battle of Actium it was combined with Crete, under Roman rule. Apollonia was an excellent naval base in a very strategic position in Cyrenaica, and Roman fleets were maintained there. The city was renamed Sozousa, when it became the capital of Upper Libya, a province created by Diocletian."

Quoting Kalliopi Baika (2013) on the *Port of Apollonia*
"Apollonia was served by two harbour basins accessible in all weathers, the prevailing winds on this coast being from the north-west. The basins were formed on the rocky coastline by a projection on the west, and by a projection (which is now two islands, Îlot Hammàm and the

smaller Îlot Sharkéa on the east) which protects them from the north.
The western harbour, that was an inner harbour communicating with the eastern one via a channel, probably originally had an entrance on its north. The eastern harbour was open on its eastern side, between Îlot Sharkéa and the coast, with a lighthouse located on the southern end of this island. The channel connecting the two basins was later walled and protected on each side by two fortification towers that were part of the city fortification system. The western harbour, which was partly included in the city walls, contained the main complex of slipways. In general, the harbour underwent several reconstructions from the Classical period onwards. The channel between the harbours was deliberately filled in late antiquity so that the eastern harbour became the only harbour.
The western harbour had at least five rock-cut complexes on its perimeter. However, only one group is now identified with certainty as slipways. This is located on the Îlot Hammàm in the north-east corner of the western basin.
The small complex in the eastern harbour on Îlot Sharkéa, which was thought to be shipsheds, is now, after underwater exploration, identified as a quarry. The other harbour remains and rock-cut structures on the west and south edges of the western harbour and now submerged could have been ship-building areas, quays or warehouses."

According to the latest research, the Glacial Hydro Isostatic Sea Level Rise in this region was only 0.30 to 0.50 m during the past two millennia (Morhange, 2014). However, the relative SLR was much different in many places as it includes tectonic movements: in Apollonia, mainly subsidence.

Quoting Kalliopi Baika (2013) on the Relative Sea Level Change at Apollonia:
"[…]. *The French team that carried out supplementary investigations at the entrance towers to the western harbour estimated a difference in sea level of 3.50 m, with a small variation for the small tides. This evidence was based on indications of lithophaga on the sides of the fortification towers facing the channel. This level was tested on all features submerged in the harbour and gave satisfactory results for 90 per cent of them. In addition, in the channel the surfaces of the walls below the ashlar superstructure are rock-cut, suggesting that they were once above sea level. The artificial blocking of the channel, which terminates at the same level as the lithophaga lines, offers additional support for the suggestion of a difference of 3.70-3.80 m since the beginning of the Christian period."*

Quoting Nic Flemming on the Relative Sea Level Change at Apollonia (personal communication, 15/11/2014):
"Knowledge of the numerous possible causes of change of local relative sea has increased greatly since the early days of research at Apollonia in the 1950's to 80's. Thus early observations in the field are generally correct, but the explanations in published articles are limited by the contemporary knowledge.
Factors which are now known to have influenced the local sea level are:

- *Glacial Hydro Isostatic Adjustment (GIA), that is the response of the sea level and the earth's crust to the melting of the ice caps at the end of the last glaciation. The most accurate estimations of this cause of relative sea level change on the Tunisian-Libyan coast are by Anzidei et al. (2011) and Lambeck & Purcell (2005).*
- *For tectonic processes see Ambraseys (1984, 1994).*
- *For an up-to-date analysis of how all the various causes interact, see Tsimplis et al (2011).*

Estimation of the total net change of relative sea level at different parts of the city of Apollonia produce different results, and there is no reason to doubt these values. In order of depth:

- *French MAF results: the Lithodomos borings are at -3.0 m-3.8 m in the Christian era.*
- *Piscina, Fish tank, Flemming (1971): the walk way is at -2.5 m, therefore the sea level was lower than this in the Roman Empire period, probably around – 2.8 m. The floor of the slipway on thick deposits of rubble is at -3.0 m, and the solid floor is deeper than this. (The fish tank is cut into solid rock, as were many piscine all over the Roman world, so they had no problem in cutting rock below the sea level).*
- *West island slipways (early period around 600-500 BC): the bottom of slips is at -2.8 m.*
- *Grid building: the depth on the harbour end of the grid, not on the masonry, is at -2.8 m.*
- *Grotto Reef tunnel: the ceiling of tunnel is just awash, so the floor of the tunnel is a bit shallower than – 2.0 m, and the sea level change must have been more than 2.0 m.*
- *'Quays': the depth in the neighbourhood of the seaward end of the quays is 2.4 m (with some, unknown sand thickness on the seabed); and 2.2- 2.3 m depth at landward end of quays.*

Further discussion of the sea level evidence yields:

- *If we take the 3.0 m or more from the French data, then the slipways on the west island are completely high and dry. They would be useless. Since there are small walls built on top of the slipways, and other walls built on the sea floor in the harbour basin below the foot of the slipways, this is consistent with a change of level between 500 BC and the time of the Roman Empire.*
- *The walkway of the Piscina would be dry by about 50 cm with a sea level change of 3.0 m, which seems a bit much, but not impossible. (A sea level of -3.5 m would make the piscine almost dry!) So, maybe the uplift continued into the Christian era.*
- *The evidence from these two dates, about 500 BC, and the Empire/Christian period indicate that the city of Apollonia was uplifted by about 50 cm between these two dates, possibly more. This must have been due to earthquake activity (tectonic) since there is no evidence at other archaeological sites for a GIA drop of sea level during this period.*
- *During the last 2000 years the city has subsided by a total of about 3.0 m, and this relative change of level is made up of about 0.30-0.50 m of rising GIA sea level, and 2.5-2.7 m tectonic subsidence.*
- *The reversal of tectonic direction is quite common. Close to a subduction or normal fault the ground is dragged one way in a "stick" mode, and then an earthquake allows the fault to "slip", and the ground moves the other way.*
- *If these figures are correct,* ***the relative sea level was about 2.5 m lower than at present in the early years/centuries of the city after its foundation.*** *The bottom of the slipways was at least 30 cm underwater, and the sea lapped between the 'quays'.*
- ***In the following centuries BC (or AD?) the city was uplifted about 50 cm****, and the slipways and the 'quays' became high and dry. The diameter of the inner harbour contracted, and a secondary group of structures was built on a smaller diameter, varying from 25-50 m in from the earlier circumference or water-front.*
- *Finally,* ***during the late Roman Empire, or later (perhaps in a famous earthquake), the city was submerged by about 3.0-3.5 m.***

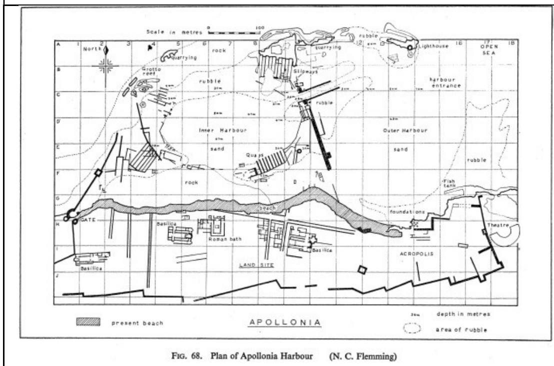
Concluding: the dates and events listed above are rough estimates, but it is absolutely evident that the buildings are adjusted to two different relative sea levels at different dates. After the uplift phase, the inner harbour basin contracted in radius by about 25-50 m, and some of the earlier waterfront structures became unusable. The outer harbour would then have been much more important."

In any case,
the oldest structures which are now 2 m under water were initially around 0.5 m above water!

Maps & pictures:

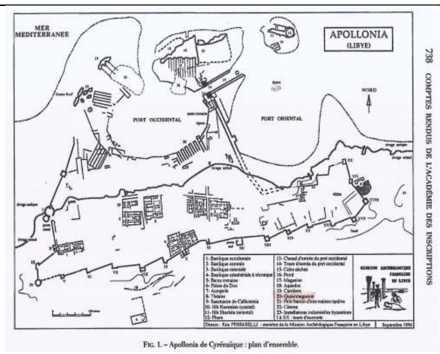
The ‘quays’ are under the sea, right behind the columns, Pic. by Misson, 60's

Pic. by AeroContractors , early 60's



Map of Apollonia, showing the underwater ruins discovered in 1958-59 by N. Flemming’s team.

Dwg. by N.Wood , first published in 1959



Dwg. by MAF 1996, Published by Laronde, 2001

The first map was drawn by Nic Flemming on the basis of original drawings by the architect Nick Wood, a member of the diving team led by Nic Flemming, back in the late fifties. It can be found in the Geographical Magazine for 1959 and 1960. It was redrawn for publication in the book “Cities in the Sea” 1971 and we provide a clean HD copy here. It is still considered as an accurate reference.

‘Nine Quays’:

These ‘quays’ are located in square E9 of Flemming’s map.
I choose to write ‘quays’ with inverted commas because the initial purpose of these structures is not agreed by all parties at this time. To put it in a few words, some believe these structures are quays for loading/unloading small oared battle ships, some believe they are warehouses. Let’s try to present the available information here.

Quoting Nic Flemming (1971):
“The ‘quays’ are not closely similar to any structure in other harbours, either ancient or modern, but can only have been used for the berthing of slender ships, either civil or military. […] the spacing of the ‘quays’ is only 3.5 m. Whether this is the maximum beam of the largest vessel, or whether only smaller vessels were berthed at the ‘quays’, is not certain. The docks between the ‘quays’ are 25 m long, and if the ships were this length they would have had a length-to-beam ratio of 7:1, which is high for a cargo boat, but very likely for a fast boat built more to be rowed than to carry a large sail area. From the rough rule that a

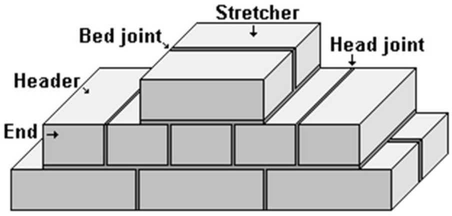
stable rowing boat draws one third of its beam, these boats would have drawn about 1 m. The top courses of stone on the 'quays' are complete in several cases, with the upper surface only 2 m wide, surprisingly narrow. It would have been impracticable to handle large cargoes in such a small area, and in any case, the heavy cargo ships of the second century BC and later had a beam of 10 m, though they were usually only 30 m long. Thus, if the 'quays' are of late date, they can only have been used for harbour lighters and local coastal boats and fishing boats, but if they were of early construction they may have been used for oar-powered military and light cargo vessels. Possibly both suggestions are partly correct, and as time went by, the docks which had once been suitable for the mightiest ships afloat were relegated to the status of a fish market much as the Vieux Port of Marseille is now restricted to fisherman and pleasure boats, while ocean-going cargo ships dock in the modern harbour outside."

Quoting Baika (2013):
"Flemming investigated nine rectangular structures spaced 3.5 m apart and 2 m wide, identified as 'quays'. The docks between the 'quays' were 25 m long. The 'quays' are constructed of ashlar masonry and the top courses are complete in several cases, with the upper surface 2 m below the water. If the identification is correct, they are too narrow to accommodate big commercial ships of any period. According to Flemming, because of their 'exceptional breadth and solidity, they may have been used as 'quays' for small merchant vessels'. These installations were surveyed recently by the French mission, which concluded that they are warehouses, and excluded the possibility that they could be used as docks."

Quoting Sintès (early 2014), diver, member of the Mission Archéologique Française (MAF):
"Pour les structures dont vous parlez, effectivement, la mission Laronde avait repris à l'origine l'hypothèse de N. Flemming, ce qui nous a amené à écrire et à parler de "docks" ou de "darses" dans les premières publications. Mais depuis, nos plongées ont prouvé que ces murs sont posés sur le sol rocheux et qu'il n'y a aucun espace entre eux permettant d'accréditer l'hypothèse de darses en eau pour petit bateaux. Cela a été vu à la suite de dégagements à la suceuse et seuls 30 à 50 centimètres de vases et sédiments se trouvent au-dessus de ce socle rocheux, présent absolument partout, en très légère pente douce de la mer vers la rive. C'est donc de magasins, ou de stockage particuliers (mâts ? barques tirées à terre ?) dont nous parlons maintenant."

This last statement was confirmed by Claude Sintès (personal communication, 24/10/2014): two trenches were dredged with an airlift (underwater vacuum cleaner) across all of the nine docks; one trench was close to the tip of the 'quays' and the other was closer to the shore; both trenches were dredged to reach the bedrock level. The result was that the sand layer thickness that could be removed was never more than a few decimetres; it was found also that the bedrock was gently sloping from the shore down to the tip of the 'quays' by no more than 0.50 m over a distance of about 20 to 25 m.

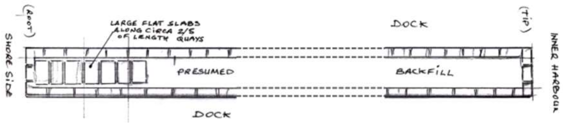
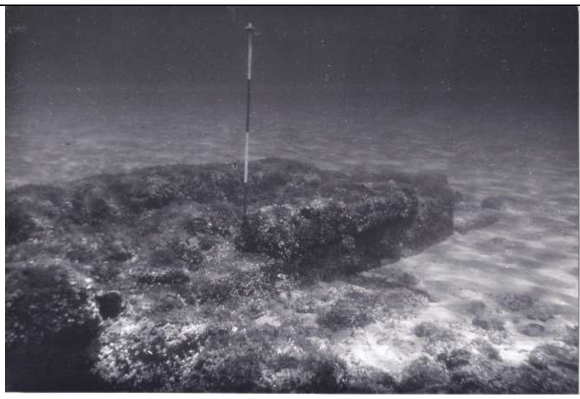
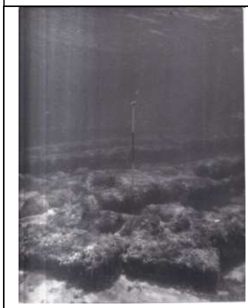
But if warehouses existed at this place, where are the remains of their roofs (tiles) and of their side walls?



We should note also that according to William Murray (personal communication 10/4/2014):

“quays that are exposed to waves tend to use headers rather than stretchers for the walls exposed to sea action. A long rectangular structure with nothing but headers in the foundation courses would seem to indicate you had a quay instead of a warehouse. […] Your structures seem to have been built in quieter water and thus could have used stretchers.”

The pictures below show some details of the 'quays' which are numbered from 1 to 10 starting on the west side. Hence, 'quays' 2 to 9 are free standing, while 'quay' 1 and 'quay' 10 are leaning against land. It is noteworthy that no back wall was found, i.e., the docks between the 'quays' end on the beach.

	Layout of a typical ‘quay’, Sketch by Misson, 2014
 Between ‘quay’ 2 (right) & 3 (left), the dock is heavily sanded up and blocks from the top perimeter layer have fallen off. Pic. looking south, by Misson, 1965	 Tip of ‘quay’ 2. Scale stick with 20 cm sections. Pic. from inside dock 2, by Misson, 1965
 Tip of ‘quay’ 2. In the background: ‘quay’ 3 & ‘quay’ 4 (barely visible). Pic. by Misson. 1965	 Tip of ‘quay’ 2. Pic. by Misson, 2012

 Inside of 'quay' 4 about halfway through its length The inside of 'quay' 4 looks empty because the (light) backfill has been swept away or has disintegrated; the bedrock is not visible and as much as 3 layers of superimposed blocks can be seen (each circa 18-20 cm thick). Pic. looking south, by Misson, 2012	 Inside of 'quay' 4, closer to shore, the series of heavy slabs can be seen in the background, top blocks of 'quay' are still in original position on the right, those on the left have fallen off, the heavy slabs in the centre are found on all 'quays', but only along circa 40% of their length, from the shore side. Pic. looking south, by Misson, 2012
	External side of a 'quay' (from inside a dock) after the winter storms had had a de-silting effect, the bedrock is not yet visible but 4 layers of blocks are visible, the total height of this 'quay' above the bedrock would be 4 x 18 to 20 cm = 72 to 80 cm. Pic. by Misson, 1965

Interpretation by JP Misson

"*In Libya, at the time, there were practically no roads inland: the communications were mainly by sea with the major settlements located along the coast. The Libyan coast is rather unprotected: practically no island where to shelter and several stretches of rocky shore where the beaching of a fragile galley is impossible. The oared vessels that were used for the task had to be slim and light to be fast. This was the only way to cover the non-beachable stretches of coast on a day's duration. It was extremely rare for galleys to navigate after sunset. The galleys were undecked and had a very small draught when empty of their crew. This is what allowed their crews to beach them when needed and where possible.*

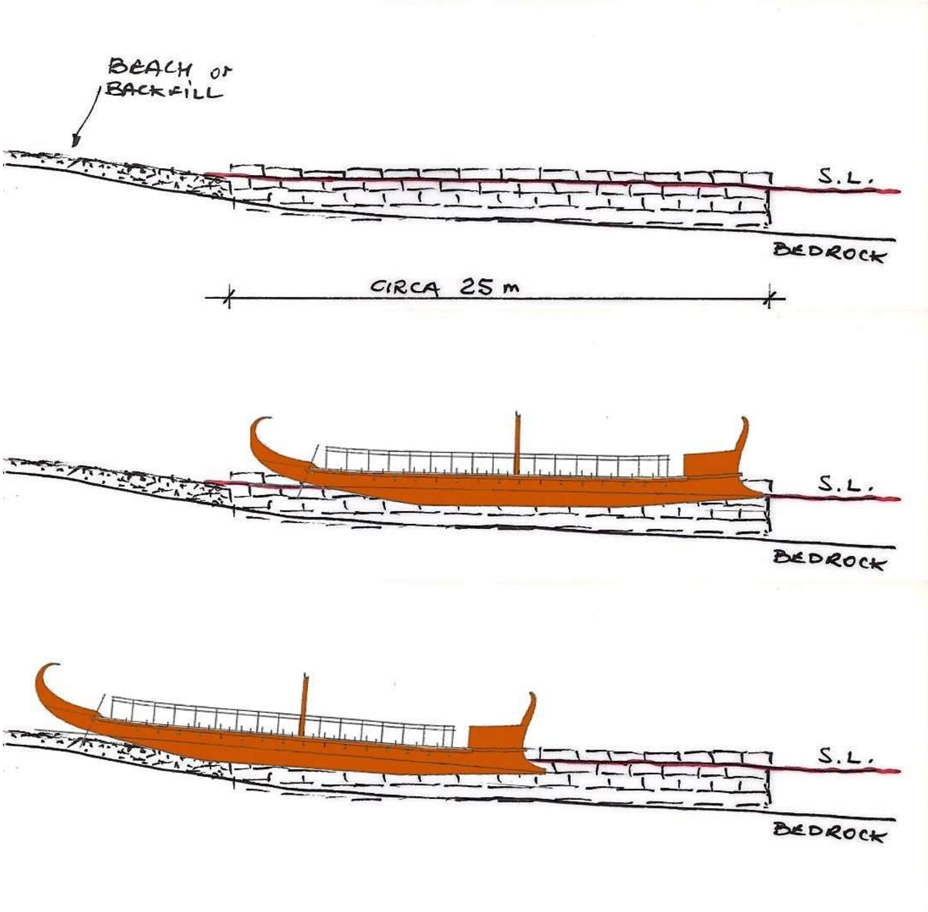
In the Inner Harbour of Apollonia, the simultaneous beaching or launching of several galleys (especially in windy conditions) would not have been easy. The 'quays' may have been built for the dockers in charge of hauling the galleys in and out of the water to stand on a hard surface (not in sand) and for crews to embark and disembark in an orderly way. If the 'quays' were only needed for the crews to walk on firm ground the 'quays' could have been just awash (flush with sea level). If the ships were galleys with practically no cargo except crew, food and water; all easy loading and unloading: no need for a particularly 'dry' quay. In any case (prior to the subsidence) the inner harbour must have been a calm water area, much better protected from the open sea than today.

The 'quays' were used as mere 'walkways' to enable the people in charge of manoeuvring the galleys to work under dry conditions and for the crew to board or disembark at ease. Executing the launching or beaching operations with people breast-deep in the water would have required a lot more people if not been altogether impossible when several crafts had to be handled simultaneously. The galleys were moved from/into the water to/from the dry land behind. This was the practice in those times for the small and light galleys. Galleys of this size (20-30 m) could be beached by their only crew, during a voyage (where beach slope made it possible) to rest and resupply. With the 'quays' in Apollonia these operations were made easier and faster. Assuming that there were many more galleys on the beach behind the docks, the simultaneous launching or beaching of 9 galleys at a time must have been possible at Apollonia. The galleys were probably kept in-between the 'quays' for a limited amount of time: beaching or launching operations with corresponding unloading or loading. They were probably never 'berthed' there. Without a back wall, the galleys could be hauled on the beach, to be parked somewhere on the terrain south of the 'quays'. The 'quays' could therefore be called 'hauling quays'.

The docks in-between the 'quays' must have therefore been a good 70 to 80 cm deep. Galleys 20-30m in length would surely have been easily floated and handled in these docks as their draught was very limited, surely much less than one meter.

Moreover, it would not have mattered had the keel of the galleys touched the seabed in the docks even halfway through their length: there would have been sufficient 'quay' length on each side to conduct any operation such as hauling, loading and unloading of the vessels. With a depth of as little as 50 cm at shore end, the docks would have been useable.

As for the top layer on the perimeter of the 'quays', seemingly above the level of the heavy slabs at the root of each quay: it could well be a raising of the structures after it appeared that the bedrock on which they were standing had started to subside. The space between the additional layer of blocks might have been simply backfilled on top of the initial slabs, and this backfill vanished with later wave action."



A Greek triaconter (2 x 15 rowers) was around 20 m long with a 3 m beam and had a draught around 0.5 m (Casson, 1995). It could thus fit the 3.5 m docks between the Apollonia 'quays'. It could be unloaded quickly and then be hauled on the beach further south where room was available for many ships.

This interpretation by Jean-Pierre Misson makes good sense from a pragmatic point of view, but it is hypothetical and would obviously need to be confirmed by more field investigations, as …

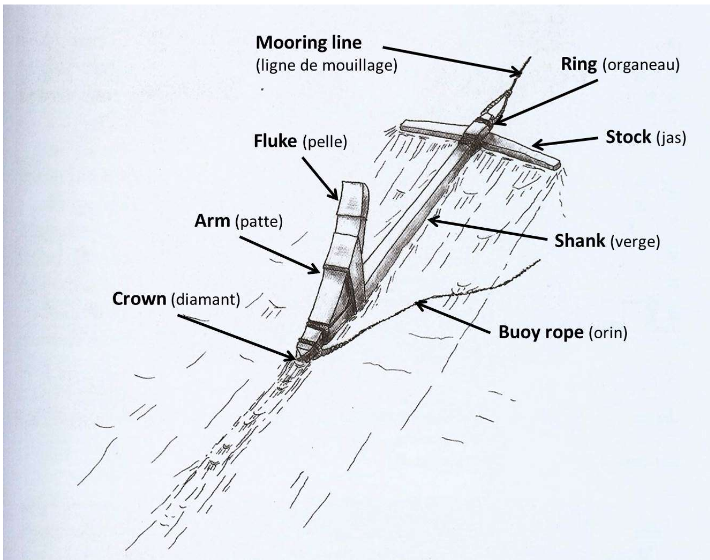
Such an arrangement is unheard of in any other ancient port.

… or do we have a similar construction at Punta Sottile, near Trieste??

(see: http://www2.units.it/adriatic/files/Terre%20di%20mare%202012.pdf , p 138)

For further information on beaching ancient ships, see Gregg Votruba, 2017, "Did Vessels Beach in the Ancient Mediterranean? An assessment of the textual and visual evidence", The Mariner's Mirror, Vol 103:1, (p 7-29).

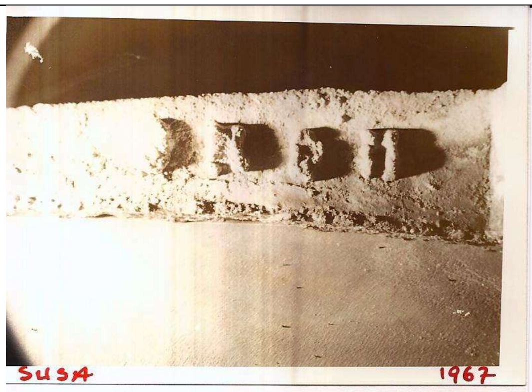
Knucklebones on a lead anchor stock:



Functioning of a wooden anchor with lead stock

Let's quote Harry R. Neilson's abstract of a paper about "Aphrodite (Venus) Euploia on Greek and Roman lead anchor stocks" (2009):

"To date, over one thousand Greek and Roman lead anchor stocks have come to light from the depths of the Mediterranean Sea. Of these, over one hundred are decorated with reliefs. The majority of these decorations comprise symbols relating to Aphrodite (Venus) Euploia. The presence of these symbols demonstrates a close connection with the sea-going manifestation of the goddess whom ancient mariners venerated as a protectress of navigation. An anchor stock recently discovered off western Sicily displays the epithet, Eiinkotu. Four stocks display dolphins and sea shells, well-known attributes relating to Aphrodite's birth from the sea. Most significantly, over seventy stocks display images of astralogoi (knucklebones) which relate to the high scoring "Venus throw" in the game of chance popular in antiquity.
Through an analysis of the inscription, the attributes, and the astralogoi, this paper illustrates that, in addition to her general association with ships and ports, mariners specifically relied upon Aphrodite Euploia while anchoring. The large number of anchor stocks with astralogoi reveals the superstitious nature of sailors who equated the precarious manoeuvre of dropping and setting the anchor with a "dice throw," betting that Aphrodite Euploia would guide the anchor to security and hold the ship fast.
Furthermore, that Greek and Roman ships carried on board as many as eleven anchors is a testament to how ancient mariners attempted to beat the odds while anchoring."

	
Lead anchor stock in situ in Apollonia. Pic. by Misson, 1967	Astralogoi on the Apollonia anchor stock. Pic. by Misson, 1967

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See also his film on the 1958-59 expedition to Apollonia.

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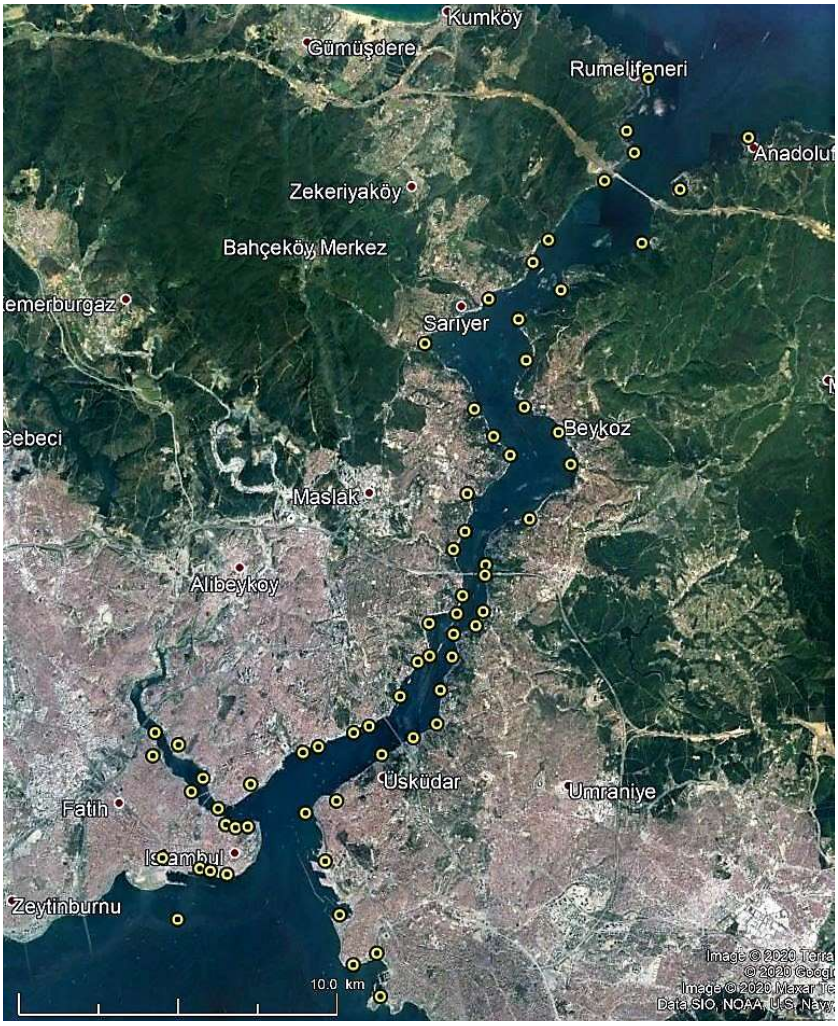
2.5 BOSPHORUS

67 ancient ports have so far been identified on both sides of the Bosphorus (see Vol. I, "The Catalogue"), but our aim in this section is to study the process of infilling of the Black Sea that took place around 8400 ^{14}C years BP (possibly around 6800 calendar years BC) (Wikipedia).



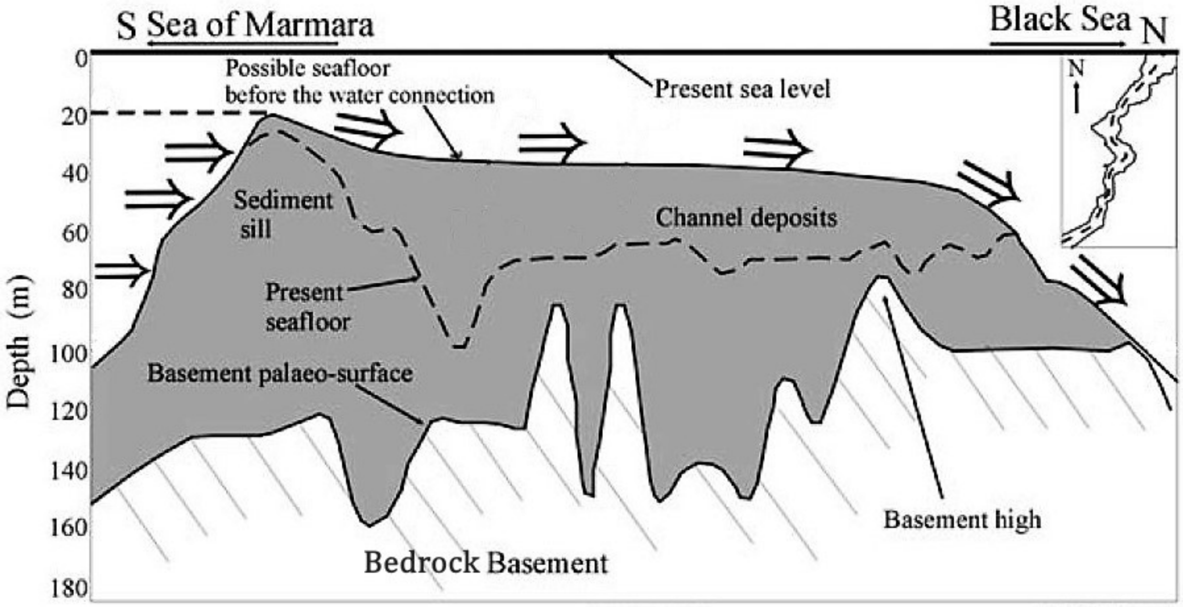
The Bosphorus with 67 ancient ports.

The Bosphorus is the northern part of the connection between the Mediterranean Sea and the Black Sea. It consists of a canyon 31 km long and around 3000 m wide at both entrances, but its narrowest section is only 700 m wide. One might distinguish a narrow part 24 km long and around 1 km wide between Dolmabatçe Palace near Istanbul and Yavuz Sultan Selim bridge at the northern end, even if that is quite a rough schematisation. The water depth varies between 13 and 110 m. As a matter of fact, the whole stream behaves much like a river with several curves and lateral deep and shallow areas. The bottom consists of alluvial sediment over a thickness ranging from 10 to 100 m on top of a bedrock basement[3].
Considerable volumes of water are exchanged through the Bosphorus between both adjacent seas. Inflow of salty water from the Mediterranean Sea into Black Sea (ca. 11 000 m^3/s or 350 km^3/year) flows underneath a less salty water outflow from the Black Sea into the Mediterranean Sea (ca. 16 000 m^3/s or 500 km^3/year). As can be expected, the outflow

[3] ALGAN, O., et al., 2001, "Stratigraphy of the sediment infill in Bosphorus Strait: water exchange between the Black and Mediterranean Seas during the last glacial-Holocene", Geo-Marine Letters 20(4), (p 209-218).

equals the inflow + discharge of rivers (Danube, Dnieper, Don) + rainfall - evaporation. The figures given above are obviously averaged[4].

It is accepted that the Black Sea was once a fresh-water lake disconnected from the Mediterranean Sea by a sediment sill in the Bosphorus located around -36 m below present sea level (deepest spot of the shallowest cross-section in the present Bosphorus, located in front of Dolmabahçe Palace).



Bosphorus sill gradually overflowed by global Sea Level Rise in the Mediterranean Sea
(Gökasan, et al. 2005[5])

This configuration existed until around 7000 BC when, due to global eustatic Sea Level Rise (SLR), Mediterranean water started to flow over the sediment sill into the Bosphorus and Black Sea-lake. The somewhat controversial questions are: how deep was the lake water level at that time, and how fast did the water level rise? Even if the lake water level was much deeper than the Bosphorus sill, e.g., -80 to -100 m acc. to Yanchilina (2017)[6], flooding must have been rather progressive because, at that time, global SLR was around 14 mm/year (see section on “Sea Level Rise”) … unless the sill in the Bosphorus collapsed, or was massively eroded.

In any case, scholars agree on the fact that after reconnection with the Mediterranean Sea, the Black Sea water level more or less followed the global eustatic SLR. This means that

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[4] GREGG, M., & Özsoy, E., 2002, “Flow, water mass changes, and hydraulics in the Bosphorus”, J. Geophys. Res., Vol. 107, DOI 10.1029/2000JC000485, (23 p).
Note that today's salinity of deep Black Sea waters (below 200 m depth) is still no more than 22 psu compared to 34 psu for Med waters (psu: Practical Salinity Unit, or g/kg). This means that some mixing between fresh surface waters and deeper waters occurs, yielding a stable 22 psu deep salinity and 17 psu surface salinity. Caricaturing, it is not 0 psu at the surface and 34 psu at the bottom, but resp. 17 and 22.

[5] GÖKASAN, E., et al., 2005, “Evidence and implications of massive erosion along the Strait of Istanbul (Bosphorus)”, Geo-Mar. Lett. 25, (p 324–342), DOI 10.1007/s00367-005-0216-3.

[6] YANCHILINA, A., et al., 2017, “Compilation of geophysical, geochronological, and geochemical evidence indicates a rapid Mediterranean-derived submergence of the Black Sea's shelf and subsequent substantial salinification in the early Holocene”, Marine Geology, 383 (2017), (p 14-34).
See also a nice summary of this controversy by:
YANKO-HOMBACH, V., et al., 2011, “Was the Black Sea Catastrophically Flooded during the Holocene? – geological evidence and archaeological impacts”, in “Submerged Prehistory”, ed. J. Benjamin, et al., Oxford Books, 2011, (p 245-262), concluding that "there is no underwater archaeological evidence to support any catastrophic submergence of prehistoric Black Sea settlements during the Late Pleistocene or Early Holocene intervals".

Neolithic and Bronze Age settlements were not affected by the controversy about the Black Sea water levels, i.e., Neolithic settlements dated around 6000-3000 BC might be found at less than 15 m depth below the present sea level.

Let's get back to the question of how fast the Black Sea water level rose by means of some hydraulic computations with a time-step of one year. We have a formula for the water discharge over a sill as a function of the upstream water level (WL). With this, we can compute the flow velocity inside the schematised Bosphorus. With this velocity, we can compute the volume of sediment transported by the flow as a function of the sediment grain-size. This leads to a rate of erosion of the bottom of the Bosphorus. This in turn gives a new bottom position for the computations to be done for the next year, and so on, until the water level in the Black Sea reaches the Global WL. Obviously, this is a simple approach with rough schematisations and several assumptions for which we will have to perform a sensitivity analysis. However, this approach will show the hydrodynamics and may give an order of magnitude of the water level rising speed in the Black Sea.

Computation details:

Computations were performed on a simple Excel spreadsheet, with one year per line. The input parameters are:

- Sill crest-level at the beginning of overflowing (set to -36 m below present sea level),
- Water level in the Black Sea at the beginning of overflowing (set to -90 m below present sea level),
- Rate of Global Sea Level Rise (set to 14 mm/year),
- Sediment grain-size on the crest of the sill and the bottom of the Bosphorus (D_{50}, median diameter, set to 20 mm),
- Density of sediment grain-size on the crest of the sill and the bottom of the Bosphorus (Delta, set to 1.65, as for common stone),
- Bosphorus schematised to a prismatic section (width of 1 km, length of 24 km).

The upstream water level at the sill is the Global WL which starts to overflow the sill in year 1. The initial discharge is obviously very small as the water sheet on top of the sill is only 14 mm. Therefore, the flow velocity inside the Bosphorus is too small to induce any erosion. But after a number of years, erosion starts, and processes accelerate drastically, e.g., the water sheet on the crest of the sill reaches several meters. After some more years, the water level in the Black Sea reaches the Global WL and the infilling process terminates.

Formulation[7]:

H: water depth on sill: WL at sill – sill-level (including erosion of previous year) (m)

Q: discharge over sill with sill formula: $Q = 1.5\ b\ H^{1.5}$ with $Q = V\ b$ (m^3/s)

V: flow velocity on sill (m/s)

b: constant sill width and Bosphorus width (m)

C: Chézy friction coefficient: $C = 18\ \mathrm{Log}\ (12\ H/D_{50})$ ($m^{1/2}/s$)

i: slope of water surface deduced from Chézy formula: $i = (V/C)^2/H$ (-)

Vo: flow velocity at initiation of movement of sediment with D_{50} and Delta:

$$Vo = 0.2\ C\ \mathrm{sqrt}(\mathrm{Delta}\ D_{50}) \quad (m/s)$$

Delta : relative density of sediment (e.g., 1.65 for granite) (-)

[7] All hydraulic formulae used in this section are well known to river hydraulicians, the Meyer-Peter sediment discharge formula is to be found in:
COUVERT, B., et al., 1999, "La gestion des rivières, Transport solide et atterrissements", Les études des agences de l'eau, N° 65.

D_{50}: median diameter of sediment (m)

Qo: discharge at initiation of sediment movement: = Vo b H (m^3/s)

Qs: sediment discharge acc. to Meyer-Peter formula: $Qs = 0.91\ i^{7/6} [1 - (Qo/Q)^{3/8}]\ Q$ (m^3/s)

Erosion: yearly eroded layer in schematised Bosphorus (m/year)

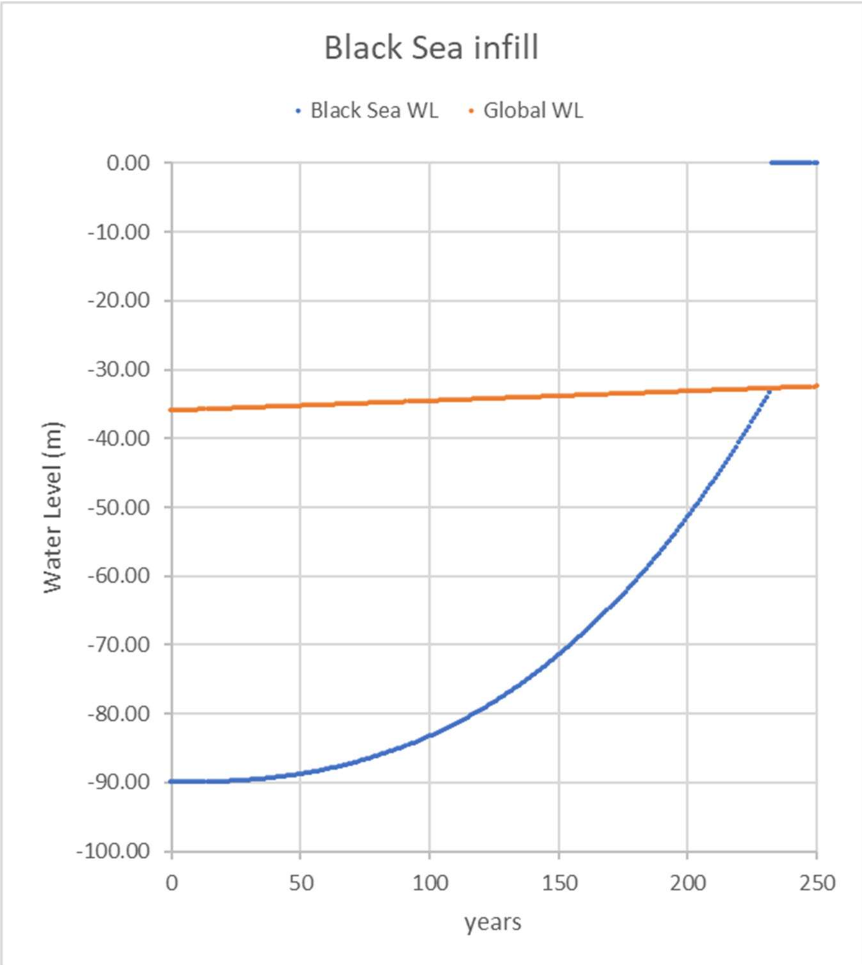
Yearly discharge of water over sill (km^3/year)

Cumulated volume of infill water (km^3 = 1000 Million m^3)

Cumulated volume of erosion (Million m^3)

Computation results:

As explained above, the Global WL increases each year and so does the discharge over the sill. After some time (around one century), erosion of the crest of the sill and of the bottom of the Bosphorus starts. This accelerates the processes and after some more time (another century), the Black Sea water level reaches the Global WL.



Black Sea water level during infill process.

With the parameter settings given above, the detailed computation results are as follows:

- No erosion occurs during the first 128 years.
- The Black Sea is completely filled when its WL reaches the Global WL of that time, that is after: 232 years, with sediment D_{50} = 20 mm.

- At that time, cumulated erosion in the Bosphorus is: 218 Mm^3, which is close to the 200 Mm^3 estimated by Gökasan et al. (2005) and Lericolais et al. (2019)[8].
- The infill process is thus quite progressive: The Black Sea WL rising speed is never larger than 1 m/year. Hence, no catastrophic deluge.

These results are valid for the above-mentioned parameter settings only. Some of the parameter values are rather uncertain and it is therefore required to check the sensitivity to parameter variations.

Sensitivity analysis

Parameters				Results		
Sediment D_{50} (mm)	Sediment Delta	Sill width (m)	Bosphorus length (km)	BS WL = Global WL after: (y)	Cumulated erosion Mm^3	BS WL rising speed (m/y)
20	1.65	1000	24	232	218	0.63
5	"	"	"	225	701	0.66
25	"	"	"	234	119	0.63
20	1.65	1000	24	232	218	0.63
"	1.5	"	"	231	292	0.64
20	1.65	1000	24	232	218	0.63
"	"	750	"	260	277	0.57
"	"	500	"	305	358	0.50
20	1.65	1000	24	232	218	0.63
"	"	"	11	227	235	0.70
"	"	"	30	233	217	0.63

Hence,

- Reducing sediment D_{50} leads to a large increase of the eroded volume and it would be really useful to find more information on the sediment characteristics on the bottom of the Bosphorus,
- Reducing sediment Delta (e.g., changing from granite to limestone) leads to an increased eroded volume,
- Reducing the Bosphorus width leads to an increased eroded volume,
- Changing the Bosphorus length leads to small changes in results.

Conclusion:

This simple hydraulic computation with a sill at -36 m shows that a 14 mm/year global sea level rise would induce a rise of the Black Sea level (from -90 m to -36 m) within around 200-300 years, inducing a gradually increasing water level rise in the Black Sea never exceeding 1 m/year. This is fast, but it is not a catastrophic flood. The « deluge hypothesis » could therefore only be explained by a sudden collapse of (a part of) the Bosphorus sill, perhaps during an earthquake, but there is no archaeological evidence (yet) for this.

[8] LERICOLAIS G, at al., 2019, "Overview of the Bosphorus Depositional Fan from Data Sets Recovered on the Black Sea Shelf off the Strait of Istanbul". Int J Environ Sci Nat Res. 2019; 17(1): 555959, DOI: 10.19080/IJESNR.2019.17.555959. 016.

2.6 CAESAREA MARITIMA

Caesarea Maritima, or Sebastos in Greek, features one of the most extensive ancient port ruins still visible today. It was built by King Herod between 21 and 10 BC, more than half a century before Rome's Portus, but later than Agrippa's naval base of Portus Iulius, near Pozzuoli, in 37 BC. It features the most advanced Roman building techniques ever found by archaeology for coastal structures.

Caesarea aerial photo (https://web.uvic.ca/~jpoleson/ROMACONS/Caesarea2005.htm).

Excavations have been conducted on land and under water for several decades at the end of the 20th c. and much has been said on this famous ancient port. Too much perhaps, and it may be useful here to list a few synthetic publications:

- NAVIS II, 2002, providing a synthetic description of the port structures,
- Raban, 2009, providing a complete description of the port structures,
- Raban, 1996, on the inner harbour,
- Oleson et al., 2014, Romacons Project on Roman concrete blocks,
- Galili et al., 2021, on subsidence of the port structures.

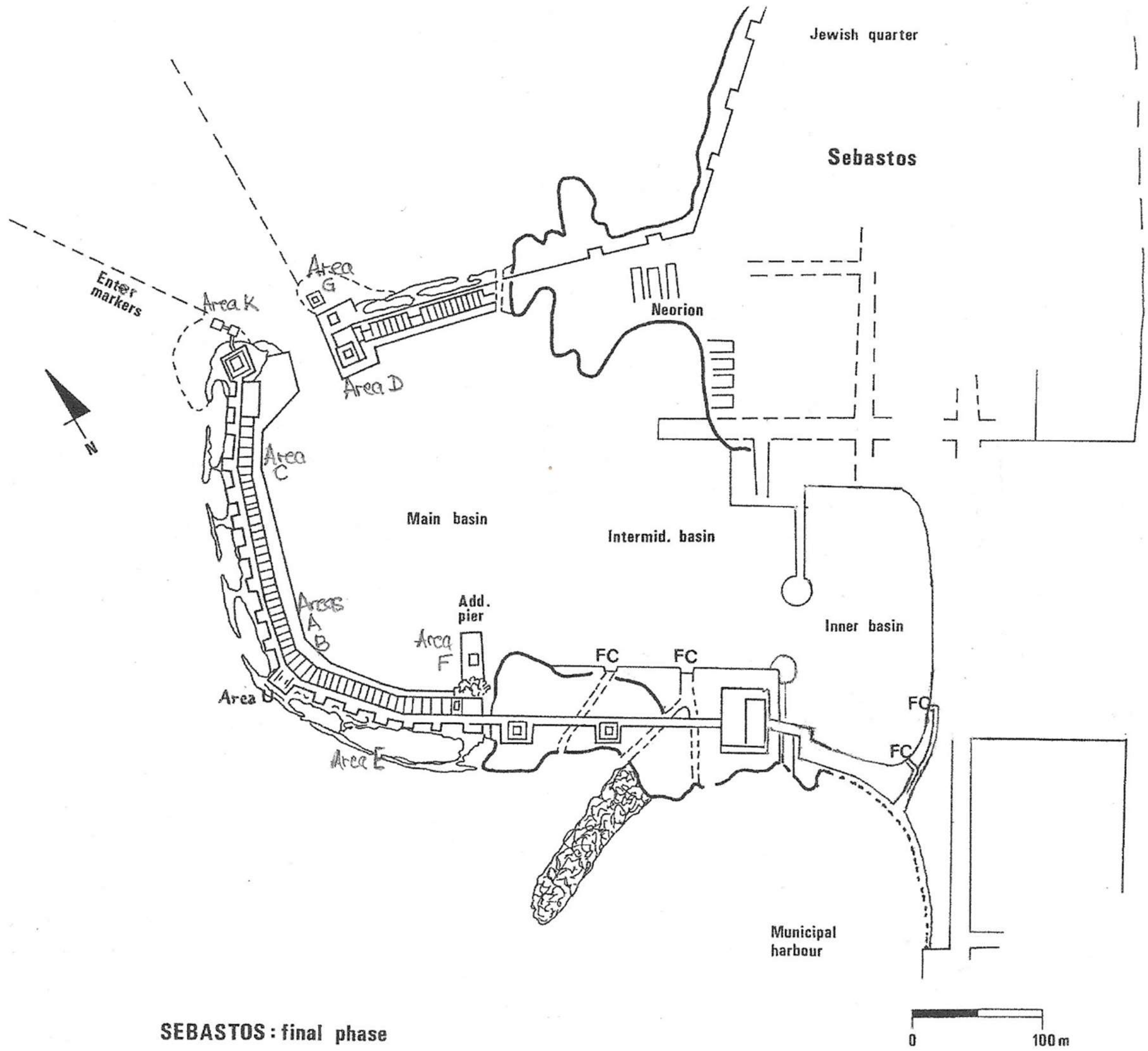


Figure 5.69. A suggested sketch plan of Sebastos at its final phase of construction (A. Raban, Caesarea Project)

Hypothetical layout of Sebastos harbour (adapted from Raban, 2009, p 121).

Three harbour areas are usually distinguished:

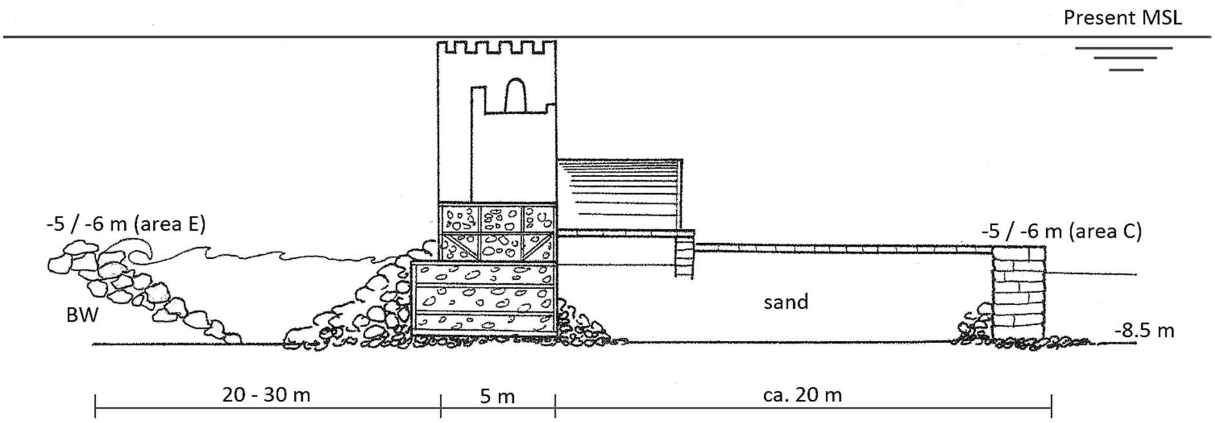
- **Inner harbour**, eastern basin, now inland, probable location of the pre-Herodian Stratonos Pyrgos limen kleistos closable harbour.
- **Middle harbour**, central basin, intermediate basin, built by Herod, with possible shipsheds ("Neorion") and flushing canals ("FC"), also used by crusaders, and still partly used today by small boats sheltering north of the southern breakwater.
- **Outer harbour**, western basin, main basin, built by Herod, now submerged, with a 30-50 m wide (closable?) entrance and a probable lighthouse (Drusion).

For the sake of simplicity, let's assume that the eustatic sea level change was no more than 0.5 m since Roman times (Yasur-Landau, 2021).

We shall not go into a detailed description of the harbours here, as this can be found in the references mentioned above. We would like to select a few aspects that need further explanation and present a few sketches of the breakwater structure.

2.6.1 Prokumia (outer breakwater)

The cross section below is adapted from Raban (2009, p 96) in order to include some measures which are obviously quite approximate. The outer breakwater “BW” was excavated in area E on the southern breakwater and the inner quay was excavated in area C at the northern part of the western breakwater (see harbour layout above). This cross-section is therefore a hypothetical reconstruction of the whole western and southern breakwater structure.



Cross-section of the main breakwater (adapted from Raban, 2009:96).

All vertical levels are related to the present Mean Sea Level (MSL). It is usually said that subsidence of the whole outer harbour amounts to 5-6 m since Roman times.

The ancient seabed was found in several places in the outer harbour at ca. -8.5 m below present MSL, and the top of the inner quay wall at was around -6 m. The centre line (“spinal line”) of the western breakwater was found to consist of large concrete blocks. Oleson (2014) measured them to be 4.7 x 3.6 m and 1.7 m high, near area E, but they seem to be present over a distance of 165 m between areas A-B and C. These blocks were placed one to several meters from each other, with rubble placed in-between them and as shoulders on both sides of them. The area between the spinal line and the quay wall was filled with sand and covered by large ashlar slabs (1.8 x 0.7 x 0.6 m).
On the sea side of the spinal line, an outer breakwater (“BW”) was found at 20-30 m of the main breakwater, possibly corresponding to the “prokumia” (wave breaker) mentioned by Josephus Flavius (Jewish War, 1, 21 (or 412) & Jewish Antiquities, 15, 9 (or 334)). The excavators found its crest at around -5 m below present MSL and its total height was estimated to 2-3 m, which leads to its base being located around the same -8.5 m as for the inner quay wall.
In addition, the excavators found one “large concrete block” in area E and conjectured that it may have been part of the prokumia which would thus be a dashed line made of concrete blocks with rubble in-between and running over the whole sea side length of the western and southern breakwaters (Raban, 2009, p 104).

Let’s now raise this structure by ca. 6 m and consider it with modern engineering eyes.
It may be said first that the concept of a double-line breakwater is used quite seldomly today because of its cost. It may be justified in cases where a low crested structure providing an open view to the sea is required in an area with a severe wave climate. It was recently used at the Beirut Central District land reclamation with an outer breakwater consisting of a wide

rubble berm and a main breakwater consisting of vertical concrete wave-absorbing caissons. Modern engineers use the concept of design wave to design breakwaters and other maritime structures. The design wave in Beirut and on a large part of the Levantine coasts is Hs = 9 m ("Significant wave height" of a "one in hundred years" storm) which is among the highest in the Mediterranean Sea. These large storms come from the west and NW. Fortunately, when travelling from offshore to the coast, such large waves break when reaching shallow waters and it may be accepted that no wave larger than ca. 5 m would reach the outer breakwater which was located on a ca. 8.5 m water depth and slightly emerging above the Roman sea level. Storms with Hs = 5 m occur once a year, as an average, in the Levantine area. Depending on the stone size, breakwater failure would occur during these repeated storms and the rubble mound breakwater would flatten out on the seabed, but the concrete blocks would resist, except for scouring and undermining.

2.6.2 Subsidence in the outer harbour

The top of five large Roman concrete blocks on the western breakwater (area K) is now at -2.5 to -3.5 m below the present Mean Sea Level (MSL) (Oleson, 2014, p 275-279). The "sunken floor" (Raban's area F) on the SE side of the outer port, 50 m west of the head of the modern southern breakwater, is now at 5 m below MSL (Raban, 2009, p 110). If these levels were raised **6 m,** the sunken floor would be at +1 m in ancient times and the breakwaters would culminate at +3 m, which both make good sense, respectively as a harbour platform and as a harbour protection structure. Similarly, in the middle harbour, a quay wall is now at -0.6 m below MSL ("LW" in Raban, 2009, p 193) and should be raised about **1 m** to be operational. These observations led many scholars to assume **tectonic movement** (in addition to limited 0.50 m eustatic sea level rise) that would rely upon a north-south fault that would be located on the limit between the middle harbour and the outer harbour (Raban, 2009, p 198).
This is challenged by Galili (2021) who provides several other possible explanations for such a subsidence and argues against any tectonic movement of the Caesarea coast.

It has been shown in our section on "Subsidence" that **wave-induced local scour** of the sandy bed in front of the main breakwater would undermine the offshore toe of the main breakwater rubble and large concrete blocks, possibly causing some tumbling of the large concrete blocks towards the sea, but not a uniform subsidence of the whole structure.

A 40-cm thick layer of rounded cobbles (up to 35 cm diameter) was found underneath one large concrete block of the Caesarea western breakwater (Raban's area CO, close to his area U, Votruba, 2007 and Oleson, 2014, p 79). This foundation layer is supposed to avoid **piping and undermining**, but it does not respect modern requirements for granular filters and would allow a strong flow within the layer. However, in this specific case of Caesarea, this flow is considerably reduced by the presence of the ca. 20 m stretch of sand filling between the large concrete blocks and the inner quay wall. Hence, undermining of the whole structure is not possible in this case.

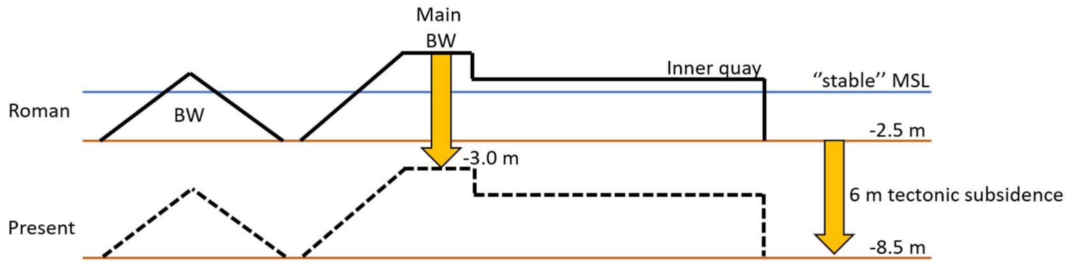
Repeated storms have been put forward as a possible explanation for the breakwater subsidence due to **wave-induced liquefaction**. As explained in our section on "Subsidence" this would induce a larger subsidence at the outer side than at the inner side of the breakwater and tumbling of large concrete blocks towards the offshore side would be observed rather than a uniform vertical subsidence.

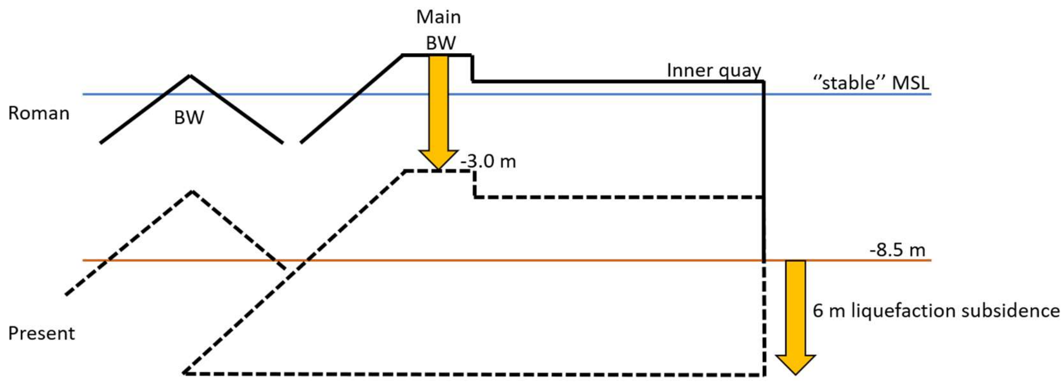
Other explanations include **earthquakes** inducing tsunamis and/or liquefaction of the sandy seabed of the whole outer harbour. Many earthquakes were felt in Antioch, Cyprus, Egypt and other places in the Levant (around 25 are known in the first 500 years AD) and may have affected Caesarea (Goodman-Tchernov, 2015).
It is acknowledged that not every **tsunami** is a devastating monster with a massive hydraulic power of destruction like the ones we have witnessed around the world in the 21st century, but the 365 AD tsunami might be one of them. It is also acknowledged that not every earthquake will induce a tsunami, but it might be accepted that out of the 25 earthquakes mentioned above, several (5-10?) tsunamis may have reached Caesarea during that period. At least four are known from ancient authors: one in 115 AD, one in 551 AD, one in 749 AD and another in 881 AD. However, smaller tsunamis may have occurred without leaving any trace in ancient literature, but adding to the gradual breakwater destruction.
Tsunamis would possibly push large blocks of Roman concrete placed on top of the breakwater into the port, rather than generating a uniform vertical subsidence.

Another possible explanation for subsidence of the western and southern breakwaters might be found in **compaction** of the sub-soil underneath these structures, because the initial seabed consisted of loosely packed sand provided by longshore transport of Nilotic sediment (Zviely, 2007). Furthermore, vibrations due to wave action and to seismic action, induced additional compaction of the sub-soil. Depending on the thickness of the sand layer, compaction could possibly amount to a few meters.
In addition, **consolidation** might occur if a layer of clayey materials was found underneath the surface layer of sand. Depending on the thickness of that layer, consolidation could possibly add a few more meters of subsidence.
Obviously, more detailed geotechnical data is badly missed here (Shtienberg, 2016 for Hadera, Galili, 1993 for Atlit-Yam).

Earthquake-generated liquefaction as explained in our section on “Subsidence”, would be a convenient explanation as it is likely to affect a large area covered with cohesionless water-saturated sand in the outer harbour, and liquefaction would not affect the rocky seabed of the middle harbour. Longshore transport of Nilotic sediment provides this kind of liquefiable sand in the nearshore area down to a water depth of ca. 10 m (Zviely, 2007).

At the end of this overview, it can be seen that local phenomena (local scour, piping and undermining, local liquefaction, and even tsunamis) may have initiated limited destruction of port structures, but do not suffice to explain the observed overall subsidence of the breakwaters in the outer harbour. Only larger-scale phenomena like tectonic movement or earthquake-generated liquefaction and compaction/consolidation might provide an adequate explanation.





Schematic options for subsidence of the Caesarea main breakwater.

With an assumed tectonic subsidence of 6 m, the outer harbour structures would have been built on a 2.5 m water depth and the western breakwater would be ca. 6 m high from its foundation at -2.5 m to its crest at say +3.5 m. The remains of this are still visible under water today.
With a subsidence due to liquefaction and without any tectonic subsidence, the outer harbour structures would have been built on an 8.5 m water depth and the western breakwater would be ca. 12 m high from its foundation at -8.5 m to its crest at say +3.5 m. The remains of only the top of this structure would be still visible under water today, and a further 6 m of the structure would be buried in the sub-soil underneath.
The second option would be an unprecedented large marine structure in its time, but it would be closer to Josephus Flavius' descriptions mentioning a water depth of 20 fathoms (36 m). Even if this value is probably exaggerated, it surely means "deep water", i.e., more than the 2.5 m water depth of the first option.

According to geologists and to Galili (2021), the tectonic subsidence option is out of the question in this area.

Hence, the earthquake-generated liquefaction option, possibly combined with long-term compaction and consolidation, is the only option remaining at this stage.

Further geotechnical study by means of corings might yield some new insights.

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The following ancient authors mention the port of Caesarea (in chronological order):

ZENON’s papyri (259-255 BC)

ANONYMOUS (2nd-1st c. BC), Stadiasmus, 272

STRABO (ca. 65 BD – 25 AD), Geogr, 16, 2

LUKE (1st c. AD), Acts, 18.22 & 21.8

JOSEPHUS FLAVIUS (37-100 AD), Jewish War, 1, 21 & Jewish Antiquities, 2, 2 & 15, 9

PROCOPIUS (ca. 500-560 AD), Anastasius, 19

2.6.4 Descriptions by Josephus Flavius

Jewish War, 1, 21 (or 410), dated around 78 AD
(transl. W. Whiston, 1737, London)

[…] for the case was this, that all the sea shore between Dora and Joppa, in the middle between which this city is situated, had no good haven, insomuch that every one that sailed from Phenicia for Egypt was obliged to lie in the stormy sea, by reason of the south winds that threatened them; which wind, if it blew but a little fresh, such vast waves are raised, and dash upon the rocks, that upon their retreat the sea is in a great ferment for a long way. But the king, by the expenses he was at, and the liberal disposal of them, overcame nature, and built a haven larger than was the Piraeus [at Athens]; and in the inner retirements of the water, he built other deep stations [for the ships also].
Now although the place where he built was greatly opposite to his purposes, yet did he so fully struggle with that difficulty, that the firmness of his building could not easily be conquered by the sea; and the beauty and ornament of the works were such, as though he had not had any difficulty in the operation: for when he had measured out as large a space as we have before mentioned, he let down stones into twenty fathom water, the greatest part of which were fifty feet in length, and nine in depth, and ten in breadth, and some still larger. But when the haven was filled up to that depth, he enlarged that wall which was thus already extant above the sea, till it was two hundred feet wide; one hundred, of which had buildings before it, in order to break the force of the waves, whence it was called *Procumatia*, or the first breaker of the waves; but the rest of the space was under a stone wall that ran round it. On this wall were very large towers, the principal and most beautiful of which was called *Drusium* from *Drusus*, who was son-in-law to Caesar.
There were also a great number of arches where the mariners dwelt; and all the places before them round about was a large valley, or walk, for a quay [or landing place] to those that came on shore; but the entrance was on the north, because the north wind was there the gentlest of all the winds. At the mouth of the haven were on each side three great Colossi, supported by pillars, where those Colossi that are on your left hand, as you sail into the port, are supported by a solid tower, but those on the right hand are supported by two upright stones joined together, which stones were larger than that tower which was on the other side of the entrance.

Jewish Antiquities, 15, 9 (or 331), dated around 93-94 AD
(transl. W. Whiston, 1737, London)

[…] and what was the greatest and most laborious work of all, he adorned it with a haven, that was always free from the waves of the sea. Its largeness was not less than the Piraeus [at Athens:] and had towards the city a double station for the ships. It was of excellent workmanship; and this was the more remarkable for its being built in a place that of itself was not suitable to such noble structures, but was to be brought to perfection by materials from other places, and at very great expenses. This city is situated in Phenicia; in the passage by sea to Egypt; between Joppa and Dora: which are lesser maritime cities, and not fit for havens; on account of the impetuous south winds that beat upon them: which rolling the sands that come from the sea against the shores, do not admit of ships lying in their station: but the merchants are generally there forced to ride at their anchors in the sea itself. So, Herod endeavoured to rectify this inconvenience: and laid out such a compass toward the land, as might be sufficient for a haven, wherein the great ships might lie in safety. And this he effected by letting down vast stones of above fifty foot in length; not less than eighteen in breadth, and nine in depth, into twenty fathoms deep: and as some were lesser, so were others bigger than those dimensions. This mole which he built by the sea side was two hundred foot wide: the half of which was opposed to the current of the waves, so as to keep off those waves which were to break upon them: and so was called *Procymatia*, or the first breaker of the waves: but the other half had upon it a wall, with several towers: the largest of which was named *Drusus*: and was a work of very great excellence, and had its name from Drusus, the son-in-law of Cesar, who died young. There were also a great number of arches where the mariners dwelt. There was also before them a quay, [or landing place,] which ran round the entire haven, and was a most agreeable walk to such as had a mind to that exercise. But the entrance or mouth of the port was made on the north quarter: on which side was the stillest of the winds of all in this place: And the basis of the whole circuit on the left hand, as you enter the port, supported a round turret; which was made very strong, in order to resist the greatest waves, while on the right hand, as you enter, stood two vast stones, and those each of them larger than the turret, which were over-against them. These stood upright, and were joined together.

2.7 CARTHAGE

Cicero (Agraria, Rullus, 2) wrote "*Carthago succincta portibus"* (Carthage surrounded by ports), which denotes a fairly complicated configuration[9]. Moreover, we are dealing with 1500 years of evolution (from ca. 800 BC to ca. 700 AD), mostly under the present soil and water levels … Our aim is to provide some synthetic information, with a few hypotheses and conjectures.

Carthage's peninsula in Roman times, showing the rectangular port, the circular port and the eastern shore (view to north, the eastern tip of the peninsula is today's Sidi Bou Saïd) (painting by Jean-Claude Golvin). Note that sand is provided to the isthmus by R Medjerda to the north and R Miliane to the south.

Most of what we know today on the Roman ports of Carthage was summarised by Henry Hurst (2010)[10]. One might schematise Carthage's port system by distinguishing three main port areas:

1. Rectangular commercial port, in Salammbô area near the Phoenician Tophet,
2. Circular military port (the Cothon), with the famous circular "ilôt de l'Amirauté",
3. Eastern shore area between "de Roquefeuil's Quadrilateral" (north) and "Falbe's Quadrilateral" (south).

Both first mentioned ports were located inside the city walls and closed by a chain (limen kleistos), and the third was located on the water edge outside the city-walls.

[9] ENNABLI, A., 2020, "Carthage. Les travaux et les jours – Recherches et découvertes, 1831-2016", CNRS Editions. See also https://en.wikipedia.org/wiki/Carthage
AOUNALLAH, S., 2020, "Carthage, Archéologie et histoire d'une métropole méditerranéenne, 814 avant J.-C. - 1270 après J.-C.", CNRS Editions, (220 p).
[10] HURST, H., 2010, "Understanding Carthage as a Roman Port", Bollettino di Archeologia on line I 2010/ Volume speciale B/B7/6, (p 49-68).

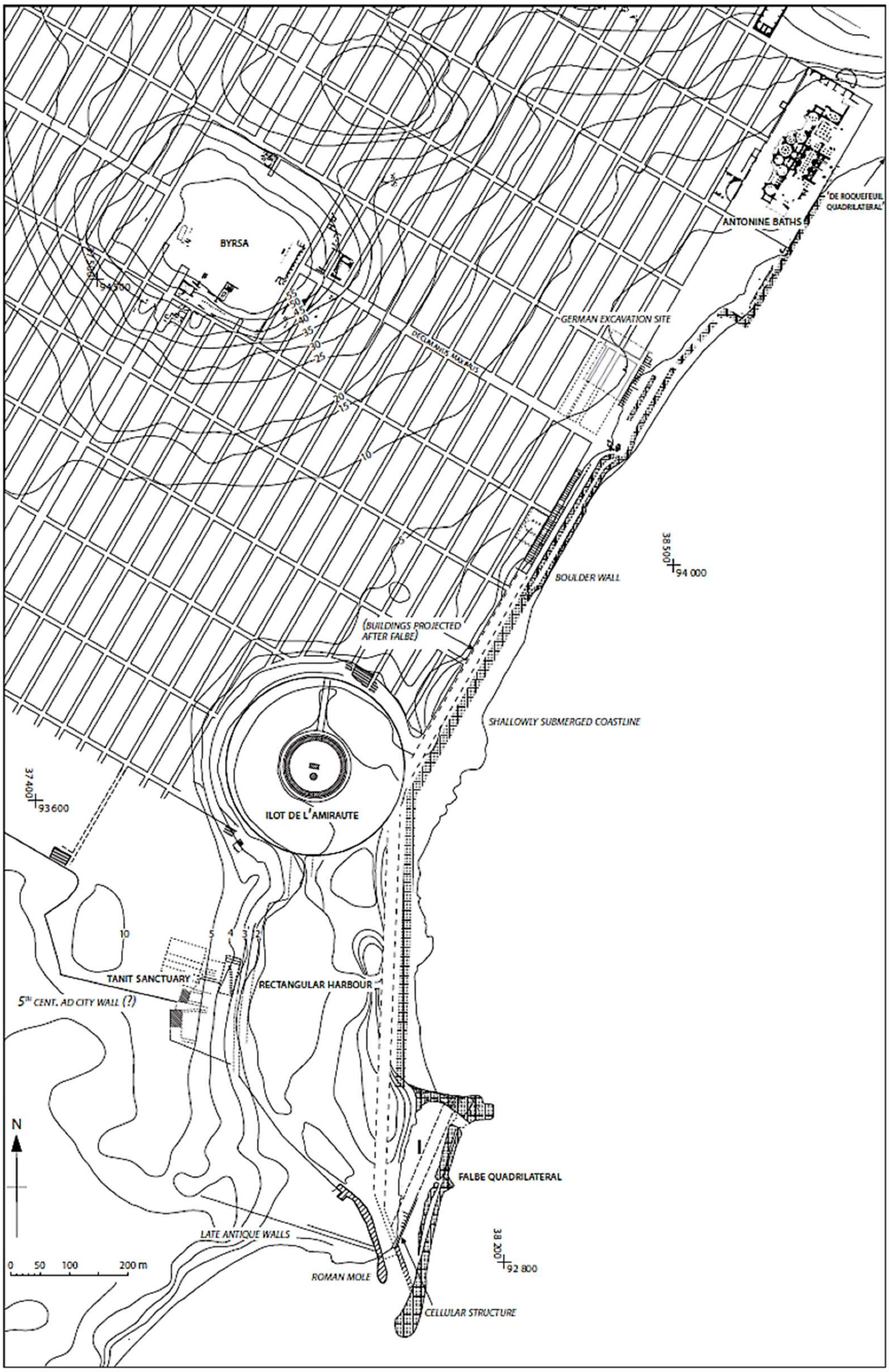

Fig. 4 – Plan of coastal part of Roman Carthage from the Antonine Baths southwards. Bordj Djedid lies immediately outside the plan to the NE. Drawn by Lacey Wallace after YORKE and LITTLE 1975, figs. 4 and 8, RAKOB 1991, beilage 36, and HURST 1999, fig. 2.

Port area between “de Roquefeuil’s Quadrilateral” (north, at modern helipad of Borj Jedid) and “Falbe’s Quadrilateral” (south, near Salammbô), showing the three port areas (picture, H. Hurst, 2010).
Note that de Roquefeuil’s Quadrilateral may not be ancient and that we have no evidence of a port at or underneath the Antonine baths.

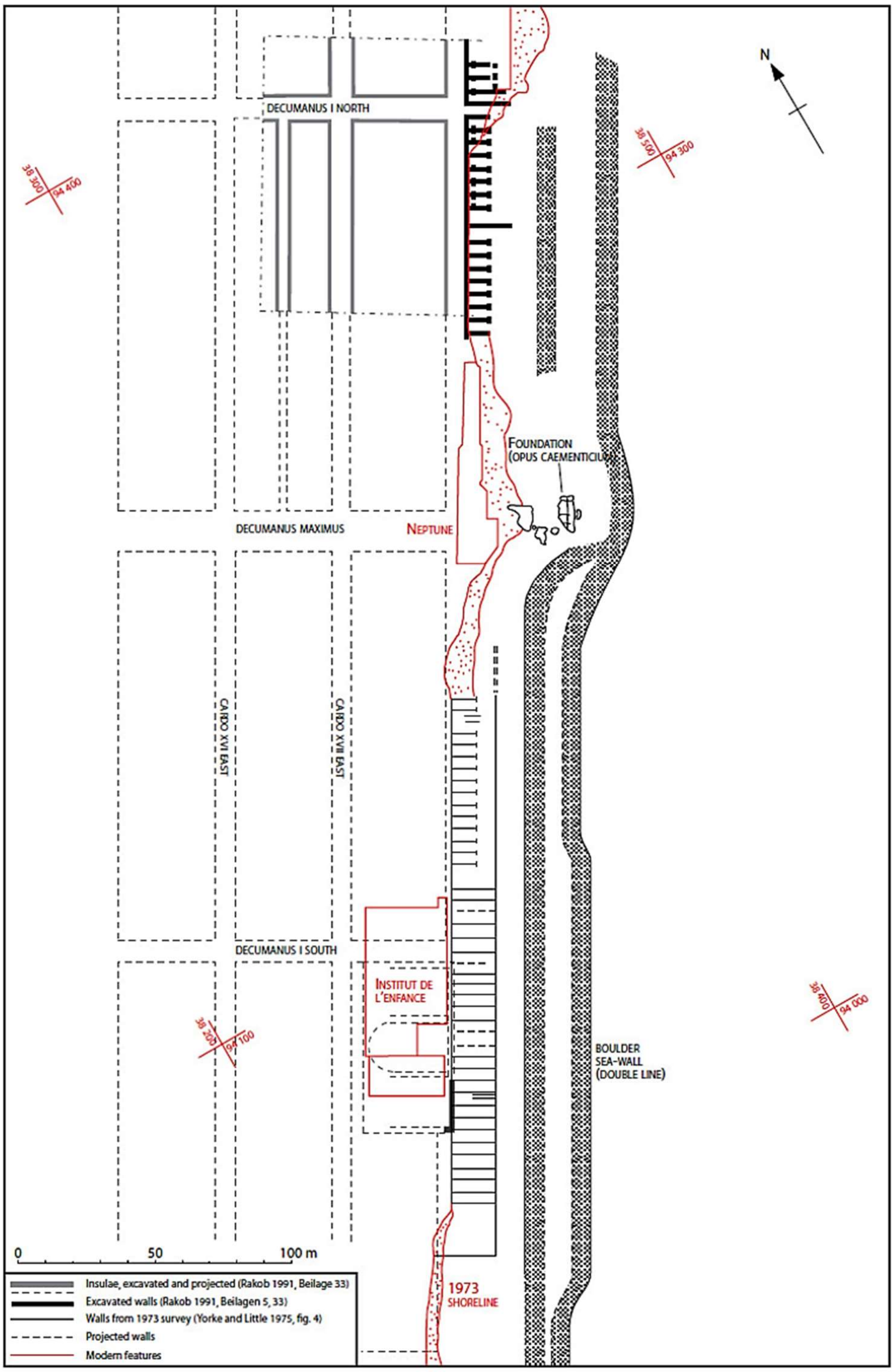

Fig. 12 – The coastal area of Carthage in the vicinity of the *Decumanus Maximus*, with the German excavation area surrounding Decumanus I North. Drawn by Lacey Wallace after YORKE and LITTLE 1975, fig. 4 and RAKOB 1991, beilagen 5, 33.

Eastern port area around “Neptune block” located in front of the Decumanus Maximus, and showing the double line of coastal protection works (“boulder sea-wall”) in front of the “cellular structure” supposed to be Roman warehouses looking out to the sea (picture, H. Hurst, 2010).

As far as we can reconstruct harbour evolutions today, Phoenicians from Sidon first settled near the Antonine baths during the Bronze Age, followed by Phoenicians from Tyre who landed on the beach in front of the Byrsa hill around 800 BC and built a fortified city on the hill. This landing place was outside the city walls, possibly sheltered by a sand spit growing from north to south as suggested by Ennabli (1992, p 200) [11], and probably soon got some timber landing stages. Some archaeological evidence was found by Hurst and Stager (1978) [12.], showing a 15 to 20 m wide and 2 m deep salt-water canal probably leading from the Tophet area to the circular port area.

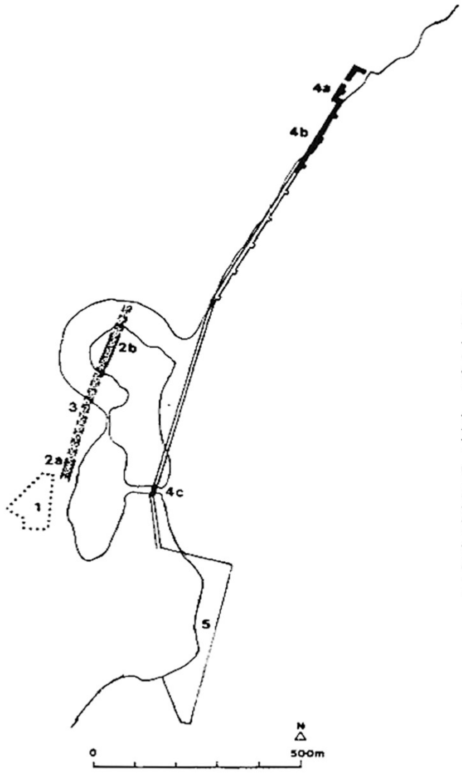

Fig. 8. — La zone portuaire (?) et le « mur de mer » de Carthage au IVe siècle.

1 : le tophet ; **2a** : tronçon de canal repéré par la mission américaine à l'ouest du port marchand ; **2b** : tronçon repéré par la mission britannique dans l'îlot circulaire (cf. H. Hurst et L. Stager, dans *World Archaeology*, vol. 9, n° 3, 1978, p. 338-339 ; **3** : prolongement hypothétique de ce canal ; **4a**, **4b** et **4c** : porte et tronçons du rempart maritime (datés à partir de la fin du Ve s.) mis au jour par la mission allemande (cf. F. Rakob, dans *MDAI, Röm. Abt.*, 91, 1984, p. 5-12 ; **5** : plan schématique du quadrilatère de Falbe *(schéma S. Lancel)*.

Archaic canal and sea walls according to Lancel (1985) [13].

It is however still unclear where the beginning and ending of this canal was located and what may have been its use. According to Hurst (2010), the Lake of Tunis never had an important function as a port, and this canal was thus not used for navigation between the Lake and the Byrsa hill. Anyway, as this canal was silted-up and abandoned during the 4th c. BC (Hurst and Stager, 1978), it might be envisaged that a new harbour basin was dug somewhat further east in the 3rd c. BC, including the Punic quay that was traced for 50 m by Stager. This would later become the so-called 'rectangular port', with the very same quay still in use in Byzantine times.

Both the rectangular commercial port and the circular military port (the Cothon) were built inside the city walls and closed by heavy chains (Appian, Libyca, 96). The coastal part of the city wall was built around 400 BC (Rakob, in Ennabli, 1992), and had a city gate in Quartier

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11 ENNABLI, A., 1992, "Pour sauver Carthage – Exploration et conservation de la cité punique, romaine et byzantine", UNESCO/INAA, Paris, (252 p).

12 HURST, H. & STAGER, L., 1978, "A metropolitan landscape: The late Punic port of Carthage", World Archaeology, 9:3, (p 334-346).

13 LANCEL, S., 1985, "La renaissance de la Carthage punique. Réflexions sur quelques enseignements de la campagne internationale patronnée par l'Unesco", Comptes rendus des séances de l'Académie des Inscriptions et Belles-Lettres, 129e année, N° 4, 1985. (p 727-751).

Magon, proving there was much activity in that eastern shore area which extended ca. 50 m further out to sea[14]. The rectangular port was built between 300 BC and 250 BC, and the circular port between 200 BC and 150 BC (Lancel, 1985 ; Ennabli, 1992). The north mole of the Falbe Quadrilateral, located near the southern end of the rectangular port was also built in Punic times and possibly used as a breakwater protecting the entrance of the ports (Hurst, 2010).

After the Roman conquest (146 BC), the city was first destroyed, and after one century, Caesar ordered its reconstruction (44 BC). Both the rectangular and the circular ports were soon refurbished as commercial ports, but their water depth was limited to a couple of meters. Around 100 AD, the rectangular basin was changed into an elongated hexagon, similar to Trajan's basin at Portus. We might conjecture that the Roman cellular structures located east of the Byrsa hill were built on top of (or behind) the ancient Punic city wall in order to provide Rome with olive oil and grain during the first centuries AD and that larger ships could moor in that area and near the "Choma" of Falbe's Quadrilateral. However, this area may have been undermined by wave action and was finally abandoned for shipping. A two-line coastal protection would then have been built in the 5th or 6th c. AD to protect the city from erosion due to wave action. At that time, the remaining double port system was called "Mandrakion (Mandracium)" by Procopius (Vandals, 1, 20).

Eastern shore area. According to de Roquefeuil's hydrographic chart (in Hurst, 2010) and to modern investigations, the seabed in this area is rocky with an occasional thin sand cover. This sand is most probably provided by R Medjerda to the north and R Miliane to the south (further sedimentological analysis might prove this) and quantities may fluctuate with the river discharges of sediment. Paskoff et al. (1991) explain that the sediment discharge of rivers was reduced after the Roman occupation because of a reduction of deforestation yielding a reduction of inland soil erosion (further geo-archaeological corings might prove this). This would open the door to coastal erosion and the initial sand spit mentioned above might have disappeared.
In order to understand erosion by wave action on the eastern shore, we must have a closer look at the wind and wave conditions. The wind climate which was studied for the port of Thapsus. From Bizerte to Cap Bon (and even Nabeul) prevailing winds are from NW all year round. East and NE winds prevail only south of Nabeul and all the way down to Djerba.
This means that in ancient times, the eastern shore area was on open sea but that it was fairly protected from prevailing NW storms and could be used for beaching ships. It would later have been used (perhaps for short stops of ships) in conjunction with the inner port after the latter was built. As this shore could be attacked by NE waves, we might conjecture that it has been eroded, so that it finally had to be protected by rubble. The second line of rubble defence was possibly added somewhat later. (Hurst, 2010, calls it "boulder seawall"). The result was that no ship could reach the eastern shore.

Inner ports area. Both the rectangular and the circular ports obviously survived better than the eastern shoreline as they were protected from the sea. The circular port was studied by many archaeologists. It was called "the Cothon" because of its saucer-like shape, more than

[14] PASKOFF, R., SLIM, H., TROUSSET, P., 1991, "Le littoral de la Tunisie dans l'Antiquité : cinq ans de recherches géoarchéologiques", Comptes rendus des séances de l'Académie des Inscriptions et Belles-Lettres, 135e année, N° 3, 1991, (p 515-546).

because it was a man-made dug-out harbour basin[15]. Both the outer perimeter and the central islet were filled with slipways with shipsheds (Blackman, 2013) [16], before becoming a market place in Roman times.


Scale model of Ilôt de l'Amirauté islet in the circular port
(Mus. du Port Punique de Carthage, picture A. de Graauw, 2018).

Remains of a slipway on the Ilôt de l'Amirauté islet in the circular port
(picture A. de Graauw, 2018).

Harbour entrance. It has been shown that the northern edge of Falbe's Quadrilateral is Punic. It reaches ca. 75 m in the sea in an eastward direction. Such a short breakwater provides limited shelter against north and NW waves for a small number of ships (say five),

[15] CARAYON, N., et al., 2017, "*Kothon, cothon* et ports creusés", MEFRA, 129/1, (p 255-266).
[16] BLACKMAN, D. & RANKOV, B., et al., 2013, "Shipsheds of the Ancient Mediterranean", Cambridge University Press, (617 p).

and no shelter for other wave directions. It might be conjectured that this breakwater was built in Punic times to provide a sheltered access to the inner rectangular port. It was later included into a Roman platform that was called Falbe's Quadrilateral in the 20th c. and where another Roman cellular structure was found by Yorke & Little (1975)[17]. The Roman entrance to the rectangular port was thus relocated southwards where large blocks of Roman hydraulic concrete (*opus caementicium*) were found by Hurst (2010, fig. 8).

Further (fascinating) reading on: https://www.romanports.org

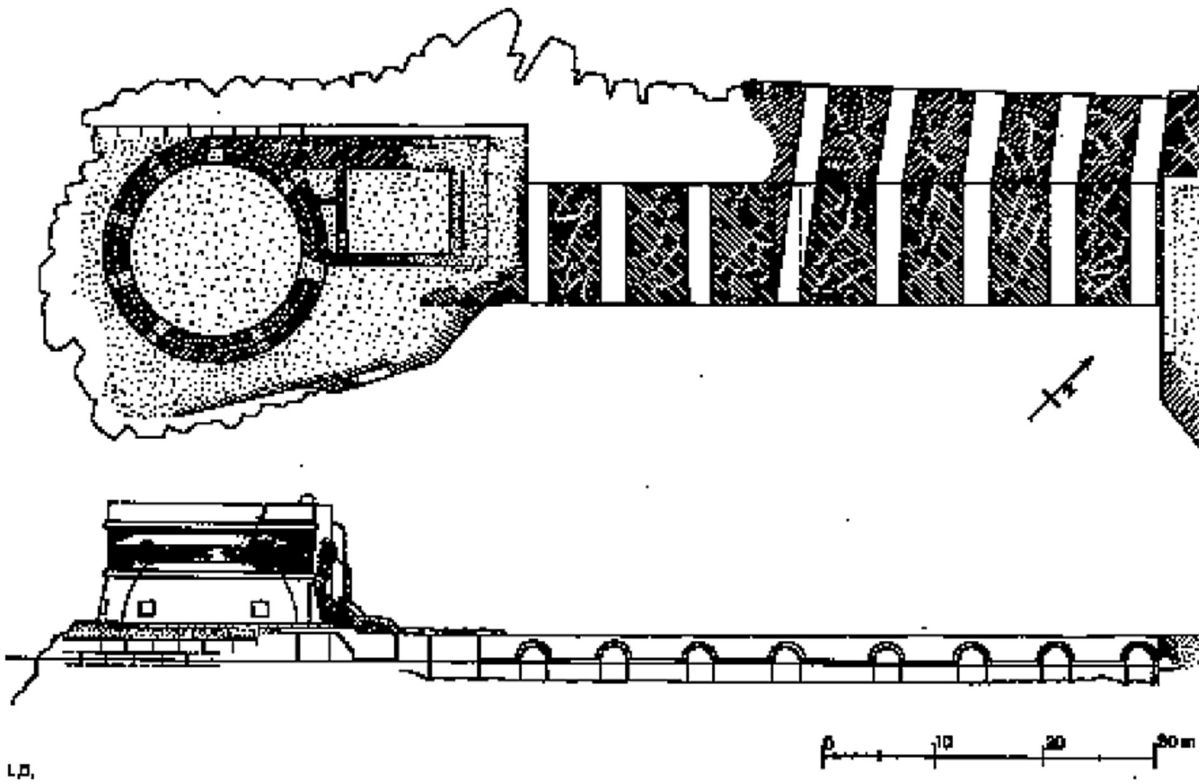
[17] YORKE, R. & LITTLE, J., 1975, "Offshore survey at Carthage, Tunisia, 1973", International Journal of Nautical Archaeology and Underwater Exploration (1975), 4.1, (p 85-101).

2.8 CENTUMCELLAE

The port of Centumcellae was built by order of Trajan by the famous architect Apollodorus of Damascus in the years 105-110 AD. The construction of one of the breakwaters was witnessed by Pliny the Younger (Letters, 6, 31) who provided us one of the very few descriptions of the construction of a Roman rubble mound breakwater in 107 AD :

> “a broad barge brings up a number of immense stones, which are thrown into the water, one on top of the other, and these are kept in position by their own weight, and gradually become built up into a sort of breakwater. […] Subsequently, concrete (pilae) will be added to the stones”, transl. J.B. Firth (1900).

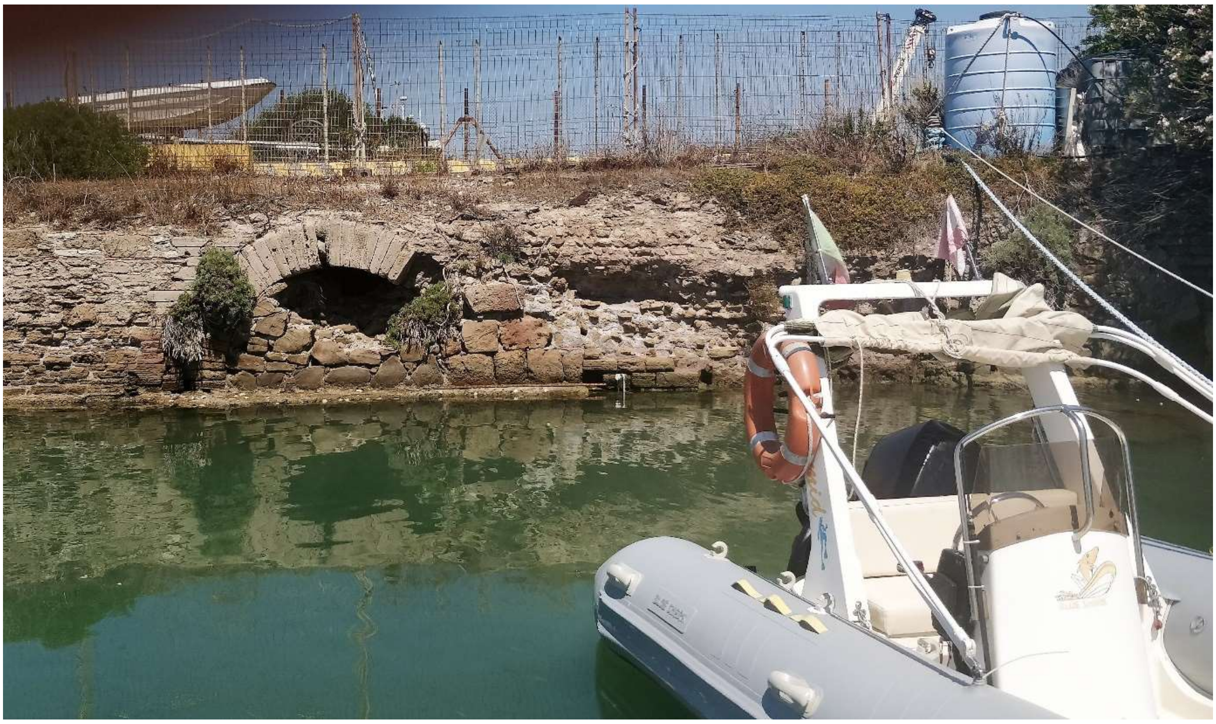
Today’s Molo del Lazzaretto is the only Roman arched breakwater still visible in the Mediterranean world. Acc. to Quilici (2004) it stands on a 3-3.5 m water depth (ca. 0.80 m less in Roman times) and reaches 2.5 m above modern Mean Sea Level (ca. 3.3 m above Roman MSL). The remaining length is ca. 100 m, out of a 250 m initial length, with 8 arches remaining today. Its width was 11 m in Roman times, which was enlarged later to ca. 20 m in order to support the “Lazzaretto”. The arches are around 2.3 m wide, with a pila width of ca. 5.3 m between the arches. The horizontal dimensions of the pilae are therefore 5.3 x 11 m and the opening is 2.3/5.3 = 0.43 pila width.



Layout of Molo del Lazzaretto and Roman lighthouse, with ducts N°1 to 8 numbered from left to right (Quilici 2004).

As it was built in the early 2nd c. AD, this structure may have inherited from previous experience with flushing a harbour without allowing excessive wave penetration. This may perhaps have resulted in the modest 2.3 m width of its ducts which would possibly provide a better balance between flushing capacity and wave penetration than in the larger structures like at Puteoli. It then may come as a surprise that similar arched breakwaters did not survive elsewhere. However, it is noteworthy that the 6th c. enlargement introduced an angle in the ducts, as if this was intended to further reduce wave penetration. Moreover, ducts N° 5, 6, 7 and 8 have been closed by masonry on the south side and ducts N° 1, 2 and 3 were obstructed by rock dumped on the north side at the toe of the tower. These modifications seem to point at a need for further reducing wave penetration entering the harbour basin from north to south.

Molo del Lazzaretto, south side, open ducts 1, 2, 3 (photo A. de Graauw, 2022).



Molo del Lazzaretto, south side, closed duct 7 (photo A. de Graauw, 2022).

Molo del Lazzaretto, north side, open ducts 6, 7, 8 (photo A. de Graauw, 2022).

Molo del Lazzaretto, north side, open duct 4 and rock dumped in front of ducts 1, 2, 3 (photo A. de Graauw, 2022).

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On Roman ports.org:

https://www.romanports.org/en/articles/human-interest/137-centumcellae-the-port-of-trajan.html

2.9 DELOS

Overview of the ports of Delos (on Google Earth 26/8/2017 picture)
Possible beaching and quays are shown with dotted lines: nearly 200 m in the Sacred Port and 800 m in the commercial port.

Delos was a famous island because of its central position in the southern Aegean Sea, halfway between Athens and Asia Minor. As the birthplace of Apollo (and Artemis), it was a holy place. It became the headquarters of the 5th c. BC Delian League, and it also became a large emporium[18].

[18] CONSTANTAKOPOULOU, C., 2017, "Aegean Interactions, Delos and its Networks in the Third Century", Oxford University Press, (350 p).

The following story is told about Apollo’s mother, Leto, looking for a suitable place to give birth to her son (Homeric Hymn to Apollo, Hymn 3, lines 51-61, 8th - 7th c. BC):

“Delos, if you would be willing to be the abode of my son Phoebus Apollo and make him a rich temple; for no other will touch you, as you will find out: I think you will never be rich in oxen and sheep, nor bear vintage nor yet produce plants abundantly. But if you have the temple of far-shooting Apollo, all men will bring you hecatombs and gather here, and incessant savour of rich sacrifice will always arise, and you will feed those who dwell in you from the hand of strangers; for truly your own soil is not rich.” (Translation, H. G. Evelyn-White, 1914).

Thucydides (History of the Peloponnesian War, Book 3, Chap. 104, 426 BC) tells this story:

“The same winter the Athenians purified Delos, in compliance, it appears, with a certain oracle. It had been purified before by Pisistratus the tyrant; not indeed the whole island, but as much of it as could be seen from the temple. All of it was, however, now purified in the following way. All the sepulchres of those that had died in Delos were taken up, and for the future it was commanded that no one should be allowed either to die or to give birth to a child in the island; but that they should be carried over to Rheneia, which is so near to Delos that Polycrates, tyrant of Samos, having added Rheneia to his other island conquests during his period of naval ascendancy, dedicated it to the Delian Apollo by binding it to Delos with a chain.” (Translation, R. Crawley, 1903).

Plutarch tells a story also (Live of Nicias, Chap., around 420 BC):

“It is matter of record also how splendid and worthy of the god his lavish outlays at Delos were. The choirs which cities used to send thither to sing the praises of the god were wont to put in at the island in haphazard fashion. The throng of worshippers would meet them at the ship and bid them sing, not with the decorum due, but as they were hastily and tumultuously disembarking, and while they were actually donning their chaplets and vestments. But when Nicias conducted the festal embassy, he landed first on the neighbouring island of Rheneia, with his choir, sacrificial victims, and other equipment. Then, with the bridge of boats which he had brought along with him from Athens, where it had been made to measure and signally adorned with gildings and dyed stuffs and garlands and tapestries, he spanned during the night the strait between Rheneia and Delos, which is not wide. At break of day he led his festal procession in honour of the god, and his choir arrayed in lavish splendour and singing as it marched, across the bridge to land.” (Translation on Lacus Curtius, Loeb Classical Library, 1916).

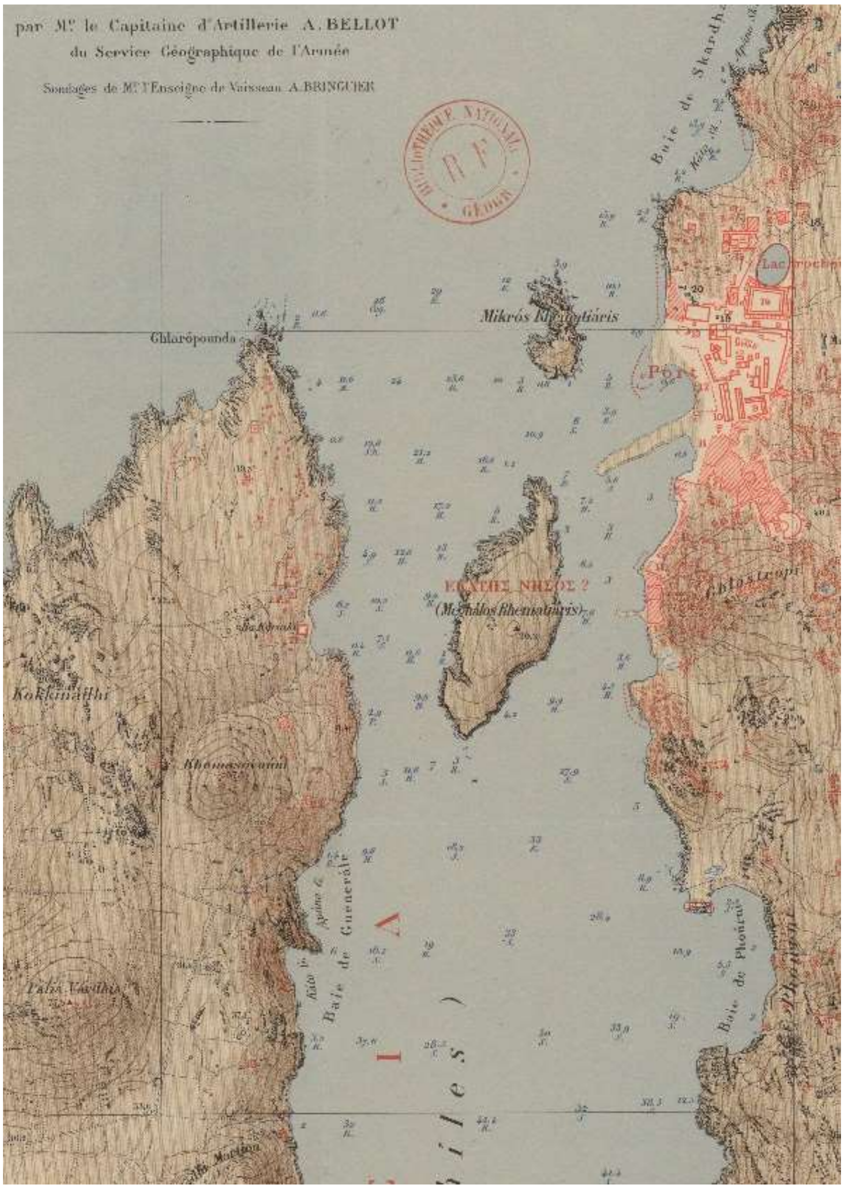
Another story comes from Strabo (Geography, Book 14, Chap. 5, around 10 BC):

“The exportation of slaves induced them [pirates] most of all to engage in their evil business, since it proved most profitable; for not only were they easily captured, but the market, which was large and rich in property, was not extremely far away, I mean Delos, which could both admit and send away ten thousand slaves on the same day; whence arose the proverb, "Merchant, sail in, unload your ship, everything has been sold." The cause of this was the fact that the Romans, having become rich after the destruction of Carthage and Corinth, used many slaves; and the pirates, seeing the easy profit therein, bloomed forth in great numbers, themselves not only going in quest of booty but also trafficking in slaves.” (Translation on Lacus Curtius, Loeb Classical Library, 1928).

The mass grave on Rheneia was found on the eastern coast at a place called Fossa Katharsis, but the exact location of Polycrates’ chain is not known. The location of Nicias’ floating bridge can be guessed from beach to beach, via the isle of Remmatia (ancient Hecate insula). The Sacred Port is located just in front of the Apollo temple and is now silted-up but still visible, and the commercial quays are disseminated along the coastline south of the Sacred Port, down to the Pointe des pilastres, and even further south to the bay of Fourni where a natural shelter against northern winds (Meltem) is available. In addition, despite the limited shelter against northern waves, a potential quay was found on the east coast at

Gourna.
Major archaeological excavations were conducted in the early 20th c. and most of the information available to us today comes from this period. However, these excavations have changed the ancient seascape so much that it became difficult to recognise the ancient port layout.
The latest archaeological source is from Duchêne[19] (2001) and geomorphological work by Dalongeville[20] (2007) shows that *the ancient sea level was ca. 2.5 m lower than today*.

Let's start with a detailed chart of the Delos strait located between the Delos and Rhenia islands:



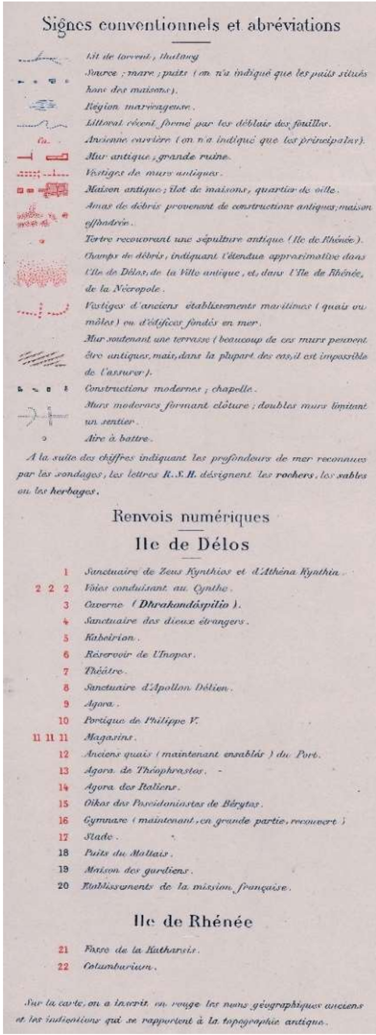


Chart of Delos island made by the École Française d'Athènes in 1907 and 1908 by Capt. A. Bellot of the French Army Geographical Service with soundings by Lt A. Bringuier.
(https://gallica.bnf.fr/ark:/12148/btv1b53061904m)
Scale : the vertical distance between the two horizontal lines is one nautical mile (1852 m).

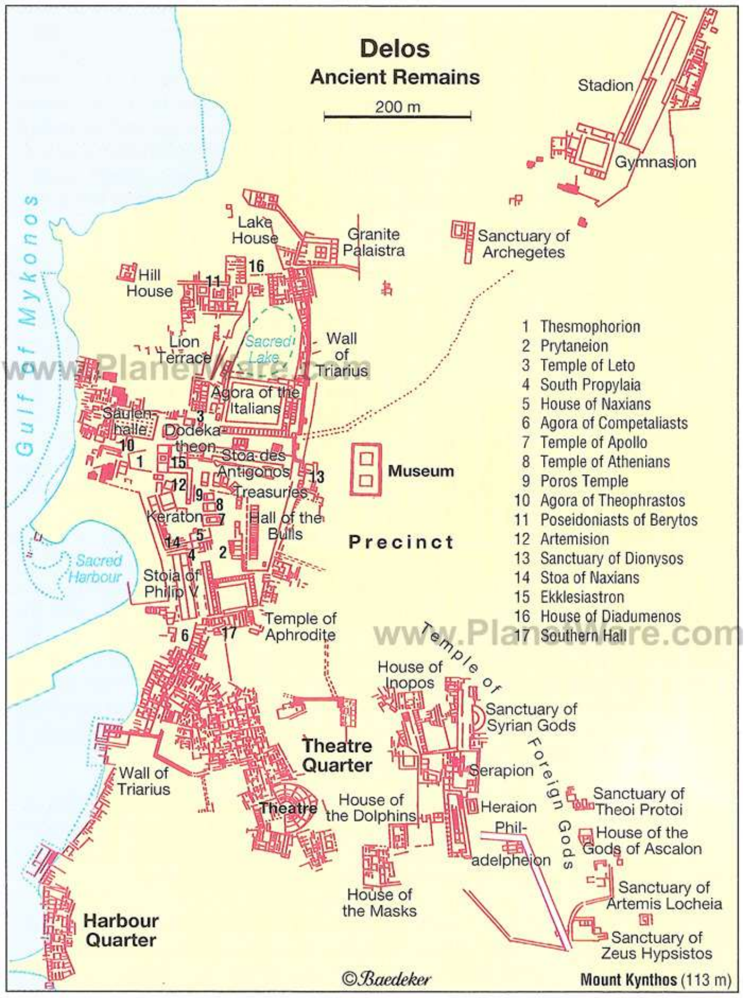
[19] DUCHENE, H., and FRAISSE, P., 2001, "Le Paysage portuaire de la Délos antique", Ecole Française d'Athènes, (192 p).
[20] DALONGEVILLE, R., et al., 2007, "Hausse relative du niveau marin à Délos (Cyclades, Grèce) : rythme et effets sur les paysages littoraux de la ville hellénistique", Méditerranée, 108 | 2007, http://mediterranee.revues.org/154 .

From north to south along the Delos coastline (right side of the chart):

- The distance between the curved "large mole" (located at the spot where "Port" is mentioned on the chart) and Lesser Remmatia (Mikros Rhematiaris on the chart) is around 150 m, with a water depth reaching 5 m (2.5 m in Antiquity) which almost closes the gap between the coast and the island, thus offering good shelter to the whole area located south of it.
- The narrow SW-oriented strip of land is made of rubble from archaeological excavations and is not ancient. It became the core of the modern breakwater.
- The water depth in the channel between Delos and Larger Remmatia (Meghalos Rhematiaris on the chart) is 6.5 to 7.6 m (4 to 5 m in Antiquity) allowing access to ancient ships coming from the north to this 100-150 m wide channel.

The northern wind (Meltem) in this area blows at more than 15 knots (Beaufort force 4) for ca. 40-50% of time in summer. A good shelter from this wind direction was obviously needed for safe anchorage near Delos and this was provided by Lesser Remmatia separated from the coastline by very shallow waters (Mourtzas, 2012)[21].

2.9.1 The Sacred Port

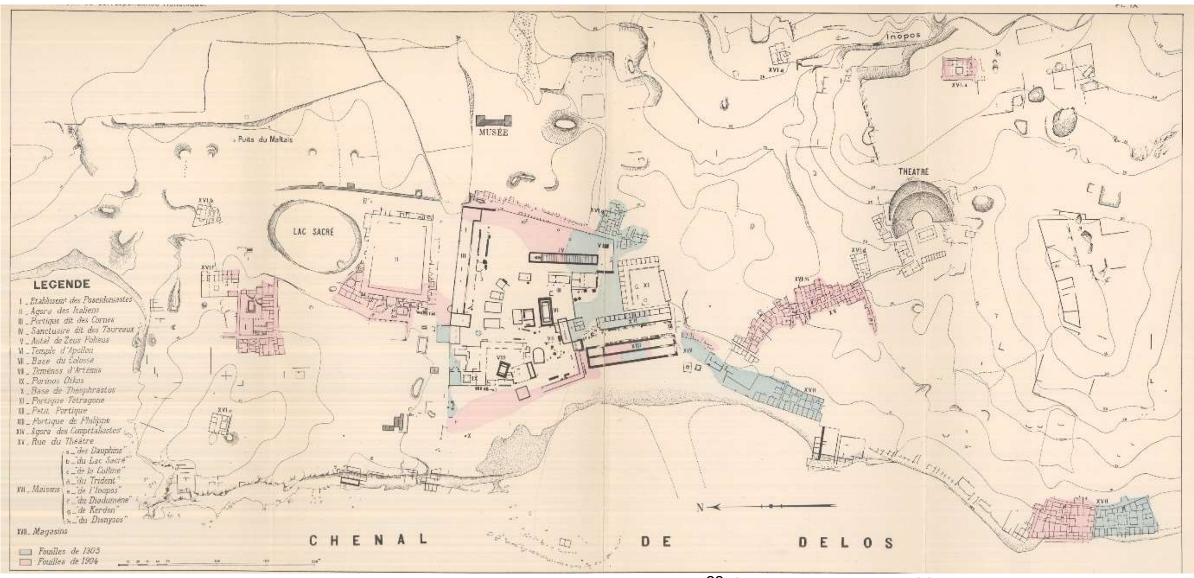


Delos map of ancient remains (2015)
(https://www.planetware.com/greece/delos-gr-aeg-delos.htm)

[21] MOURTZAS, N., 2012, "A palaeogeographic reconstruction of the seafront of the ancient city of Delos in relation to Upper Holocene sea level changes in the central Cyclades", Quaternary International, 250, (p 3-18).

View of the port of Delos, with Rhenia island (right) and Paros island (background), drawing by Théodore d'Aligny (1843-45) showing the Sacred Port, looking south towards the Pointe des pilastres.

The picture above was made before any archaeological excavation took place and is therefore not showing the modern breakwater which would be located in the centre of the bay. The ancient large mole is located beyond the right side of the picture.
The modern breakwaters just south of the Sacred Port and south of the Pointe des pilastres are the result of archaeological excavations which have dumped abundant rubble material into the sea at both of these locations, thus creating some protection of the coastline against northern wave attack, as shown on the map provided by Convert after Jardé's excavations in 1903 and 1904.

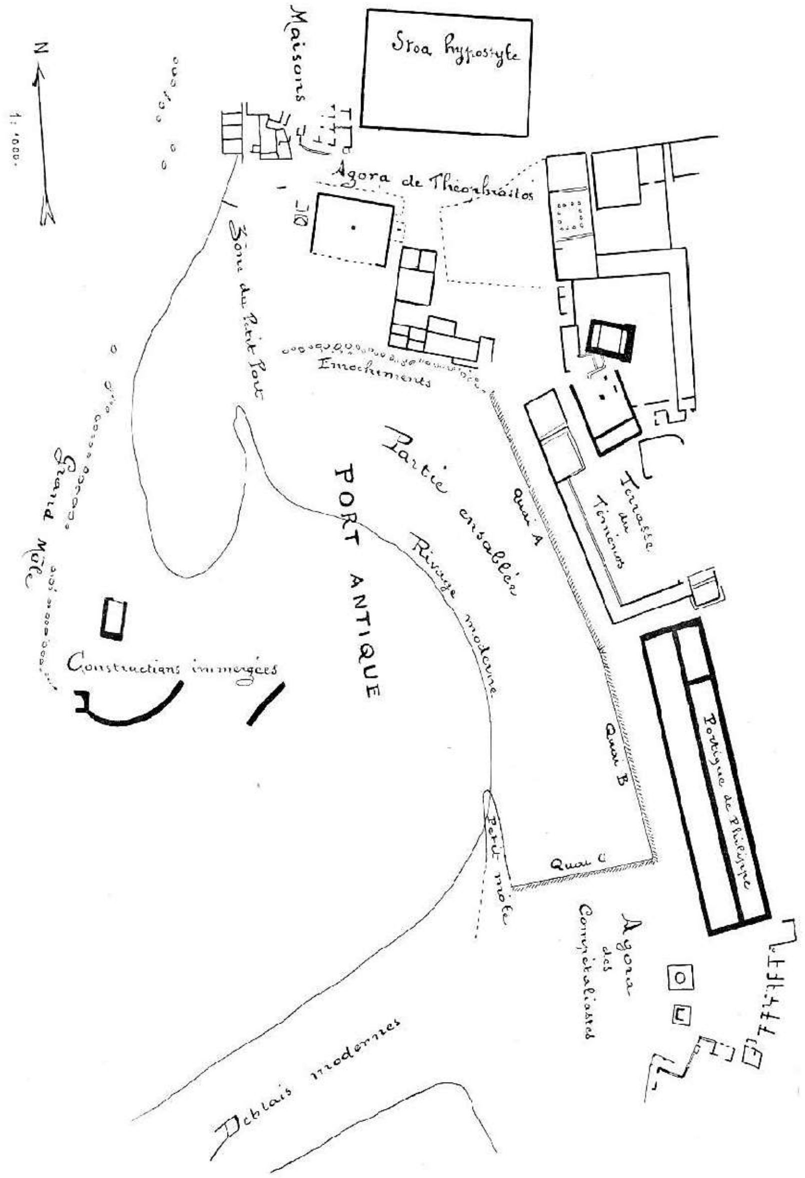


Excavations by A. Jardé in 1903 and 1904[22] (North is to the left).

[22] CONVERT, H., 1906, Bulletin de Correspondance Hellénique, N° 30.

According to Ardaillon[23] (1896) the large mole consisted of an existing reef reinforced by stones placed on top of it, resulting in a kind of coastal protection running parallel to the shore on a distance of 280 m.

Holleaux[24] (1909) produced the map below showing the large mole ("Grand môle") and three quays (A, B, C) assuming a traditional port layout with a breakwater protecting three quays. The area between his quays A and B and his coastline ("Rivage moderne", which is fairly close to today's coastline around one century later) was silted-up ("Partie ensablée").

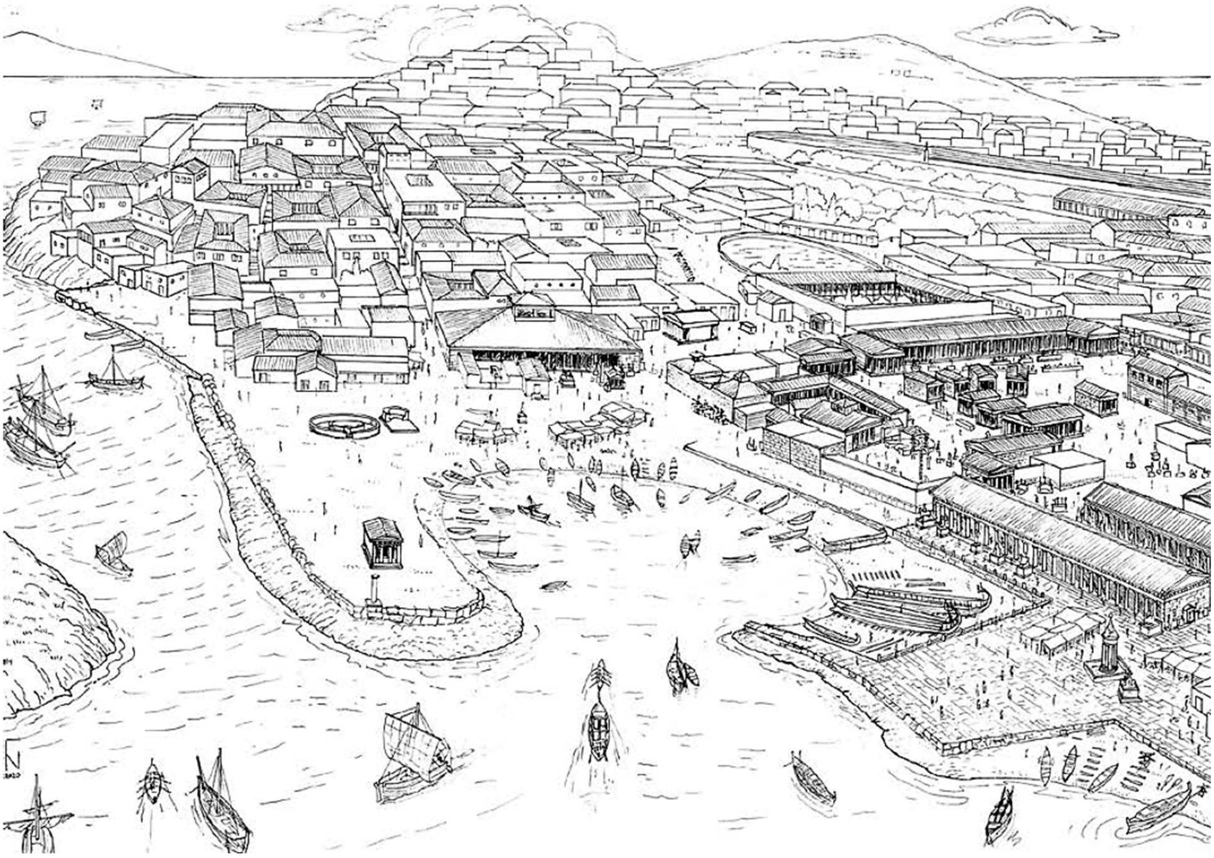


Delos Sacred Port (Holleaux, 1909) showing quays A (81 m, the oldest one), B (63 m) and C (the most recent one) and a large mole ("Grand môle") on the north side, and a small mole ("Petit môle") near quay C on the southern side. The latter was covered by dumping of archeaological rubble ("Déblais modernes").

[23] ARDAILLON, E., 1896, "Rapport sur les fouilles du port de Délos", Bulletin de Correspondance Hellénique, N° 20, (p 428-445).

[24] HOLLEAUX, M., 1909, " Rapport sur les travaux exécutés dans l'île de Délos par l'École française d'Athènes pendant l'année 1908", in: Comptes rendus des séances de l'Académie des Inscriptions et Belles-Lettres, 53e année, N° 5, 1909, (p 397-417).

The Sacred Port was initially probably no more than a protected beach area, and a retaining wall was added in front of Apollo's temple with a beach in front of it. The large mole would then just shelter a beach where only small ships would have access[25].



Restitution of the northern coast by Nakas (2022) showing the
Sacred Port and a narrow beach (looking north).
Note this picture assumes a 2.2 m Sea Level Rise since Antiquity.

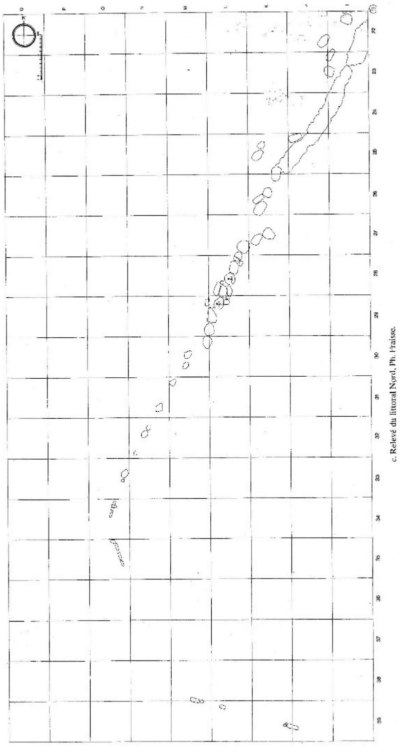
The excavation dump ("Déblais modernes" of Holleaux's map) became the core of a modern breakwater structure with a quay on its southern side where today's ferries bring tourists from Mykonos for day trips to Delos.

It can be seen on the Google Earth picture below. This picture also shows a nice wave pattern due to a mild northern Meltem wind. Waves propagate mainly on the western side of both Remmatia islands and the Sacred Port is somewhat sheltered by the Lesser Remmatia islet (see detail picture below).

[25] NAKAS, I., 2020, "Ships and harbours of the Hellenistic and Roman Mediterranean: a new approach", Honor Frost Foundation, Maritime Archaeology Graduate Symposium, 22-23 February 2020, Short Report Series, (25 p).
NAKAS, I., 2022, "The Hellenistic and Roman Harbours of Delos and Kenchreai", BAR International Series 3099, Nautical Archaeology Society Monograph Subseries, Volume 6, (186 p).

Wave pattern in Delos Channel with mild northern Meltem wind (Google Earth 24/7/2017)
showing fair shelter in Sacred Port thanks to Lesser Remmatia islet
and remains of northern “large mole”.
See also wave diffraction pattern around the remains of the large mole.

The remains of the large mole were surveyed by Philippe Fraisse at the end of the 20th c.



Survey of the large mole by Fraisse (2001)
Scale: each square is 10 m, north is top.

Fraisse's survey of the large mole placed in its natural context (approximate location).

The large mole shown on this picture is around 200 m long, including the curve inside the port. This structure is continued for another 80 m to the north as a coastal protection.

Unfortunately, no complete survey is available which would show the extend of the structure as it is today after 2000 years of wave action, but Duchêne & Fraisse (2001) mention: "The large mole with a granite structure protecting the Sacred Port and its southern end - the oldest part - with Cycladic polygonal ashlar".

This large mole might be as old as the first coastal structures, i.e., the 8th c. BC.

Planche XXXIV

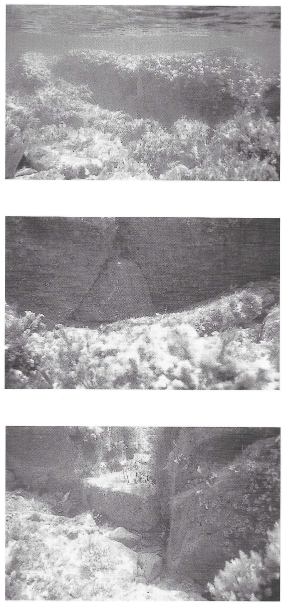


Fig. 1-3. — La jetée Nord du Port sacré. Détails de l'extrémité Sud.

Pictures: Details of the southern end of the large mole of the Delos Sacred Port. (Duchêne & Fraisse, 2001)

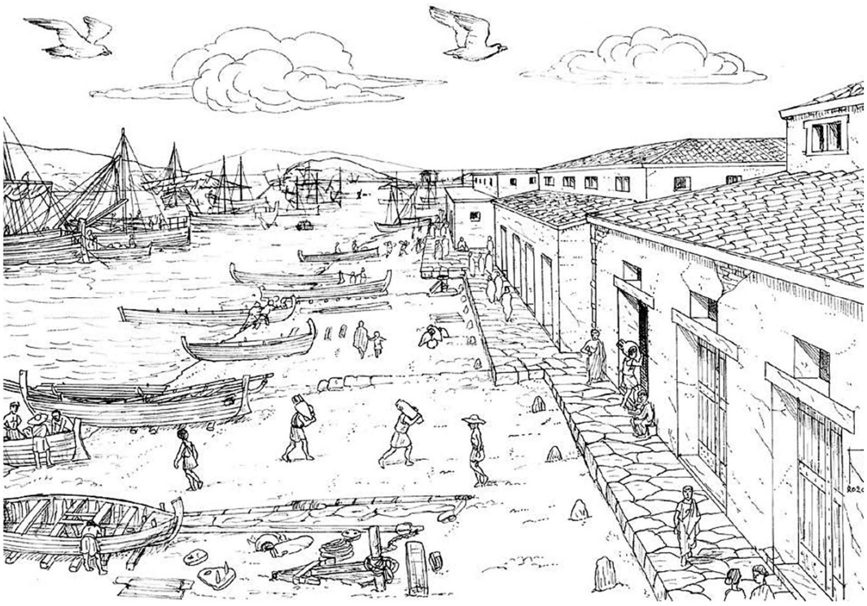
2.9.2 The Commercial Port

Although some erosion occurred and the sea level rose by ca. 2.5 m, the best-preserved port remains are found at the Pointe des pilastres and south of it.

Pointe des pilastres (Google Earth 16/4/2016) is shown at the top of this picture
(the outcrop seen at the bottom side of this picture
is an archaeological dump of excavation rubble)

The commercial port extends over around 800 m south of the Sacred Port. Shops and warehouses are aligned next to each other on the water side. They seem to have been literally on the water edge, with a narrow beach in front of them[26]. However, the water depth in a narrow channel between Delos and Remmatia islands may have reached 4 to 5 m allowing uneasy access to large ships.

[26] HASENOHR, C., 2012, "Ariarathès, épimélète de l'*emporion* et les magasins du Front de mer à Délos", in: Tout vendre, tout acheter. Structures et équipements des marchés antiques., edt Ausonius, (p 245-260).



Restitution of the southern coast by Nakas (2022) showing the
Commercial Port with warehouses and a narrow beach (looking north).
Note this picture assumes a 2.2 m Sea Level Rise since Antiquity.

La Pointe des pilastres, fouilles de J. Pâris, 1909.

Quay at the Pointe des pilastres (Pâris[27], 1909), looking south towards the remaining pilasters,
with the isle of Rhenia in the right background.

It was noted by archaeologists that the warehouses were not as large as might be expected in a large commercial port (Duchêne, 2001). It is therefore envisioned that business located at the Pointe des pilastres, was mainly for local consumption of Delian inhabitants. No significant transshipment was operated, and no large storage area was available on land[28]. Delos would thus be seen as a place of transit were ships anchor in a fairly poor shelter between Delos and Remmatia islands, where cargo is negotiated without unloading the ships, and from where ships sail to new destinations.

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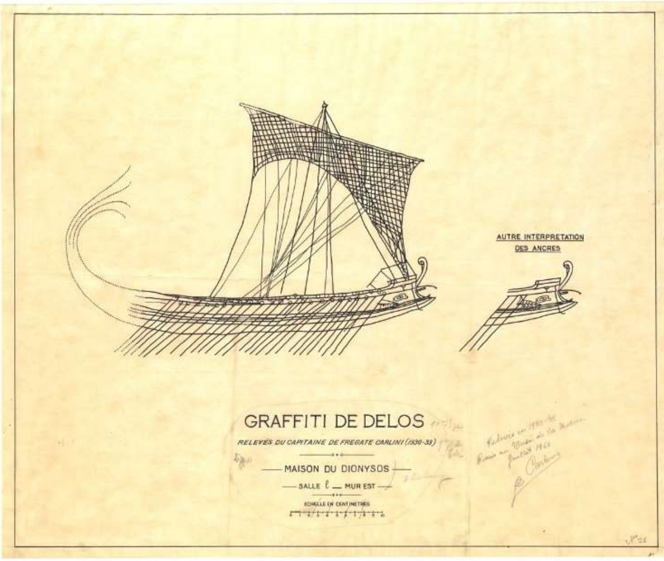
[27] PÂRIS, J., 1916 “Contribution a l’etude des ports antiques du mond Grec”, Bulletin de Correspondance Hellénique,N° 40, (p 5-73).

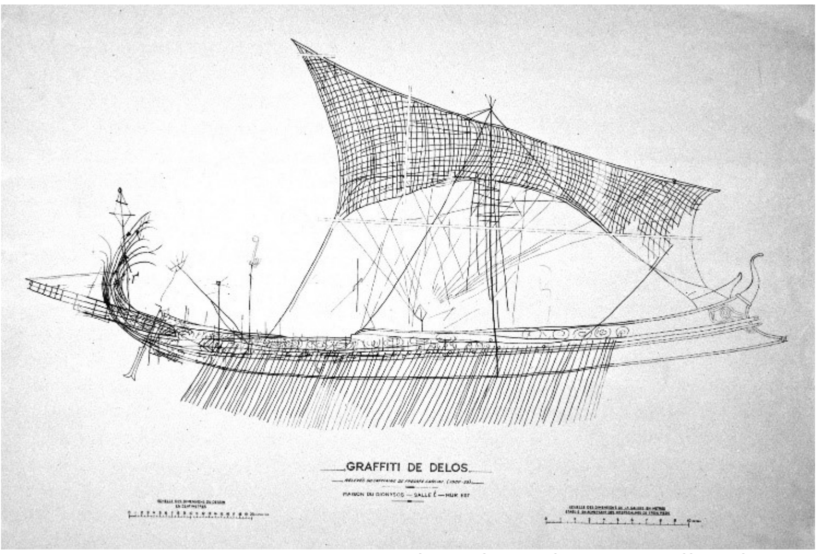
[28] NAKAS, I., 2022, "The Hellenistic and Roman Harbours of Delos and Kenchreai", BAR International Series 3099, Nautical Archaeology Society Monograph Subseries, Volume 6, (186 p).

2.9.3 Carlini’s graffiti reproductions

We cannot visit the isle of Delos without speaking about ancient ships. A few of the famous reproductions made by Capt. Carlini are shown hereunder. The real graffiti are available in the beautiful Delos Museum, but almost nothing is now left of them.



Galley showing 28 oars copied by Capt. Carlini from the graffito of the House of Dionysos on Delos Island in 1930-33.
If each sketched oar represents 3 levels of one oarsman, then this ship is a trireme with 170 oarsmen (Musée de la Marine, Paris).



Trireme showing 85 oars copied by Capt. Carlini from the graffito of the House of Dionysos on Delos Island in 1930-33.
The graffito was over 1 m long and surely is one of the finest pictures of a trireme (Musée de la Marine, Paris).

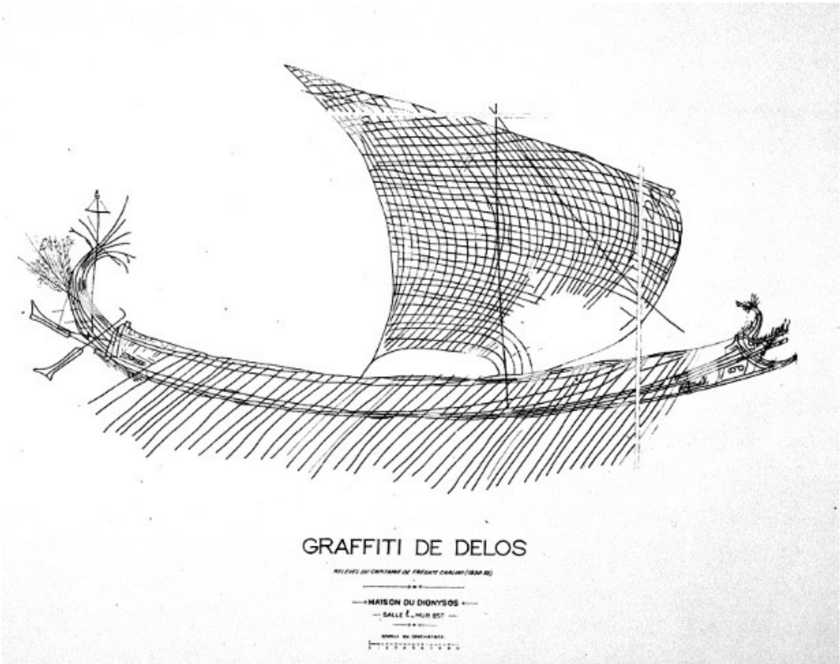
2.9.4 The Bull's Monument

The Bull's Monument takes its name from the statues of bulls, but has no further connection with these beasts. It was probably built around 330-320 BC by Athens and its dimensions are 69.4 x 10.4 m. It was a neorion hosting an ex-voto Athenian trireme of 35-40 x 5-6 m[29].

The east side of the Bull's monument, features a vast open space without any ancient construction, and Lucien Basch believes that this is the location of the "Delos ship", which was the flagship of the Macedonian king Antigonus II Gonatas in the naval battle off Cos against Ptolemy II Philadelphus of Egypt, around 250 BC. The largest warships in antiquity were built In this period.

This mega-ship, named "Isthmia", may have had 18 oarsmen per side, on two levels of 9 oarsmen, i.e., 36 oarsmen on a transversal section. With 50 similar sections, a total of 1800 oarsmen would have been on board. The ship would then have to be around 70 m long and possibly 20 m wide.

Lucien Basch suggests the graffiti below might have represented this ship. This is pure conjecture, but fascinating!

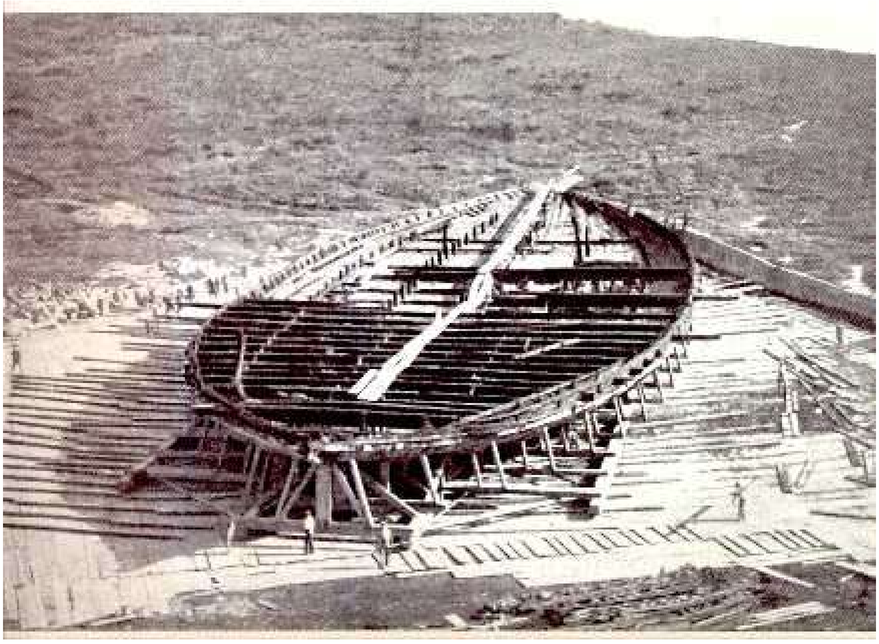


Galley showing 50 oars copied by Capt. Carlini from the graffito of the House of Dionysos on Delos Island in 1930-33. The graffito was 85 cm long and if each sketched oar represents 2 levels of 9 oarsmen, then this ship has 1800 oarsmen. (Musée de la Marine, Paris).

Some believe that Caligula made a replica of this ship (ca. 40 AD) which is known as the "Nemi I" because it was used for naval games on Lake Nemi, north of Rome. This ship (and a second one) were found burried in the mud on the bottom of the lake, they were recovered and studied in 1927-32, but unfortunately disappeared during a fire in 1944[30].

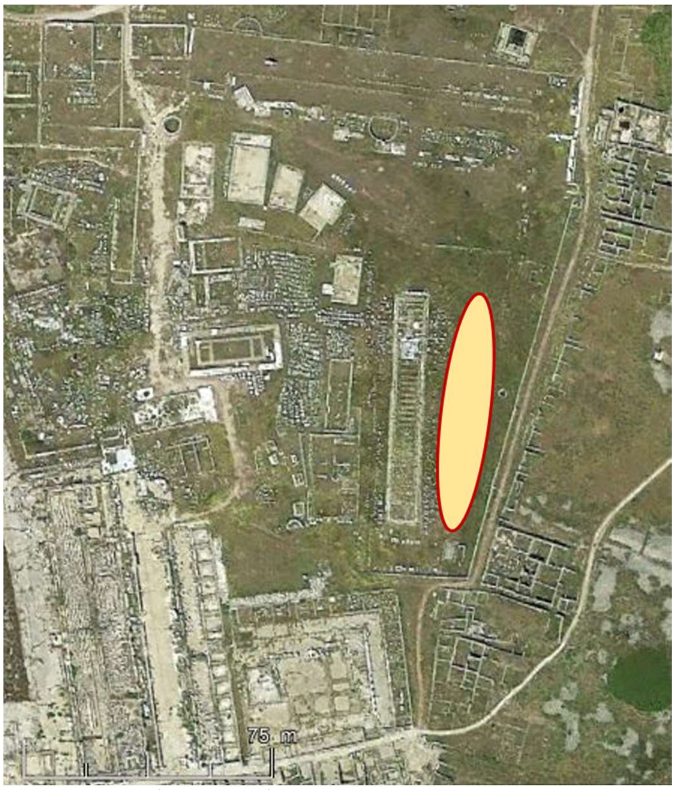
[29] BASCH, L., 1989, "Le "navire invaincu à neuf rangées de rameurs" de Pausanias (1, 29.1) et le "monument des taureaux", à Delos", Tropis III, (p 43-72).

[30] UCELLI, G., 1950, "Le Navi di Nemi", Libreria dello Stato, Roma, (386 p).



Caligula's Nemi I ship on Lake Nemi (picture 1930).
Ship size 70 x 20 m, note the size of the persons standing in front of the ship.

According to Lucien Basch, this ship would fit perfectly in the open area east side of the Bull's monument …



"Delos ship" (70 x 20 m) tentatively located by Lucien Basch
near the neorion of the Bull's Monument.

2.10 EL HANIEH

El Hanieh is located 25 km NW of Bayda (El Beida) in Cyrenaica (Libya)
at 32.835° of latitude north, 21.51° of longitude east.

It is believed to be the ancient Aptouchou Hieron, or Aptoucha.

El Hanieh ancient anchorage

The sheltered area is around 150 x 100 m, that is 1.5 hectares.

A number of ancient stone anchors were found there in the sixties by the diver Jean-Pierre Misson. More than 12 stone anchors have been retrieved, to date. They are all less than 25 kg in weight: for fairly small boats. Not a single lead stock of anchor has yet been found in El Hanieh, seemingly indicating that no large ships used the anchorage on an extended period of time. Several lead stocks of anchors were found in Apollonia and a 50 kg stone anchor is waiting to be lifted up. The stone anchor on the picture above was retrieved in 2012. These places have ample surfaces for ships to manoeuvre. Was the "deep" portion of the El Hanieh anchorage too narrow for large ships but good enough for small boats?

JP Misson also identified two channels cut into the rock on the rock outcrop located on the western side of the site. The present document shows his pictures and finds.
It makes use of Google Earth imagery at various dates.

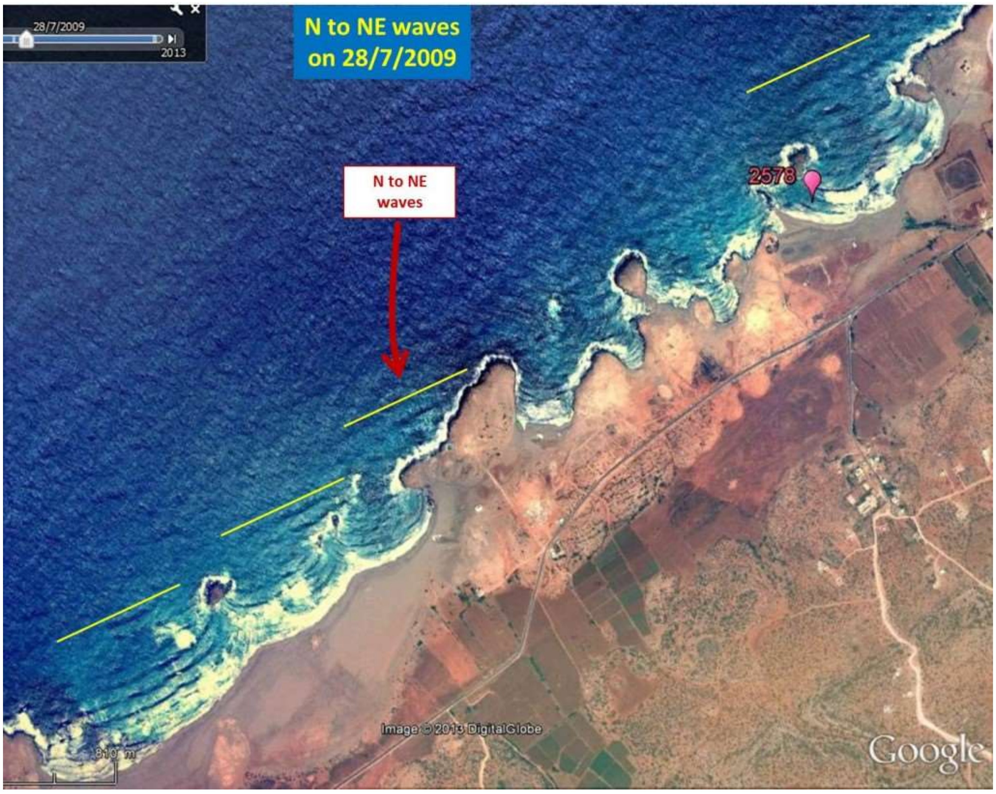
Channel 1 (south)

The southernmost channel, ‘channel 1’, is shown on these pictures.

It is remarkably horizontal with a length of around 40 m and a width of 4 m. In addition, a square central groove of nearly 10 cm runs in the centre of the bottom of the channel, on the whole length. However, the channel is considered too horizontal to be a slipway.

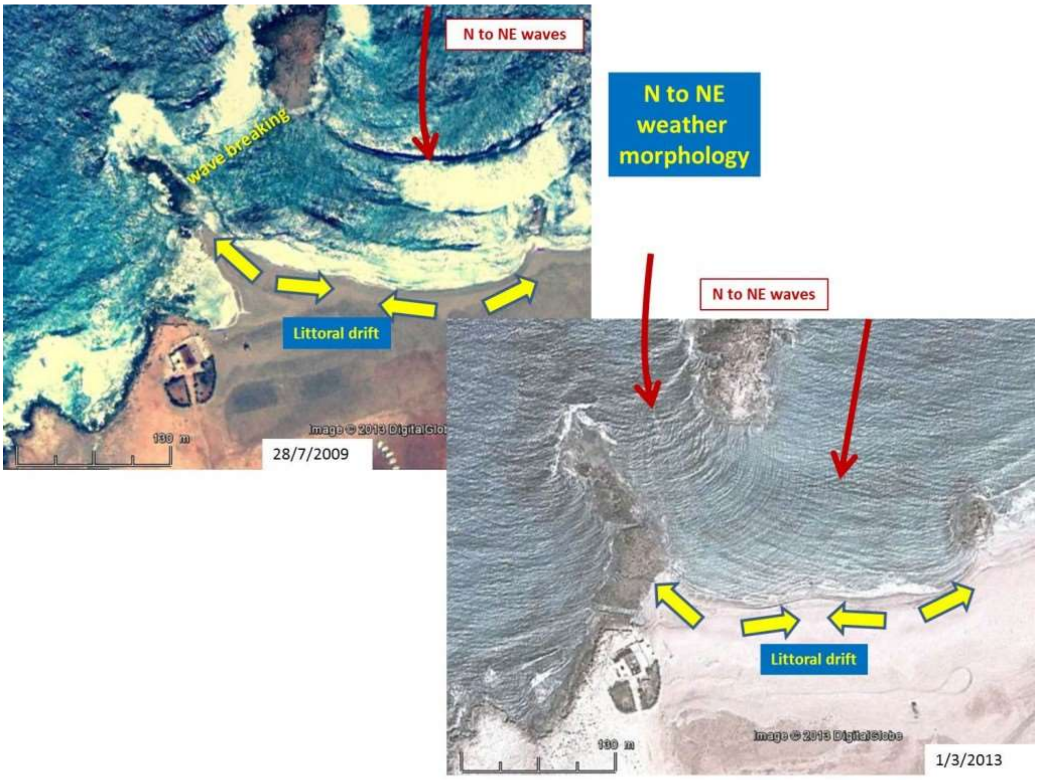
It might have been useful in ancient times to be able to move boats from one side of the rock outcrop to the other to find shelter under all wind conditions but the water depth is too small in Channel 1 for a boat to be floated along, particularly as the sea level rose by around 0.50 m since antiquity. Tectonic movements of the underground are not know of in this area ...

So, we are left with a question as to the use of a shallow channel with a central groove.
Perhaps a ship transfer system in the dry?
A semi-submerged sliding frame?



July 28, 2009 N to NE waves

On July 28, 2009, remaining swell from N to NE was seen by the satellite and reported by Google Earth. This seems to be a fairly infrequent event in summer time.



N to NE wave pattern at the anchorage

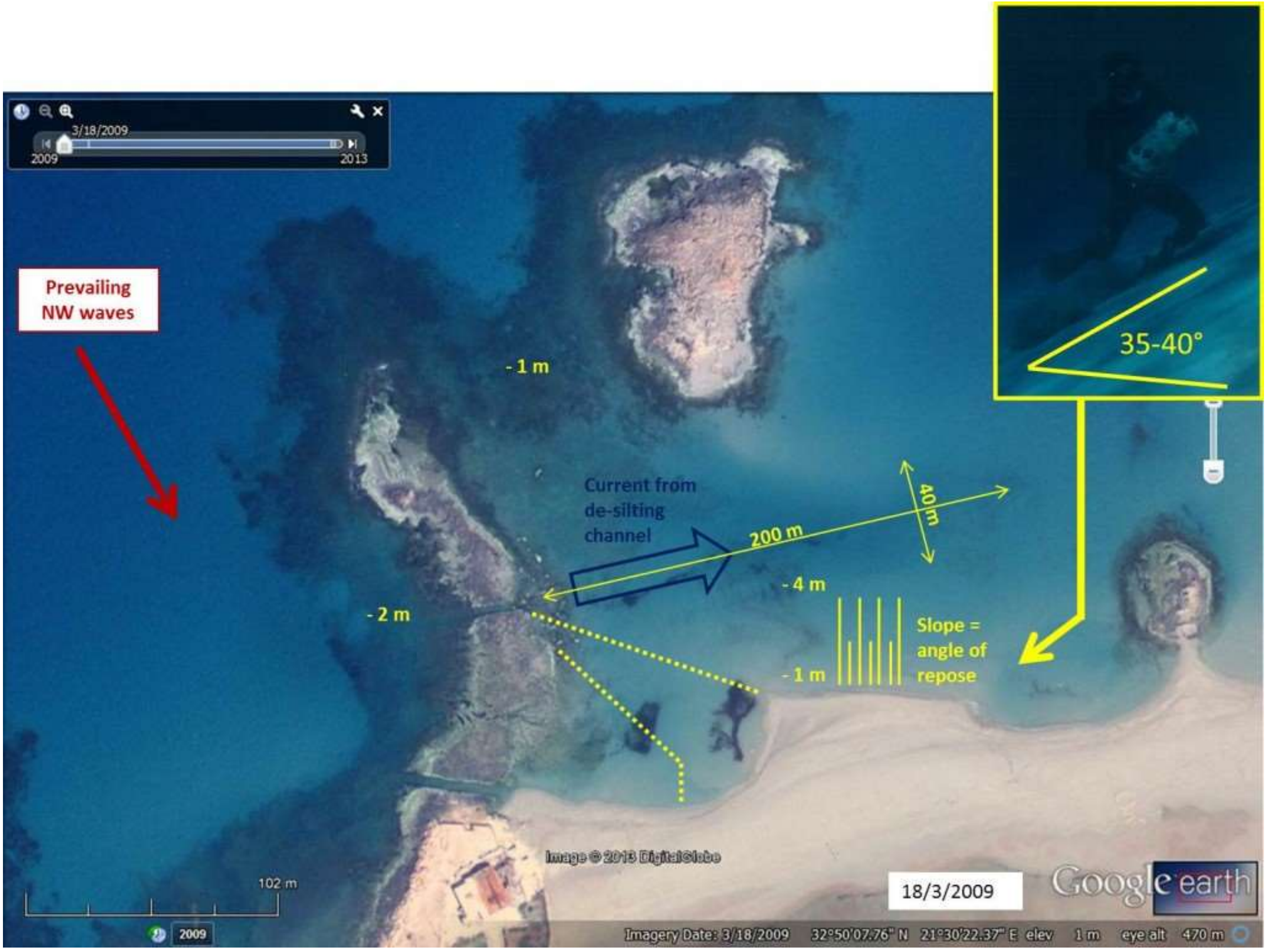
A detailed picture of wave action during this 2009 event illustrates the littoral drift (sediment movement along the coast generated by wave action). It can be seen that channel 1 is closed by sand accumulation. Channel 2 is still open.

The March 1, 2013 picture shows a similar, but milder, wave pattern. Waves are refracting and diffracting around the islet showing a double pattern of waves inside the anchorage area which explains sand movements along the coast line.

Calm weather conditions at the anchorage

Three pictures are available in calm weather conditions, showing morphological features above and under water.

Sand tends to reach out towards the islets as a consequence of the local shelter provided by the islets. This morphological feature is called a tombolo and shows very clearly the mean direction of approach of waves: N to NW.



De-silting current from Channel 2

Channel 2 was identified by JP Misson as a de-silting channel cleaning the anchorage area from sand deposits.

The current in this channel is due to waves incoming from the N to NW direction, i.e., wave set-up due to wave breaking leading to a slightly higher water level on the western side than on the eastern side of the rock outcrop. Similar de-silting channels seem to have been built also at Centuncellae (Italy), Caesarea Maritima (Israel), Sidon (Lebanon).

This current seems to have maintained the El Hanieh anchorage area at a water depth of around 4 m over a length of around 200 m and a width of around 40 m. This is remarkably efficient!

The south slope of the anchorage area is made of sand staying at its angle of repose of 35-40° as can be seen on the underwater picture.

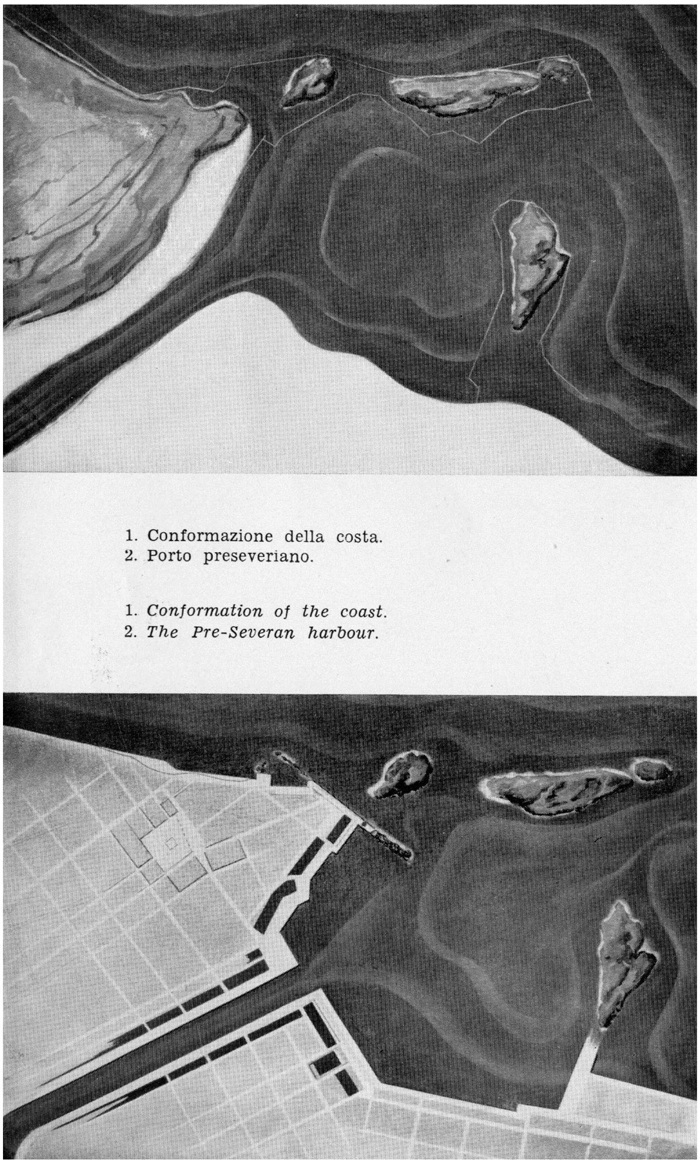
The stretch between the rock outcrop on the west side and the northern islet is around 1 m deep and consists of rock that might possibly be the remains of an ancient breakwater.

Let's hope further underwater investigations will provide some answers to these questions.

2.11 LEPTIS MAGNA

Leptis Magna, also spelled Lepcis Magna, is a Phoenician city in present Libya. It is located about 110 km east of Tripoli. An archaic quay was located on the north coast without any protection from the waves. Its date is not yet determined. After closure of the gaps between the islets, a port was built on the west bank of wadi Lebda with good shelter from western winds. The quay was rebuilt during the reign of Nero (54-68 AD). The port was then enlarged to encompass the whole wadi outlet area. A large 220 m long dam was built 2 km upstream of the wadi outlet. This dam was used to divert the flow from the wadi to the sea west of the city, to fill some cisterns with fresh water and to stop sediment from flowing into the harbour basin.

Leptis Magna and its ancient port is well-known because of emperor Septimius Severus (reign 193-211 AD) who was born there in 146 AD.



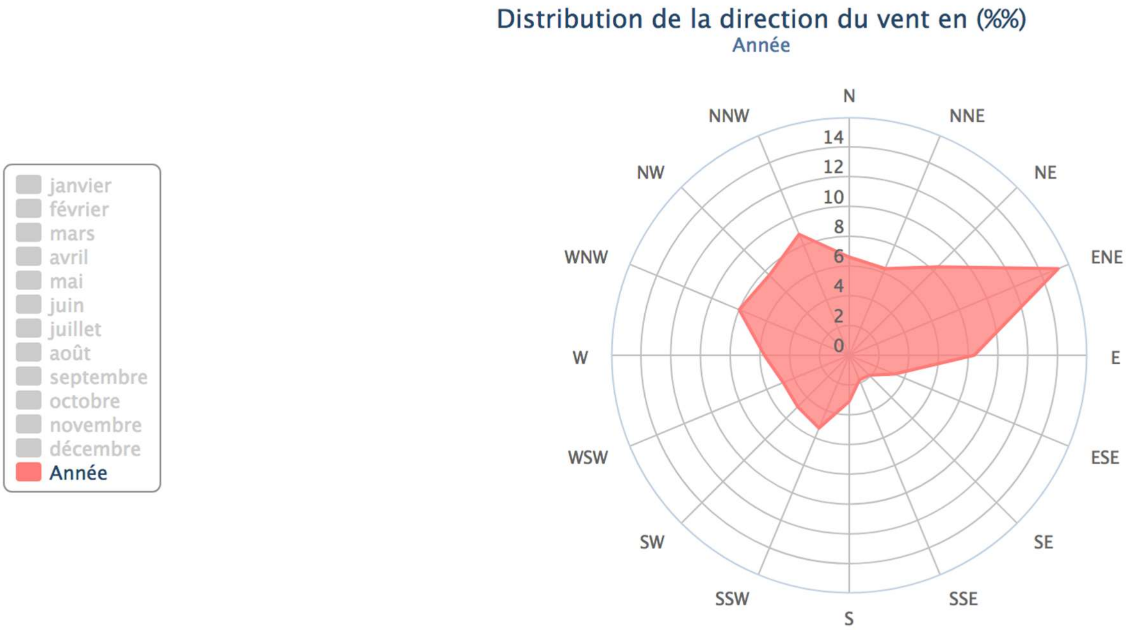
Configuration of the wadi Lebda outlet, acc. to Bartoccini, 1958.

Major investigations were conducted by Renato Bartoccini and published in 1958 after 30 years of field work (see http://www.ancientportsantiques.com/a-few-ports/leptis-magna/ for his detailed drawings of the port). The ‘Mission Archéologique Française en Libye’ also did much field work published by André Laronde in 1988, 1994 and 2005. Preliminary surveys were undertaken by the Universita Roma Tre between 1998 and 2007 (published by Luisa Musso et al. in 2010) and by the Universities of Oxford and Leicester in 2010 (published by Katia Schörle and Victoria Leitch in 2012). An underwater survey was performed by Carlo Beltrame in 2009 and published in 2012 (see references below).

Eastern winds prevail in summer (April-October) and the shelter was not really good for these winds, even if in the second half of the summer (August-October) eastern winds were milder: winds over Beaufort force 4 (10 to 15 knots) occur only 13 to 19% of time.

Mois de l'année	janv. 01	févr. 02	mars 03	avril 04	mai 05	juin 06	juil. 07	août 08	sept. 09	oct. 10	nov. 11	déc. 12	Année 1-12
Direction du vent													
Probabilité du vent >= 4 Beaufort (%)	24	26	24	27	25	26	25	13	19	15	13	13	20
Vitesse du vent moyenne (kts)	8	8	9	9	9	9	9	8	8	8	7	7	8
Temp. de l'air moyenne (°C)	16	16	18	22	24	27	29	30	29	26	22	17	23

Monthly averaged wind statistics (source www.windfinder.com).



Annualy averaged wind statistics (source www.windfinder.com).

2.11.1 Brief historical review

Leptis Magna’s main historical milestones are the following (Laronde, 2005):

- Founded by Phoenicians from Tyre in the 7th c. BC, on the location of the later Roman ‘Old Forum’.
- Becomes a large free city under protection of Carthage in the 4th c. BC.
- Chooses for Roman protection in 111 BC, after the fall of Carthage.
- Grows further as a free trading city and becomes a Municipium around 75 AD and a Colonia in 110 AD.

- Favoured by Septimius Severus as from 193 AD, especially after his presumed visit in 203; the city area then culminates at 280 hectares.
- Suffers from the 3rd c. economic crisis when the city area is halved to 130 hectares.
- Devastated by the tsunami generated by the Cretan earthquake in 365.
- Taken over by the Vandals in 435, but the port is already silted up.
- Sacked by the Levatha Berbers around 530.
- Christianised by the Byzantines in the 5-6th c. but the city area is further reduced to 18 hectares.
- Gradually abandoned after the Arab conquest in 642.

2.11.2 Leptis Magna's north coast

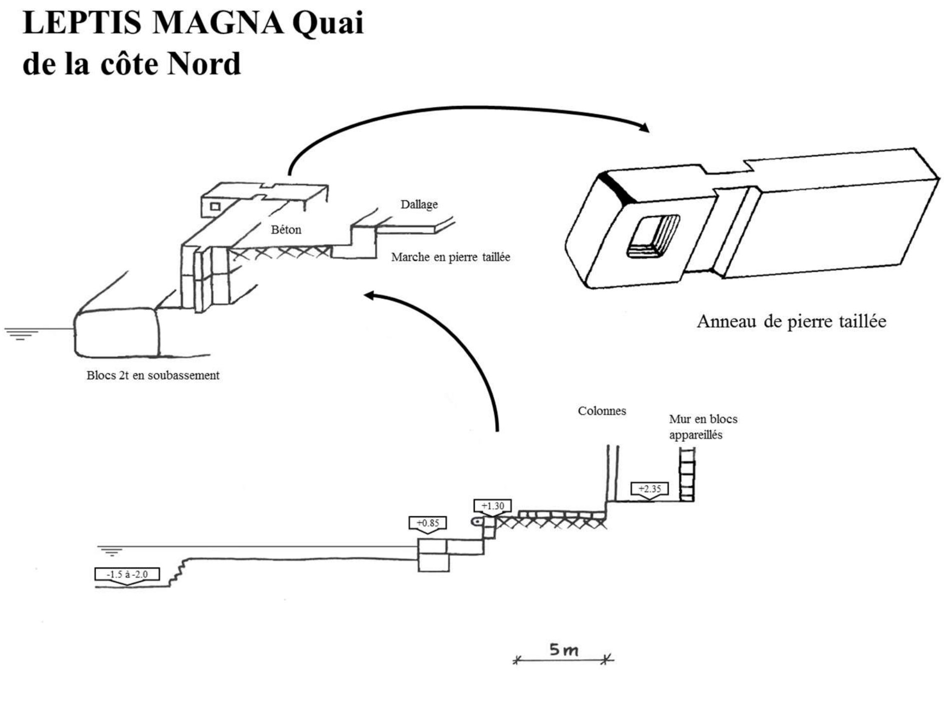
The following observations were made on August 24, 25 and 26, 2000, thanks to the kind hospitality of the late Professor André Laronde during his year 2000 campaign of the "Mission Archéologique Française en Libye".

We walked from west to east from the eastern end of the beach close to the small temple and we were heading for the ancient lighthouse located about 1 km away (NB: distances indicated hereafter are approximate as they were measured in paces on an irregular terrain, but the total distance was known from the available charts).

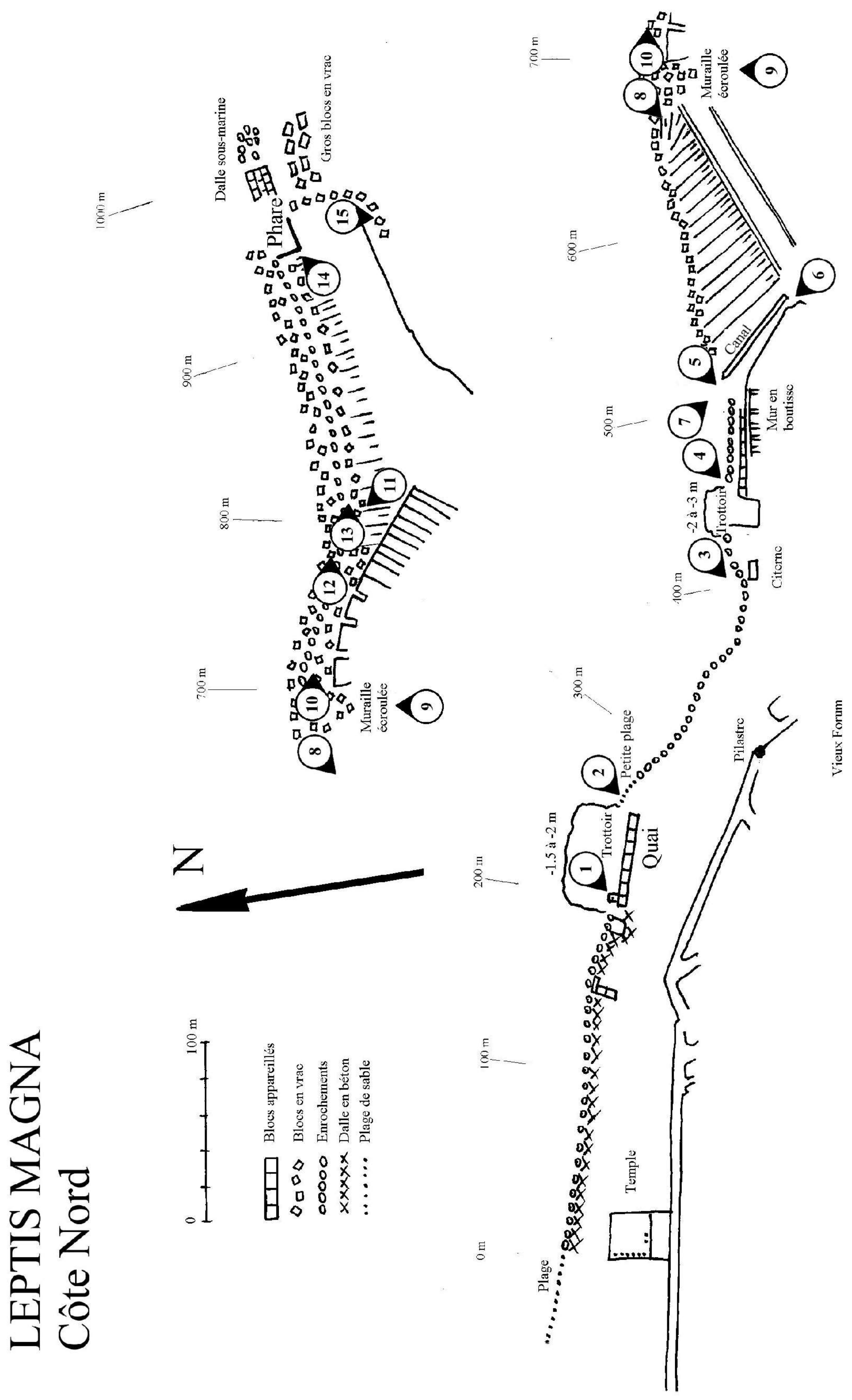
> 0 – 150 m: Straight concrete slab protected by rubble on the beach.

> 150 – 200 m: Idem in a broken line.

> 200 m: Stone ring imbedded into a quay (see sketches). This ring was mentioned by Alberto Carlo Blanc in an annex to Bartoccini's work in 1958.
"Trottoir" (recent geological feature, less than 2000 years) on 10 to 20 m width behind the sandy seabed located around - 1.5 to - 2 m (Photo 1).



Quay on the north coast of Leptis Magna (A. de Graauw, 2000)



Map of the north coast of Leptis Magna (A. de Graauw, 2000)

> 200 – 250 m: Quay with 2 levels oriented N290-N110 (see sketches). Constructions behind the quay front over about 15 m (levels acc. to A. C. Blanc) (Photo 2):

- quay at + 0.85 m on approx. 4 m width, consisting of blocks of approx. 2t,
- level of + 1.30 m on approx. 5 m width, partly consisting of a stone pavement,
- level of + 2.35 m on approx. 5 m width: colonnade passage.

> 250 – 270 m: Small sandy beach.

> 270 – 420 m: Rubble on the beach.

> 290 m: Pilaster of the Old Forum.

> 400 m: Cistern coated with hydraulic plaster (with shards of pottery having a similar effect as pouzzolan). West of the cistern, the remains of what could have been a bathroom are found (?) (Photo 3).

> 430 – 450 m: Concrete walls forming a small building with a curved vertical opening whose use is unclear.
"Trottoir" in the sea behind the sandy seabed located around -2 to -3 m (Photo 4).

> 450 – 490 m: Wall with headers behind what seems to be a quay. Rubble on the beach (Photo 5).

> 510 m: Concrete canal coated with hydraulic plaster. The inside width of this canal is approx. 2 m. The canal connects the inner port to the sea and is around 220 m long according to Bartoccini. It is located at the edge of primitive port and the Severian port near the Neronian portico. It is more or less oriented towards NW. The beach-side end of the canal is sharp ended mortar and seems to close the canal. A dogleg staircase is found on the NE side. A trench is found on the SW side, perhaps an old archaeological excavation along this side of the canal (Photos 6 and 7).

This structure was perhaps seen as a breakwater protecting the primitive port from waves (E. Salza Prina Ricotti), but the U-shape coated with hydraulic plaster is difficult to explain in another way than a canal. It would be worthwhile to explore the inside of the canal, to check the slope and to excavate the mouth to confirm the hypothesis of a canal. It would then have to be seen what may have been its use.

> 510 – 670 m: Slope at the toe of the wall, with pavement made of random blocks on the beach (Photo 8).

> 670 – 700 m: Collapsed wall: former passage between the two primitive islets? Foundation problem on the seabed? (Photos 9 and 10).

> 700 – 770 m: Wall with rubble on the beach and in the sea down to a depth of around 5 m located at around 50 m of the shore. Rubble is rounded on the beach and angular on the upper beach and under water. Quarry blocks smaller than 500 kg (decommissioned building blocks?) seem to have been used as a coastal protection. Their weight is not sufficient and they have been rolling in the wave breaking area during storms, which may explain their rounded shape due to abrasion. This kind of coastal protection was reinvented in northern Europe in the seventies under the name "Berm breakwater" (Photos11, 12 and 13).

> 770 – 950 m: Steep slope with rubble on the beach and in the sea like mentioned above.

> 950 – 980 m: Ancient lighthouse (Photo 14).

> 980 – 1000 m: Underwater pavement around -3 m.

> 980 – 1030 m: Blocks of 10 to 20 t placed randomly on an alignment parallel to the above mentioned pavement.

> Further south: Submerged breakwater oriented to NE and consisting of stones and large concrete masses (one of them must weight hundreds of tons). This breakwater probably formed the outer harbour of Leptis Magna. Its T-shape is visible on photo 17 and by the dark areas on the seabed on photo 19. Photo 20 reproduces an aerial photo showing the size of wadi Lebda and the silting up of the ancient port.


Photo 1


Photo 1r


Photo 2


Photo 3


Photo 4


Photo 5


Photo 6


Photo 7


Photo 8


Photo 9


Photo 10


Photo 11

Photo 12

Photo 13

Photo 14

Photo 15

Photo 16

Photo 16r

Photo 17

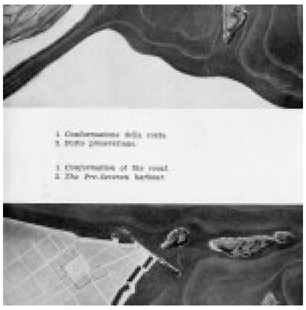


Photo 18

Photo 19

Photo 20

2.11.3 Dam on wadi Lebda

A large 220 m long dam was built 2 km upstream of the wadi outlet and was primarily meant to divert water and sediment to avoid them from flowing into the port.

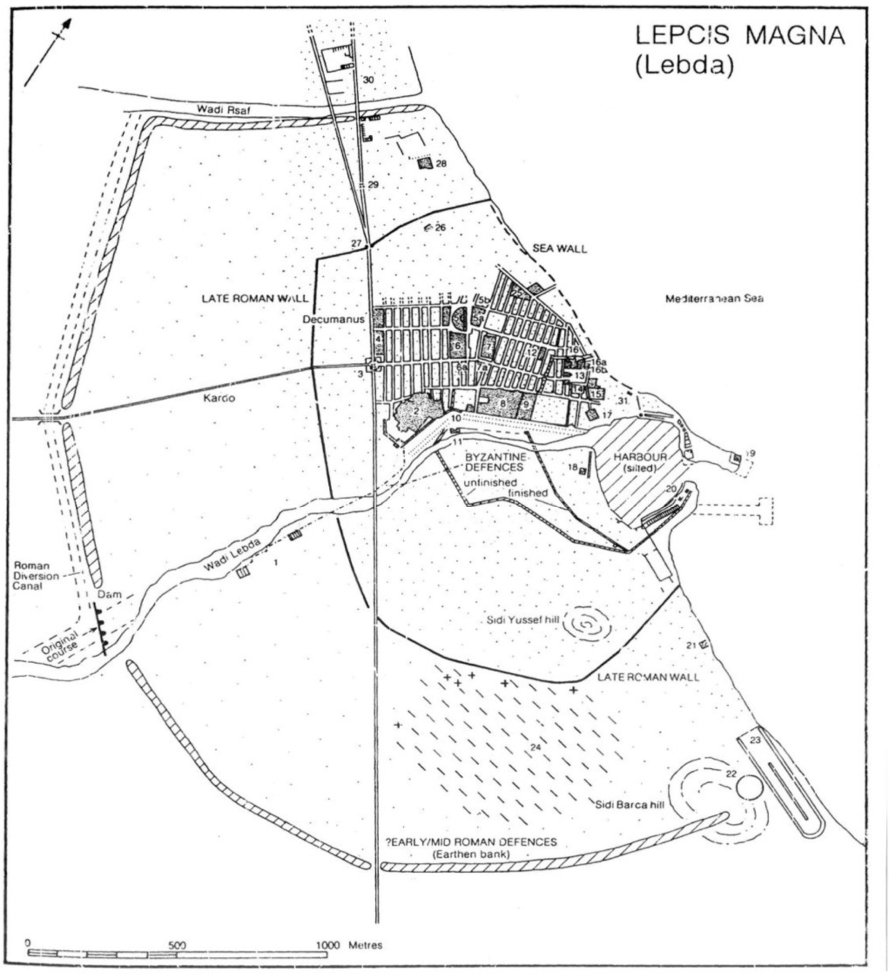
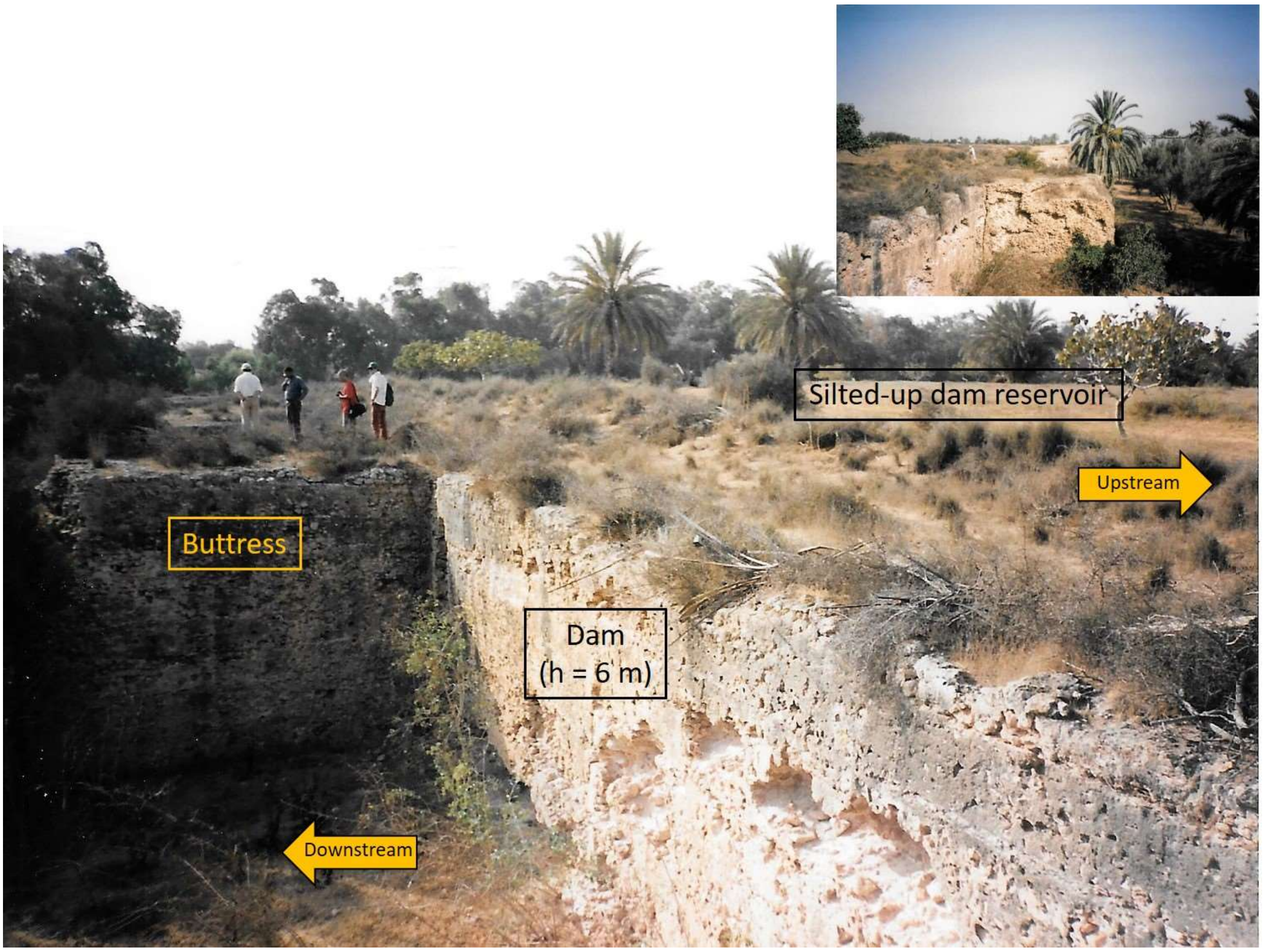


FIG. 1. — Plan de Lepcis Magna,
d'après D. Mattingly, *Tripolitania*, Londres, 1995, p. 117.

Earthen levees built around the city and the canal
diverting the wadi Lebda waters further north into wadi Rsaf.

Any dam or sill placed across a river will collect the larger particles flowing near the bottom and let go the so-called 'suspended load' flowing in the upper layers of the stream. Hence, the area upstream of the dam *will* silt up.

The question of the *rate* of silting up is a difficult matter because estimates of the sediment discharge in semi-arid areas are extremely difficult to provide as they result from only a few flash floods per year. Reality can be approached only with orders of magnitude, e.g., it might be accepted that the sediment discharge of wadi Lebda is 10 000 m^3/year (see also Pucci, 2010), but it could easily be several times more … or less. Hence, the time required to fil the volume upstream of the dam (ca. 750 000 m^3 acc. to Pucci, 2010) could be *anything between a few decades and a few centuries*. This is disappointingly unprecise. Additional doubt must be mentioned as wadi Lebda may have changed its regime from a perennial year-round flowing river into the dry river with flash floods we see today (a famous flash flood occurred in November 1987).



Dam across Wadi Lebda now completely silted up (A. de Graauw, 2000).

Maintenance dredging in the area upstream of the dam would have been helpful, but was surely quite difficult and expensive and therefore required strong motivation from the port authority and related commercial actors.

Anyway, after some time, the area upstream of the dam got silted up and the wadi found a way to get around the dam by its eastern side, where it still flows today. It is to be noted that the dam is quite well preserved today and that according to Pucci (2010) "The structure of the dam does not show any type of damage that could have been caused by a local earthquake or by the occurrence of a destructive earthquake that hit a large part of the eastern Mediterranean, such as the 365 A.D. Creta earthquake."

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2.12 MARIUS’ CANAL

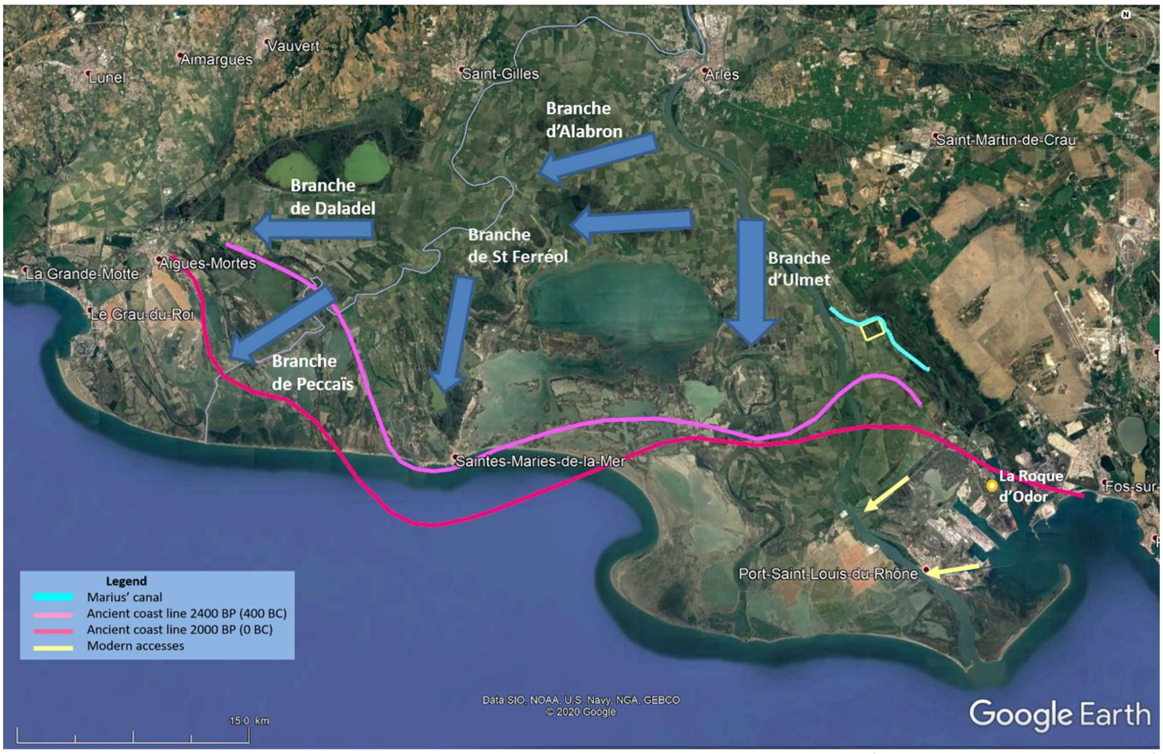
Let's first read Stabo (Geog. 1, 4, 8) about the entrance to the Rhodanus river:

> *“With respect to the mouths of the Rhodanus: Polybius reproves Timaeus by saying that there are not five but two; Artemidorus says three; Marius, later, seeing that, in consequence of the silting, its mouths were becoming stopped up and difficult of entrance, cut a new channel, and, upon admitting the greater part of the river here, presented it to the Massiliotes as a meed of their valour in the war against the Ambrones and Toÿgeni; and the wealth they carried off from this source was considerable, because they exacted tolls from all who sailed up and all who sailed down it. Nevertheless, the mouths still remain difficult of entrance for ships, not only on account of the impetuosity of the river and the silting up, but also of the lowness of the country, so that in foul weather one cannot descry the land even when close to it. Wherefore the Massiliotes set up towers as beacons, because they were in every way making the country their own; and, in truth, they also established a temple of the Ephesian Artemis there, after first enclosing a piece of land which is made an island by the mouths of the river.”*

Caius Marius (157-86 BC) reorganised the Roman army and raised the number of soldiers per legion from 4000 to 6000, i.e., 10 cohorts of 600 soldiers, each made up of 6 centuries of 100 soldiers. Plutarch (46-125 AD) tells that he arrived to fight the Ambrons and the Teutons near Aquae Sextiae (modern Aix en Provence), probably in 104 BC. He had to wait for them and finally crushed them in 102 BC. His army has been estimated to 5 legions, i.e., around 30 000 soldiers. While waiting for the enemy, he kept his army busy by digging a canal between the sea and his camp in order to ease supply from the sea (see: https://fr.wikipedia.org/wiki/Fosses_Mariennes).

A probable section of the canal, and possible remains of the camp have been found recently by Otello Badan and Mario Maretti (published respectively in 2013 and 2017).

2.12.1 Marius’ canal?



Ancient coastline near Marius' canal (acc. Provensal et al, 2003)

A 5 km long section of a canal was identified by both investigators in 2012-2014, and confirmed by an excavation in 2013 and geophysical surveys in 2014 (published in annual reports of Les Amis du Marais du Vigueirat). At the north, the canal section ends in the present Grand Rhône leading to Arles. At the south, the canal section is lost in the wetlands.

Let's try to put this into its geomorphological context.

In Roman times the central Saint Ferréol branch of the Rhône river was silting up and the coastline of the Saintes Maries de la Mer was regressing. The western Peccaïs branch was growing, as a precursor of the present Petit Rhône, and pushing the coastline to SW. The eastern Ulmet branch became the main stream, as a precursor of the present Grand Rhône, and the coastline was moving south. River sediment reaching the coastline was transported eastward by waves and the coastline was moving to the south between Grand Boisviel and Rebatun quite fast at a rate of around 10 m/year.

Upon arrival of Marius in 103 BC, the coastline was located somewhere between both positions mentioned on the figure as 2400 BP (around 400 BC) and 2000 BP. Marius' canal must therefore have had its outlet in the area near the modern LNG terminal Fos Tonkin. The islet La Roque d'Odor (now destroyed) was obviously a nice landmark for seafarers who had no other landmark for landing in this region[31].

The only feature that is missing somewhat in this landscape is Plutarch's outlet « sheltered from waves » (Marius, chap. 16), except if a sand spit like the They de la Gracieuse would have existed, even if for only a few decades, and this is not unrealistic from a geomorphological point of view.

Another interpretation problem of ancient texts concerns the discharge of Marius' canal which was supposed to take « the major part of the Rhône waters » according to Strabo (Geogr., 4, 1), or at least a « large part of the water of the river » according to Plutarch (Marius, chap. 16). Indeed, the width of the canal, which is estimated to 35 m, does not allow for more than 5 to 10% of the mean discharge of the Rhône river (1000 to 2000 m^3/s depending on the month in the year).

As a matter of fact, if the canal could discharge as much as the Rhône river of that time, the silting problem at its outlet (the 'bar' feared by seafarers) would have been exactly the same and Marius would just have moved the outlet together with all its silting problems!! It therefore seems more likely that he (or the 'Marseillais' coming after him) would have tried to regulate the upstream river discharge in order to:

1. provide sufficient discharge to 'clean up' the canal down to the Pleistocene substratum, without eroding the bank protected by wooden piling,
2. maintain the outlet by pushing the bar further offshore,
3. and, most of all, deviate the Rhône river floods.

He could have installed a kind of ancestor of our modern locks.

Nature nevertheless had the last word and the canal outlet was eventually closed by sand travelling along the coast to the east. The canal then became a dead arm where black clays brought down by the Rhône river could settle and fill the canal.

The difficult access to river outlets mentioned by Plutarch and Strabo are very common and still exist at the present Grand Rhône outlet, so that additional accesses were installed by means of the Port Saint Louis and Barcarin locks.

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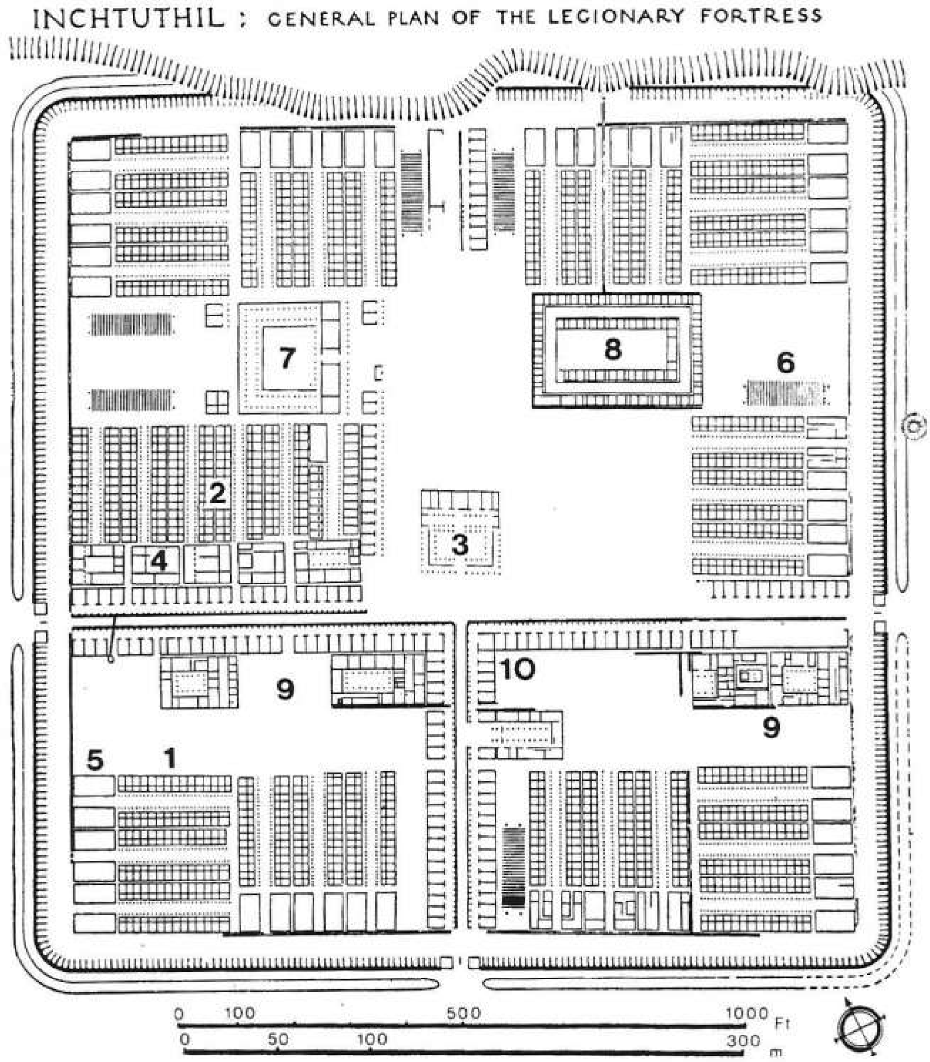
2.12.2 Marius’ camp?

What are we looking for?
We have some information about a large Roman fortress that was built at Inchtuthil in Scotland (56.5409°N, 3.4264°W), and abandoned shortly after that in the 1st c. AD, i.e., nearly two centuries after Marius stayed in the south of France (Breeze, 2002).

Forts, fortresses, fortlets and towers 41



33. The legionary fortress at Inchtuthil, abandoned uncompleted probably in 86 or 87 (plan drawn by I. A. Richmond, but with additions). All the barrack-blocks had been completed but only six of the ten granaries. The barrack-blocks (e.g. 1) were arranged in cohorts, with the first cohort (2) situated in the place of honour to the right of the headquarters building (3): the houses for the centurions of the first cohort (e.g. 4) are larger than those for the other centurions (e.g. 5). The walls and raised floors of the granaries were supported on posts set in rows of parallel trenches (e.g. 6). The fort also contained a workshop (7) and a hospital (8). South of the *via principalis* lay several of the officers’ houses (9), but others remained to be built. Small store rooms (e.g. 10) lay along the streets behind a colonnade.

Inchtuthil fortress, after D. Breeze “Roman Forts in Britain” (2002)

This camp was meant to host one complete legion and covered an area of around 25 ha (450 x 550 m). Supposing that each of Marius’ five legions would require the same camp layout, we might deduce that his army would need 5 times more space than at Inchtuthil, i.e., 125 ha, e.g., an area of 1000 x 1250 m.

This is the kind of area we must look for in the Rhône delta to find Marius' camp …

Further to their discovery of a section of the presumed Marius' canal, Otello Badan and Mario Maretti continued their search with great success. They found an extensive pavement located inside a curve of the canal at about 0.50 to 0.70 m below the present ground level. An accurate GPS positioning was conducted, showing 30 to 40 m wide stretches paved with pebbles placed in the typical fashion used in the French Provence and locally called 'calade'.

Roman 'calades' discovered by O. Badan and M. Maretti, surveyed by R. Fabre.

The total length of the paved stretches shown above is around 2200 m, covering over 7.5 hectare.
A wild guess would be that these paved stretches are border walkways of the camp. The rectangular camp of 1000 x 1250 m mentioned above would then nicely fit here.

Further field investigations will obviously have to be conducted in this area.

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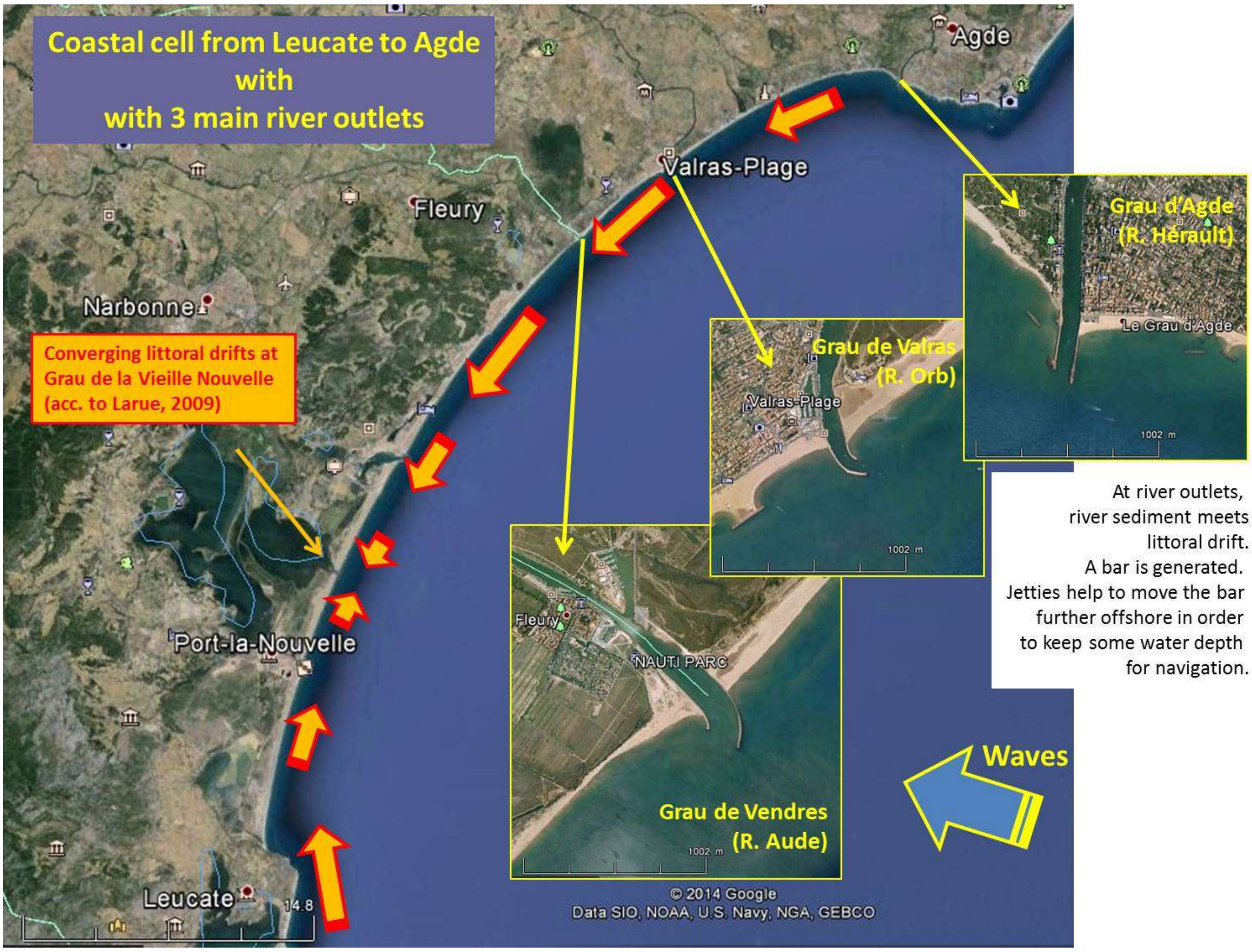
2.13 NARBONNE

Thanks to recent excavations by French archaeologists (Corinne Sanchez and others) the main port of ancient Narbo is now believed to be located at Le Castelou. This location is inside a series of coastal lakes that were more widely open to the sea in ancient times. The dominant NW wind direction in this area makes sailing difficult.
The port was located at the ancient outlet of the Aude river and this proved to be another problem, as sedimentation had to be kept outside the port that was therefore built as a canal that probably had to be extended periodically.

Let's first try to understand natural phenomena related to coastal hydraulics and to river hydraulics, before having a closer look at the wind climate and to related sailing routes.

2.13.1 Maritime hydraulics



Littoral drift is due to oblique wave incidence on the coastline (Larue, 2009, Kulling, 2017).

Wave incidence induces a littoral drift towards SW between Agde and Gruissan and conversely, a littoral drift towards NE is induced between Leucate and Port La Nouvelle. At places where both littoral drifts converge (at Grau de la Vieille Nouvelle), the mean wave incidence must be nil.

Fluvial sediment transport is generated mainly during river floods, i.e., rather unsteady: one or several hundreds of thousand m^3 may be brought in in a few days, while littoral drift, which is more steady, does not exceed a few tens of thousands m^3 per year. This means that most of the river sediment is carried offshore: that is the finer fraction of sediment brought in by the river.

The coarser fraction of river sediment (i.e., sand) settles near the river outlet where the flow velocity is reducing. This sediment gathers as a "bar" located at the place where river and marine currents meet and which is under influence of both, depending on their relative strength.

By building jetties, higher flow velocities are maintained and the bar is pushed offshore, where the water depth is larger, yielding more draught for shipping. However, littoral drift is interrupted by the jetties, inducing accretion on one side and erosion of the same volume on the other side of the outlet. This problem is like that of harbour breakwaters, even without any river outlet. This problem is still unresolved as mechanical transfer of sediment aiming at restoring the interrupted littoral drift is usually too expensive.

2.13.2 River hydraulics

Sky water runs down our mountains and flows into our plains. The order of magnitude of the Aude river discharge ranges between 10 and 100 m^3/s for an average year, but it can reach several thousands of m^3/s during exceptional floods with a return period of around one century (that is as much as the normal Rhône river discharge!).
River beds are covered with fine and coarse sediment. These sediments are moved by water flows: it is usually considered that the sediment discharge is proportional to the water discharge. Hence, a flood will temporarily increase the sediment discharge by eroding the riverbed. The order of magnitude of the sediment discharge of the Aude river was formerly in the millions of m^3/year, but modern works reduced this by a factor 10 according to Ifremer. Similarly, if a structure locally increases the flow velocity, erosion will occur to satisfy the locally increased transport capacity of the flow. As an example, longitudinal dikes (called 'levees' or 'training walls') aiming at containing the flow, induce a flow acceleration and thus riverbed erosion (see picture below from G. Degoutte's book).

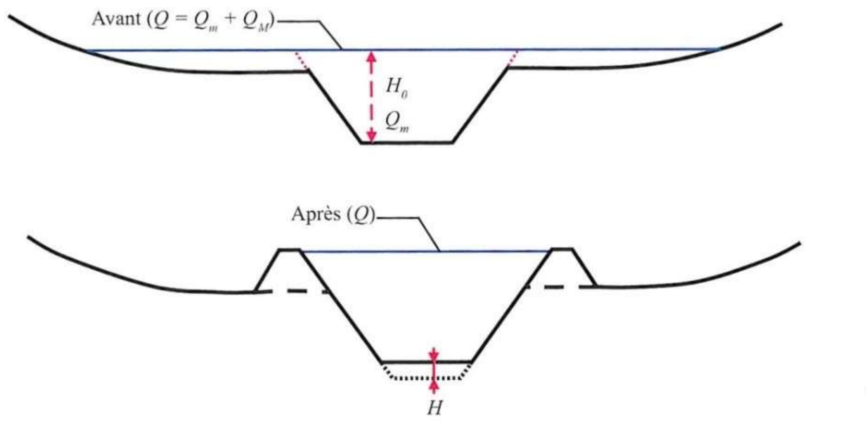
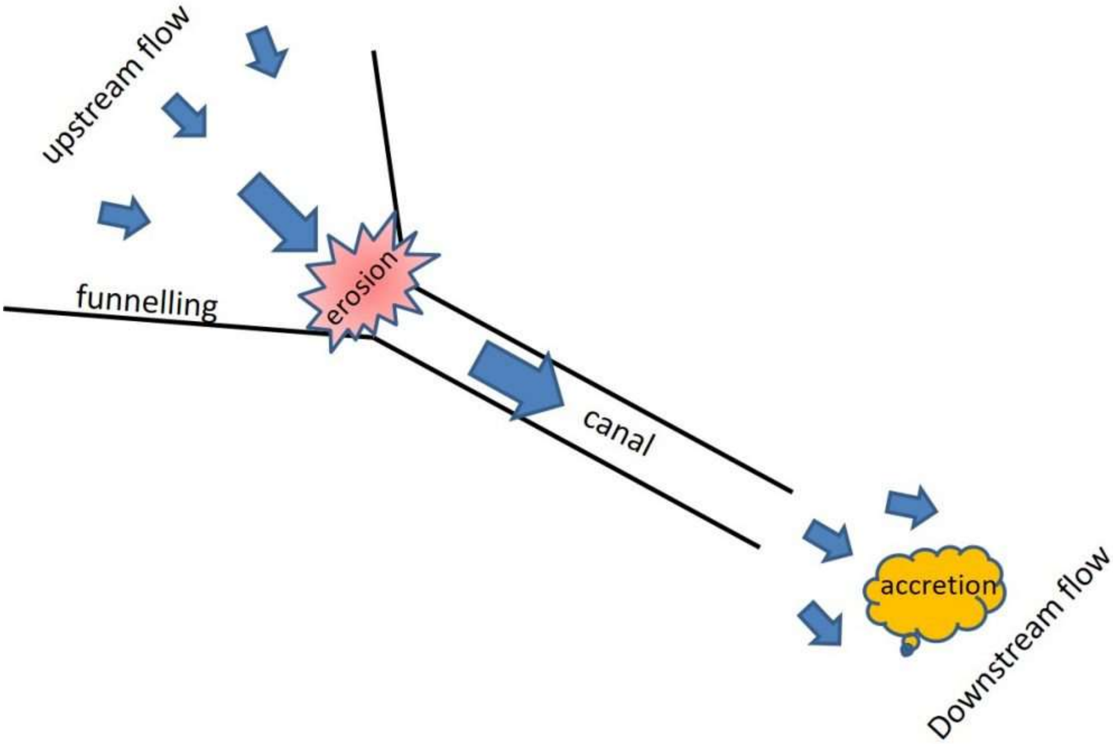


Figure 4.5. Élévation du niveau de l'eau et enfoncement du lit mineur dus à la suppression des débordements dans le lit majeur.

Rising of water level and sinking of river bed level due to stopped lateral overflow on floodplains.

It is therefore possible to determine the width of a canal in order to keep a certain water depth according to the sediment grain size ... if one remembers that beginning of movement of sand with 0.5 to 1 mm diameter is around 0.5 m/s, on 1 to 5 m water depth.



Sediment transport in a canal showing erosion at the intake upstream,
and accretion at the outlet downstream.

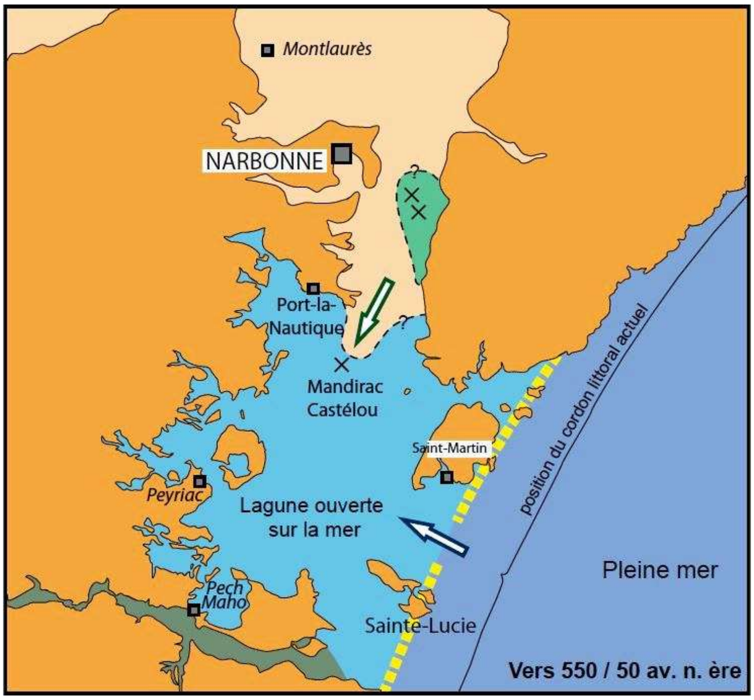
However, two collateral effect must be kept in mind:

1. The upstream flow must be guided towards the canal intake, including during floods, and this may require quite extensive funnelling guide walls (called wing walls) to avoid water flows wandering around during floods.
2. Accretion must be anticipated at the downstream outlet of the canal because of the local decrease of flow velocity. The outlet must therefore be located at a water depth allowing some sedimentation before navigation is hampered. Once the minimum water depth for navigation is reached, the outlet must be dredged ... or the canal length extended!

Obviously, canal extension cannot be indefinite as hydraulic resistance increases with canal length which means that the water level increases at the upstream end of it and eventually the river flows around the wing walls into the flood plains. In other words, the river searches other ways that are more 'open' ... This seems to have been the case in the 14th c. when the Aude river moved to its present estuary north of the Massif de la Clape.

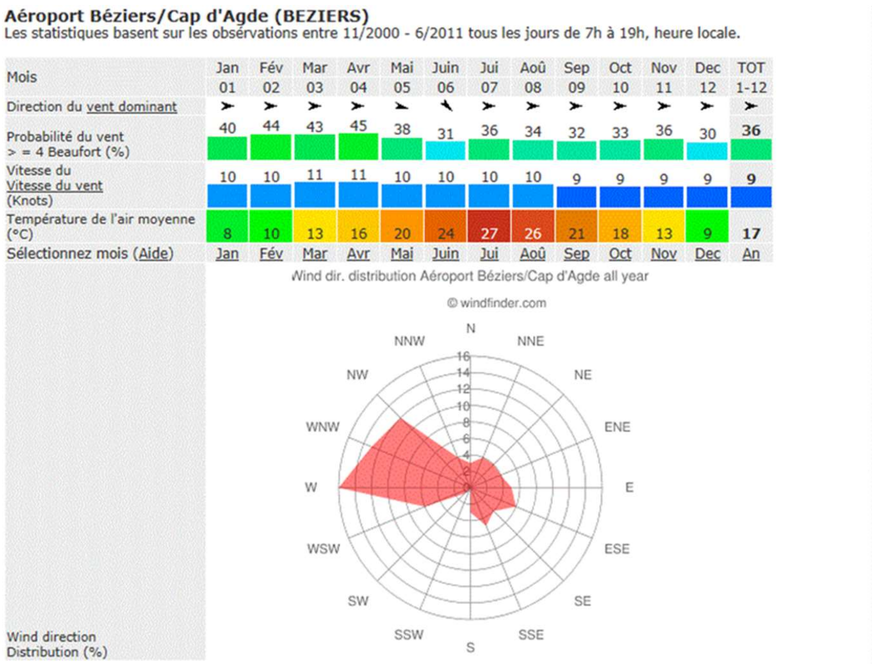
Nature always has the last word.

2.13.3 Sailing routes



Bay of Narbo in ancient times (acc. Salel, 2014)

At the beginning of Christianity, before the Etang de Sigean silted up, the Narbo bay could be entered between the isles of Sainte Lucie and Saint Martin, close to the present Grau de la Vieille Nouvelle (see Faïsse & Salel, 2014).
NW winds made this access to the ancient port of Narbo rather difficult. However, no ship wrecks were found so far in that area ...



Aéroport Béziers/Cap d'Agde (BEZIERS)
Les statistiques basent sur les observations entre 11/2000 - 6/2011 tous les jours de 7h à 19h, heure locale.

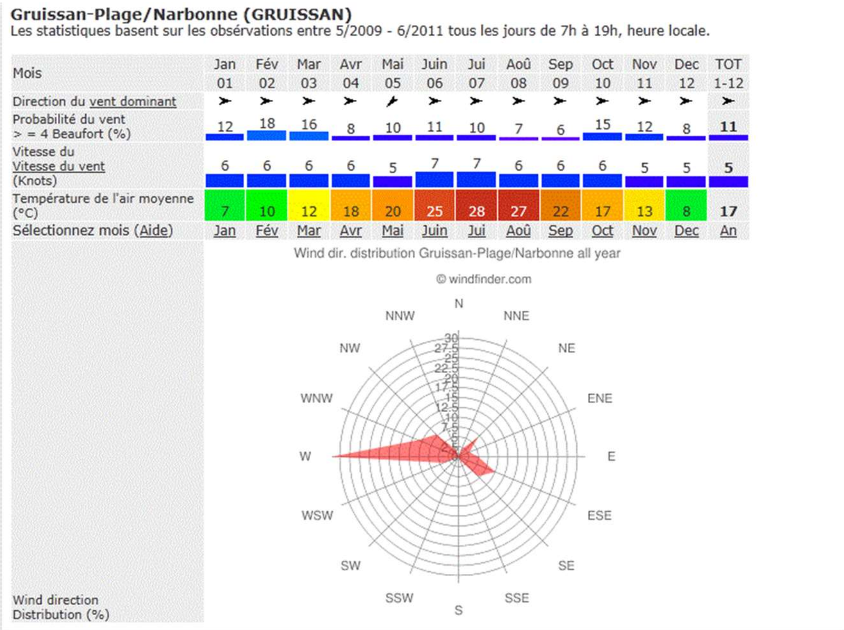
Mois	Jan 01	Fév 02	Mar 03	Avr 04	Mai 05	Juin 06	Jui 07	Aoû 08	Sep 09	Oct 10	Nov 11	Dec 12	TOT 1-12
Direction du vent dominant	➤	➤	➤	➤	➤	↖	➤	➤	➤	➤	➤	➤	➤
Probabilité du vent > = 4 Beaufort (%)	40	44	43	45	38	31	36	34	32	33	36	30	36
Vitesse du Vitesse du vent (Knots)	10	10	11	11	10	10	10	10	9	9	9	9	9
Température de l'air moyenne (°C)	8	10	13	16	20	24	27	26	21	18	13	9	17
Sélectionnez mois (Aide)	Jan	Fév	Mar	Avr	Mai	Juin	Jui	Aoû	Sep	Oct	Nov	Dec	An

Wind direction Distribution (%)

Wind statistics at Beziers airport (2001-2011).

These statistics (©fr.windfinder.com) show wind-direction roses (yearly averages). Monthly averages are also given together with probabilities of wind larger than 4 Beaufort ('Moderate

breeze' of 10-15 knots) which is quite sportive for an ancient ship sailing at close reach.
Beziers airport provides stats over 10 years in an open area.



Gruissan-Plage/Narbonne (GRUISSAN)
Les statistiques basent sur les obsérvations entre 5/2009 - 6/2011 tous les jours de 7h à 19h, heure locale.

Mois	Jan 01	Fév 02	Mar 03	Avr 04	Mai 05	Juin 06	Jui 07	Aoû 08	Sep 09	Oct 10	Nov 11	Dec 12	TOT 1-12
Direction du vent dominant	➤	➤	➤	➤	↗	➤	➤	➤	➤	➤	➤	➤	➤
Probabilité du vent > = 4 Beaufort (%)	12	18	16	8	10	11	10	7	6	15	12	8	**11**
Vitesse du Vitesse du vent (Knots)	6	6	6	6	5	7	7	6	6	6	5	5	**5**
Température de l'air moyenne (°C)	7	10	12	18	20	25	28	27	22	17	13	8	**17**
Sélectionnez mois (Aide)	Jan	Fév	Mar	Avr	Mai	Juin	Jui	Aoû	Sep	Oct	Nov	Dec	An

Wind statistics at Gruissan (2009-2011).

Gruissan's stats are from an area more protected from NW winds because of the local landscape (Massif de la Clape).

Let's conclude that winds on the Etang de Sigean and the Etang de Bages are mostly NW and larger than 4 Beaufort during 30 to 40% of time.
At Gruissan, winds are mostly westerlies larger than 4 Beaufort only 5 to 15% of time.

Sailing options from the sea to the port of Narbo.

In order not to be facing the wind, sailing ships have to tack reaching an angle with the wind direction of not less than around 60° (see more on this in 'Ancient sailing') as shown on the picture above. In front of the hill of Bages ships made a starboard turn towards Le Castelou where it is believed the main port of Narbo was located on the ancient Aude river estuary. However, this tacking sailing technique is very unconfortable for both ship and crew, and it was used only if there was no other choice.

Access was probably also possible through the Grau de Gruissan and/or the Grau de Grazel, ships sailed on the the Etang de Gruissan at the toe of the Gruissan village on top of its hill (Guy, 1981). Sailing north or south of the Gruissan village, they had to cross two narrows with a minimum width of 250 to 350 m between the hills. Passing both narrows was difficult with head winds from west to NW and this area probably required help of land-based hauling. Nevertheless, sailing this route was easier than the route via the Grau de la Vieille Nouvelle and Bages, and it was obviously even more easy with the rather infrequent easterlies. Moreover, a group of around ten shipwrecks was found near Gruissan, perhaps showing the sailors' preference for that access to Narbo.

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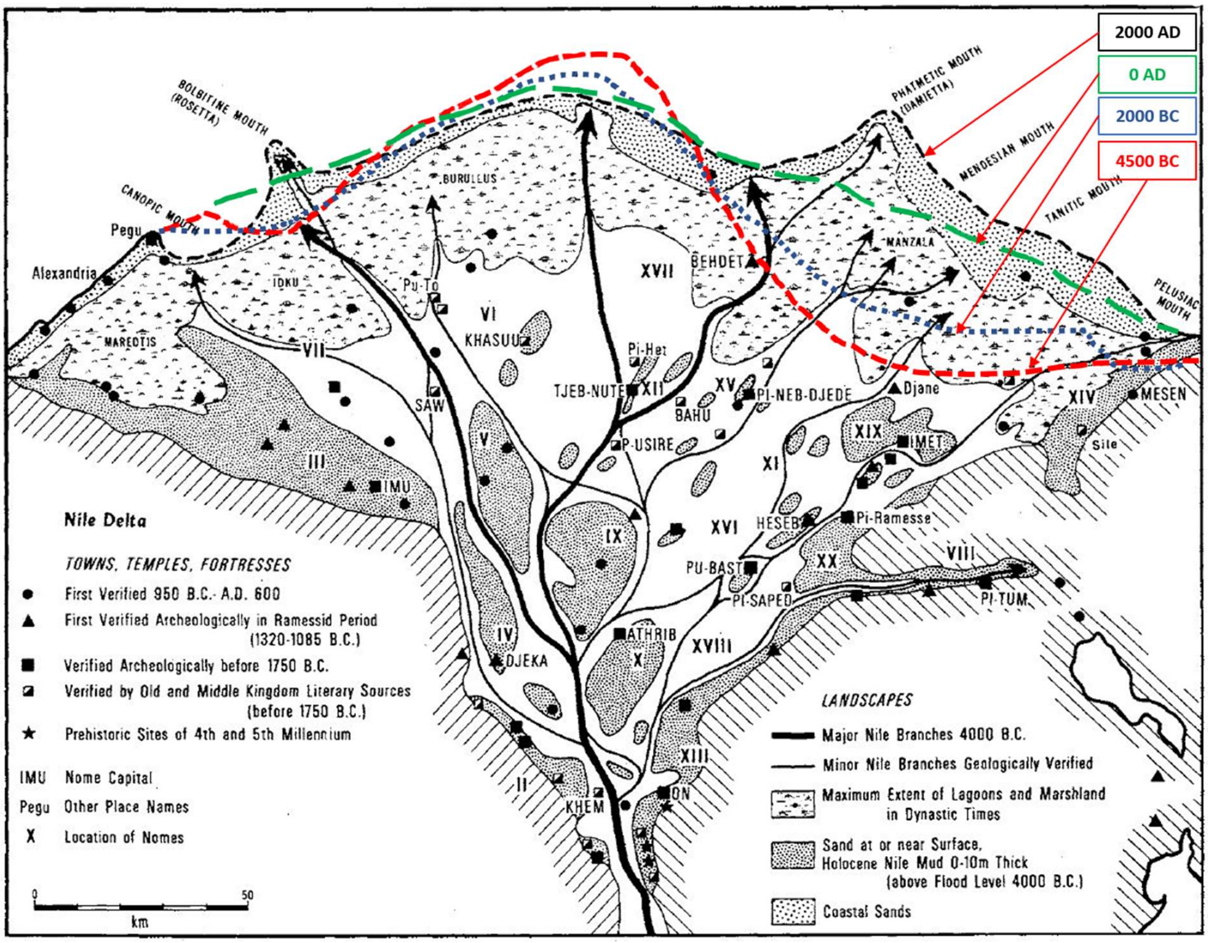
See also the nice and detailed Ports antiques de Narbonne (in French)

2.14 The NILE DELTA

Our aim in this short study is to put some order into the various ancient branches and outlets of the Nile … An almost impossible task as archaeology can help finding the location of ancient water courses and even dating them, but it will usually not provide their names (with the notorious exception of 'Darius' canal', also called 'Necho's canal').

But let's try by starting with the pre-dynastic Nile Delta.



The Nile Delta, from 4500 BC to 2000 AD (based on Butzer, 1976, with coastlines from Stanley, 1998).

As shown in the figure above, the Nile flowed straight to the north from Memphis towards modern Baltim, via ancient Athribis, Bousiris and Sebennytos. The bell-shaped coastline shows the effect of massive sedimentation around this main outlet of the "Great River" Nile. Sediment was moved eastward along the coastline due to action of dominant waves from NW. When this central Nile branch lost power, the Damietta branch took over and sediment accumulated in the eastern part of the Delta (Stanley, 2017). In addition, two lateral branches existed already at an early time: the Pelusiac branch to the east, and the Canopic branch (also called Herakleotic branch) to the west.

This description is very close to Herodotus' one.

Nile Delta acc. to Herodotus (History, book 2, chap. 17), ca. 450 BC
(source: Loeb Classical Library, 1920, https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Herodotus/2A*.html)

> Now as far as the city Kerkasoros [north of Memphis] the Nile flows in one channel, but after that it parts into three. One of these, which is called the Pelusian mouth, flows eastwards; the second flows westwards, and is called the Canopic mouth. But the direct channel of the Nile, when the river in its downward course reaches the

sharp point of the Delta [i.e., the apex of the triangle, near Memphis], flows thereafter clean through the middle of the Delta into the sea; in this is seen the greatest and most famous part of its waters, and it is called the Sebennytic mouth. There are also two channels which separate themselves from the Sebennytic and so flow into the sea, by name the Saïtic and the Mendesian. The Bolbitic and Bucolic mouths are not natural but dug channels.

From Herodotus, we understand that at least four other branches exist in addition to the three main branches, leading to a total of seven branches.

A similar picture is provided by Strabo, about four centuries later, where seven outlets are still mentioned, but it is noteworthy that he mentions three main branches (Pelusiac, Pathmitic and Canopic-Herakleotic), with other outlets in-between.

Nile Delta acc. to Strabo (Geography, book 17, chap. 1), ca. 25 BC
(source: https://penelope.uchicago.edu/Thayer/E/Roman/Texts/Strabo/17A1*.html)

> [4] The Nile flows from the Aethiopian boundaries towards the north in a straight line to the district called "Delta," and then, being "split at the head," as Plato says, the Nile makes this place as it were the top of a triangle, the sides of the triangle being formed by the streams that split in either direction and extend to the sea - the one on the right to the sea at Pelusium and the other on the left to the sea at Canopus and the neighbouring Herakleium, as it is called, - and the base by the coast-line between Pelusium and the Herakleium. […] Now these are two mouths of the Nile, of which one is called Pelusiac and the other Canopic or Herakleotic; but between these there are five other outlets, those at least that are worth mentioning, and several that are smaller; for, beginning with the first parts of the Delta, many branches of the river have been split off throughout the whole island and have formed many streams and islands, so that the whole Delta has become navigable. […]

> [18] After Canopus, one comes to the Herakleium, which contains a temple of Heracles; and then to the Canopic mouth and the beginning of the Delta. […] After the Canopic mouth one comes to the Bolbitic mouth, and then to the Sebennytic, and to the Pathmitic, which is third in size as compared with the first two which form the boundaries of the Delta [the Canopic and Pelusiac branches]; for not far from the vertex of the Delta, the Pathmitic splits, sending a branch into the interior of the Delta. Lying close to the Pathmitic mouth is the Mendesian; and then one comes to the Tanitic, and, last of all, to the Pelusiac. There are also others in among these, pseudo-mouths as it were, which are rather insignificant. Their mouths indeed afford entrance to boats, but are adapted, not to large boats, but to tenders only, because the mouths are shallow and marshy. It is chiefly, however, the Canopic mouth that they used as an emporium, since the harbours at Alexandria were kept closed, as I have said before. After the Bolbitic mouth one comes to a low and sandy promontory which projects rather far into the sea; it is called Agnu-Ceras. And then to the Watch-tower of Perseus and the Wall of the Milesians; for in the time of Psammitichus (who lived in the time of Cyaxares the Mede) the Milesians, with thirty ships, put in at the Bolbitic mouth, and then, disembarking, fortified with a wall the above-mentioned settlement; but in time they sailed up into the Saïtic nome, defeated the city Inaros [unlocated] in a naval fight, and founded Naucratis, not far above Schedia. After the Wall of the Milesians, as one proceeds towards the Sebennytic mouth, one comes to two lakes, one of which, Boutic, has its name from the city Bouto, and also to the Sebennytic city, and to Saïs, the metropolis of the lower country.

Another ancient author is **Chaeremon of Alexandria (Book of Phtomyris, book 2, chap. 73), ca. 85 AD**, who was born in Naucratis, more or less confirms the above descriptions.

Ptolemy adds a distinction between “outlets” (or mouths) and “branches”.

Nile Delta acc. to Ptolemy (Geography, book 4, chap. 5), ca. 150 AD
(source: Brady Kiesling, https://topostext.org/work/209)

> [4.5.10] The seven mouths of the Nile [with Longitude , Latitude in degrees, minutes]:
>
> the Herakleotic or Canopic mouth: 60°50' , 31°05'
>
> the Bolbitic mouth: 61°15' , 31°05'
>
> the Sebennytic mouth: 61°30' , 31°05'
>
> the Pineptimi pseudo-mouth: 61°45' , 31°05'
>
> the Diolkos pseudo-mouth: 62°10' , 31°10'
>
> the Pathmitic mouth: 62°30' , 31°10'
>
> the Mendesios mouth: 62°45' , 31°10'
>
> the Tanitic mouth: 63°00' , 31°15'
>
> the Pelusiac mouth: 63°15' , 31°10'
>
> [4.5.39] The so-called Great Delta begins where the Agathodaimon branches off from the Great river and flows through the Herakleotic mouth [and ends] into the so-called Boubastic, which flows out through the Pelusiac mouth. The position of the fork of the Delta is 62°00' , 30°00' [Memphis-Babylon is located by Ptolemy at 62°15’ , 30°00’]
>
> [4.5.40] The so-called Little Delta is where the Boubastic river splits into the Bousiritic river, which flows out through the Pathmitic mouth, position of which [fork] is 62°40' , 30°20' [north of Bousiris which is located by Ptolemy at 62°30’ , 30°15’, probably at Sebennytos located at 62°20' , 30°20'].
>
> [4.5.41] One might even mention a third delta somehow between the two aforementioned, where the Boubastic forks into the one that flows through Athribis city and the Pineptimi mouth. This is at 62°15' , 30°05' [a few km north of Memphis-Babylon which is located by Ptolemy at 62°15’ , 30°00’].
>
> [4.5.42] At the Great Delta two rivers branch off toward the north from the river Agathodaimon; the first is called the Thermouthiac or Phermouthiac river, which flows out through the Sebennytic mouth; its fork is at 61°30' , 30°15' [south of Nikiou which is located by Ptolemy at 61°30’ , 30°20’].
>
> [4.5.43] Second is the so-called Taly river, which flows through the Bolbitic mouth; the branching of the Taly river is at 61°00' , 30°50' [Hermopolis Mikra is located by Ptolemy at 61°00’ , 30°50’].
>
> [4.5.44] The Boutic river which runs along at a nearly equal distance from the seacoast joins the Thermouthiac, the Athribitic, the Bousiritic and the Boubastic, from which others springing from adjacent marshes and lakes flow into the sea through the remaining mouths, some of which are connected, as we have said, with the Great river.

The main features of Ptolemy’s description are a) a list of coordinates of 7 river outlets and 2 pseudo-outlets (chap. 4.5.10), b) a list of river names with coordinates of 4 forks (embranchments, confluents) (chap. 4.5.39 to 43) and c) a stream flowing in an east-west direction (chap. 4.5.44). In addition, Ptolemy provides a description of the nomes and major cities of Delta in his chapters 4.5.46 to 4.5.54.

In order to locate the 4 forks mentioned by Ptolemy, we added the names of the nearest ancient cities according to Ptolemy’s own coordinate system in brackets ([city]).

These texts are referring directly to rivers and outlets, but other texts also refer indirectly to them (Redon, 2018).

River outlets

We know that Ptolemy was somewhat mistaken on his longitudes (see http://www.ancientportsantiques.com/ancientmaps/#2) but the distances between two places may give a valuable indication. Furthermore, we know that one minute of longitude (1' = 1/60 degree) near Alexandria is ca. 1570 m.

Ptolemy's longitudes of the Canopic and Pelusiac mouths are respectively 60°50' and 63°15', that is an east-west distance of 2°25', or 145', or 228 km. If we place the Canopic mouth at Izbat as Sittin (31.28°N, 30.15°E), just east of the recently discovered ancient city of Thonis-Herakleion (https://www.franckgoddio.org) and measure an east-west distance of 228 km, we end up within a few kilometres of the ruins of Pelusion. This confirms that the scale of Ptolemy's east-west distances is quite correct in the Nile Delta and that we might try to locate other river outlets with his longitudes.

River forks

Although the above shows quite a good accuracy for east-west positioning of river outlets, we shall avoid further use of Ptolemy's coordinates as we know that each time this was attempted in the past, it ended up in a very distorted picture because of the many approximations (and possible errors) in his data (Litinas, 2015). We shall rather use his coordinates to locate ancient cities, the locations of which are known in the modern WGS 84 coordinate-system (EES Delta Survey, 2016).

Even the location of the upstream fork where the Nile first splits into branches at the apex of the Delta near Memphis-Babylon-Kerkasoros (Greater Cairo), is a subject of discussion for Mark Lehner (2020) in his search for the early pharaonic ports near Gizeh.

River branches

Quite clearly, the names of the river branches are related to the cities they were leading to. At this stage, we may try to put some order into the available data by listing branches and outlets from west to east:

Name of river branch	Fork location (confluence)	Name of river outlet	Ptolemy's distance east of Canopic mouth	Name/location of modern outlet	Ancient authors
Agathodaimon, Herakleotic branch	Memphis-Babylon (or Kerkasoros?)	Canopic mouth, Herakleotic mouth	0 km	Izbat as Sittin, west of the port of Maadiyya	Ht St Pt
Taly Potamos	Hermopolis Mikra	Bolbitic branch			Pt
Bolbitic branch	South of Cabasa?	Bolbitic mouth	39 km	Rosetta is at only 27 km	Ht St
Thermouthiac, Phermouthiac branch	South of Nikiou	Boutic mouth (Sebennytic mouth: Pt)	63 km	Bouto is at 56 km	St Pt
Great River Athribitic branch, Sebennytic branch	Memphis-Kerkasoros	Sebennytic mouth (Pineptimi pseudo-mouth: Pt)	86 km	Baltim is at 89 km	Ht St Pt

Boutic branch	Sebennytos?	Thermouthiac branch			Pt
Saïtic branch	Natho?	Thermouthiac branch?			Ht
Perhaps an ancient track of the Bousiritic branch? or the man-made Bucolic branch?	Diospolis Inferior?	Diolkos pseudo-mouth	126 km	Gamasa is at 133 km	Ht Pt
Bousiritic branch	Sebennytos, near Bousiris	Pathmitic mouth	157 km	Damietta is at 157 km	Pt
Mendesian branch	?	Mendesian mouth	181 km	Birket el-Amriti? At 181 km	Ht Pt
Tanitic branch	?	Tanitic mouth	204 km	Port Saïd is at 205 km	Pt
Boubastis branch	Memphis-Kerkasoros	Sebennytic branch at Sebennytos			Pt
Pelusiac branch	Near Boubastis	Pelusiac mouth	228 km	Pelusion	Ht St Pt

Ancient authors: Ht: Herodotus, Pt: Ptolemy, St: Strabo

Both Herodotus and Ptolemy mention the Canopic and the Pelusiac outlets. The Herakleotic branch leads from Memphis to Naucratis, to Hermopolis Mikra and to the Herakleotic (Canopic) mouth. The track of the Pelusiac branch is less certain, especially near the Pelusiac mouth, and it must be remembered that the pre-dynastic coastline was far inland in this area, probably on a line from Herakleopolis Mikra to Panephysis (Bietak, 1975, 2011; Chartier Raymond, 1992; Stanley, 1998).

Herodotus adds that the Sebennytic outlet, yielding the largest stream of the “Great River”, flows straight north of Memphis to Athribis, Natho, Bousiris and Sebennytos. The outlet must be near Paralios (modern Baltim) as this area shows the largest accretion pushing the coastline to the north (Stanley, 1998). Herodotus’ Sebennytic outlet must therefore be the same as Ptolemy’s Pineptimi “pseudo-outlet”. This peculiar way of calling this outlet a pseudo-outlet might be due to the fact that this outlet was already clogged in his time. This makes sense from a hydraulic point of view, as the Sebennytic branch was getting just too long and was thus hampered by a large hydraulic resistance which would favour other branches like the Mendesian and the Tanitic branches which were the shortest way to the sea at that time. Massive sedimentation of the eastern side of the Delta would occur as from that time (Stanley, 1998). In a similar way, the Diolkos pseudo-outlet is possibly an ancient sedimented outlet that was used as a slipway for ships in Ptolemy's time. It could also be the man-made outlet of the Bucolic branch mentioned by Herodotus which would flow from Diospolis Inferior near the Bousiritic branch, to the sea.

In the western Delta area, Ptolemy mentions the Taly Potamos flowing to the Bolbitic outlet (probably via the Bolbitic branch) after splitting off from the Herakleotic branch near Hermopolis Mikra. However, he does not mention the Saïtic branch and we do not know where was its outlet. After splitting off from the Herakleotic branch south of Nikiou, the Thermouthiac branch flows to Strabo’s Boutic outlet, near Bouto (Wilson, 2012) which is called “Sebennytic mouth” by Ptolemy.

Herodotus' Saïtic branch is not mentioned by Ptolemy, but from Herodotus' description, we might conjecture that this branch might be a link between the central Great River (Sebennytic branch) and the western branch (Thermouthiac branch) flowing to the west from Natho to Saïs via Tawa. Similarly, Herodotus' Mendesian branch would flow to the east via Mendes. The Tanitic branch is not mentioned by any of the three ancient authors, but may be supposed to flow to Tanis from Boubastis or from Avaris.

Let's now consider the Boubastic branch which probably causes most of the confusion in the overall Delta picture. This branch is mentioned both in the south (with the Pelusiac outlet) and in the north with the Bousiritic branch flowing to the Pathmitic outlet. This branch must thus flow from Memphis to Boubastis first, where the Pelusiac branch splits off, and then head for Bousiris, where the Bousiritic branch splits away towards the Pathmitic outlet. The Boubastic branch is supposed to end up into the Sebennytic branch at Natho (Redon, 2018).

The last flow mentioned by Ptolemy is the Boutic branch between the Thermouthiac, Athribitic, Bousiritic and Boubastic branches. A closer look at the map will show that this branch needs to flow between Bouto (on the Thermouthiac branch) and Sebennytos located at the junction of the Athribitic and Bousiritic branches, and connected with the Boubastis branch further south. It would pass at Xoïs. This branch would thus be much shorter than shown by other authors (Talbert's Barrington Atlas, 2000; Schiestl, 2021).

The Nile to Red Sea canal

Special attention should be devoted to Necho's Nile to Red Sea canal (Nekou Diorux), even if it was Darius who realised it about a century later, we should remember that pharaoh Necho II was very interested in maritime expeditions as he was the one who launched a circumnavigation of Africa around 600 BC. Several places are explicitly mentioned as harbours on the Pithom stela (Arsinoe, Per Atum), and by Agatharchides (Arsinoe), Diodorus (Arsinoe), Strabo (Arsinoe, Cleopatris), Pliny (Daneon Portus) and Lucian of Samosata (Clysma).
The Nile to Red Sea canal was called Nekou Diorux and located in the archaic Tjekou valley, today's wadi Tumilat connecting the Pelusiac Nile branch to the Bitter lakes. As a possible lead for the location of this canal, we might consider that when Darius had it (re)dug (ca. 500 BC), he placed his four commemorative quadri-lingual stelae at places where many people would see them, e.g., at ports on the Nile to Red Sea canal. The first stela was near Tell el-Maskhuta (ancient Tjekou, Heroonpolis) which is the closest to the Pelusiac branch of the Nile Delta. The 2nd stela was located at Serapeion, Serapeum, about 10 km south of Ismailia. The 3rd stela was near the promontory called Mahattat al Kibrit, Kabret, located between the Small and the Great Bitter lakes, at Chalouf, Shaluf. The 4th stela was at Koubri, 6 Km north of Suez (Tuplin, 1991).

But let's widen our perspective on the available documentation:

- *The four Darius stelae (515 BC)* inform us that Darius had a canal dug from Tell el-Maskhuta to Koubri, if we assume the four stelae have been placed along the canal.
- *Herodotus (ca. 450 BC)* describes a canal first built by Necho (ca. 600 BC) from the Pelusiac branch of the Nile near Bubastis, to the Red Sea which he locates near Patumos.
- *Aristotle (ca. 350 BC)* notes that both Sesostris and Darius feared an inundation of the Nile Delta if they finalised the Nile to Red Sea canal.
- *The Pithom stela (264 BC)* tells us that Ptolemy II founded Arsinoe in Kemwer province (the latter probably located near the Bitter lakes, acc. to Thiers, 2007) from where his ships left to the southern Red Sea, returning laden with elephants and precious goods and welcomed back by the king at Per Atum.
- *Diodorus (1st c. BC)* mentions the same canal ending with locks at Arsinoe.

- *Strabo (ca. 25 BC)* tells us about the lock closing the canal built by Ptolemy II. Strabo also tells about the construction of Aelius Gallus' fleet at Cleopatris, which should therefore be located not too far from the open sea. Furthermore, he informs that the canal could be used by large ships and that it was connected to the Pelusiac branch at Phakoussa, which is 30 km downstream of Bubastis yielding a fairly impossible north-south connection to the Nile to Red Sea canal crossing a 30 m high hill east of al-Qorin.
- *Pliny (ca. 75 AD)* might be slightly reinterpreted for Daneon Portus from where a canal of 62 500 paces (92.5 km) would lead to the Pelusiac branch (near Bubastis), but only 37 500 paces (55.5 km) were built by Ptolemy II, leading near Tell el-Maskhuta. The distance from Déversoir (northern end of the Great Bitter lake, near Difarsuwar air base) to the Pelusiac branch near Bubastis is around 87 km and Daneon Portus might therefore be near Déversoir.
- *Claudius Ptolemy (ca. 150 AD)* mentions Arsinoe at 20' of latitude due north of Clysma, which leads near Mahattat al Kibrit, which may have been a fort and where a major police station on the modern Suez Canal is still located today.
- *Lucian (ca. 175 AD)* mentions navigation from the Nile to Clysma, inducing an operational canal in the 2nd c. AD.

Aubert (2004) provides a superb review of the history of the Nile to Red Sea canal. Excavations were conducted at Qulzum in 1930-32 and reported by Bruyère (1966). Cooper (2009) provides an estimated route of the canal and a redrawing of a survey by Bourdon (1928) showing the location of the supposed lock at the Suez entrance of the canal, next to an inner- and an outer-harbour and next to a ford crossing to the Sinai Peninsula.
As reported by Strabo (Geog. 17.1.25), we can understand fears to jeopardise the water quality of the Bitter lakes, the Nile to Red Sea canal and even the Nile Delta, but we can confirm today that a lock preventing the risk of inundating the Nile Delta during high Red Sea water levels (only 1 or 2 m above its Mean Sea Level, resulting from high tide combined with southern wind) was not required. However, the risk of changing the existing fresh water Bitter lakes into salt water lakes was real when creating a connection with the Red Sea, and this justified a lock. Such a lock was useful as long as the Nile would provide a volume of fresh water large enough to compensate the severe evaporation on the Bitter lakes[32].
When both Bitter lakes were fresh water lakes, they could not be considered as a marine area and Clysma (Suez) must therefore have been the only true sea-port at the northern end of the Red Sea since archaic times. Cargo was most probably transhipped there on- or from large sea-going ships onto smaller vessels sailing on the Nile to Red Sea canal, even if Strabo notes that the canal could be used by large ships. The location of the eastern end of this canal was depending on its sedimentation and on the Nile floods. It could therefore be at Tell el-Maskhuta in Necho's days, at Déversoir, at Qulzum in Darius' days and back at Tell el-Maskhuta in Ptolemy II's days.

Concluding, it might perhaps be suggested here that although Ptolemaic Arsinoe-Cleopatris and Greco-Roman Clysma are located near Kom el-Qulzum, locating Arsinoe-Cleopatris at Kabret (or at Déversoir) also makes sense. Déversoir, might be another, not yet found, port on the canal, possibly Pliny's Daneon Portus, at ca. 87 km of the Pelusiac branch. Serapeion might also be a port at ca. 75 km of the Pelusiac branch. Further upstream, Tell el-Maskhuta is Archaic Tjekou, Per Atum, Pitoum, Patumos, Heroonpolis, at ca. 54 km of the Pelusiac branch, and Tell el Retabeh is archaic Pithom at ca. 40 km of the Pelusiac branch (Thiers, 2007).

[32] The modern Suez Canal (opened in 1869, initially 8 m deep, now 24 m) changed this situation completely as no locks were included and salt water could flow freely into the Bitter lakes, and due to above mentioned evaporation, the Bitter lakes are now even more salty than the Red Sea.

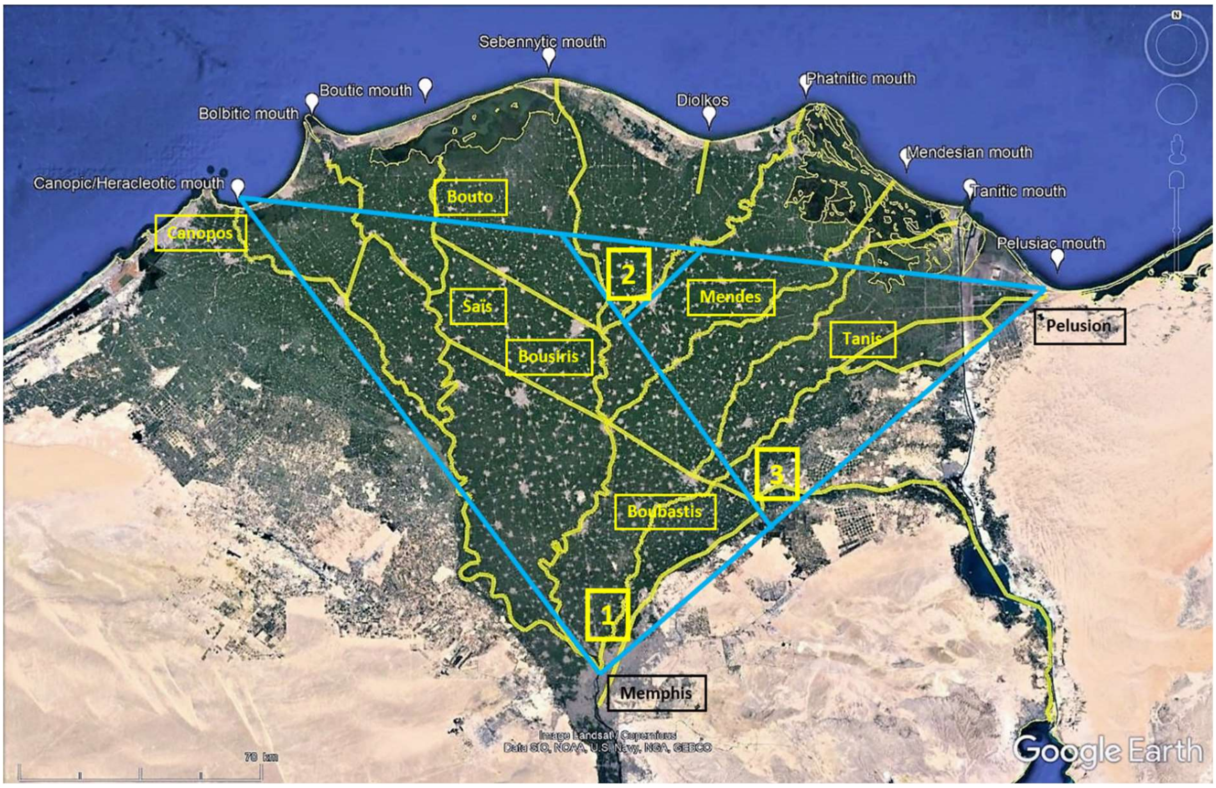
For completeness, it may be noted that Ptolemy mentions a later addition to the canal, called Traianos Potamos (Trajan's river), flowing through Babylon (Memphis), Heliopolis and Heroonpolis.

Conclusion

As most Nile branches have been moving around due to natural meandering, it makes little sense to look for a single fixed track for each of them. The Nile branches mentioned in this study are shown on the map hereafter where they have been placed on the present streams when possible. However, some tracks are completely unknown to archaeology and are therefore pictured by straight lines.

Concluding, it may be said that all river branches, forks and outlets mentioned by Herodotus, Strabo and Ptolemy have been satisfactorily positioned on the map without much need for changing coordinates, names, or accepting errors by the ancient authors. In addition, Ptolemy’s beautiful scheme with three imbricated deltas is validated.

It must be realised that this short study aims at providing an overall view of the Delta river branches and outlets. However, many uncertainties remain, and there is still a great deal of work to be done to locate ancient watercourses.



Three imbricated deltas of the Nile Delta.

List of modern coordinates

Ancient name	Modern name	Latitude (°N)	Longitude (°E)
Athribis	Tell el-Atrib	30.47060	31.18800
Boubastis	Tell Basta	30.57250	31.51200
Bousiris	Abusir	30.90630	31.24100
Bouto	Tell Fara'un	31.19556	30.74222
Canopus	Abu Qir	31.32250	30.05830
Herakleopolis Mikra	Tell Belim	30.97880	32.17200
Hermopolis Mikra	Damanhur	31.02160	30.42080
Memphis-Babylon	Cairo, Hanging Church	30.00510	31.23010
Memphis-Kerkasoros	Cairo, Rod El Farag	30.08600	31.22900
Mendes	Tell el-Ruba	30.95800	31.51650
Nikiou	Zawiyet Razin, Kom Manous	30.41000	30.84800
Panephysis	el-Manzala	31.15000	31.93330
Pelusion	Tell el-Farama	31.03770	32.54960
Saïs	Sa el-Hagar	30.96500	30.76850
Sebennytos	Samanud	30.95820	31.24490
Tanis	Tell San el-Hagar	30.97490	31.87714
Tawa	Tantah	30.78390	30.99910
Thonis-Herakleion	Abuqir bay	31.28160	30.11980
Xoïs	Sakha, Djeqapir	31.08950	30.95090

Hypothetical ancient Nile Delta with river outlets and river branches.

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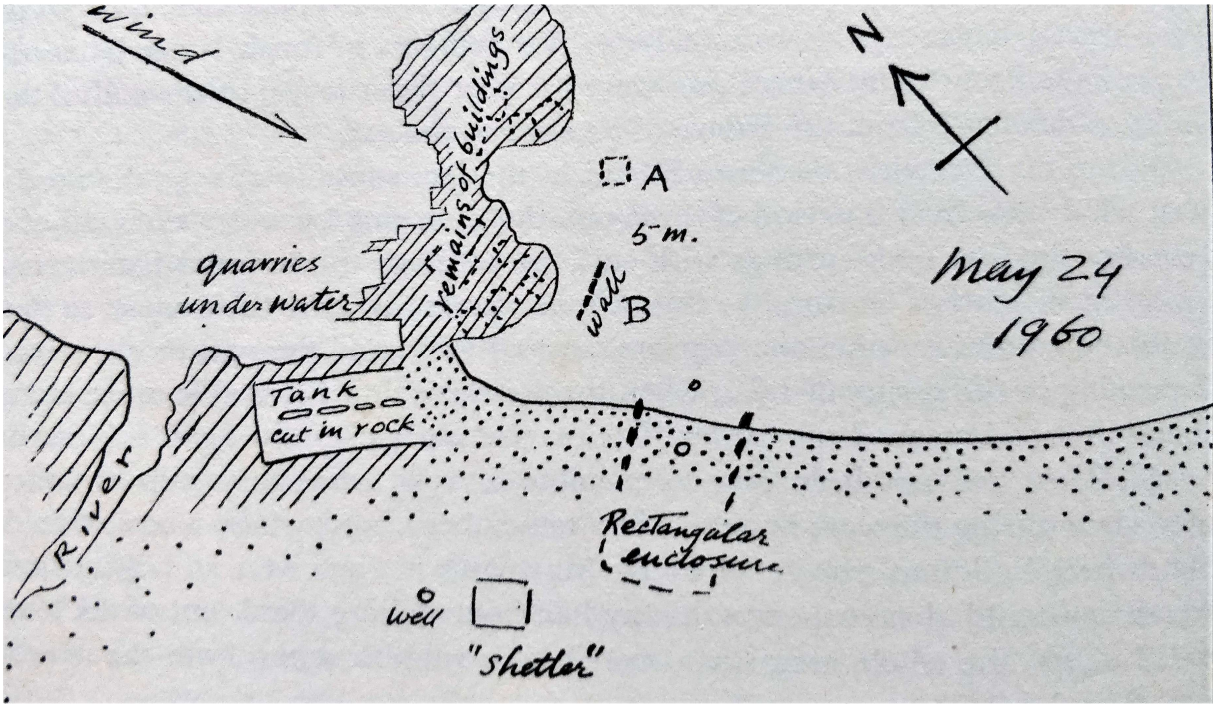
2.15 NIROU KHANI

This rock-cut structure has been inspected by several authors. Let's quote them first.

Frost (1963, p 107-109):

"*Evans himself, Dr Marinatos and other archaeologists recognized the remains as being part of a harbour. […]*

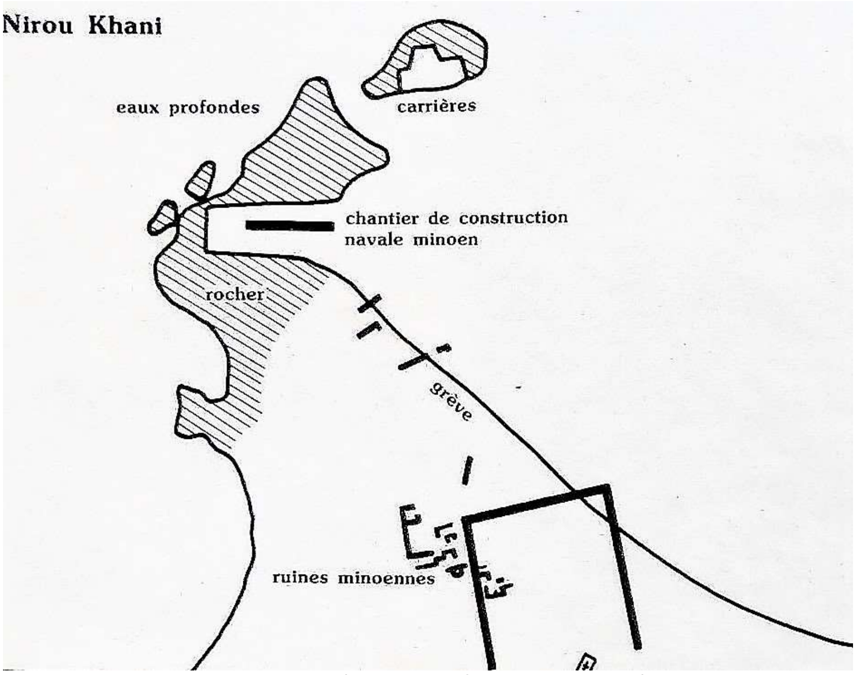


Nirou Khani; some harbour installations from a sketch in my log book.
Hatching indicates rock, and stippling sand (Frost, 1963).

The sketch was a personal aide mémoire, the various features were drawn relative to each other but without being measured. I have since added the buildings mentioned by Dr Marinatos.
The windward or north-westward slopes of the promontory are cut at water level and below by quarries. […}
In the report describing Dr Marinatos' excavations of 1926 two structures, 'a flagged shelter of poros stone containing quantities of late Minoan jars and perforated ceramic spheres', and also a water well, were excavated in the field now covered by rubbish dump. 'A large rectangular space with walls of big limestone blocks, one meter across' started in the field, to the east of the well and 'shelter', ran across the beach and ended in the sea. The clou of the whole area was the tank-like cutting at the junction of the rocky promontory and the beach. This cutting '40 meters wide and 42 meters long is divided into two unequal compartments by a wall; the whole is now about 1.80 meters below sea level. The use of the construction will only be explicable if it is possible to determine the degree of subsidence of the land. In any case it was either a mooring for boats or a Minoan shipyard. The port which was the first Minoan example to be discovered, must have had connections with Knossos'
I have translated this passage from the original report on Nirou Khani, but I suspect that there must have been a misprint where distances are concerned. The tank in question is nearer 10 x 12 meters than 40 x 42."

Flemming & Pirazzoli (1981, p 74-76):

> *"Une structure rectangulaire taillée dans la roche a été différemment interprétée. Marinatos (1926), qui estimait la profondeur de l'eau à 1.8 m, à l'intérieur, y voyait une darse ou un chantier de construction naval. Frost (1963, p 107-109) parle pour Nirou Khani de carrières et de ce qu'elle croit être une construction submergée. Elle en déduit pour ce site une submersion de 4-5 m. Cette interprétation implique que la 'darse' était à sec. Or, d'après les observations de N.C. Flemming, la submersion a été inférieure à 5 m.*



Nirou Khani (Flemming & Pirazzoli, 1981)

> *Cependant le bassin ne semble avoir la forme ni d'une darse, ni d'une cale, ni même d'un chantier de construction. D'autre part, la submersion des carrières et des murs minoens à l'est du bassin indique une montée du niveau de la mer d'au moins 1.75 m. Cette submersion apparait insuffisante pour inonder la structure rectangulaire, qui était donc à sec lors de son utilisation."*

In the same article Flemming & Pirazzoli estimate the relative sea level rise between 1.2 and 2 m at Nirou Khani, indicating that the structure bottom was close to the seawater level in ancient times.

Blackman (2013, p 12):

> *"A promising parallel for the Minoan 'shipsheds' at Kommos has recently been discovered on the north coast of Crete at Poros/Katsamba (Herakleion) […]. We thus have a plausible parallel for Minoan 'storage shipsheds', but Minoan parallels for the later 'covered slipways' have not been found, unless one accepts some remains on the shore at Gournia. The rock-cut basin at Nirou Khani has been suggested as a parallel."*

However, Blackman does not mention the Nirou Khani structure any more in his book.

Theodoulou (2023, p 145):

> *"The most striking, though enigmatic, finding of Marinatos' work concerns the large rectangular cuttings at the base of the rocky cape. Its length is 47.4 m, and its width is 10 m. It is divided longitudinally with stonework, in two uneven zones, 4.95 m wide at the south and 4.25 m in the north. Marinatos, considering that the bottom of the cutting was below the sea level, by about 1.80-2.00 m, considered that the brush was*

on dry land during the Minoan times, arguing its possible use as a shipshed. Recent underwater research shows that the northern compartment of the cutting is closed off and could not have been used for keeping a ship in, except perhaps for the storage of its equipment. However, the 47.4 x 4.95 m open south-eastern compartment is considered to be more suitable for the construction, repair or guarding of two or more ships. Confirming its use, however, requires an investigation."

What can we add in order to clarify this matter?

Nirou Khani (Google Earth picture taken on 1/9/2018)

On the day this picture was taken, the sea was calm (no Meltem blowing). The dimensions of the rock-cut basin are visible:

- Width: around 10 m, with a separating wall
- Length: up to 47.5 m

To the south of both basins, a slightly higher area looks like a quarried area.

A slope cannot be seen on the picture and the various visitors did not mention anything about a slope as the bottom of the basin is probably horizontal.

The Nirou Khani rock-cut basin is therefore not a port, as it is too small, but the size of the southern basin corresponds very well to a slipway. However, if it had no slope, it must have been difficult to haul a ship inside or to keep the workers feet dry.

In any case, the large sheltered area on the south-eastern side of the rock-cut basin may have been a safe harbour.

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2.16 PORTUS AUGUSTI

In the following sections, we will concentrate on the overall sedimentation and erosion processes, on the structural aspects of the breakwaters and on the port capacity. Our aim is to understand *how it happened and how it was built.*

2.16.1 Pictures of the port

Thousands of documents deal with Portus Claudius, Portus Trajanus or Portus Augusti Ostiensis. The oldest pictures of Portus Claudius are on Nero's coins of one sestertius (64 AD).

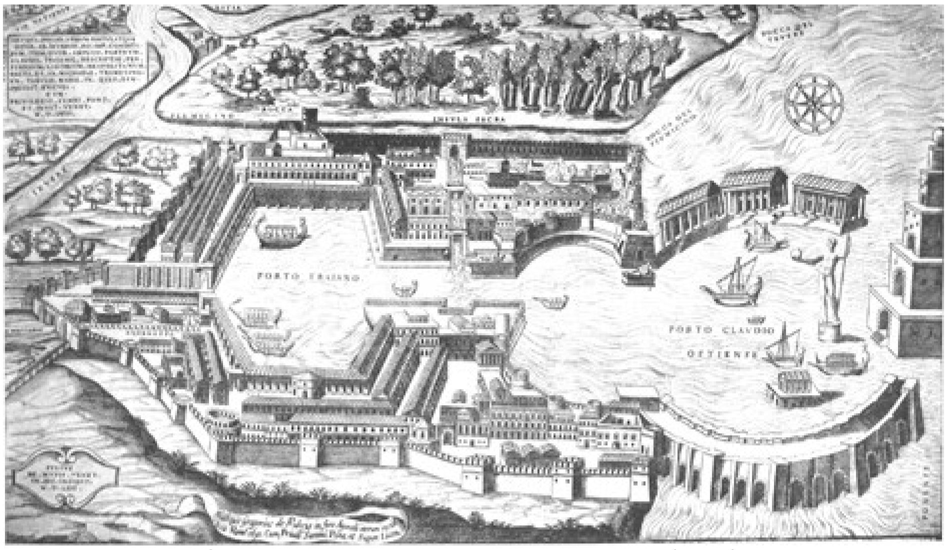
Portus on a sesterce issued by Nero, in 64 AD.
Legend: *AVGVSTI | S POR OST C = Portus Ostiensis Augusti, senatus consulto.*
© Classical Numismatic Group. Reproduced with permission.

Fig. 4.5. Reverse of Nero's Portus issue (Courtesy of the British Museum; CM BMC132, AN31942001).

Nero’s coin of one sestertius showing Portus, Lugdunum, 66 AD, 33 mm,
picture C. Jacquand, Wikimedia, (Mus. civilisation gallo-romaine, Lyon).

The sea is on top of the coin pictures, north is to the right.

The right, or north, breakwater has been interpreted (first by Pirro Ligorio in 1554) as an open breakwater supposed to allow water flowing through it.

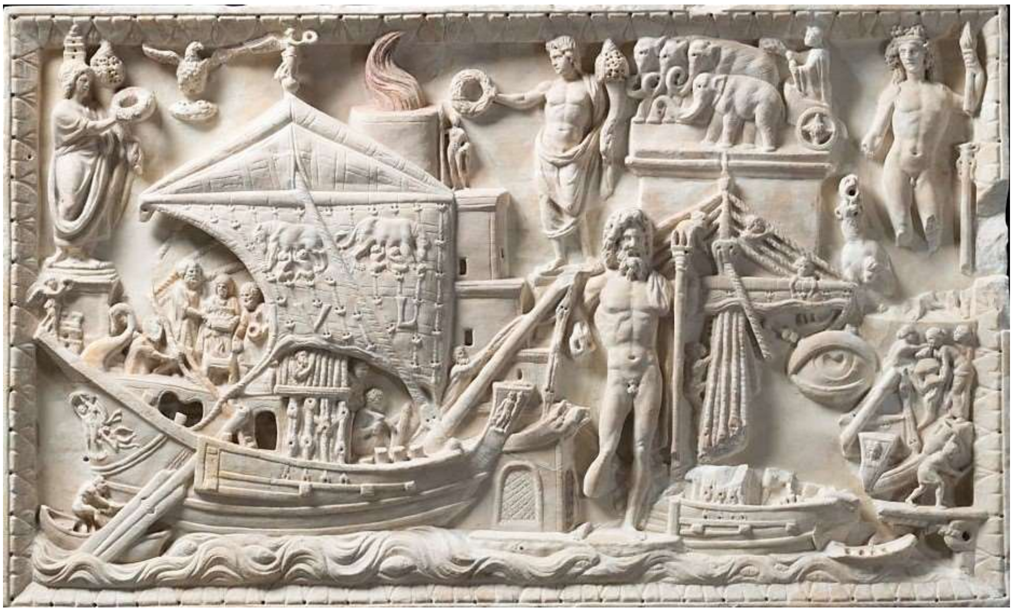


Oldest Portus interpretation by Pirro Ligorio (1554).

On the British Museum coin, we might even see water flowing around the arch piers, very much like the bow wave of a ship. This concept of 'arched breakwater' was designed to avoid harbour siltation, and similar 'pilae' constructions were found in Puteoli, Misenum and Nisida, in the Bay of Naples, but no ancient literary evidence is available.

The left, or south, breakwater supports a row of buildings (warehouses?) with a larger structure at the seaward end (temple? lighthouse?).
At the entrance, between both breakwater heads, a large statue seems to represent the well-known lighthouse island.
A ship is leaving the port under oar on the right side and another ship is entering the port under sail on the left side.
Three ships with furled sail are inside the port.
Several smaller boats under oar could be tugs (multiple oars) and service boats (single oars).

For further info see Mary Jane Cuyler (2014), (University of Sidney)[33].



Torlonia relief of Portus
(photo credit: Zètema - Roma Capitale).

For a brilliant description of Portus, see Simon Keay (2014)[34].

2.16.2 A few words on coastal morphodynamics

Coastal engineers are supposed to predict the impact of new coastal structures (i.e., ports, seawalls, man-made beaches, etc.) on the adjacent coastal morphology. Their methodology is usually as follows:

1. Understand coastal processes at hand (waves, tides, morphodynamics);
2. Build numerical models of these processes (physical scale models are used also) and calibrate them on the past decade(s) if enough data is available;
3. Use these models to predict trends over future decade(s).

The following (very) short summary can be deduced from coastal engineering textbooks (e.g., Komar, 1998)[35].

As ports and harbours are supposed to be “low energy” areas (with reduced waves and currents in order to provide sheltering for ships) they are subject to sedimentation.

[33] CUYLER, MJ., 2014, "Portus Augusti: The Claudian Harbour on Sestertii of Nero", in 'Art in the Round': New Approaches to Ancient Coin Iconography, Tübinger Archäologische Forschungen, Band 16.
[34] KEAY, S., 2014, “The Role Played by the Portus Augusti in Flows of Commerce between Rome and its Mediterranean Ports”, in “The Roman Economy”, edt. B. Woytek, Austrian Academy of Sciences, (147-192).
[35] KOMAR, P., 1998, “Beach processes and sedimentation”, 2nd ed., Prentice Hall.

Sediment (sand and silt) moves both along the coastal zone (longshore littoral drift) and across the coastal zone (cross-shore sediment movement). The coastal zone runs from the dune to a certain water depth (frequently in the order of 10 m). The energy required for sediment motion is mainly provided by wave action (and wind and tidal currents, if any).

- The source of sediment for littoral drift can be fluvial sediment load from river outlets, or erosion of another stretch of the coast. Waves push sediment in front of them when they break with an oblique angle on the coastline. Hence, depending on the wave direction, the rate, and even the direction, of littoral drift can vary in time.
- Cross-shore sediment movement occurs mainly during storms when sediment is taken away from the top of the beach or dune down to deeper water. Reconstruction occurs in milder weather and wind will take fine sediment back to the top of the dune, especially in a tidal area.

Let's have a look at a typical river outlet with Piero Bellotti[36].

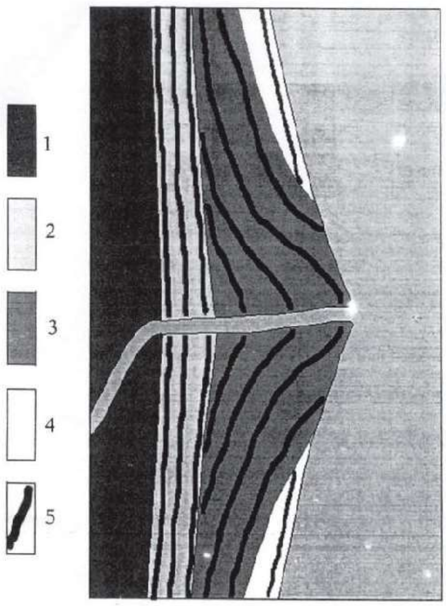


Fig. 9 - Meccanismi di progradazione riconosciuti nei delta tirrenici. Nel primo tipo il depocentro delle sabbie è disposto lungo la battigia, nel secondo tipo è ubicato nell'area di foce, nell'ultimo è spostato lungo le ali. 1) piana deltizia interna, 2) progradazione di primo tipo, 3) progradazione di secondo tipo, 4) progradazione di terzo tipo, 5) cordoni litorali.
– Progradation mechanisms in tyrrhenian deltas. In the first type sand depocenter is located long the shoreline, in the second one sand depocenter is close by river mouth, in the last type sand depocenter is located long delta wings. 1) Inner delta plain, 2) first type progradation, 3) second type progradation, 4) third type progradation, 5) beach ridges.

Beach ridges (5) show the progradation of the shoreline due to sediment supply from the river. In this case, wave propagation is perpendicular to the initial shore line (waves move from right to left on this picture). Waves spread the sediment on both sides of the outlet leading to a shape that will remind the Fujiyama (3).

It can be seen also that the total volume of sediment between two equidistant ridges increases in time because the lateral extent is increasing. Hence, the speed of progradation of the outlet cone reduces in time (if the fluvial sediment load is constant).

Obviously, the ratio *fluvial sediment load / wave power* is a dominant parameter here: more wave action and/or less sediment input lead to a flatter cone, and reverse.

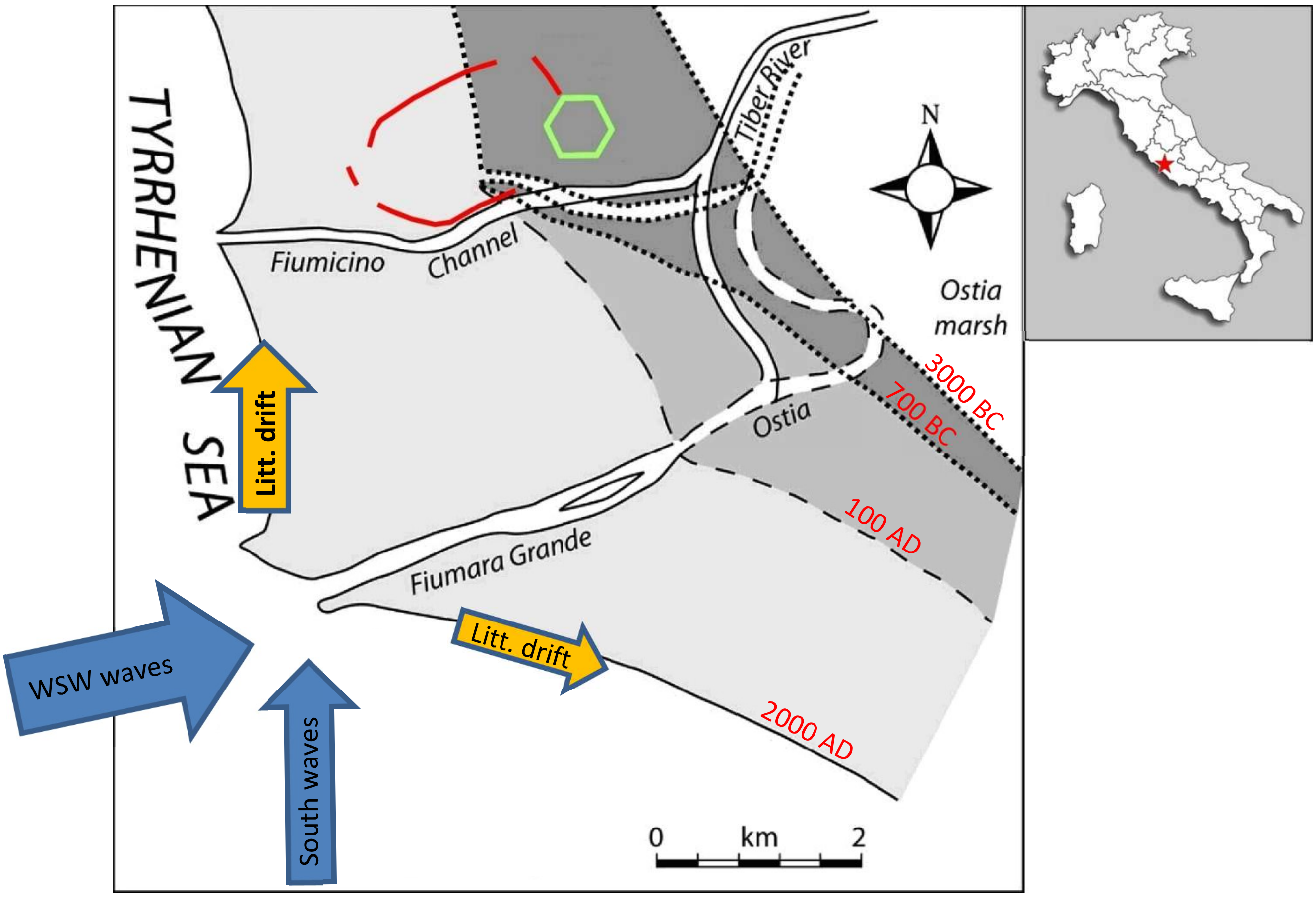
If, for some reason, this ratio is reduced (e.g., reduced fluvial sediment load due to reduced fluvial water discharge, due to a drought), the cone will be flattened out and sediment will drift laterally on both sides (4).

What happens if men interact with Nature? e.g., building some obstacle in an area with littoral drift.

[36] BELLOTTI, P., 2000, "Il modello morfo-sedimentario dei maggiori delta tirrenici italiani" Boll. Soc. Geol. It., 119 (2000), (p 777-792).

This picture shows the initial shoreline near Cotonou (Benin) (straight yellow line). This was the shoreline before any human construction (a port) was built in the sixties. This coast is known for its littoral drift of around one million cubic meters per year from west to east (left to right on the picture).
Fifty years later, the western shoreline progressed more than 1 km in the offshore direction to the south (i.e., around 20 m/year!). The same volume of sediment was taken away by wave action on the eastern side, inducing erosion over many kilometres … What Nature gives with one hand, she takes back with the other hand.
After some more time, sand will by-pass the harbour entrance which will gradually silt up and reduce draught for navigation[37].

2.16.3 Claudius' southern breakwater



Coastal morphodynamics near Portus.

[37] MANGOR, K., et al., 2010, "Bypass harbours at littoral transport coasts", PIANC MMX Congress, Liverpool.

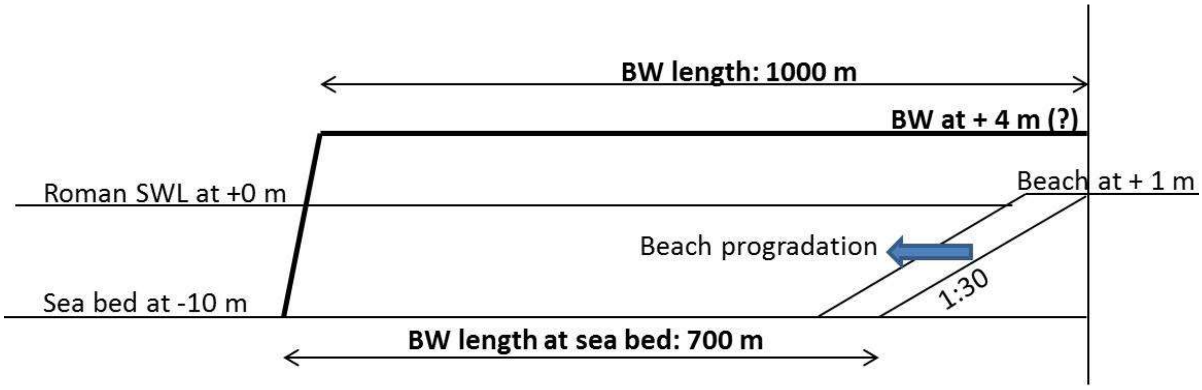
The picture above (based on P. Bellotti's, 2011 study[38], see also Giraudi, 2009[39]) shows that the Tiber outlet moved from the north (into the future Roman ports) to the south (close to future Ostia), probably around the 7-8th c. BC, before Ostia developed in the 5th c. BC. It also shows that the shoreline between the present Fiumicino Canale and Fiumara Grande progressed 3.5 to 4 km between 100 AD and 2000 AD. That is an average close to 2 m/year. A more detailed analysis shows that this value might vary locally and reach 5 to 10 m/year near both outlets (Bellotti, 2011).

Further information is found on the DIGITER web site of Antonia Arnoldus-Huyzendveld and in her 2016 publications on coastline evolution and on Claudius' harbour[40].

Waves are dominant from SE to SW according to data taken from the Wind and Waves Atlas of the Mediterranean Sea (2004) at locations 42°N-11°E (west of Civitavecchia) and 41°N-12°E (south of Fiumicino).

Considering the local coastal morphology, the fluvial sediment load from the Tiber is supposed to flow as a littoral drift on both sides of the outlet, and offshore. The present total sediment load is 0.3 million ton/year (Milliman, 2014[41]) (that is around 150 000 cubic meter/year). It must be noted here that this fluvial sediment load was drastically reduced by a factor thirty (30!) during the 20th c. due to upstream dam building. Anyway, the finer fraction (silt) flows offshore and only the coarse fraction (sand) remains in the coastal area (estimation of 50 000 to 100 000 cubic meter/year over the past centuries). The south breakwater of Portus Claudius obviously was a large obstacle to sediment movement towards north and sedimentation took place on the south side of the south breakwater.

Let's see this in a simplified vertical cross-section placed just south of the south breakwater (looking north), and just after its completion.



NB: Roman Sea Water Level is around 0.8 m below present SWL[42]
(sketch distorted and not to scale)

[38] BELLOTTI, P., 2011, "The Tiber river delta plain (central Italy): Coastal evolution and implications for the ancient Ostia Roman settlement" The Holocene, 21(7), Sage Publications Ltd, (p 1105-1116).
[39] GIRAUDI, C., 2009, "Late Holocene Evolution of Tiber River Delta and Geoarchaeology of Claudius and Trajan Harbor, Rome", Geoarchaeology, Vol 24, N° 3.
[40] ARNOLDUS-HUYZENDVELD, A., et al, 2016, "How the coastline of Ostia changed over the centuries", Foro N° 41, Friends of Ostia, (13 p).
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[41] MILLIMAN, J., 2011, "River Discharge to the Coastal Ocean: A Global Synthesis", Cambridge University Press, UK (384 pp).
[42] GOIRAN J.-P., et al, 2009, "Découverte d'un niveau marin biologique sur les quais de Portus: le port antique de Rome", Méditerranée, 112, (p 59-67).

Sediment from the prograding beach will start to get around the toe of the breakwater (BW) after a distance of 700 m. Sedimentation will start inside Portus Claudius at this moment. In the simplified scheme shown above (1:30 slope on a 10 m water depth, note that Morelli found 15 m[43]) and considering the 5 to 10 m/year progradation, the *beginning* of harbour sedimentation would be expected after 70 to 140 years, say one century, and *that is well after Trajan decided to build his Portus Trajanus*. This leaves many more years for the harbour to be still (partly) operational, as long as the water depth is at least 4 to 5 m inside the harbour. This seems to have been the case until at least 879 AD (Paroli[44]). We would consider nowadays that this is fairly overdesigned …

It would however not be surprising that Claudius' engineers anticipated this, at least in a qualitative way, and this would then explain why they built such an expensive, long and deep, south BW, as they did not need a 10 m water depth for contemporary ancient ships, but *they had to create a large sedimentation trap outside the harbour*.
In the same line of thought, Claudius' engineers may also have decided to use the concept of an arched breakwater on the northern side of the port, as this concept was already in use at Puteoli, Nisida and Misenum (by Agrippa in the thirties BC) for around one century. Such an arched breakwater was supposed to allow currents to flow through the breakwater, providing some flushing which would possibly help reducing siltation (modern engineers do not agree any more with this idea, see section on 'harbour silting-up').

2.16.4 Hypothetical Sequence of construction

According to Dio Cassius (Roman History, 60, 11, transl. in Oleson, 2014, p 33) "*First, he [Claudius] excavated a considerable plot of land near the coast, built quay walls all around it, and let in the sea. Next, in the sea itself he laid down great moles on either side of the basin entrance and thus enclosed a large body of water, and in it he fashioned an island carrying a lighthouse*". Hence, Claudius clearly built Portus in two stages: first inland near Monte Giulio as modern archaeology has recently shown[45], and second, both large breakwaters built into the sea.

If Claudius' engineers realised that sediment coming from the Tiber was flowing north along the coastline as littoral drift, they must have thought that they had to build the south BW *first* in order to stop this material from settling inside the future harbour area against the northern BW, if that one were built first. They may not have realised that if sedimentation was to occur on the south side of the south BW, then erosion was to occur on its north side, i.e., inside the future harbour … That was quite a nice opportunity to let Nature do the work of cleaning up the area that would have to be dredged anyway … After some time, they would decide to start building the north BW and the coastline would readjust with some erosion near the northern side of the south BW combined with some sedimentation near the southern side of the north BW. The coastline between both breakwaters would then be stabilised. No problem so far.
However, as sedimentation on the southern side of the south BW continued, erosion had now to occur on the northern side of the north BW and this would soon start to undermine the landward end of the brand new north BW.

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[43] MORELLI, C., 2011, "Porto di Claudio: Nuove scoperte", in "Portus and its hinterland: Recent archaeological Research", ed. Simon Keay & Lidia Paroli, The Britisch School at Rome, (p 47-65).
[44] PAROLI, L., 2005, "History of past research at Portus", in KEAY, S., & MILLETT, M., in "Portus in Context", The British School at Rome.
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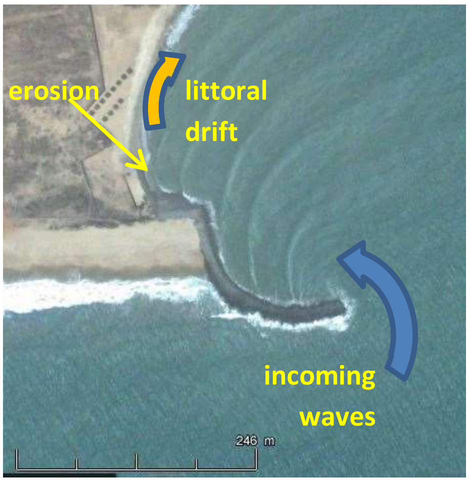


Waves diffracting around the breakwater head, inducing erosion at the breakwater landward end (Cotonou, Benin)

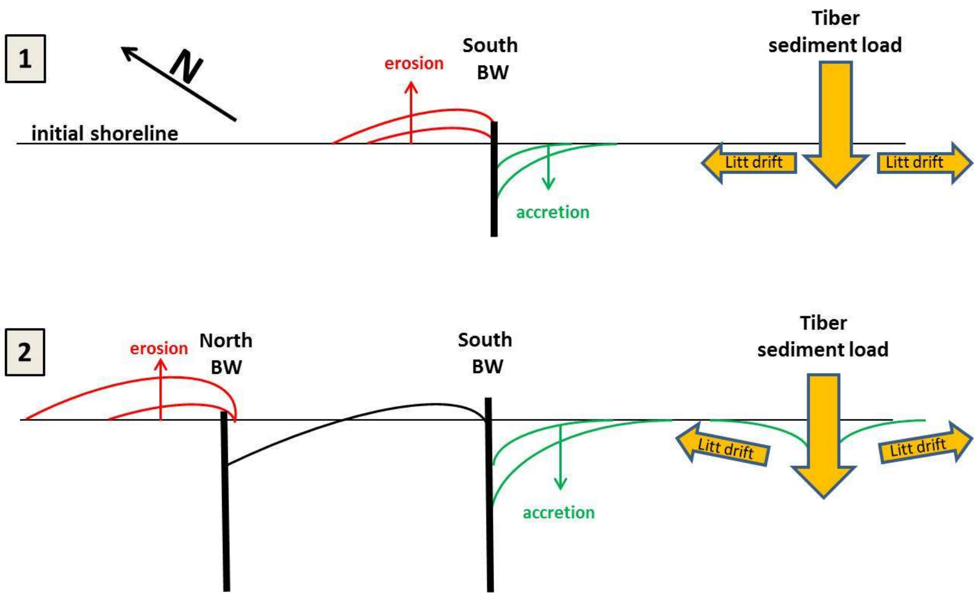
This picture shows the erosion area east of Cotonou where diffracted waves turn around the breakwater head, then follow the curved breakwater and take sand away at the landward end of it.

Portus' configuration is reversed: waves follow the breakwater on the north side and "try to enter" the port from north to south by getting around the landward end of it, while sand is taken away further north.

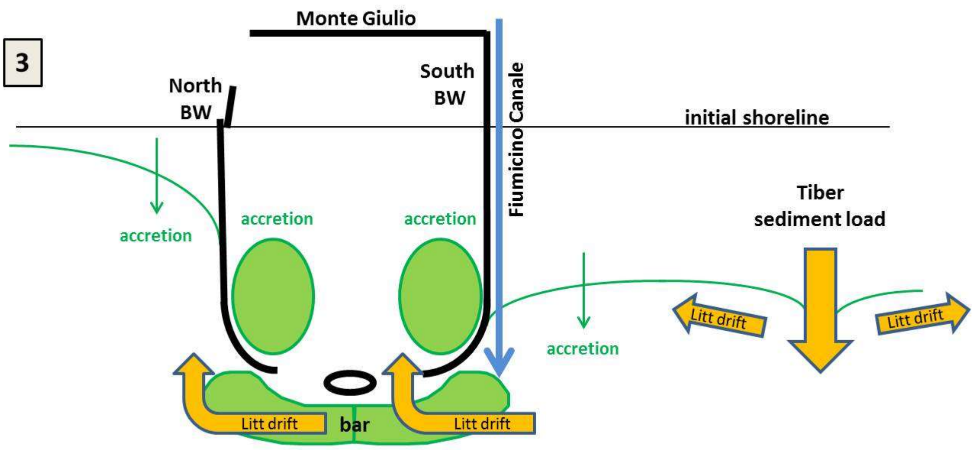
This may be an explanation for the somewhat hectic layout of the north BW near Monte Arena[46], where several designs are used, *possibly showing repair actions*. A northern access channel for ships[47] may not have been anticipated from the onset by Claudius' engineers, but the opportunity provided by this local erosion may have been taken to use it, and even to enhance it artificially, for river transit from Portus Claudius through the northern canal leading to the Tiber.

In the meantime, fine marine sediment was driven into the sheltered harbour area not only by residual waves behind the breakwaters, but also by small sea level variations such as those due to barometric variations, tidal effects and wind action. This fine sediment is therefore now found underneath coarser fluvial sediment that entered the harbour much later, coming from Fiumara Grande and drifting north along the coast to the harbour entrance.

These processes are summarised on the following hypothetical geomorphological evolution of the Portus Claudius area:



[46] FELICI, E., 2013, "Il Porto di Claudio e Vitruvio", Atlante tematico di topografia antica: ATTA : rivista di studi di topografia antica, 23(2013), Roma: «L'ERMA» di BRETSCHNEIDER.
[47] GOIRAN J.-P., et al, 2008 "Portus, la question de la localisation des ouvertures du port de Claude : approche géomorphologique", *Mélanges de l'Ecole Française de Rome*, 121, (p 217-228).



Hypothetical construction sequence of Portus Claudius
1) Construction of first breakwater (south),
2) Construction of second breakwater (north),
3) Coastal progradation and harbour sedimentation.

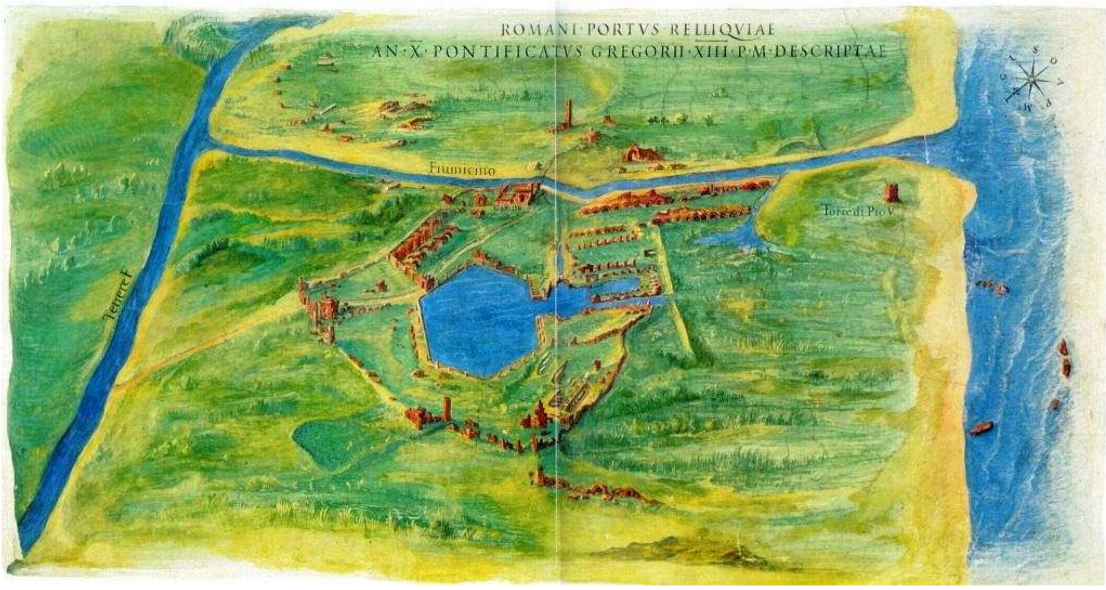
Note that the so-called "Iseum" located just south of the via della Scafa viaduct over the Fossa Traiana (Lat 41.7727°, Long 12.2554°), was most probably built later than the Portus Claudius south breakwater. Hence, sedimentation on the south side of this breakwater was already progessing and the temple could be built on the new beach.

2.16.5 Fiumicino Canale – Fossa Traiana

Let's stay on this southern side, where it remains to be explained how Fiumicino Canale could survive with such a large volume of sediment drifting to the north from the Fiumara Grande outlet. Many centuries after the Tiber outlet moved from the north to the south, Fiumicino Canale was artificially dug in the 1st c. AD and later wrongly called "Fossa Traiana". It provided a short connexion between the port (via Canale Trasverso) and the upstream river portion leading to Rome. Although this canal is the shortest way for the Tiber to sea, it was narrower than the branch flowing to Ostia and therefore did not attract a lot of river discharge water (and sediment). It is said that nowadays, the discharge ratio is 20% via Fiumicino Canale and 80% via Fiumara Grande, but that may have been very different at times (droughts, floods). A small hydraulic power of Fossa Traiana would not enable to keep its outlet open against massive sedimentation coming from the south and it seems likely that the outlet was closed periodically (if not permanently) near the landward end of the south breakwater, downstream of the Portico Claudio.

Rutilius' observation[48] shows that such variations could happen, as in his time it was safer to sail out to sea via Fossa Traiana than via Ostia where a dangerous 'bar' had probably formed. He also states that they spent the night inside the port. As he does not mention a direct connexion of Fossa Traiana with the sea via a separate outlet, he might have sailed out to sea directly from Portus Claudius.

[48] RUTILIUS NAMATIANUS, 5th c. AD, "De Reditu Suo", Book 1, Verse 179: "Then at length, I proceed to the ships, where with twy-horned brow the branching Tiber cleaves his way to the right. The channel on the left is avoided for its unapproachable sands […]. We hesitate to make trial of the sea; we tarry in the haven […]. In the half-dawn we weigh anchor, […], we make way along the nearest shores […]."

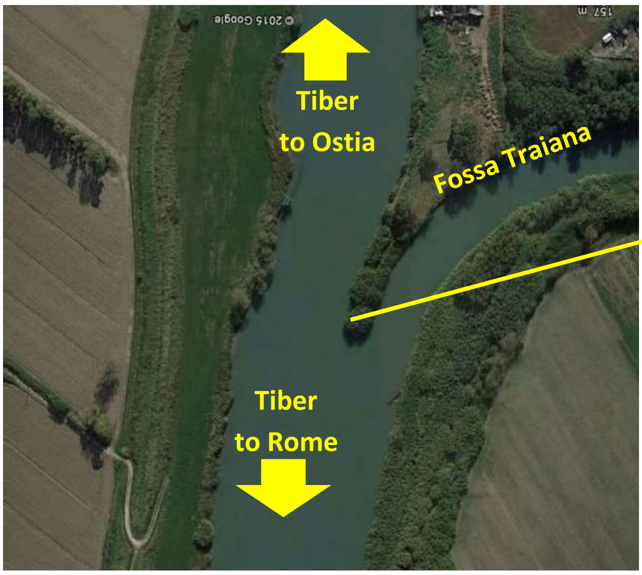


Ignazio Danti's fresco, 1582 (Vatican Gallery of Maps).

Paroli (2005) tells us that Fiumicino Canale remained navigable certainly until 1118 AD, but that it was closed in 1461. However, Danti's famous fresco shows an open Fiumicino Canale in 1582! His picture is quite accurate, showing various port remains, including in the sea, and we have no reason to doubt that the Fiumicino Canale was correctly drawn.

To achieve this, a training wall (e.g., rubble mound running parallel to the south breakwater) would be required to keep the outlet free from sedimentation and such a structure was not found by archaeologists, but it was perhaps destroyed by port development in 1612 inside Fiumicino Canale when it was re-opened towards the sea (Paroli, 2005).

On the other hand, the Tiber being known for its strong floods (up to say 2000-3000 m^3/s), it might be accepted that Fossa Traiana was periodically swept by such floods which would clean up the canal and enforce an opening to the sea at least once a year (possibly with some human assistance). By the way, a low sill (e.g., 1 m high) would help to prevent bed load sediment from penetrating into Fossa Traiana. The modern-day shape of the intake of Fossa Traiana on the Tiber at Capo Due Rami seems to confirm that special care is taken there:



Inlet of Fossa Traiana at Capo Due Rami.

The intake structure is obviously calibrated to divert a certain fraction of the flow. It is reinforced in order not to be moved around by erosion.
This arrangement may have been inherited from an ancestral (Roman?) tradition.

We are thus left with uncertainty as to the opening of the sea outlet of Fiumicino Canale between 1118 AD and 1612 AD …

Summarizing the morphodynamics in the Portus area: sand brought by the Tiber was spread along the coastlines north and south of its outlet. The south BW of Portus Claudius stopped the littoral drift to the north inducing: a) sedimentation south of the south BW, b) closure of the seaward outlet of Fossa Traiana, and c) erosion north of the northern BW. After around one century, sand started to enter Portus Claudius by its main access channel, probably settling near the entrance, while finer materials entered further inside the port. Later on, sand bypassed the port entrance and spread on the coastline north of the port. Even later, the port was filled with sand and the coastline prograded in front of it.

2.16.6 Claudius' breakwater remains

Engineers usually distinguish vertical breakwaters (BW) and rubble mound BWs. The first are built with caissons filled with hydraulic concrete (e.g., Caesarea Maritima, Israel). The latter are built by dumping stones from a lorry, and concrete can possibly be found on top of the rubble mound (above sea level where it is easier to pour); as we still do today (see http://fr.wikipedia.org/wiki/Brise-lames):

Fujairah breakwater under construction.

This picture (Fujairah) shows a modern BW under construction: large artificial blocks of concrete are used nowadays instead of rock, they are placed on top of, and as an armour layer of, a rubble mound made of quarry rock of several tons, which are themselves placed on a core made of quarry run. The crest structure (under construction) has a kind of "L" shape.

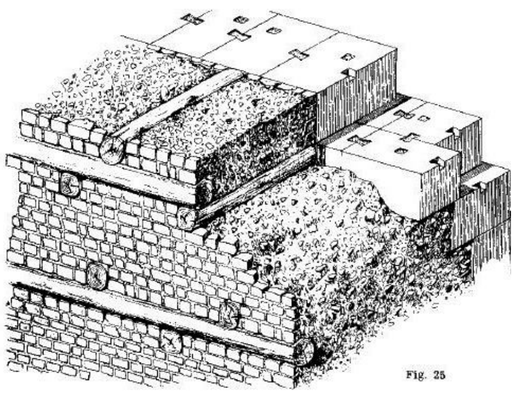


Fig. 25

The emerging part of the north BW of Portus Claudius is made of concrete, which was probably cast in the way described by Bartoccini[49].

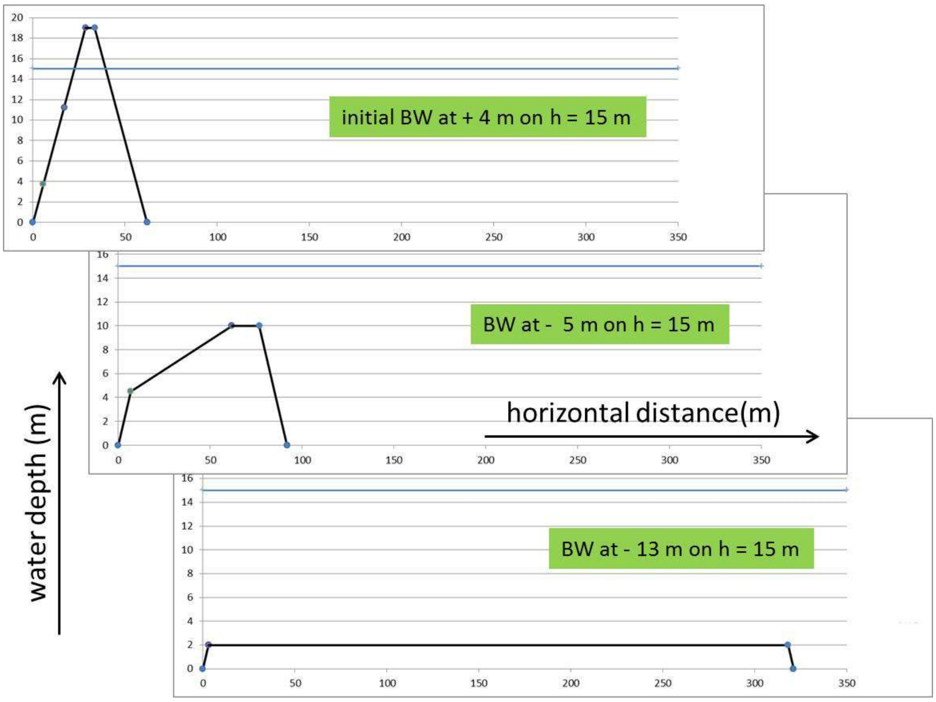
Morelli's report on corings[50] show that the crest of the deep section parts of the breakwaters are located at approx. 5 m below present Sea Water Level (SWL) (i.e., ca. 4 m below Roman SWL) with a total remaining structure height of around 10 m reaching approx. 15 m below present SWL. The initial BW may thus have been a 15 to 20 m high structure. We thus have two options: it could have been built higher and been partly destroyed by long term wave action, or have been built as a low crested BW from the onset. The first option is usually built as an emerging BW, built out from land with lorries, involving considerable logistics (lorries meeting each other on top of the BW, etc.). In the second option, building a BW that does not reach the water surface is done with barges from the water surface (like Pliny the Younger described at Centumcellae / Civitavecchia), and consequently the remaining upper level of the BW is built out from land with lorries, with ashlar blocks and/or possibly, with hydraulic concrete poured into wooden formworks to create a massive or arched structure. In any case, the upper level of the Portus breakwaters would have been lost over the years: possibly due to re-use of stones during the Renaissance ... or possibly due to wave action.

Let's consider the latter case and assume (until further data is made available) that the deep section of the breakwaters consists of a rubble mound with an average stone diameter of 0.50 m.

We know from coastal engineers that because of wave breaking, waves cannot be larger than around 0.6 times the local water depth; hence in shallower water, waves are smaller and the required rock size for a stable BW is smaller too; conversely, a BW must thus have an increasing rock size when building out to sea on increasing depth. When we move into even deeper water, say over 10-15 m, breaking waves (of over 6-9 m) will not occur often, but just during storms; however, we may consider that any size of big storm will have occurred during the past 2000 years: so, if the water depth allows big waves to exist, they *will occur* in the long term and destroy the BW accordingly.
Clearly, 0.50 m rock (typically a 2 to 500 kg class of rock) is not stable with waves larger than only 1 m, which occur many times a year.
This is valid for frontal wave attack (wave crests parallel to the axis of the BW). Most of Portus' BWs are not subject to frontal wave attack, but to (very) oblique wave attack, which is far less destructive. It is nevertheless expected that this 0.50 m rock placed on a water depth of 10 to 15 m should suffer frequent damage during storms, especially at the roundheads and at the lighthouse island which are both subjected to frontal wave attack.

This is perhaps a first start for explaining why the crest of the deep sections of the breakwaters are located at approx. 5 m below present SWL. Coastal engineers tell us that a rubble mound will be lowered by repeated wave attack until it is no more than a submerged breakwater. Its elevation above the seabed depends on the size of rock (see Failure of rubble mound breakwaters in the long term). In the case of Portus, with a water depth of 15 m and a rock size of 0.50 m diameter, the crest of the submerged BW would be lowered to 13 m below the water surface, i.e., 2 m above the seabed *if waves were strong enough.* But this is not the case in the area around Portus.
In addition, the total volume of rock cannot change. Hence, if a BW is flattened out by wave action, rocks must be spread over the seabed in the following way (with Roman water levels):

[49] BARTOCCINI, R. 1958, "Il Porto Romano di Leptis Magna", Boll. Centro Studi per la Storia dell'Architettura, N°13.
[50] MORELLI, C., et al. 2011, "Porto di Claudio: Nuove scoperte", in "Portus and its hinterland: Recent archaeological Research", ed. Simon Keay & Lidia Paroli, The Britisch School at Rome, (p 47-65).



Destruction of a breakwater due to wave action.

This is however not (yet?!) confirmed by archaeology … and large blocks of hydraulic concrete were not (yet?!) found either … It therefore seems more likely, at this moment, that the north BW was not made entirely of rubble, but that another structure (concrete or ashlar? massive or arched?) was built on top of a rubble mound having its crest at a few meters below Roman SWL. If this structure was not destroyed by wave action, ashlar blocks could have been dismounted during the Renaissance. The structure would thus have protected the underlying rubble mound from wave action for at least 1400 year until they were removed. After that, the rubble mound would be exposed to wave action and partly destroyed (see Failure of rubble mound breakwaters in the long term). This would explain why rubble was recently found on top of a thick harbour sedimentation layer[51].

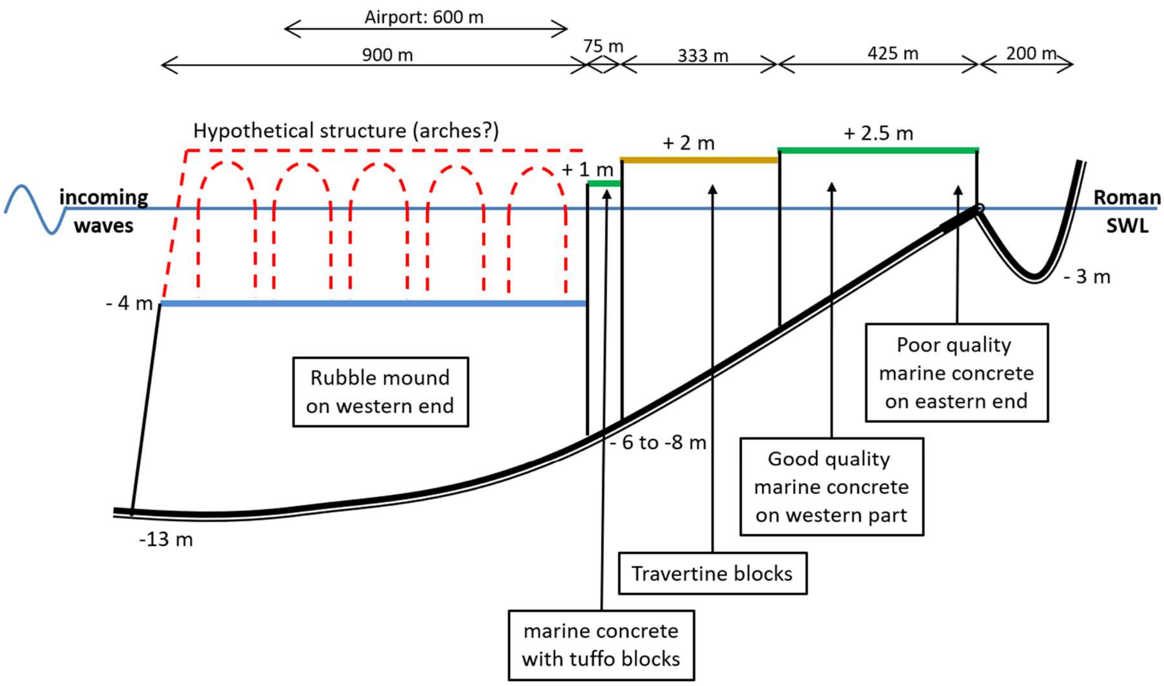
As a very temporary conclusion on the northern breakwater, four sections can be distinguished (see also Google Earth: http://www.ancientportsantiques.com/the-catalogue/italy/):

1. Eastern landward end of the emerging breakwater, 425 m long, in the eastern part of which Oleson[52] (2014) made corings POR.2002.01 & 03, showing poor quality hydraulic concrete, possibly resulting from repair actions in this area further to local erosion and a temporary 200 m wide northern port access (Goiran[53], 2011); further west, good quality hydraulic concrete was poured into wooden caissons from the seabed up to 2.5 m above the Roman SWL, and still visible on land;
2. Central part of the emerging breakwater, 333 m long, where travertine blocks were found up to around 2 m above the Roman SWL;

[51] ARNOLDUS-HUYZENDVELD, A., 2016, ‘’The hidden harbour’’, Foro N° 63, Friends of Ostia, (9 p).
[52] OLESON, J., BRANDON, C., HOHLFELDER, R., JACKSON, M., 2014, “Building for Eternity – The history and Technology of Roman Concrete Engineering in the Sea”, Oxbow Books, (327 p).
[53] GOIRAN, J-P., et al., 2011, “Caractéristiques sédimentaires du basin portuaire de Claude: Nouvelles données pour la localisation des ouvertures”, in "Portus and its hinterland: Recent archaeological Research", ed. Simon Keay & Lidia Paroli, The Britisch School at Rome, (p 31-45).

3. Western part of the emerging breakwater, 75 m long, ending near Goiran (2011) corings CL3/4, where hydraulic concrete and tuffo blocks were found by Testaguzza[54] (1970);
4. Submerged western section, about 900 m long, where Morelli (2011) made corings PL04/05 and many others, showing rubble without any hydraulic concrete from the seabed at 13 m below Roman SWL, up to 4 m below Roman SWL, and a possibly disappeared upper layer, possibly arched and made of ashlar.

Testaguzza (1970) identified the three emerging parts of the ancient breakwater, but he did not find the submerged western section that was burried deeper than he could excavate at that time.



Hypothetical longitudinal section of Portus' north breakwater
(Beware the 1:50 distorted scale!)

Next enigma: where are the arch-blocks??!

[54] TESTAGUZZA, O., 1970, "Portus, Illustrazione dei porti di Claudio e Traiano e della citta' di porto a Fiumicino", edt Julia, Roma, (263 p).

2.16.7 How safe was Portus Claudius?

Tacitus (Annals, 15, 18) reports that 200 ships were sunk inside the port during a storm in 62 AD. Some believe that this event was a tsunami, although no sedimentological evidence has been found so far to support this hypothesis[55]. In this study, we will show that a somewhat exceptional storm may also have induced this catastrophic event.

Layout of Portus Augusti deduced from recent archaeological surveys.
Note that only a small part of the island supposed to protect the harbour entrance has been located.

The remains of the main north and south breakwaters of Portus Claudius shown on the picture above leave a large harbour entrance for both ships … and waves. This wide opening is supposed to be sheltered by the offshore island which was only partly located by archaeology.

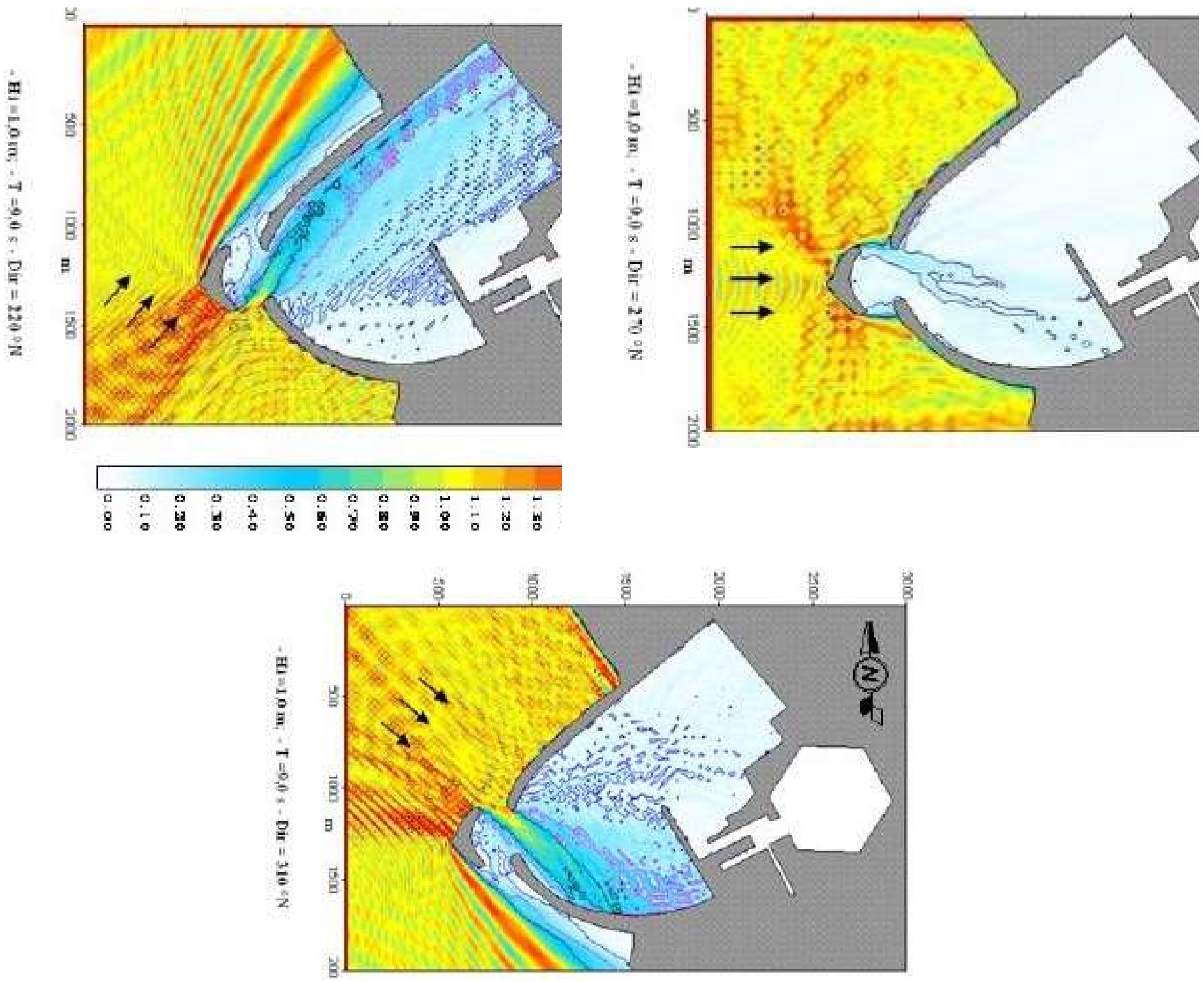
Obviously, the breakwater layout must be an optimum between limited wave penetration on one hand, and easy (wide) access for ships on the other hand. Ships may then shelter behind the main breakwaters, depending on the wave direction: ships may shelter behind the north breakwater with northern waves, and behind the south breakwater with southern waves. This is satisfactory with stable meteorological conditions. However, should the wave direction change from W to S and to E, or the other way round, dangerous situations for ships anchored inside Portus might occur because of wave directions turning around the

[55] DELILE, H., & SALOMON, F., 2020, "Palaeotsunami deposits at the Tiber River mouth (Ostia Antica, Italy): Do they really exist?", Earth-Science Reviews, EARTH 103268, Elsevier, (59 p).

harbour entrance. A sudden change could even generate a serious problem for ships anchored inside Portus, if it happened within a short time like one hour, because sailors would not have enough time to move their ships to a better sheltered area inside the harbour.

Wave penetration inside the port

Back in 2009, Noli and Franco performed wave penetration computations inside Portus Claudius, based on its assumed configuration[56]. Results from their work are shown here for waves from NW (310°), W (270°) and SW (220°). The protection provided by the (350 m) island compared to the (250 m) port opening determines the wave climate inside the port. As a result, very few western waves penetrate inside this layout of the port, but much more waves from SW and NW penetrate.



Wave penetration computations inside the Portus Claudius,
for 3 wave directions of 220°, 270° and 310° (Noli & Franco, 2009).

A sheltered anchorage was thus provided behind the southern breakwater, say around 20 hectares, enough for say 200 ships at anchorage. However, should waves suddenly change their direction from the usual W - S sector to a NW sector, then the south anchorage area

[56] NOLI, A., & FRANCO, L., 2009, "The ancient ports of Rome: new insights from engineers", Archaeologia Maritima Mediterranea, 6

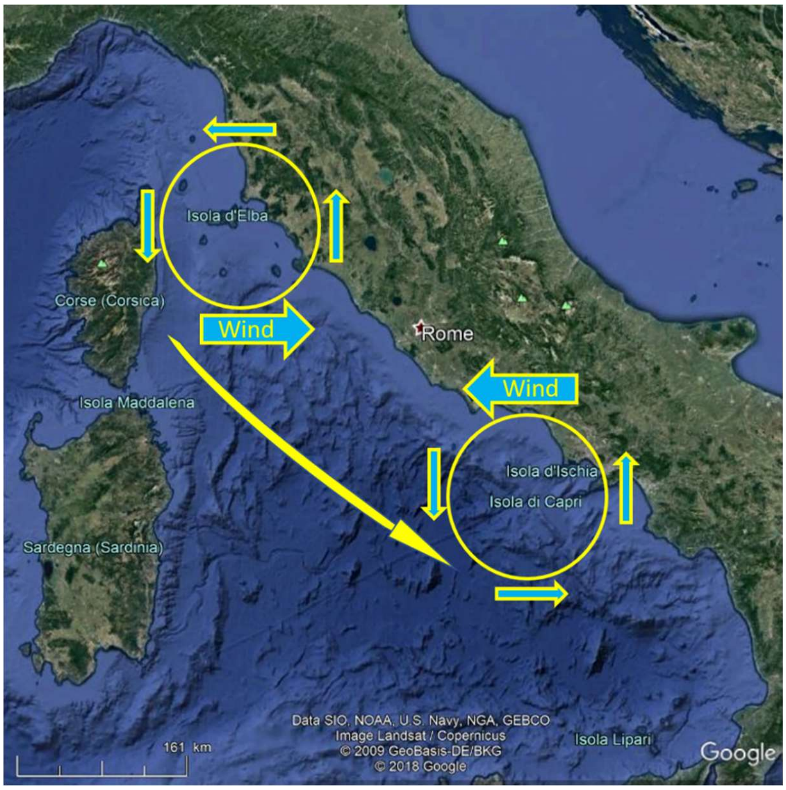
would be exposed to heavy wave penetration. In order to find out if such meteorological conditions could occur, we have to analyse the wave climate.

Waves in the Tyrrhenian Sea

As Murray (1987) has shown that the ancient wind climate is fairly close to the present one[57], we are going to use modern waves statistics for this study.

Wind waves are generated by wind blowing over the sea surface for a certain lapse of time and over a certain distance. During a storm, waves are thus generated under the wind field and propagate from there in the same direction as the wind. If the wind stops, the waves continue their trip with rather small loss of energy and some waves travel hundreds (even thousands) of kilometres outside their initial wind field. Such waves are called swell. This complex phenomenon is rather well understood today, enabling engineers and meteorologists to operate mathematical models predicting the wave climate in a certain area.

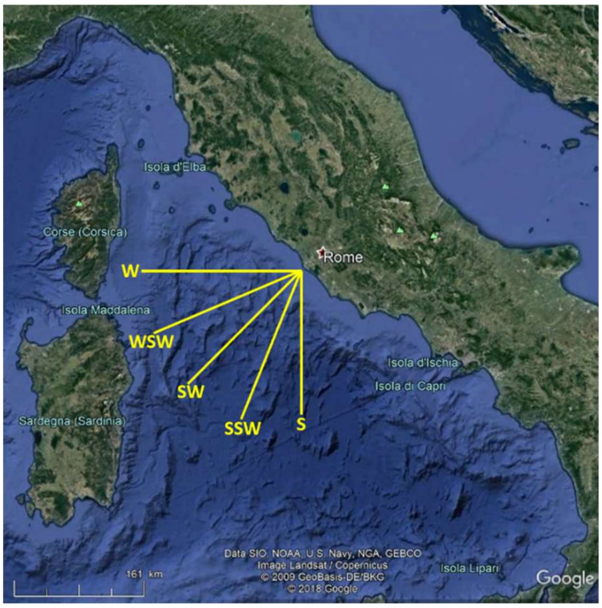
If we wish to understand waves, it is useful to understand how meteorological depressions travel over land and sea. In western Europe most depressions travel from west to east at variable speed. The winds that are associated with a depression usually flow in a counter-clockwise direction (in the northern hemisphere). In the Tyrrhenian Sea, depressions frequently stop and deepen in the Gulf of Genoa before moving on to SE. Hence, a depression travelling along the Italian mainland generates western winds (Libeccio) on its southern edge in the Tyrrhenian Sea. If such a depression travels more south, it generates southern winds first (Scirocco), followed by eastern winds, and possibly even northern winds, later on. This is of course a simplistic representation, aiming at clarifying this vast subject.



Typical path of depressions in the Tyrrhenian Sea.

[57] MURRAY, W., 1987, " Do modern winds equal ancient winds?", Mediterranean Historical Review, 2, (p 139-167), https://doi.org/10.1080/09518968708569525.

In the Tyrrhenian Sea, the waves can really approach the coast near Rome only from a sector from west to south because other wave directions such as SE and NW provide waves that propagate more or less parallel to the coast. Such waves will bend towards the coast sooner or later (due to refraction) while losing much of their energy. Wave statistics computed for Ostia confirm that most large waves come from a WSW direction, with some smaller waves from south.



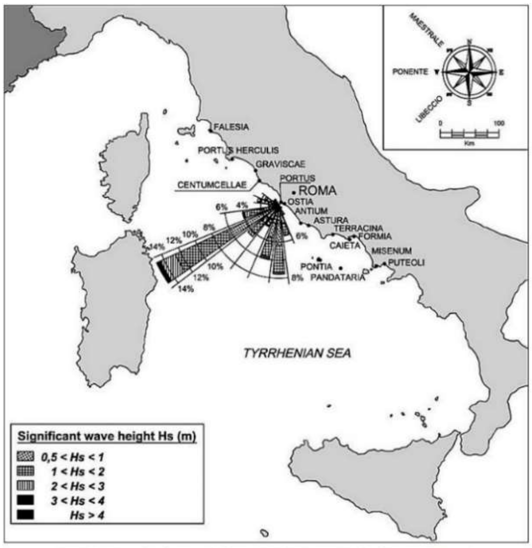


Fig. 2. Geographical map with location of main ancient harbours near Rome and representation of the directional wave climate offshore Ostia after transposition of Ponza buoy records 1989-2005.

Wave climate offshore of Rome (source: Noli & Franco, 2009).

Analysis of wave data from a buoy near Ponza (ancient Pontia)

Our objective is to identify individual storms and identify sudden wave-direction reversals during each storm, if any.

The buoy is located at 40.866°N, 12.950°E, on 115 m water depth, offshore between Rome and Naples. Its registration period is 1989-2008, but the first period until end of 2002 provided records only every 3 hours which is not detailed enough for our purpose. In the period of 2003, the measurement of wave directions was not satisfactory. A new (Triaxys) buoy was apparently installed early January 2004 and a coherent set of 43876 records from 22/1/2004 to 30/3/2008 was chosen for the present analysis.

The data is recorded every 30 min providing Hs (significant wave height in m), Dir (wave direction in degrees to north), Tp (period of the peak of the wave spectrum in s), Tm (mean wave period in s). The sampling is at 1.28 Hz on each 20 min time-series, which means that a 6 s wave is described with 7 to 8 points, and that around 200 waves are analysed for each 20 min record.

A storm in this area can be defined as Hs > 1.5 m. It may be called a “large storm” when Hs = 4 m and more. The storm durations are taken as Hs > 1.5 to 2 m. A change in wave direction is called “sudden” when it occurs within 30 min.

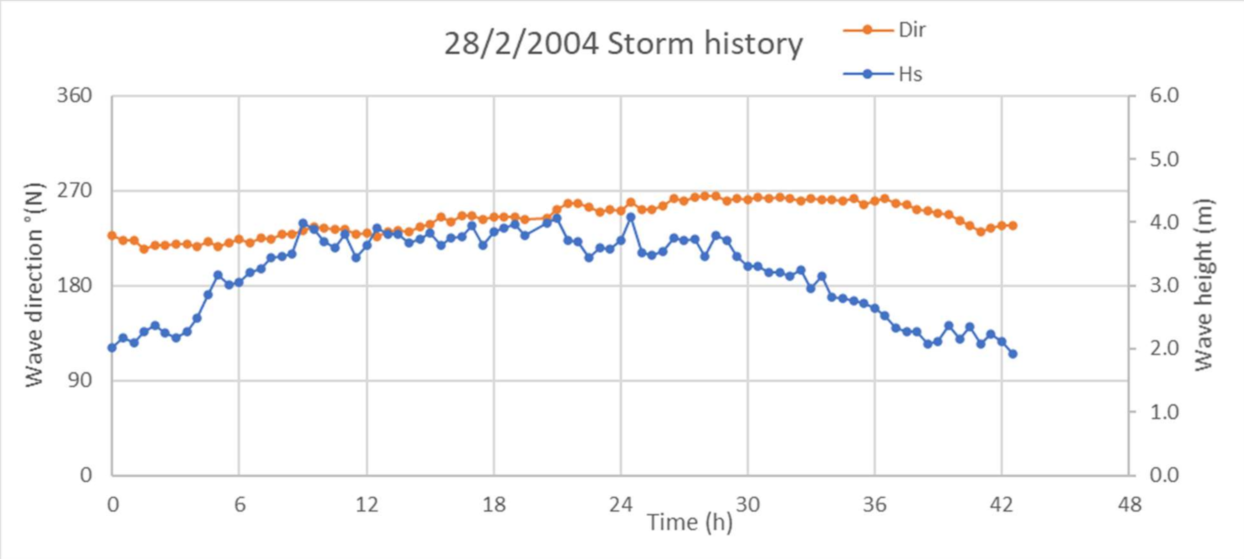
Obviously, the waves from N and from E that are registered at Ponza, do not exist or are very small at Portus. Wave-direction changes from W to N, or from S to E are thus favourable for ships anchored inside Portus, as waves reduce during such an event, even if the wind may remain a problem.

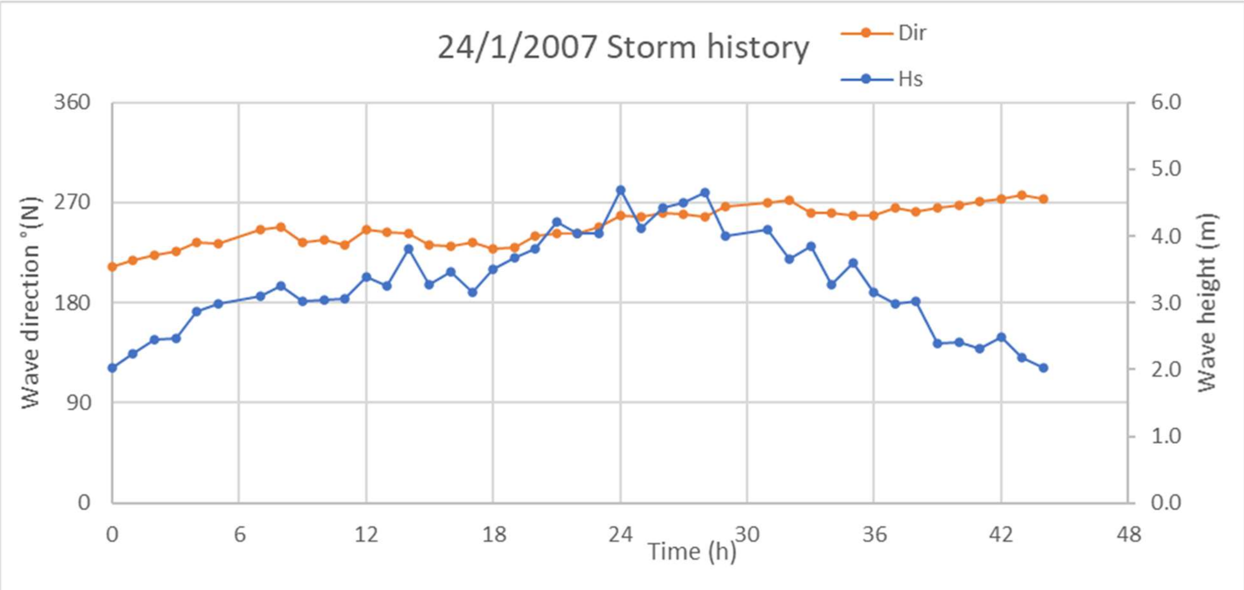
The following results were found:

1. Identified storms:

   28/2/2004, 1.5 days, Hs = 4 m, Dir 225° => 270° (gradual change of 45° over 24h)
   24/3/2004, 1.5 days, Hs = 4 m, Dir 270° (stable)
   25/9/2004, 1.5 days, Hs = 3 m, Dir 270° => 360° (gradual 90° change)
   8/11/2004, 1 day, Hs = 2 m, Dir 115° => 315° => 115° (two sudden 200° reversals)
   20/11/2004, 1 day, Hs = 4 m, Dir 270° => 90° (sudden 180° reversal)
   25/1/2005, 1 day, Hs = 2 m, Dir 270° => 90° (sudden 180° reversal)
   4/8/2005, 0.5 day, Hs = 1.5 m, Dir 295° => 90° (fast 155° reversal)
   8/8/2005, 0.5 day, Hs = 1.5 m, Dir 270° => 180° (fast 90° change)
   27/9/2006, 0.5 day, Hs = 1.5 m, Dir 250° => 360° => 270° (two sudden 90° changes)
   2/11/2006, 1 day, Hs = 3 m, Dir 270° => 45° (sudden 135° near-reversal)
   2/1/2007, 1 day, Hs = 4 m, Dir = 270° (stable)
   24/1/2007, 2 days, Hs = 4-5 m, Dir = 220° => 270° (gradual change of 50° over 36h)
   28/5/2007, 1.5 days, Hs = 4 m, Dir = 270° (stable)
   21/10/2007, 2 days, Hs = 2 m, Dir = 115° => 360° => 295° (one sudden 245° reversal, one sudden 65° change)
   8/12/2007, 3 days, Hs = 4 m (twice), Dir = 270° (stable)
   23/1/2008, 1 day, Hs = 1.5 m, Dir 270° => 70 ° (sudden 160° near-reversal)

2. We found 7 large storms with max Hs = ca. 4 m during the registration period of ca. 4 years, and that is an average of 1 to 2 large storms per year, but 3 large storms were found in 2004 and in 2007, and none occurred in 2005 and 2006. All large storms (save one on 28/5/2007), occurred during the winter months (November - March).
3. The storm durations are between 0.5 and 2 days (save one in 2007 lasting 3 days).
4. For large storms, the mean wave period Tm = 7 to 9 s, which yields a wave length of 60 to 80 m on a 10 m water depth, and 45 to 60 m on a 5 m water depth. Smaller storms feature Tm = 5 to 6 s, which yields a wave length of 35 to 50 m on a 10 m water depth, and 30 to 40 m on a 5 m water depth.
5. The dominant wave direction is from SW to W, both for small storms (Hs > 1 m) and for large storms (Hs > 3.8 m).
6. Four large storms and many other storms show stable wave directions. Five storms show gradual wave direction changes.
   Two gradual wave direction changes have been found (45° over 24 h on 28/2/2004 and 50° over 36 h on 24/1/2007) but it may be considered that this did not induce serious problems for ships moored inside the port.
   One case with a somewhat faster gradual change in wave direction was found on 25/9/2004 when the change from W to N occurred within 2.5 h near the end of the storm when waves were decaying from Hs = 2 m to Hs = 1 m.
   Even faster changes occurred within 1 h and 1.5 h on 4 and 8/8/2005 respectively. On 4/8/2005, the reversing from NW to E, via N, occurred in 60 min, with Hs = 1 to 1.5 m. On 8/8/2005, the reversing from W to S occurred within 90 min when waves were Hs = 1.5 m.


28/2/2004 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
0
90
180
270
360
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
6
12
18
24
30
36
42
48


24/1/2007 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
0
90
180
270
360
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
6
12
18
24
30
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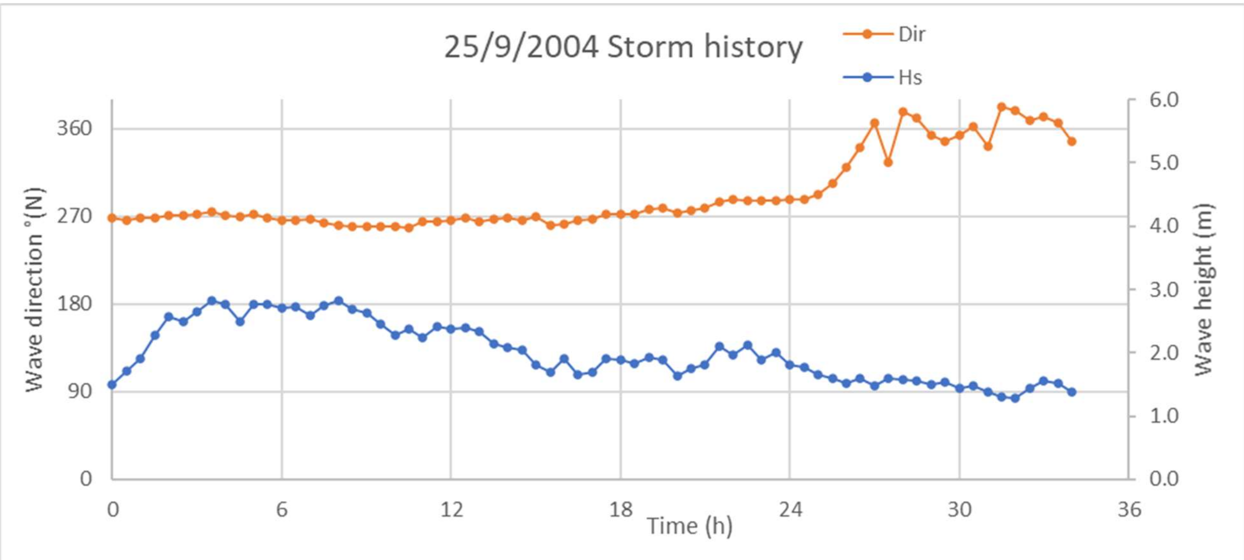
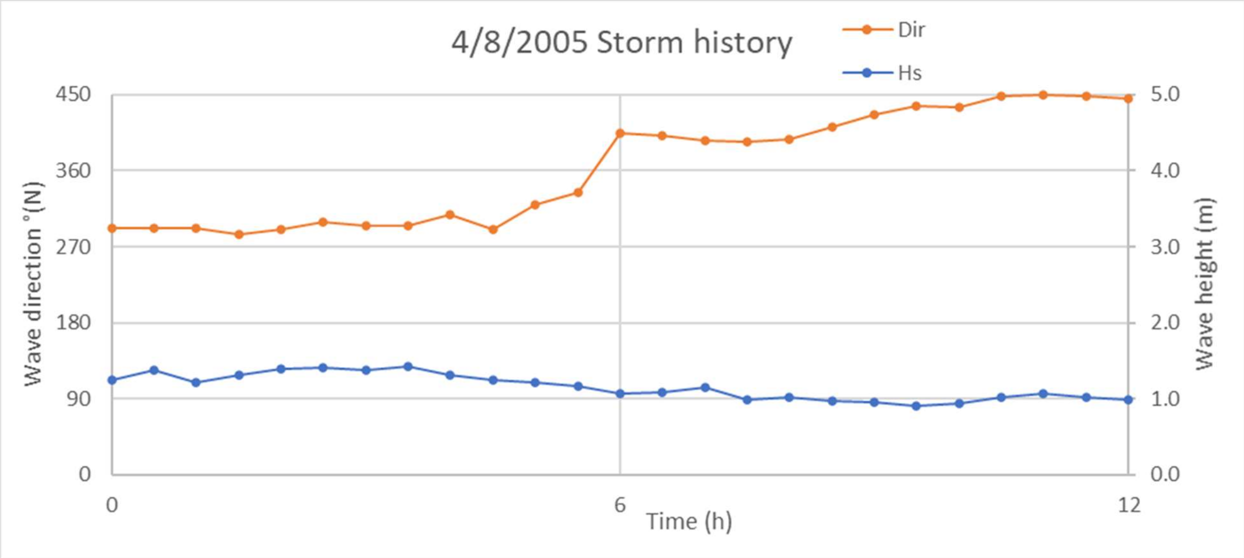
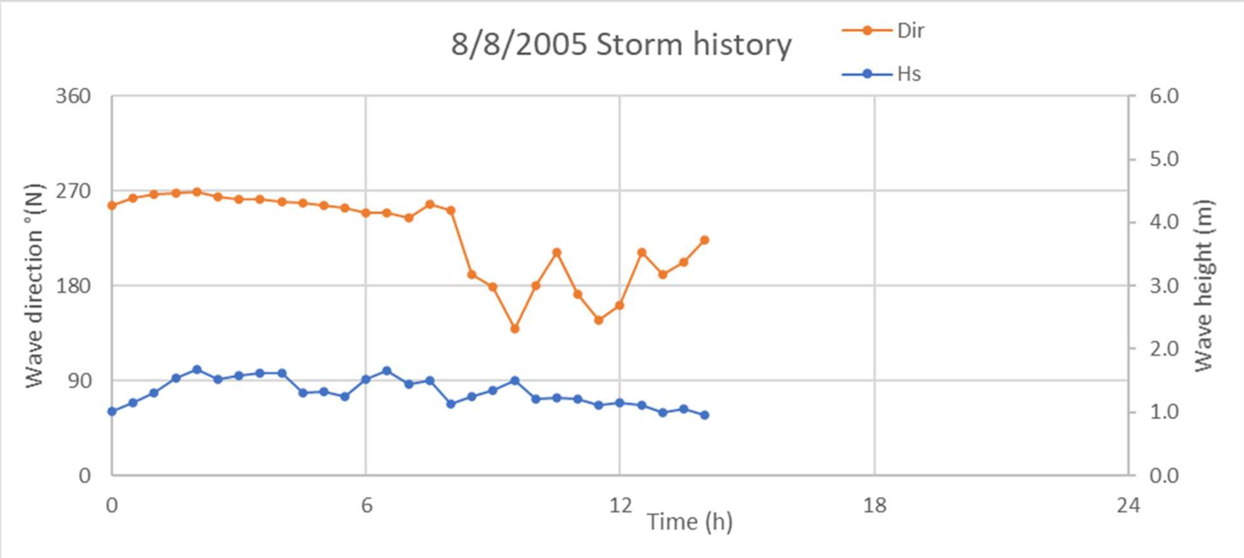
42
48

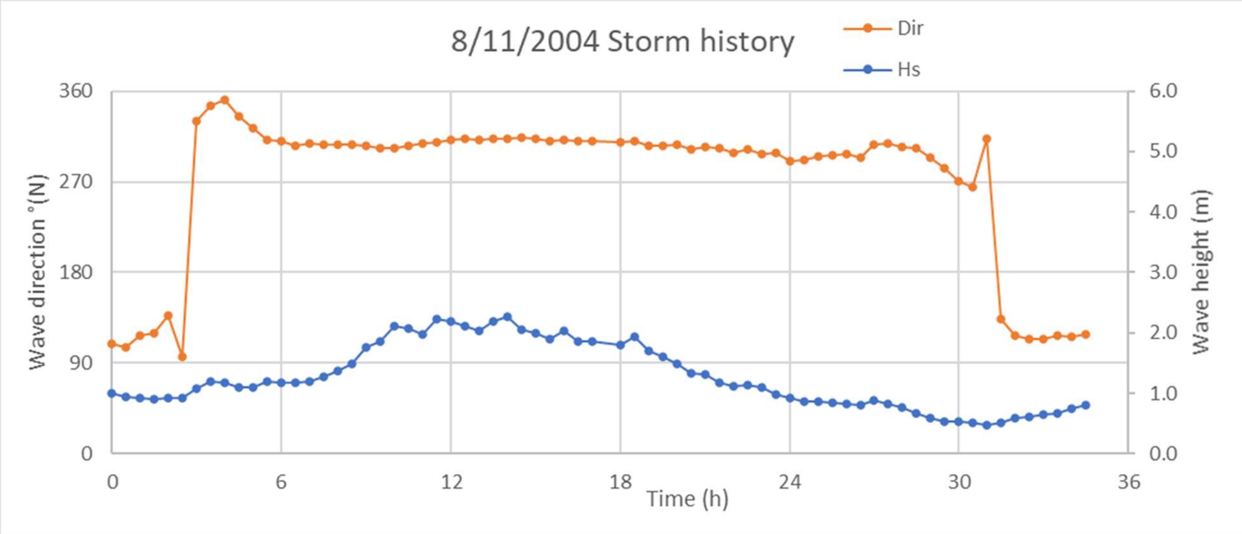

25/9/2004 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
0
90
180
270
360
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
6
12
18
24
30
36

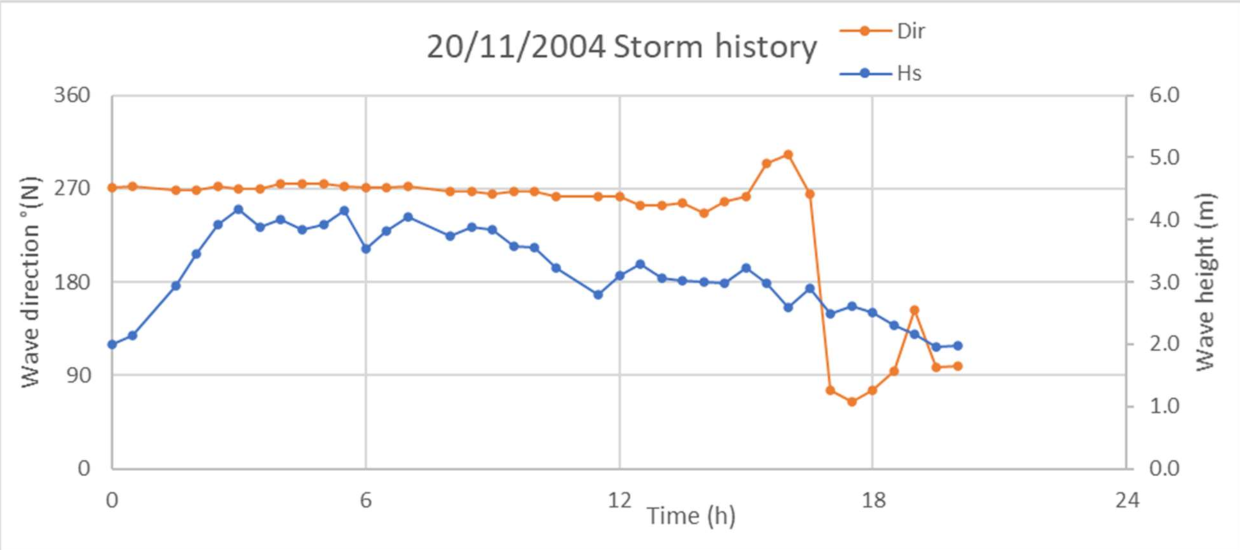


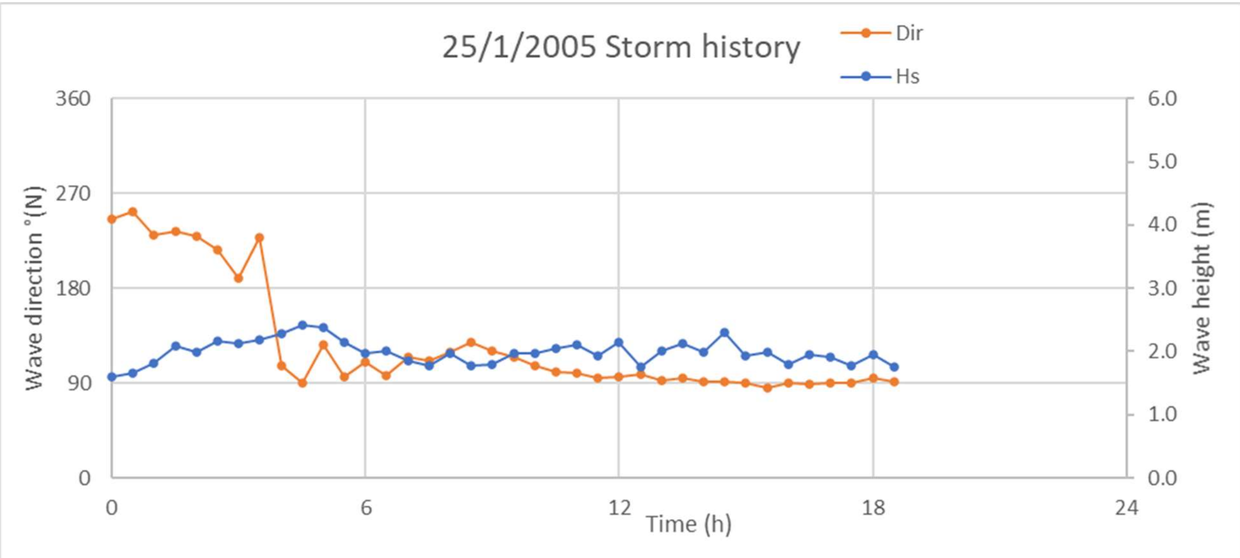


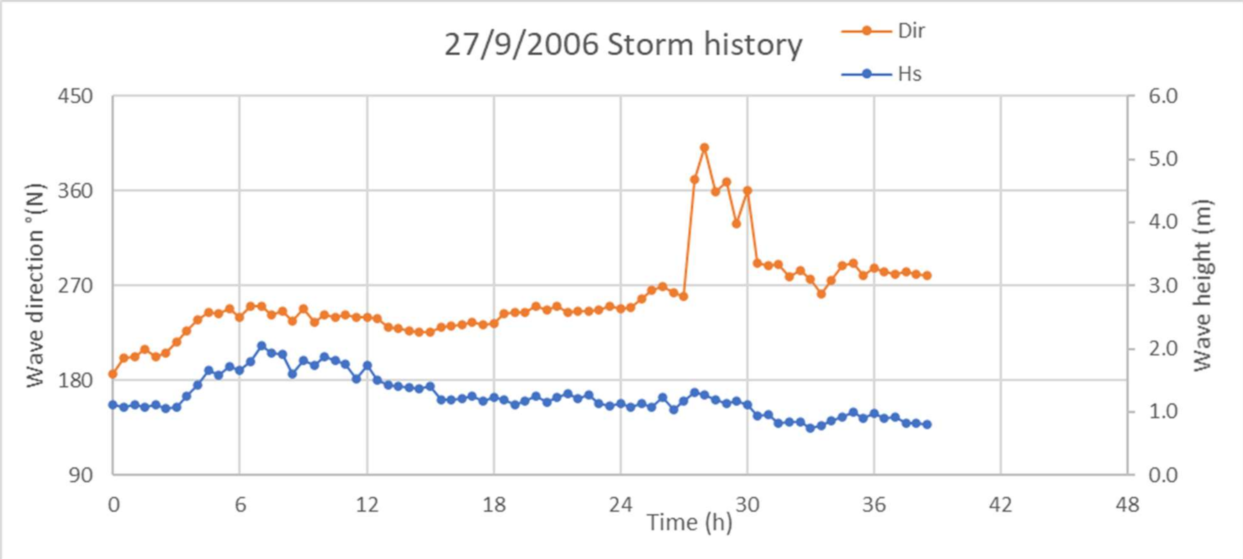
7. Sudden 90° to 180° changes in wave directions have been found <u>10 times during the 4-year period</u> of observation:

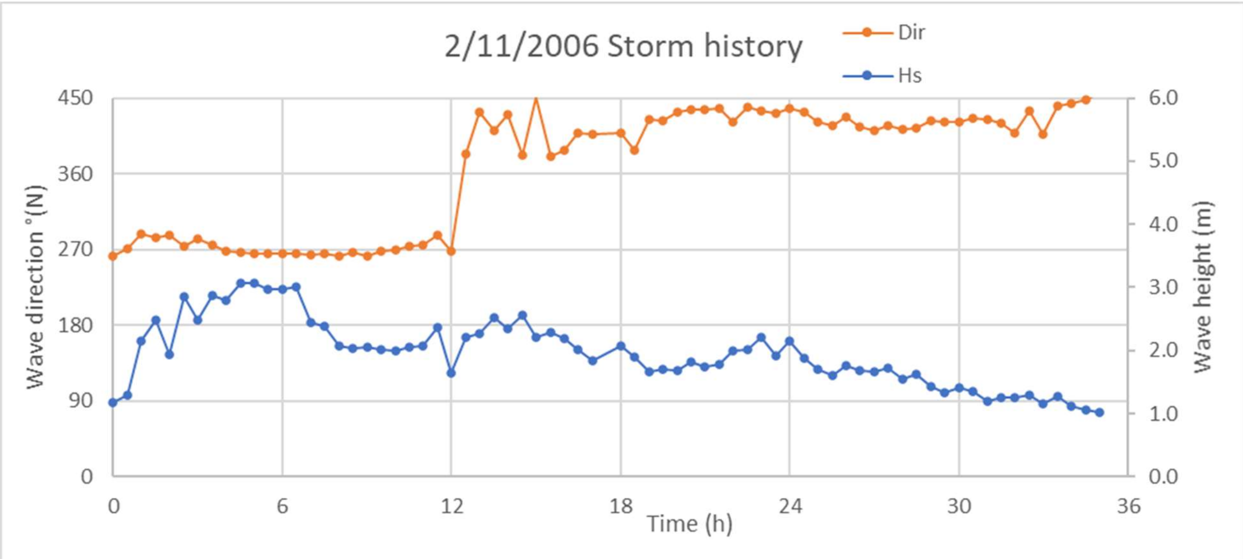
   On 8/11/2004, the change from E to NW occurred within 30 min at the beginning of the storm with waves were increasing from Hs = 1 m to Hs = 1.5 and 2 m.
   On 8/11/2004, a sudden reversal from NW to E occurred at the end of the storm.
   On 20/11/2004, the reversing from W to E occurred within 30 min near the end of the storm when waves were decaying from Hs = 3 m to Hs = 2 m.
   On 25/1/2005, the reversing from W to E occurred within 30 min near the beginning of the storm when waves were Hs = 2 m.
   On 27/9/2006, the change from WNW to N occurred within 30 min when waves were Hs = 1.5 m.
   On 27/9/2006, 2.5 hours after the first change, waves turned further from N to W.
   On 2/11/2006, the reversing from W to NE occurred within 30 min when waves were Hs = 2 m.
   On 21/10/2007, the change from E to N occurred within 30 min when waves were Hs = 1.5 m.
   On 21/10/2007, 3 hours after the first change, waves turned further from N to NW.
   On 23/1/2008, the reversing from W to NNE occurred within 30 min when waves were Hs = 2 m.

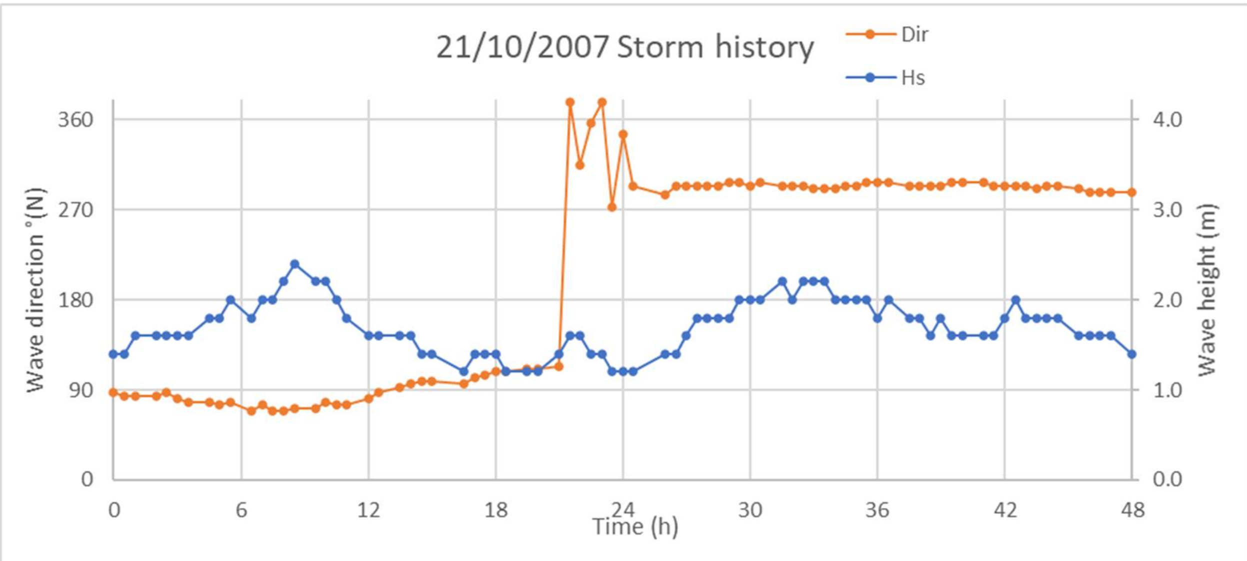

8/11/2004 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
360
270
180
90
0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
6
12
18
24
30
36

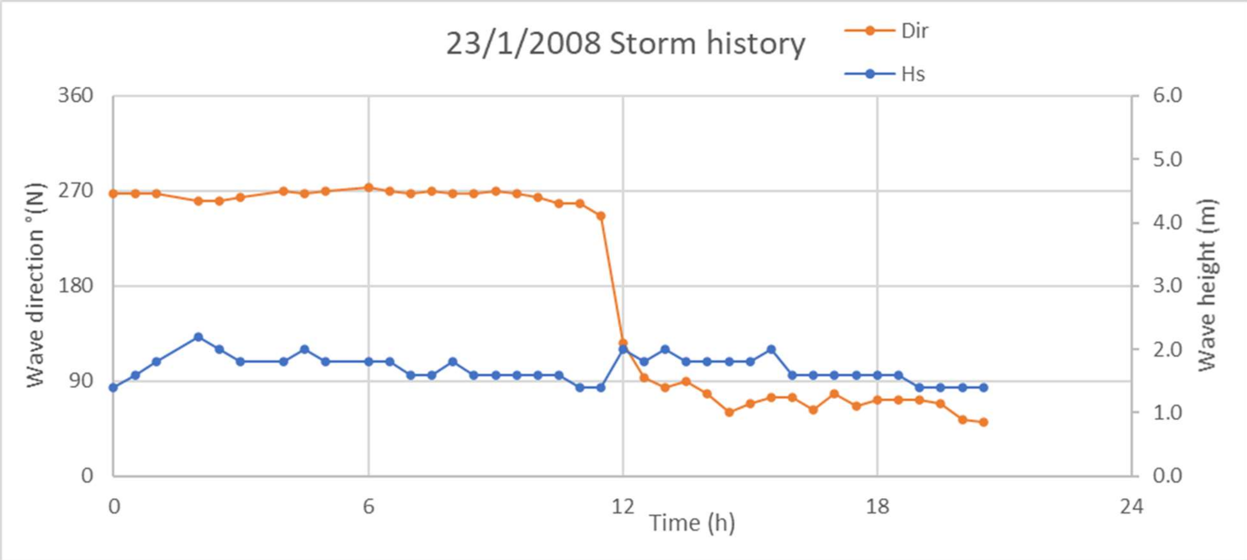

20/11/2004 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
360
270
180
90
0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
6
12
18
24


25/1/2005 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
360
270
180
90
0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
6
12
18
24


27/9/2006 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
450
360
270
180
90
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
6
12
18
24
30
36
42
48


2/11/2006 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
450
360
270
180
90
0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
6
12
18
24
30
36


21/10/2007 Storm history
Dir
Hs
Wave direction °(N)
Wave height (m)
Time (h)
360
270
180
90
0
4.0
3.0
2.0
1.0
0.0
0
6
12
18
24
30
36
42
48



8. Out the 10 cases shown above, 4 show a sudden change from W to S and to E, corresponding to the usual path of meteorological depressions, as explained before. Several other cases show waves suddenly turning to N.
   Only one case on 8/11/2004 shows a sudden change from E to S and to NW.

Imagine a storm like the one on 8/11/2004: the wave-direction change from ESE (115°) to NW (315°) occurs within around half an hour which is really short for sailors to move their ships to seek better shelter inside the port. Two or three hundred ancient ships are at anchor in the lee of the southern breakwater with a gentle eastern wind and almost no waves inside the port. Ships are using their own anchors or fixed mooring boxes placed on the seabed. The water depth is quite large (5 to 10 m) and the mooring lines are long. The ships' sterns are located at 30-50 m from their anchor. Everything is under control and only one or two sailors remain on board of each ship for safety.

Now, suddenly, within half an hour, the wind and waves turn to NW, first with Hs = 1 m waves outside, then growing to 2 m within a few hours. The sheltered area in the lee of the southern breakwater now receives 0.5 m waves (growing to 1 m). The ships simultaneously turn around their anchors to align in the wind direction. No big problem so far. However, waves start to shake the ships who are pulling on their anchor lines and anchors will start to rip on the seabed. Anchor lines that are tied up to fixed mooring boxes may break.

That is the beginning of a drama ... Unmoored ships are quickly blown towards the southern breakwater where they crash on each other. Such an event might end up in a drama like in year 62 when 200 ships were sunk in Portus Claudius.

2.16.8 Berthing capacity of Portus Trajanus

Trajan’s coin showing the hexagonal Portus Traiani
(source: www.ostia-antica.org).

Like today: *Bread and games to ensure social peace …*
(« Panem et circenses » Juvenal, Satires, 10.81)

Let's try to think like a Roman port engineer in 105 AD ...

Concerning the games, we have the Coliseum (built between 72 and 80 AD) and concerning bread, we need a harbour basin enabling us to ensure Rome’s supply of food. We already have Portus Claudius (around 200 ha, built between 42 and 54 AD) but 200 ships were sunk in this port during a storm in 62 AD. Indeed, when observing the areas sheltered from waves in L. Franco’s computations[58], a sheltered area of around 20 ha is found close the south breakwater for SW waves, and around 40 ha is found close the north breakwater for western waves (NB: dominant waves are from SW to W). As around 10 ships of 25 x 7 m can anchor on one hectare of water area, it can be seen that around 200 ships could be anchored safely in Portus Claudius. That is quite a lot of ships but a disaster like the one in 62 AD could occur if the wind would suddenly change direction.
We therefore need to add a new basin with better protection from storms: the construction of Portus Trajanus (33 ha) will be undertaken from 106 to 113 AD.

This new basin will combine very well with the existing Portus Claudius that can be used as an outer harbour allowing sailing in under full sail and furling sails in a sheltered area. This existing basin offers a shelter for around 200 ships at anchor while waiting for unloading. The new basin will not only offer better shelter against storms, but also have many warehouses and a new canal to the Tiber from where goods will be moved faster upstream over around 30 km to Rome on hauled barges. Traffic will be separated: sea-going ships on one side of the new basin and river barges on the other side near the new canal, with warehouses in

[58] NOLI, A., & FRANCO, L., 2009, “The ancient ports of Rome: new insights from engineers”, Archaeologia Maritima Mediterranea, 6.

between. This separation is still in use in some ports nowadays (e.g., Rotterdam) as it separates the marine world from the river world.

The logistic chain is thus completely redesigned.

Around 200 000 to 400 000 tons/year of grain coming from North Africa (Egypt, Tunisia) must be provided to feed the one million people of the city. Other goods must be added to this (olive oil, wine, garum, etc.). The total traffic can be estimated at 500 000 tons/year, as an average[59].

With 200- to 500-ton ships making two trips a year, 1000 ships are required to provide 2000 shiploads averaging 250 tons per load[60]. This is obviously quite approximate and variations around these figures can be thought of, e.g., a part of these shiploads might go through Puteoli[61] and further to Ostia by means of smaller coasters that would pass the sandy bar at the entrance of the Tiber, and probably even be towed all the way to downtown Rome.

Hence, let's stick to *1800 shiploads/year transiting through Portus Trajanus*.

These ships sail mainly (and not 'only') during the good season (early April to the end of October) using the "summer winds" from NW that blow on the eastern Mediterranean in July-August and allowing a fast trip from Rome to Alexandria (one or two weeks, but at least double on the trip back to Rome). A concentration of ships arriving at Portus may thus be expected before and after July-August, in June and in October.

As each 250-ton grain ship carries around 8 000 sacks of one artaba (ca. 39 l) weighting around 30 kg each (see section on "Ancient measures"), and if unloading is organised as a continuous file of individuals, it might be possible to unload a ship within a few days, but it is more realistic to expect 10 days for unloading a 250-ton ship and to take in provisions and settle formalities [62]. If we wish to host 900 ships in June (first trip) and 900 ships in October (second trip), then *we need a basin with quays for around 300 ships* (i.e., 3 groups of 300 ships staying for 10 days each).

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[59] REDDE, M., 2005, "Voyages sur la Méditerranée romaine", Actes Sud, (p 44).
BRANDT, J., 2005, "The Warehouse of the World", A Comment on Rome's Supply Chain during the Empire, Orizzonti. Rassegna di archeologia 6 (2005), (p 25–47).
TCHERNIA, A., 2011, "Les Romains et le commerce", Centre Jean Bérard, (p 275-287).

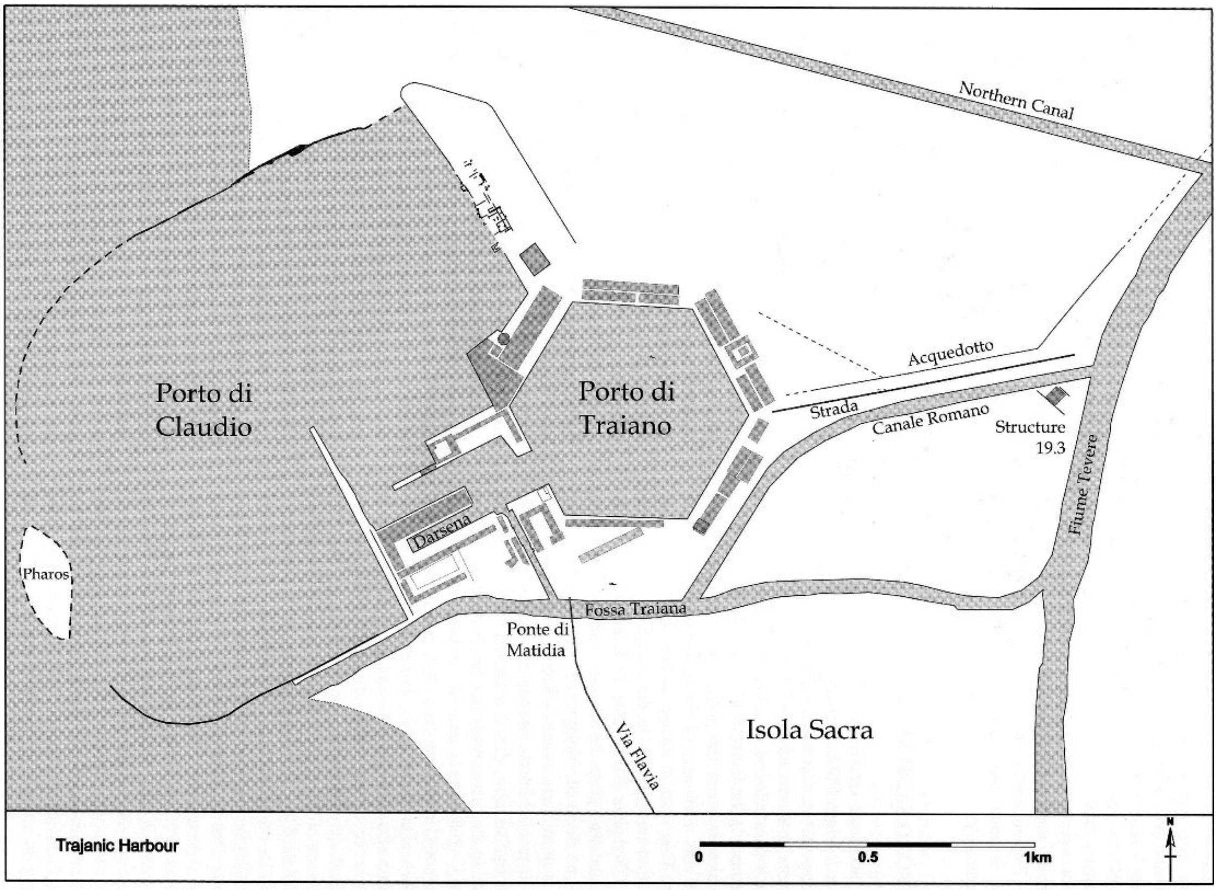
[60] ARNAUD, P., 2016, "Conclusion", in "The Sea in History: The Ancient World - La Mer dans l'Histoire L'Antiquité", Edited by Pascal Arnaud and Philip de Souza, General editor Christian Buchet, Woodbridge, The Boydell Press, (p 623). See also section on ancient merchant ships.

[61] Large merchantmen sailing from Alexandria would surely prefer calling at Puteoli than at Portus, as they would save some precious time to return back to Alexandria as soon as possible for their second yearly trip.

[62] BOETTO, G., BUKOWIECKI, E., MONTEIX, N. et ROUSSE, C., 2016, "Les Grandi Horrea d'Ostie", in "Entrepôts et trafics annonaires en Méditerranée", Marin B. et Virlouvet C. (dir.), Ecole Française de Rome, 522, (p 177-226). This paper informs us that 3 days are needed to unload 70 tons and refers to POMEY (1978) who speaks of 2 to 4 days to unload a small- to medium-size ship. Pomey refers to ROUGE (1952) who speaks of 2 days to unload and 4 days to load a ship of untold size. Rougé refers to WILCKEN (1912) who translates a letter of Eirenaios to his brother in Egypt, telling him that he arrived in Portus on June 30 and that his (probably large) ship was unloaded on July 12 (2nd or 3rd c. AD). Rougé also refers to ASHBURNER (1909) who translates a contract telling us that the captain has 4 days to unload 250 artaba (a small ship) in 236 AD.
In addition, KEAY, S., 2014, "The Role Played by the Portus Augusti in Flows of Commerce between Rome and its Mediterranean Ports", in "The Roman Economy", edt. B. Woytek, Austrian Academy of Sciences, (147-192) mentions 2 to 6 days for unloading a 150- to 350-ton ship (p 161). This order of magnitude was also confirmed by BRANDT (2005).
Note also that, depending on (possibly corrupt) friends the shipper has in the port, administrative formalities may take more time and require the ship to be anchored away from the quay walls.

On the layout map of Portus Claudius[63], 1000 m of quay walls are found outside the "Darsena" (the Darsena itself, 48 x 230 m, is supposed to be used by river boats). In addition, a further 700 m can be found along the Portico di Claudio (300 m) and Molo di Claudio ("Nord-Sud") (2 x 200 m). The total quay-wall length available for large sea-going ships thus does not exceed ca. 2000 m. Hence, *the total number of sea-going ships docked in Portus Claudius is limited to a maximum of ca. 100 ships, plus 100 ships on Portico di Claudio + Molo Nord-Sud, available only in good weather conditions.*

Enlarging the port is therefore a necessity.



Layout of Portus Claudius and Portus Trajanus (Simon Keay et al, 2005)

HARBOUR BASIN SHAPES

Let's suppose we get a phone call from the emperor ordering the digging of a new harbour basin for 300 ships of 25 x 7 m … We would first need to provide a quay length of 300 x 7 m = 2100 m (all ships being docked bow first, like on the Torlonia relief). Any basin shape might be accepted, from a straight-line of 2100 m to a circle with 668 m diameter, including a triangle, a rectangle, a hexagon, etc.

For all angular shapes, some length is lost in the angles if ships are not to hinder each other.

The circular shape would be tempting to reduce the volume of excavation, but the circular shape does not provide linear quays that are preferred for port operations.

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63 KEAY, S., & MILLETT, M., 2005, "Portus in Context", Portus, an archaeological survey of the port of imperial Rome, The British School at Rome.
BUKOWIECKI, E. & MIMMO, M., 2021, "Infrastructures portuaires à Portus - Les entrepôts dits de Trajan et le môle nord-sud", Colloque Fréjus, 2018.

Angular shapes have better perimeter/surface ratios. Let's start with an isosceles triangle which offers 30% more perimeter for the same surface as a circle, but quite some length is lost in its sharp angles. Then come the square, the rectangle and multi-faced shapes like pentagon, hexagon, etc. and finally, the circle. The total length lost in the angles obviously increases with the number of angles, but at the same time the length lost at each angle reduces, and it is seen on parameter C below that both effects more or less compensate each other.

Let's have a closer look at Portus Trajanus. It consists of a hexagon with six 358 m sides which is thus inscribed in a circle with a 716 m diameter. This hexagon has a perimeter of 2148 m and an area of 33.3 hectares. This seems quite close to what we need to berth 300 ships with a length of 25 m and a width of 7 m as it has a little more than the 2100 m of quay length we are looking for.

Let's now go back to polygons with a 2148 m perimeter. We computed the number of ships that might be aligned bow or stern first side by side in polygonal basins with an increasing number of sides. We also computed the basin area and the number of ships per unit of area to be excavated.

N = total number of ships in the basin

n = number of sides of the basin

a = length of each side of the polygon

L = length of ships (25 m)

b = width of ships (7 m)

D = diameter of the circle in which the polygon is inscribed

C = total quay length lost in the angles

P = perimeter of the polygon = quay length to be built

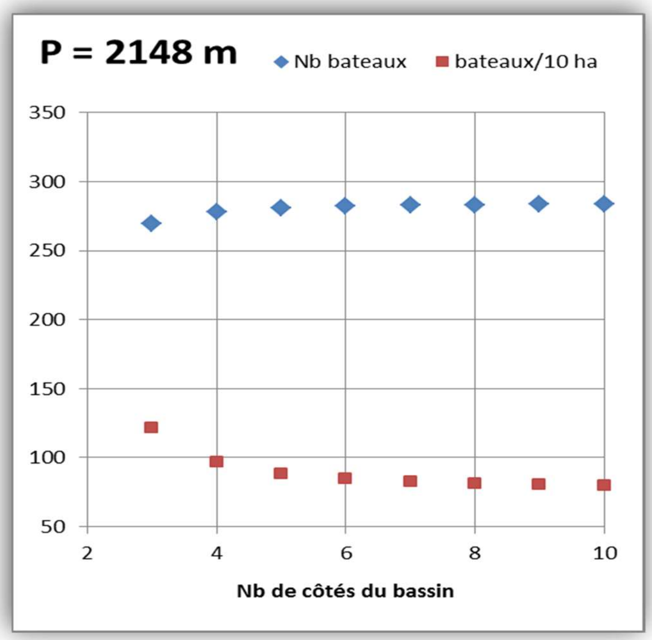
S = surface of the polygon = surface of the basin to be excavated

N/10 S = number of ships per 10 excavated hectares

Computation of the number of ships in a polygonal basin with n sides.

n	>> a (m)	>> D (m)	>> S (ha)	>> C (m)	>> P-C (m)	>> N	>> N/10S
3	716	827	22,2	259,8	1888	270	122
4	537	759	28,8	200,0	1948	278	97
5	430	731	31,8	181,6	1966	281	88
6	358	716	33,3	173,2	1975	282	85
7	307	707	34,2	168,6	1979	283	83
8	269	702	34,8	165,7	1982	283	81
9	239	698	35,2	163,8	1984	283	80
10	215	695	35,5	162,5	1986	284	80
20	107	687	36,4	158,4	1990	284	78
50	43	684	36,7	157,3	1991	284	78
100	21	684	36,7	157,1	1991	284	77

(Computation with a constant perimeter of 2148 m)



Computation of the number of ships in a polygonal basin with n sides.

The number of sides of the polygon is set out horizontally and the number of ships in the basin is set out vertically. It can be seen that the number of ships does not vary much (around 280) with the number of sides. The triangle provides a little less quay length than the other shapes.

It can be seen that between 8 and 10 ships per excavated hectare can be hosted (except for the triangle which can host over 12 ships/ha).

It must be noted that a linear basin consisting of only 2 long quays of 1000 m each would also host around 285 ships. The surface would be only around 10 hectares (assuming a basin width of 4 ship lengths), leading to 28 ships/ha and to a much smaller volume of excavation.

As a conclusion, it can be said that for 2148 m of quays to be built (including a little less than 2000 m really available for docking), around 280 ships can be docked bow first in a basin with four or more sides. Obviously, a smaller number of larger ships would be docked in the same basin, e.g., less than 220 ships of 35 x 9 m, instead of 280 ships of 25 x 7 m.

A linear or a triangular shape would be optimal if the volume to excavate was to be minimised, but this approach was clearly not chosen. The volume to excavate was therefore not the main design parameter and it may be accepted that (like today) excavation in a sandy subsoil was relatively cheap compared to the cost of quay wall building.

The hexagonal shape is not particularly optimal from a point of view of number of berths or volume of excavation. It must therefore have attracted the Roman designers for other reasons:

- integration into existing geography and land use,
- inspired by the famous circular 'cothon' at Carthage?
- with each of the six sides specialising on particular goods and warehouse types.

ALGEBRAIC FORMULATION

Sorry for those who hate maths: they are exempted to read …

$$a_n = D_n \sin\frac{\pi}{n}$$

$$P_n = n\, D_n\, \sin\frac{\pi}{n}$$

$$S_n = \frac{n\, D_n^2}{8} \sin\frac{2\pi}{n}$$

$$D_n = \frac{P}{n\, \sin\frac{\pi}{n}}$$

$$S_n = \frac{P^2}{4n\, \mathrm{tg}\frac{\pi}{n}}$$

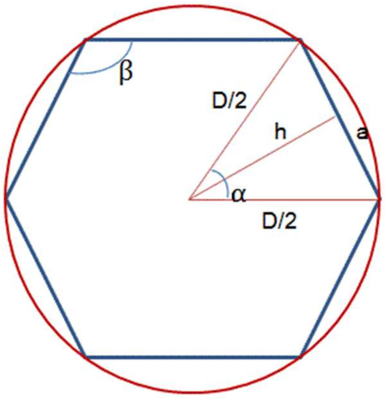
Linéaire perdu dans les angles :

$$C_n = \frac{2nL}{\mathrm{tg}(n-2)\frac{\pi}{2n}}$$

Nombre de bateaux par côté :

$$N = (P - C_n)/b$$

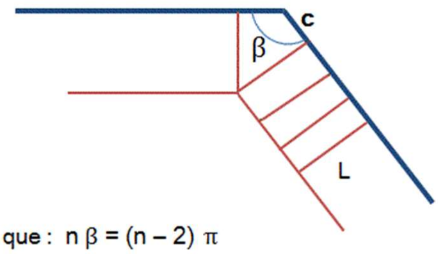
Polygone à n côtés : $\alpha = \frac{2\pi}{n}$ pour $n \geq 3$



Périmètre : $P_n = n\, a$

Surface : $S_n = n\, s = n\, h\, a/2$

Linéaire C perdu dans les angles:



Sachant que : $n\, \beta = (n - 2)\, \pi$

2.17 PORTUS PISANUS

The Roman poet Rutilius Namatianus, who travelled in the 5th c. AD by boat from Rome to Gaul, visited various ports, including Portus Pisanus:

*"From there we make for **Triturrita**: that is the name of a residence, a peninsula lying in the wash of baffled waves. For it juts out into the sea on stones which man's hand has put together, and he who built the house had first to make sure building ground.*
*I was astonished at the haven close by, '**Pisarum Emporio**', which by report is thronged with sea-borne wealth. The place has a marvellous appearance. Its shores are buffeted by the open sea and lie exposed to all the winds: here there are not sheltering piers to protect any inner harbour-basin capable of defying the threats of Aeolus. But, fringing its own deep-water domain, the tall sea-weed is like to do no damage to a ship that strikes it without shock; and yet in giving way, it entangles the furious waves and lets no huge roller surge in from the deep. […]*
*So then I moor my ships in the safe anchorage, and myself drive to **Pisa** by the road the wayfarer goes afoot. […]*
I scan the ancient city of Alphean origin, which the Arno and the Ausur gird with their twin waters; at their junction the rivers form the cone of a pyramid: the opening front offers access on a narrow tongue of land; but it's the Arno that retains its own name in the united stream, and in truth the Arno alone arrives at the sea."
(de Reditu suo, Book 1, verse 527, Transl. Lacus Curtius).

This interesting description shows several features:

1. Coming with a ship from the south (from Rome) they first pass a man-made peninsula with a villa maritima called Triturrita. An 18th c. chart shows that this villa (Turrita) is located at the modern 'Cimitero comunale dei Lupi'.
2. The port where he moors his ships, called Pisa's emporion, is not protected by breakwaters, but by a field of sea-weed that is known to reduce wave action without damaging the ship's hull when passing through it. This may be a lagoonal area near the estuary of river Cigna. Recent archaeological discoveries were made at San Stefano ai Lupi (Allinne et al. 2014).
3. A clear distinction is made between 'Pisarum Emporio' and the city of 'Pisa' that is to be reached on foot.
4. Pisa was built at the confluence of the Arno river and the Auser river now called Serchio and flowing further north. By the way, Strabo (Geog. 5, 2, 5) warns that sailing the Arno river from the sea to the city, located two nautical miles upstream, is very difficult for sea ships.

18th c. chart showing the lagoon and Triturrita island

(Targioni Tozzetti, 1768-1779)

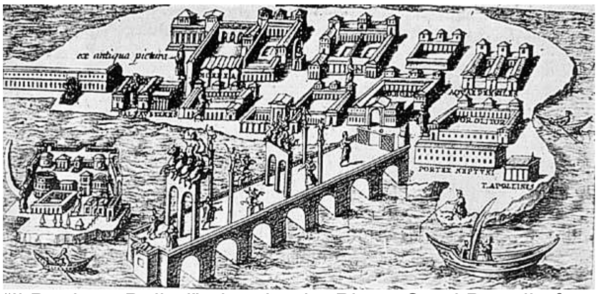
Further (fascinating) reading on: https://www.romanports.org/

2.18 PUTEOLI & NESIS

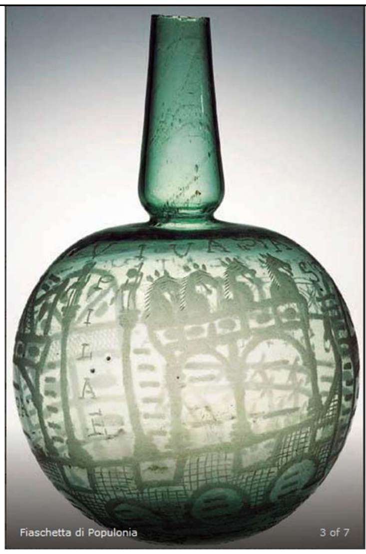
2.18.1 Puteoli

Puteoli (now Pozzuoli) was a major Roman port. It was sheltered by the most famous arched breakwater resting on pilae. This breakwater was buried under the modern breakwater (!) but it was still visible in the 19th c. and known as “Molo Caligoliano”:

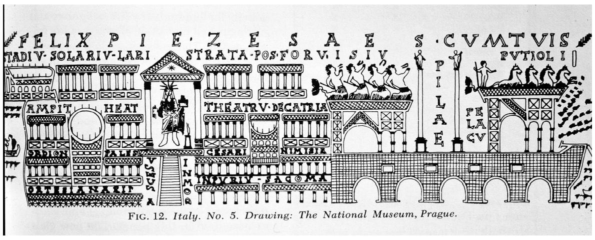
Puteoli breakwater fresco at Villa Stabiae, Pompei (1st c.)
(source: http://www.marine-antique.net/Port-de-la-maison-de-Stabie-Pompei)



“Il Designo Bellori”, drawing by Pietro Santi Bartoli after a 3rd c. fresco found at Esquilino (Rome) (now vanished) and published by Bellori in 1673.
(source: http://www.vesuviolive.it)



Puteoli breakwater on a souvenir glass flask known as Fiascetta di Populonia and showing the pilae (4th c.)
(source: http://www.archeoflegrei.it/i-souvenir-di-puteoli/)



Puteoli breakwater on a souvenir glass flask kept at the National Museum of Prague and showing the pilae (4th c.)
(source: https://web.uvic.ca)

See also: Picard, C., 1959, “Pouzzoles et le paysage portuaire”, Latomus, T. 18, Fasc. 1, (p 23-51).

Castrum Puteolanum in the 17th c. (?) (detail)
(source: http://www.archeoflegrei.it/i-castra-flegrei/)

Puteoli breakwater after Paoli (1768)
(source: http://www.archeoflegrei.it/portodiputeoli/)

Puteoli breakwater after Morghen (1769)
(source: https://www.e-rara.ch/zut/content/pageview/14428247)

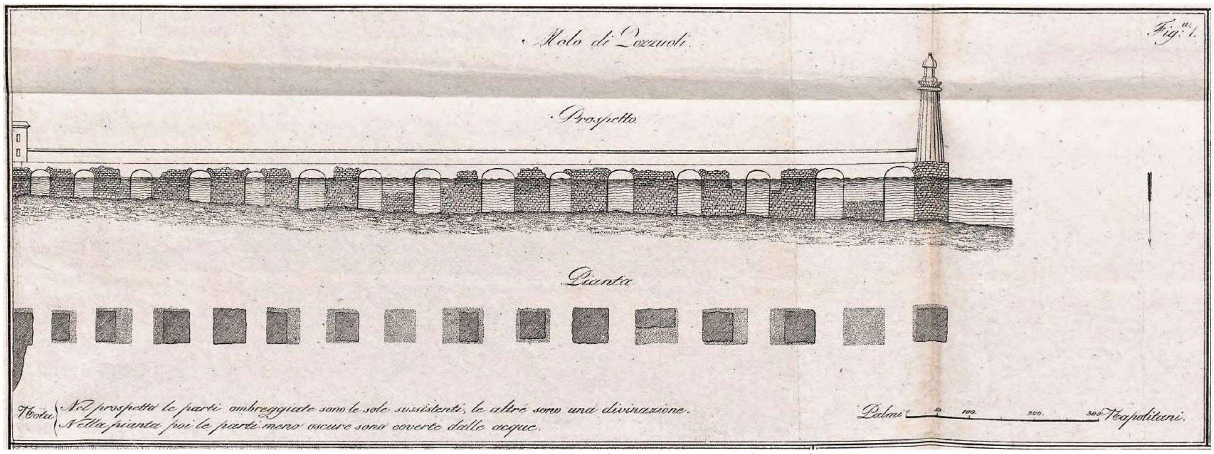
Puteoli breakwater after Hamilton (1776)
(source: https://commons.wikimedia.org/wiki/File:William_Hamilton_-_Campi_Phlegraei,_Pozzuoli.jpg)

Puteoli breakwater after Smargiassi (ca. 1840)
(source: http://www.artvalue.com/)

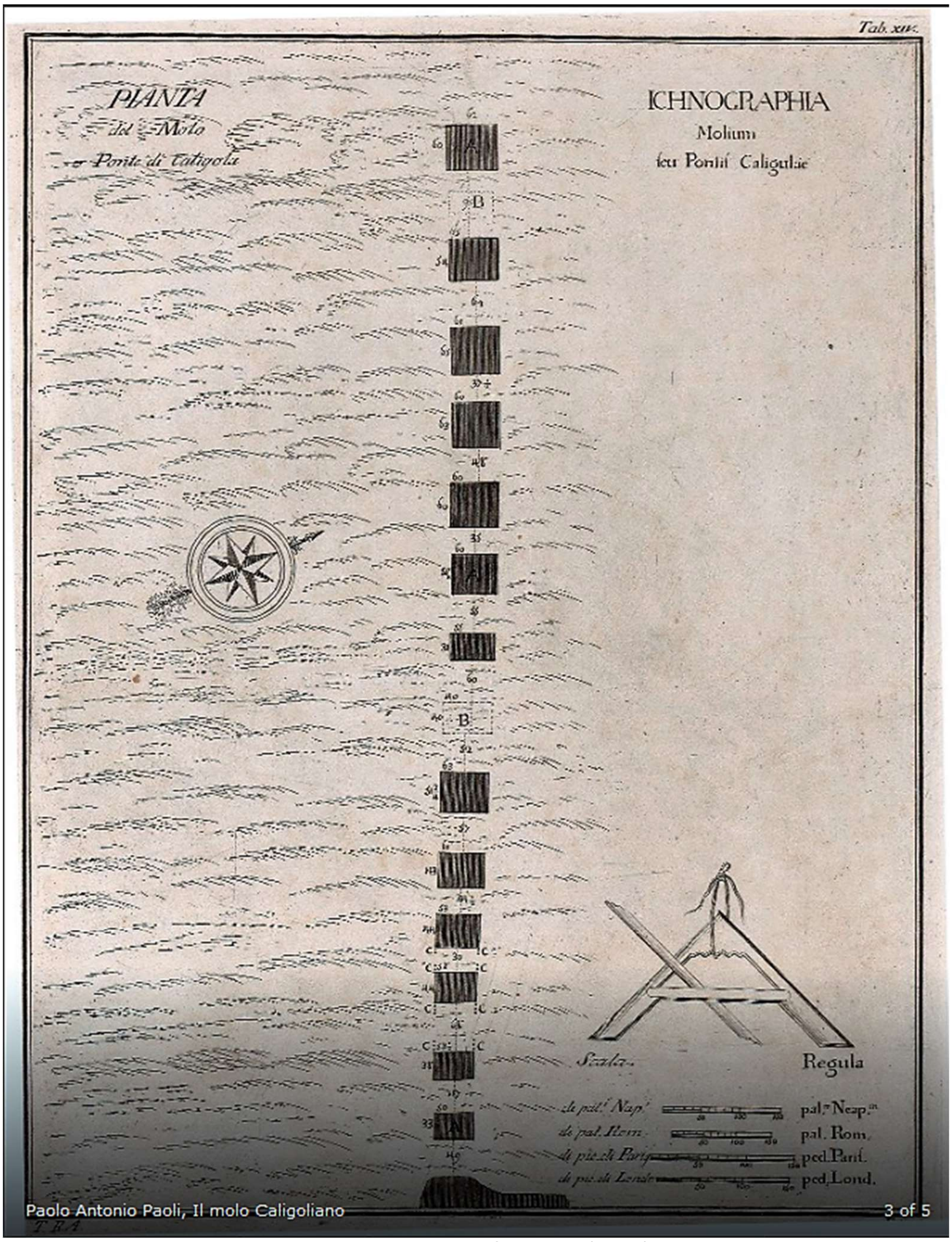
Puteoli breakwater after Leitch (1840)
(source: http://www.antiquemapsandprints.com)

It can be seen from the dates of these pictures that the pilae were still in place in the 19th c. They were covered by a modern breakwater in the early 20th c.

Paolo Antonio PAOLI, provided the dimensions of the ancient arched structure in his "Antichita di Pozzuoli" in 1768 (with some later editions, including Giuliano DE FAZIO in 1828).
(source: http://www.archeoflegrei.it/portodiputeoli/):



Pilae at Pozzuoli, after De Fazio (1828)



Pilae at Pozzuoli, after Paoli (1768)

The drawings show 15 pilae (including 2 submerged pilae) over a distance of 372 m (acc. to C. Dubois, 1907[64]). However, the inscription CIL X.1641 dated 139 AD, mentions repairing 20 pilae and adding a new protection embankment ("munitione"). In his Book of Phtomyris (1, 53) Chaeremon (ca. 85 AD) even speaks of "around 30 arches". The largest pilae of ca. 15 x 15 m are at the offshore end of the structure. The nearshore pila is somewhat smaller: ca. 8

[64] DUBOIS, C., 1907, "Pouzzoles Antique (Histoire et Topographie)", Paris. He was one of the last observers of the ancient breakwater as he visited the place during construction of the modern breakwater on top of the ancient one. He estimates that many arches were 10 m wide, and that most pilae were 16 x 16 m. They were made of hydraulic concrete for their underwater part and of dry masonry for their emerged part (that was also underwater when Charles Dubois saw it, because of a ca. 2 m subsidence). He also suggested a double row of pilae in a staggered arrangement, but archaeological evidence is poor.

x 12 m. The opening between adjacent pilae (8 to 11 m) varies from 0.5 to 0.9 pila width, which is close to the values for the pilae found for Portus Iulius and Misenum.

The area north of the structure had to be protected from waves incoming from south and the arched structure cannot have been very efficient as a breakwater. On the other hand, the massiveness and the height of this structure above the seawater level makes it even less acceptable as a simple jetty for loading/unloading ships, even if some mooring stones have been found.

2.18.2 Nesis

Nesis (now Nisida) is located about 5 km SE of Puteoli and had a similar arched breakwater which could still be seen in 1635:
(source: http://www.archeoflegrei.it/storia-del-lazzaretto-dellisola-di-nisida/mpd_07_069-21-aprile-1635-conde-de-monterrey-al-rey/).

Arched breakwaters at the isle of Nisida, by Bartolomeo Picchiatti (1635)
(looking southward)

The best-preserved remaining pila is at the NE side of the island and was studied in detail by Matteiet al.[65] showing its large dimensions (ca. 14.5 x 14.5 m) and deep-water location (ca. 10 m now, and ca. 7 m in Roman times). It may be noted that this structure is very similar, but more exposed to SW wave attack than the one in Puteoli.

A very peculiar, and puzzling, aspect of this pila is the presence of *opus reticulatum* at its bottom end. Pictures are provided by Mattei (2018) and also by Brandon (2008)[66] at 6 m water-depth on a nearby place called Secca Fumosa (a third example is known at Egnazia on a 6 m water-depth). The divers show *cubilia* blocks of 8-10 cm (Secca Fumosa) and 15 cm (Nesis) which are neatly arranged and it must be concluded that this work had to be performed in dry conditions as it is hard to imagine Roman divers doing such a job 7 m below the water surface. We then have two options: either the block was built in a dry-dock on land, either it was built inside a watertight cofferdam in the sea.

In the cofferdam option, it thus stood on a 7 m water-depth and keeping it upright and watertight would be a remarkable feat. The cofferdam would be reinforced by vertical and by horizontal beams (the inprints of 7 horizontal beams were found at Nesis near the ancient water level). Similar beams would also have been used near the bottom of the cofferdam in order to take-over the tremendous lateral water pressure (7 t/m^2). In addition, the side walls would have to be deeply driven into the subsoil in order to prevent seepage. A layer of hydraulic concrete would have to be poured on the bottom of the cofferdam before pumping water out, to provide a plug against seepage and horizontal support for the foot of the cofferdam walls. However, this plug should have a mass large enough to counterbalance a 7 m high water pressure and this would require around 4.5 m of hydraulic concrete with a unit weight of around 1.6 t/m^3. This simply does not allow opus reticulatum near the seabed.

In the second option, the block would, at least partly, be built on land in a dry-dock, it would have to be floated to its location and then lowered down to the seabed, some 7 m below the water surface. According to Golvin[67], a timber caisson would be filled partly in-the-dry with hydraulic concrete and include an opus reticulatum facing. The dry-dock containing the caisson would then be flooded and the caisson would float. Considering a unit weight of around 1.6 t/m^3 for hydraulic concrete and 1.0 t/m^3 for wood and for water, a 2.5 m layer of hydraulic concrete in the caisson would yield a 4 m draught when the caisson is floating. This would be convenient for leaving a 5 m deep dry-dock with 1 m keel clearance. Once on site, the caisson would be tethered to prepositioned barges and the filling with hydraulic concrete would continue until the caisson would touch the seabed (when the layer of hydraulic concrete reaches ca. 4.5 m). After that, the filling with hydraulic concrete would continue until reaching the water surface. Above water, the filling might consist of traditional masonry or concrete without pozzolana.

Partial onshore prefabrication of such large pilae is thus a huge entreprise, but it seems easier than completely building them in a cofferdam at sea.

It must be noted that, in both cases, it would not have been required to use hydraulic concrete that may be cast under water: traditional concrete would suffice. However, the builders may have been aware of the better longevity of hydraulic concrete in seawater.

[65] MATTEI, G., TROISI, S., AUCELLI, P., PAPPONE, G., PELUSO, F., STEFANILE, M., 2018, “Sensing the Submerged Landscape of Nisida Roman Harbour in the Gulf of Naples from Integrated Measurements on a USV”, Water 2018, 10, 1686, (31 p).
[66] BRANDON, C., 2008, “The Concrete Construction of the Roman Harbours of Baiae and Portus Iulius, Italy: The ROMACONS 2006 field season”, *The International Journal of Nautical Archaeology* (2008), 37.2, (p 374–392).
[67] COULON, G., and GOLVIN, J-C., 2020, “Le Génie maritime romain”, Actes Sud/Errance, (201 p).

2.19 SHARM YANBU - Charmuthas

Let's first go back to the initial description of this port by Agatharchides of Cnidus, in "On the Erythrean Sea" (text lost, around 140 BC), after Diodorus of Sicily (Hist, 3, 21, around 40 BC), translated by BURSTEIN, S., 1989, "Agatharchides of Cnidus - On the Erythraean Sea", The Hakluyt Society, London, (202 p):

Travelling along the Arabian coast from north to south:

"[…] This coast, then, is occupied by the Arabs called Thamoundeni. A good sized gulf occupies much of the next segment of coast. Scattered islands lie off it which are in appearance similar to the Echinades [islands near Oeniades, now Katoxi, Greece]. The next part of the coast is dominated by dunes which are infinite in their length and breadth and black in colour. After these dunes, a peninsula and harbour named Charmuthas, the finest of those known in history, come into view. For behind a superb breakwater, which inclines towards the west, there is a gulf which is not only remarkable in appearance but also far surpasses others in its advantages. A densely-wooded mountain range extends along it and encircles it on all sides for a 100 stades [15 to 20 km, depending on the length of a stadium]. Its entrance is 200 feet wide [60 m], and it furnishes a sheltered harbour for 2000 ships. In addition to these advantages, it has an extremely good supply of fresh water since a large river flows into it. Also, in the middle of the gulf there is an island which has a good supply of fresh water and is able to support gardens. In general, it is very similar to the harbour at Carthage which is called Cothon … A multitude of fish from the sea congregate in it because of its calmness and sweetness of the waters that flow into it. […]"

Sharm Yanbu, located 15 km north of Yanbu (S. Arabia) is close to Diodorus' description:

- the total circumference is 23 km (close to his 100 stades);
- the central island might be now connected to the mainland on the NE side where siltation occurred over time, near the outlet of the wadi;
- the total area might have been between 2000 and 3000 ha (ample space for his 2000 ships);
- the entrance is now 300 m wide (more than his 200 feet = 60 m) but this depends much on coral growth which may have varied in time and with urbanisation.

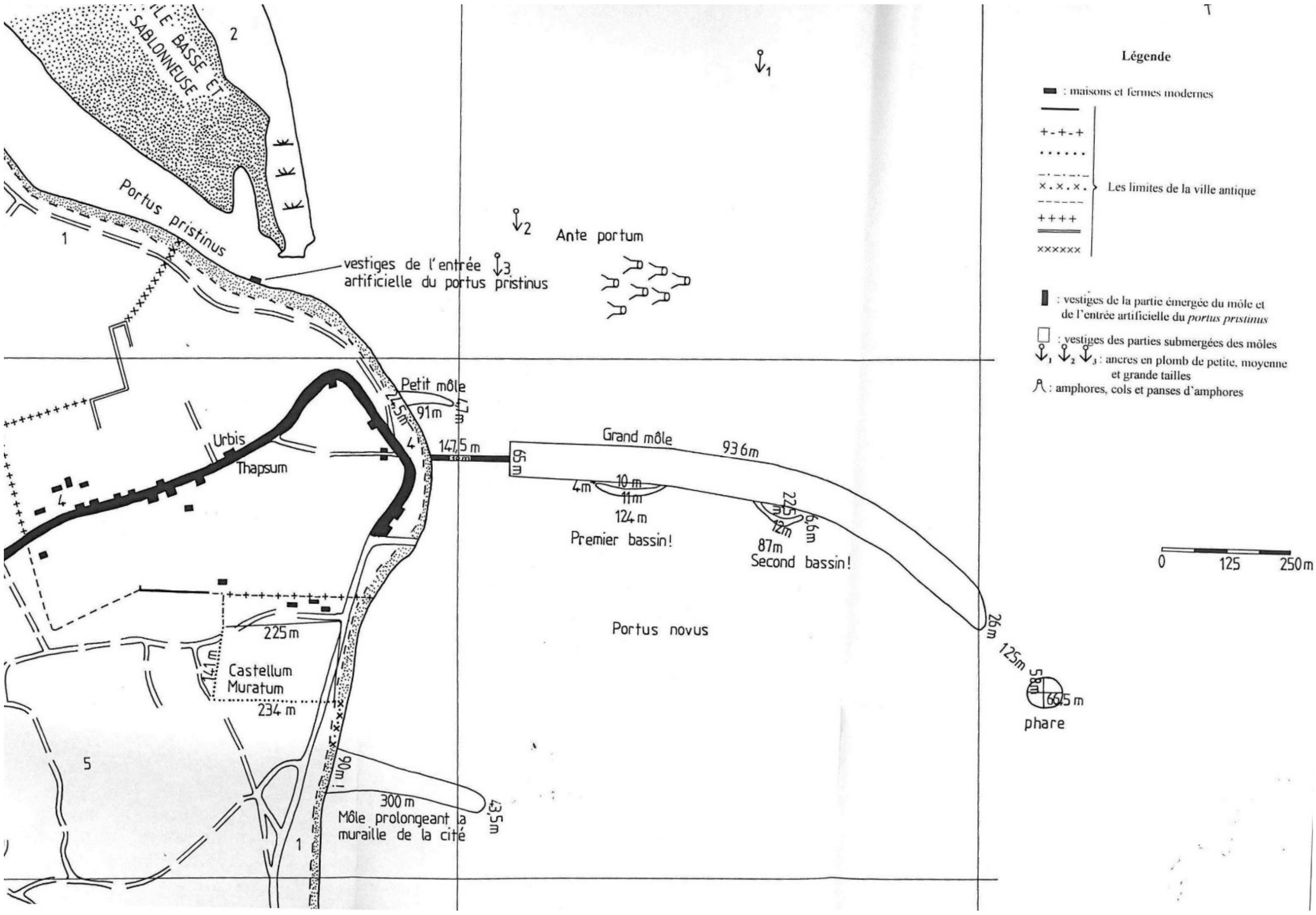
No archaeological remains are known so far and it might be worth having a look around …

2.20 *THAPSUS – Ras Dimas, Bekalta*

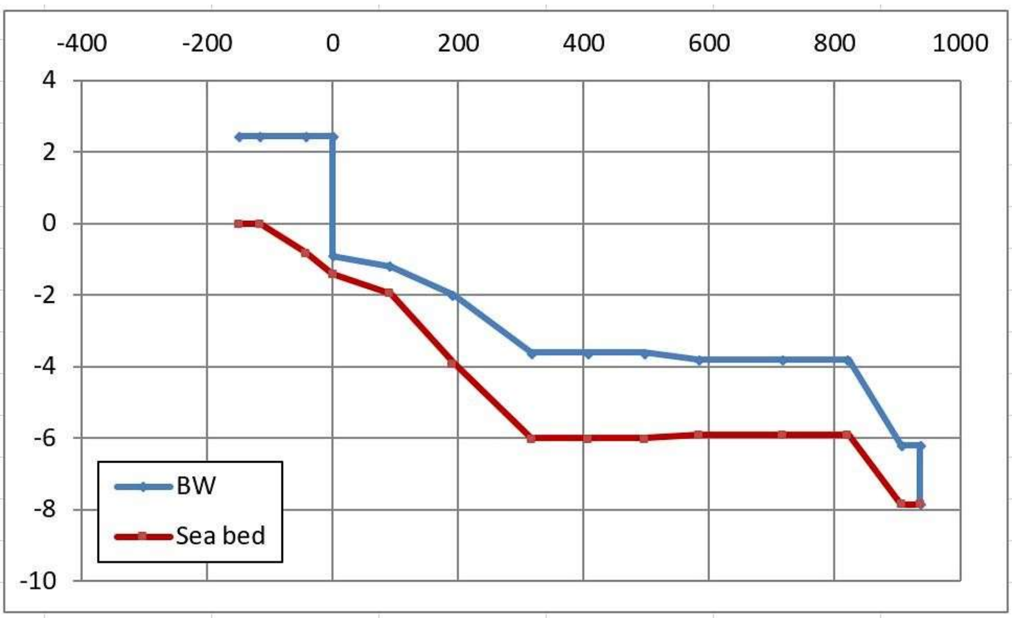
Thapsus is located at Bekalta, Ras Dimas, on the eastern Tunisian coast, between Lamta (ancient Leptiminus) and Mahdia (ancient Gummi).

Tunisian east coast

Thapsus has two ports. The so-called “Portus Pristinus” located in a natural shelter behind a large sand spit oriented towards the NW, and the main port sheltered by one of the longest ancient breakwaters in the Mediterranean Sea.



Outlines of the Thapsus ports (Younes, 1997, fig. 180)



Longitudinal profile of the main breakwater (BW)

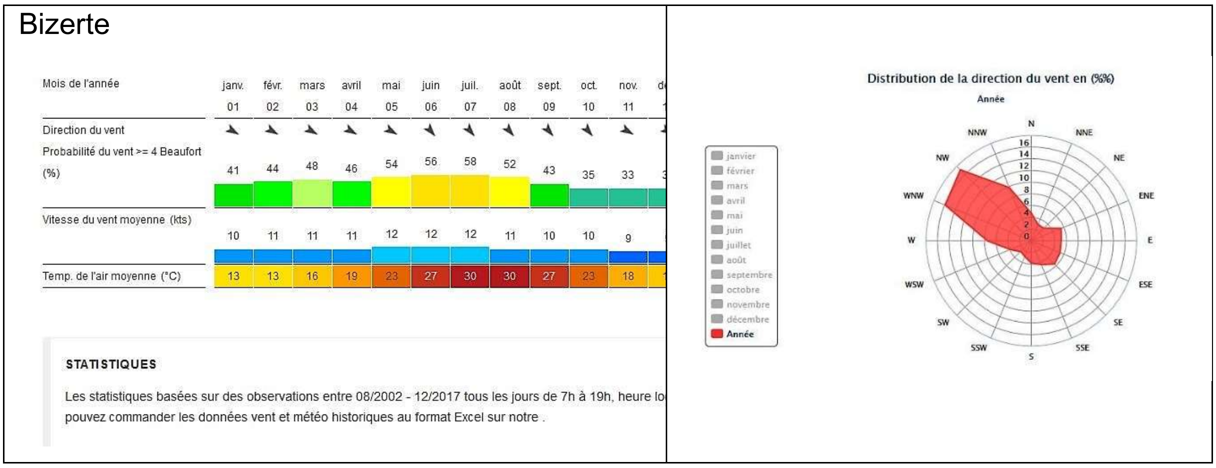
The main breakwater is nearly 1100 m long and has been described by several authors:

- Daux (1869)[68]: onshore part of breakwater,
- Lézine (1961)[69]: idem, but with better interpretation of holes in the concrete,
- Yorke (1966)[70]: first underwater survey of the offshore part of the breakwater,
- Younes (1997)[71]: detailed measurement of the offshore breakwater remains,
- Davidson (2014)[72]: transversal and longitudinal sections of the breakwater remains.

The general feeling is that this breakwater is made of Roman concrete, but much natural rock is also scattered around the site. The question one may ask is why a large section of the offshore part is now at 4 m under water. This can clearly not be caused by sea level rise which is accepted to be no more than ca 0.5 m since Roman times. This cannot be caused either by some tectonic movement, which would need to be very local as the onshore part of the breakwater seems still to be at a correct level of a few meters above sea level.

Our aim here is to formulate some hypotheses about the structure of this breakwater and possible scenarios for its destruction, hoping that detailed underwater archaeological surveys will be conducted soon. We will first summarise the local meteorological conditions, and secondly try to compute the long-term stability of the breakwater.

WIND STATS ON THE TUNISIAN EAST COAST (from north to south)



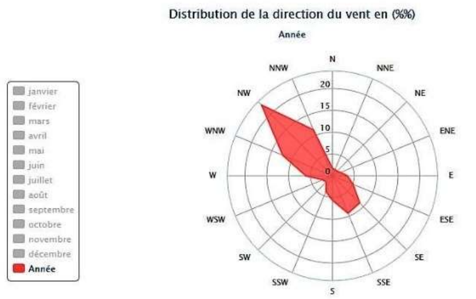
[68] DAUX, A., 1869, "Recherches Sur l'origine et l'emplacement des Emporia Phéniciens dans le Zeugis et le Byzacium", Imprimerie Impériale, Paris, (p169-171).
[69] LEZINE, A., 1961, "Le mole de Thapsus", Architecture romaine d'Afrique, Université de Tunis, Presses universitaires de France, (9 p).
[70] YORKE, R., 1966, "Cambridge expedition to Sabratha", Report, (43 p).
[71] YOUNES, A., 1997, "Recherches sur la ville portuaire de Thapsus et son territoire en Byzacène dans l'antiquité", Thèse de doctorat, Université Grenoble II, (484 p).
[72] DAVIDSON, D., 2014, "The Enigma of the Great Thapsus Harbour Mole", International Journal of Nautical Archaeology, 43.1, (p 35-40).

Nabeul

Mois de l'année	janv. 01	févr. 02	mars 03	avril 04	mai 05	juin 06	juil. 07	août 08	sept. 09	oct. 10	nov. 11
Direction du vent											
Probabilité du vent >= 4 Beaufort (%)	31	33	42	46	41	37	34	25	23	21	24
Vitesse du vent moyenne (kts)	10	10	11	11	11	10	10	9	8	8	9
Temp. de l'air moyenne (°C)	13	13	15	19	22	26	29	29	26	23	18

STATISTIQUES

Les statistiques basées sur des observations entre 03/2004 - 12/2017 tous les jours de 7h à 19h, heure lo
pouvez commander les données vent et météo historiques au format Excel sur notre .



Monastir

Mois de l'année	janv. 01	févr. 02	mars 03	avril 04	mai 05	juin 06	juil. 07	août 08	sept. 09	oct. 10	nov. 11
Direction du vent											
Probabilité du vent >= 4 Beaufort (%)	38	43	47	52	55	47	47	42	39	33	33
Vitesse du vent moyenne (kts)	10	11	12	12	12	11	11	11	10	10	10
Temp. de l'air moyenne (°C)	14	15	17	20	23	27	31	31	28	25	20

STATISTIQUES

Les statistiques basées sur des observations entre 08/2002 - 12/2017 tous les jours de 7h à 19h, heure lo
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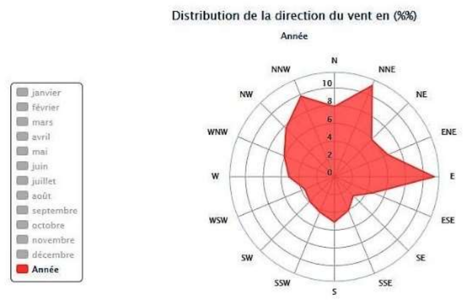

Mahdia

Mois de l'année	janv. 01	févr. 02	mars 03	avril 04	mai 05	juin 06	juil. 07	août 08	sept. 09	oct. 10	nov. 11
Direction du vent											
Probabilité du vent >= 4 Beaufort (%)	16	20	22	19	19	16	13	12	12	16	16
Vitesse du vent moyenne (kts)	8	8	8	8	8	8	7	7	8	7	8
Temp. de l'air moyenne (°C)	14	14	16	18	21	25	28	29	27	24	19

STATISTIQUES

Les statistiques basées sur des observations entre 04/2008 - 12/2017 tous les jours de 7h à 19h, heure lo
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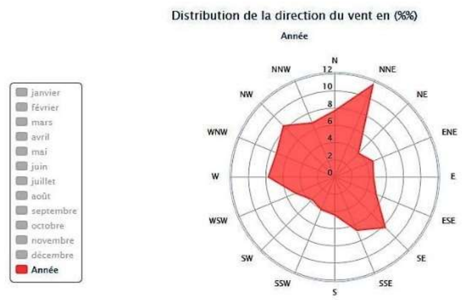

Sfax Thyna

Mois de l'année	janv. 01	févr. 02	mars 03	avril 04	mai 05	juin 06	juil. 07	août 08	sept. 09	oct. 10	nov. 11
Direction du vent											
Probabilité du vent >= 4 Beaufort (%)	28	33	35	40	40	35	29	25	25	21	23
Vitesse du vent moyenne (kts)	9	10	10	10	10	10	10	9	9	9	8
Temp. de l'air moyenne (°C)	14	15	18	21	24	28	31	31	28	25	20

STATISTIQUES

Les statistiques basées sur des observations entre 08/2002 - 12/2017 tous les jours de 7h à 19h, heure lo
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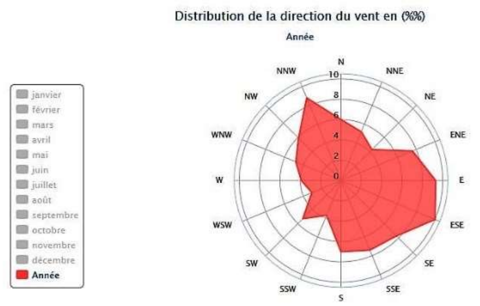
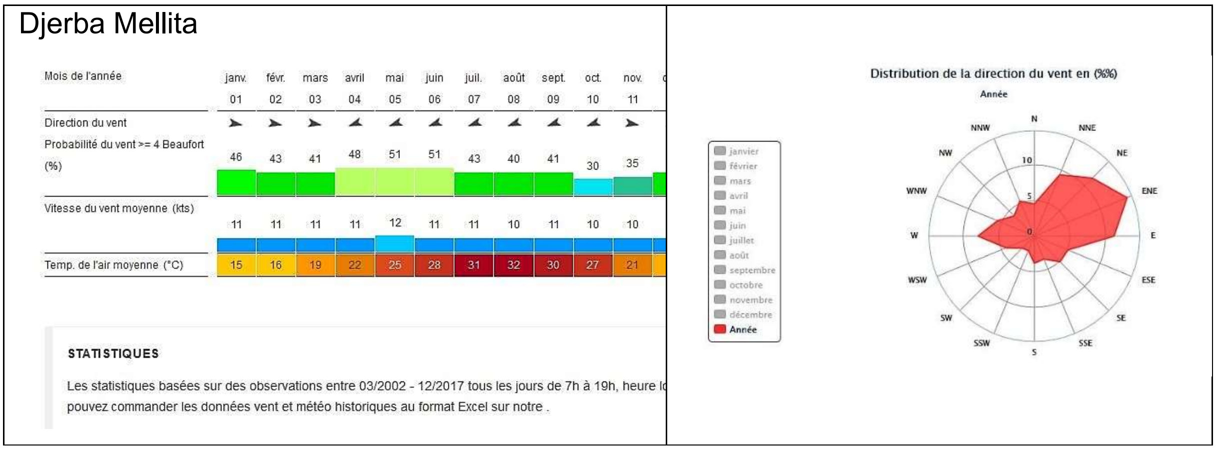




Djerba Mellita

Mois de l'année	janv. 01	févr. 02	mars 03	avril 04	mai 05	juin 06	juil. 07	août 08	sept. 09	oct. 10	nov. 11
Direction du vent											
Probabilité du vent >= 4 Beaufort (%)	46	43	41	48	51	51	43	40	41	30	35
Vitesse du vent moyenne (kts)	11	11	11	11	12	11	11	10	11	10	10
Temp. de l'air moyenne (°C)	15	16	19	22	25	28	31	32	30	27	21

STATISTIQUES

Les statistiques basées sur des observations entre 03/2002 - 12/2017 tous les jours de 7h à 19h, heure l
pouvez commander les données vent et météo historiques au format Excel sur notre .

Data taken from www. windfinder.com (2018)

It can thus be seen that north of Nabeul the wind climate is rather different from that south of it: the famous 'etesian winds' from NW blowing in Egypt in the summer are not found south of Nabeul.

Two seasons are defined by wind directions south of Nabeul:

- Summer (April-Oct): E and NE winds
- Winter (Nov-March): W and NW winds

The wind velocities are characterised here by the percentage of time with winds over 10 to 15 knots (i.e., wind force over 4 Beaufort):

- Bizerte has a tough wind climate > 4 Bft for 35-55% of time in summer (blowing from NW all year round)
- Nabeul has milder winds > 4 Bft for 20-45% of time in summer (NW all year round)
- Monastir has a tough wind climate: > 4 Bft for 35-55% of time in summer (E and NE)
- Mahdia area has the mildest wind climate: > 4 Bft for 10-20% of time in summer (NE), but is this correct?!
- Sfax has: > 4 Bft for 20-40% of time in summer (E)
- Djerba has: > 4 Bft for 30-50% of time in summer (E)

Unprotected structures on these coasts may thus have quite some downtime. If we consider the wind force of 4 Bft (10 to 15 knots) as a limit for safe port operation in ancient times, then we may assume around 20 to 50% downtime during daytime, that is 6 to 15 days/month. This might be acceptable for commercial traffic that can wait a few days, provided downtimes are not too much concentrated, e.g., one week or more in a row.

TIDES ON TUNISIAN EAST COAST

Tidal ranges (spring tide) acc. to the North Africa marine pilot by Graham Hutt (IMRAY, 2012): tidal ranges are usually less than 0.5 m, but in the Gulf of Gabès, higher values appear:

- Sfax: 1.4 m
- Kerkennah islands, Sidi Youssef: 1.0 m
- La Skhira: 1.6 m
- Gabès: 1.8 m

- Zarat: 1.8 m
- Djerba, Houmt Souk: 1.0 m
- Bou Ghrara (inside the bay): 0.5 m
- Zarzis: 0.8 m

The largest tidal range is 1.8 m near Gabès.

Note that the tidal range is somewhat smaller on the Kerkennah Isles and inside the bay of Bou Ghrara.

Spring tides at Bekalta (Thapsus) range around 1.0 m, further reducing north of Monastir.

Little is mentioned about the tidal currents, but they can be strong (1 to 5 knots) near Djerba (Houmt Souk and Ajim).

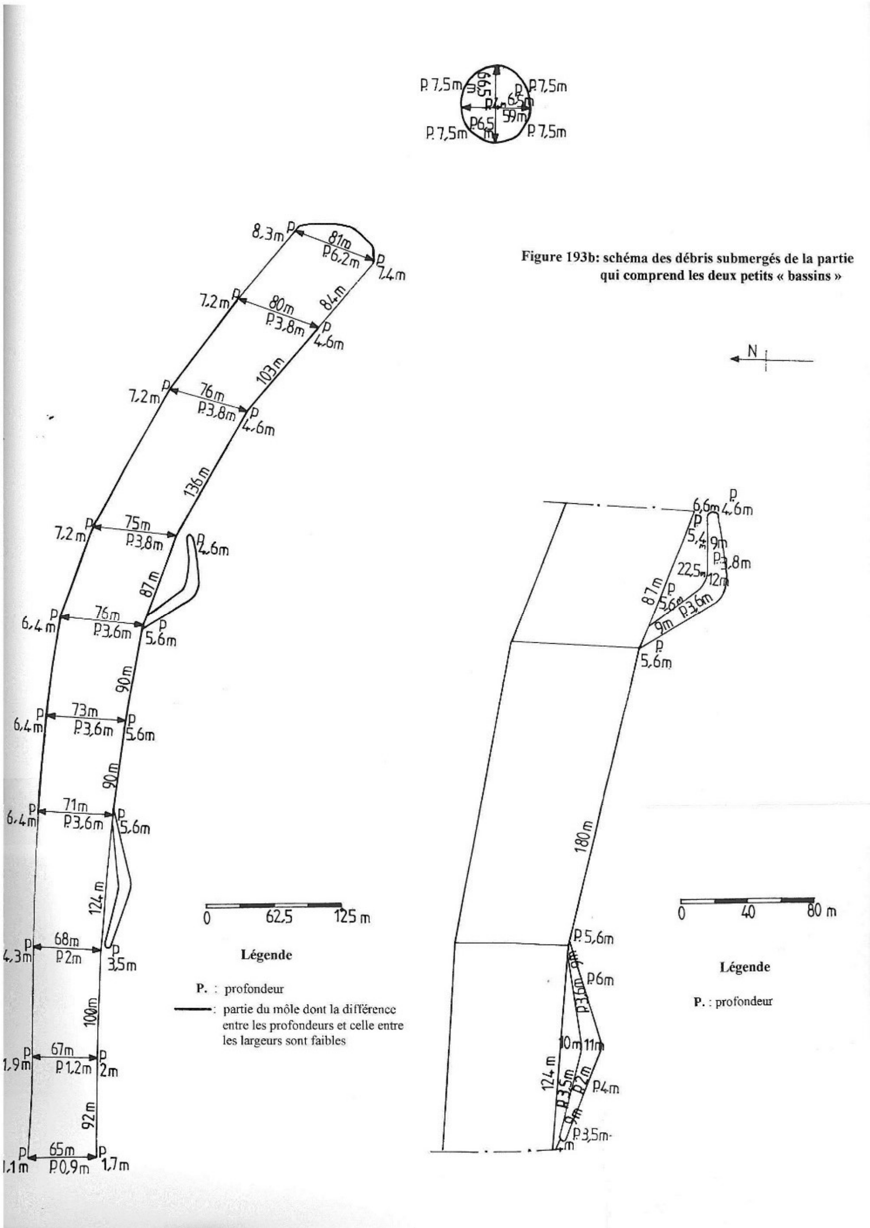
DESCRIPTIONS OF THE BREAKWATER AT THAPSUS

Lézine (1961) describes the onshore breakwater (p 145) *"L'ouvrage est construit en blocage, mais celui-ci présente deux parties nettement différentes : une couche inférieure de 2 m 40 de hauteur, dont le mortier de couleur foncée comporte une forte proportion de pouzzolane ; une couche supérieure (1 m 30), dont le liant – beaucoup plus clair – contient des grains d'une roche dure de teinte noire ou verte […] Les trous qui percent la masse ne sont pas les soupapes de sureté imaginées par Daux, mais simplement les logements de rondins qui ont disparus depuis longtemps"*. This is clearly a structure built with concrete poured into wooden caissons, like in Caesarea Maritima (Israel).

Yorke (1966) mentions (p 15) *"concrete and large squared blocks of average size 1.5 x 1 x 8 meters"*. He estimates the total volume of the breakwater remains to 0.2 million cubic yards (153 000 m^3).

Younes (1997) explains (p 207) *"La face nord bien exposée à ces vents est revêtue d'un parement de pierres de bonne taille et de gros blocs en béton. Ces blocs s'étalent sur une longueur d'environ 936 m à partir de la fin du môle. Ainsi, à l'origine, la face nord bien exposée aux vagues est parementée de gros blocs de béton et de pierres dont la taille est en rapport avec la profondeur et par conséquent avec la taille et la force des vagues. Quant à la face sud abritée des vagues, elle est parementée sur sa grande partie de pierres de petite taille et fournit un quai permettant aux navires de s'y amarrer".* Hence, the north side consists of large concrete slabs composing a vertical wall which is protected by smaller rock placed in front of it. This construction method is still used on some modern breakwaters.

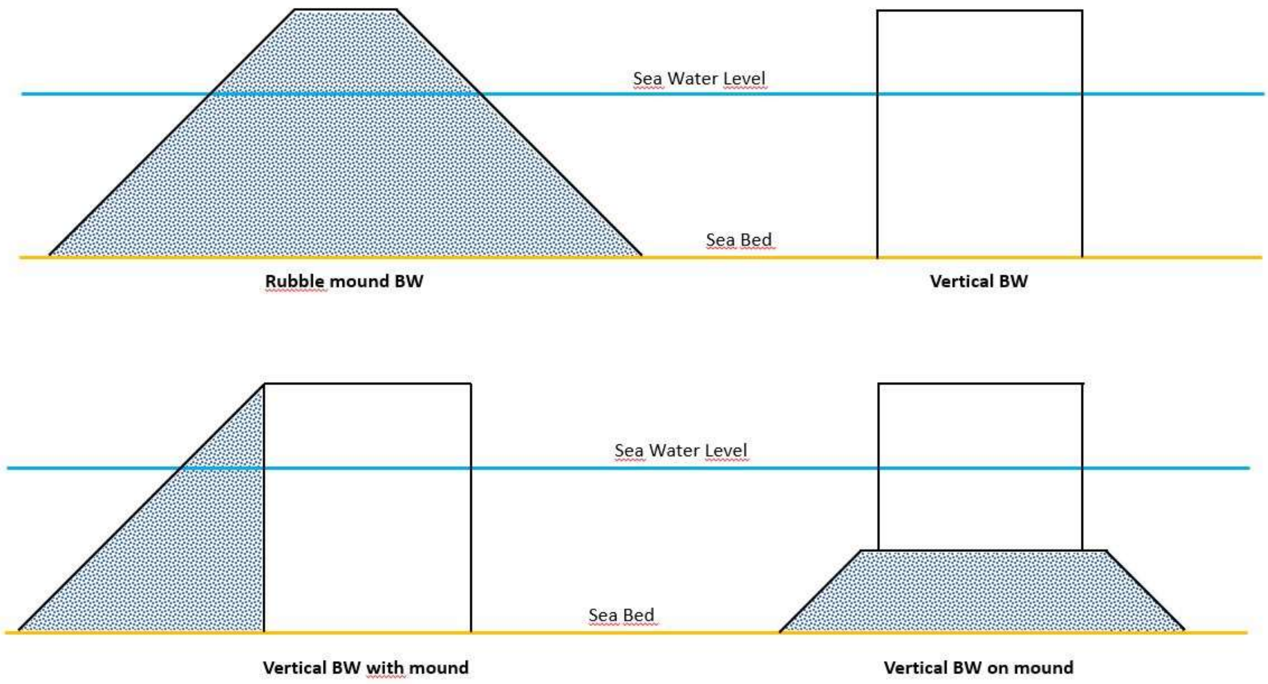
Davidson (2014) was on site with Yorke in 1966 and tells us (p 36) *"The visible part of the structure was clearly made by the classic Vitruvian process of casting concrete into wooden caissons confirmed by the existence of holes in the mole with vestiges of the horizontal timbers that had once tied the sides of a caisson together. The submerged part of the mole was made by another traditional Roman process. This involved tipping large quantities of quarried rocks from carts, or over the sides of boats, for long enough and in the right place for the surface eventually to be broken and a shelter from the weather thereby formed".* According to him, the offshore and the onshore parts of the breakwater were not constructed according to the same methods.



Survey of the Thapsus breakwater (Younes, 1997, fig. 193b)

Younes' survey shows that the offshore breakwater remains have a width of 65 to 81 m. The water depth is 1.1 m, to 8.3 m on the north side, and 1.7 to 7.4 m on the south side. The figures show that the southern side was around 1 m above the northern side, probably due to some sedimentation inside the inner port.

Younes computed the volume of the breakwater remains found under water at 131 450 m^3 and showed that this volume is close to that of a vertical offshore breakwater that would be made on the same design as the onshore breakwater (around 100 000 m^3). Our own computations show that this volume increases to around 140 000 m^3 if a rubble mound was built in front of the vertical breakwater on its northern side. Our computations also show that a traditional rubble mound breakwater with 5 m crest width at 4 m above seawater level and 1:1 slopes would have a similar volume of around 140 000 m^3. The combination of a vertical breakwater placed on top of submerged rubble mound would yield a similar volume.



Cross-section of various types of breakwater

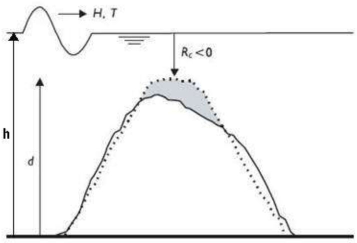
In any of the cases shown above, the volume of remains corresponds to a completed breakwater, contradicting Davidson's "enigma" of an unfinished structure.

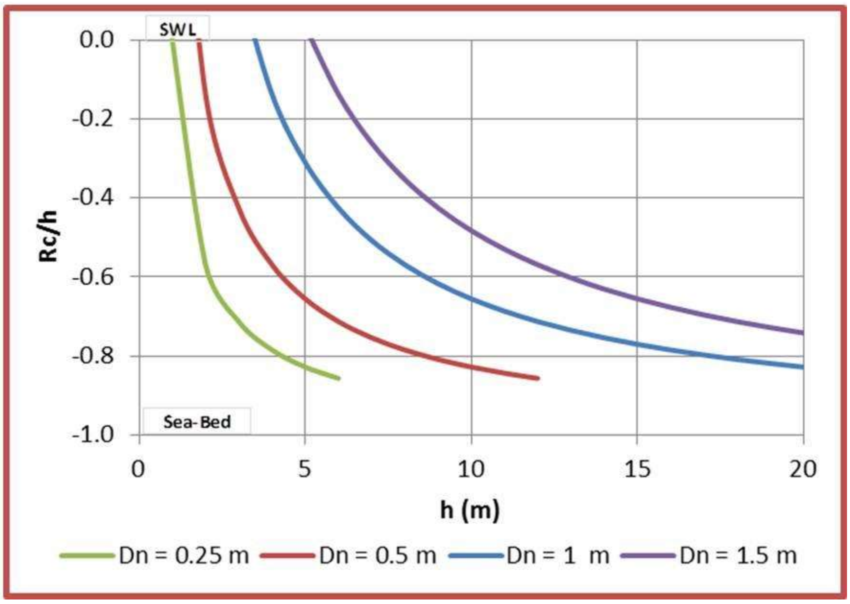
The volume of the submerged remains indicates that the breakwater was built by men and destroyed by the sea and we are going to show hereunder that the breakwater could indeed not survive without damage during a 2000 year-period.

STABILITY OF A RUBBLE MOUND BREAKWATER AT THAPSUS

An analysis of long-term stability concentrates on the worst possible wave conditions, considering that they will eventually occur in the long term. This means that we consider only cases with waves breaking near the submerged structure. Hence, the local wave climate must include waves large enough to break on the water depth in front of the breakwater. The location of Thapsus on the Tunisian coast allows for large waves to approach the breakwater from north and from NE. It is widely accepted that random waves are breaking when their significant height Hs is around 0.6 h (h is the local water depth). Hence, on the 6 m water depth in front of the Thapsus breakwater, waves with Hs = 4 m can exist just before breaking. Such waves most probably occur at least once each year in this area of the Mediterranean Sea. We are thus allowed to use the graph below[73].

[73] DE GRAAUW, A., 2014, "The long-term failure of rubble mound breakwaters", Revue Méditerranée, http://journals.openedition.org/mediterranee/7078)





Stable submerged breakwater with breaking waves

Let's look at the part of the breakwater located on a water depth of h = 6 m, and let's consider the rock size Dn = 0.5 m: the crest of the breakwater remains will then be at 0.7 h below the seawater level, that is around 4 m below SWL, which is confirmed on site. However, should the rock size be larger, e.g., Dn = 1 m, the crest of the remains should then be around 2.5 m below SWL.

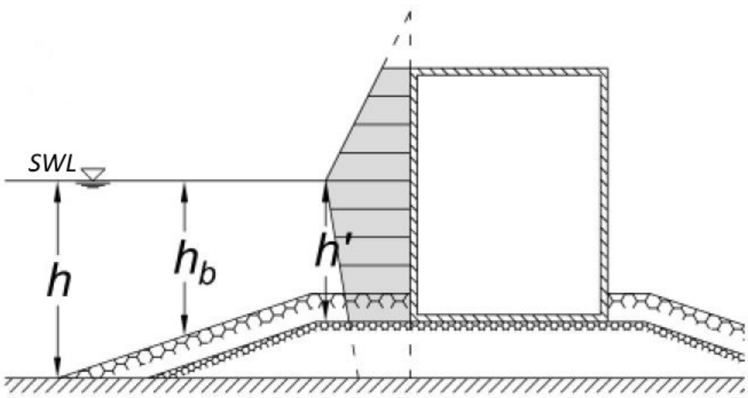
STABILITY OF A VERTICAL BREAKWATER AT THAPSUS

Let's now consider a supposed vertical structure consisting of several layers of Roman concrete poured into wooden caissons. Each layer of concrete adheres more or less on the layer below it and can thus be moved by wave action. In other words, an ancient vertical breakwater is not monolithic (like modern breakwaters usually are) and can therefore be destroyed layer by layer by wave action.

Yoshimi Goda[74] provided a computation method to estimate the maximum wave pressure on vertical walls. In the case of Thapsus, the horizontal wave pressure is around 15 ton/m^2 at the seawater level and a bit less near the seabed. The cross-section of the concrete slabs being 1.5 x 1.0 = 1.5 m^2, the horizontal wave force on a block is 15 x 1.5 = 22.5 ton.
The block resists to this wave force through its friction on the underlying block, and this is estimated to 0.75 x the weight of the block: 0.75 x 1.5 x 1 x 8 m^3 x 2 ton/m^3 = 18 ton. In other

[74] GODA, Y., 1974, "New wave pressure formulae for composite breakwater", Coastal Engineering Conference, Copenhagen, ASCE, (p 1702-1720).

words, the block can resist a horizontal wave force of up to 18 ton, but the actual wave force is over 22 ton, inducing sliding of the block.



Goda's distribution of wave pressure

Concluding this short study, the Thapsus breakwater was not stable in the long term. The volume of the breakwater remains could be from a vertical breakwater made of layers of Roman concrete as well as from a rubble mound breakwater, or some kind of combination. Further underwater survey of the remains might give an answer: a vertical breakwater would show large slabs of Roman concrete, and a rubble mound breakwater would show smaller quarry rock.

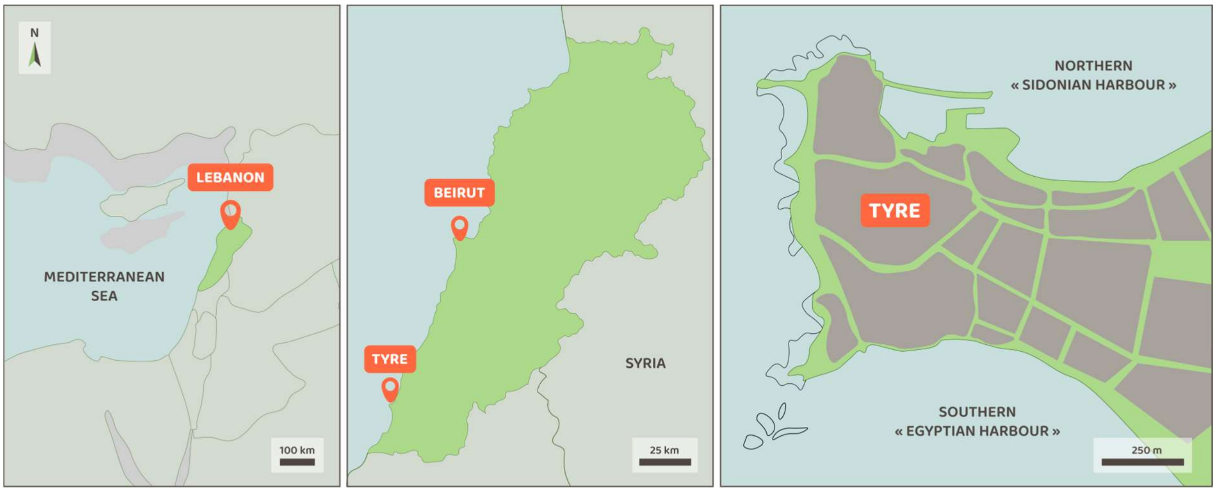
2.21 TYRE

This paragraph was prepared by Arthur de Graauw, Gilles Brocard, and Jean-Philippe Goiran. It features breaking news about the harbour history of Tyre, particularly the southern harbour, known as the "Egyptian Harbour".

Introduction

The renowned Phoenician city of Tyre (Lebanon) is one of the finest examples of major changes triggered by the construction of a causeway affecting the development of its harbours. Building sustainable ports along coastlines is a difficult endeavour because coastlines are among the most rapidly changing landscapes on Earth. This challenge is faced worldwide today. Besides, the erection of coastal structures alters coastal dynamics in such a way that new structures tend to affect earlier constructions. The study of ancient harbours shows that it has been a nagging problem in coastal management since Antiquity. Therefore, investigating ancient cases is interesting because it provides more time depth into these changes than the modern cases, owing to the centuries of coastal changes that have elapsed since the structures started to alter their environment.

Tyre city was founded on a small coastal island from which it resisted invasions and sieges for many centuries. In 332 BCE, Alexander-the-Great eventually succeeded in seizing the city after building a causeway 4 stades long [75] and 2 plethra wide [76], which was laid in water depths reaching 3 fathoms[77]. The causeway interrupted longshore sand transport, forcing sand to pile-up against and on top of the causeway, thus creating a sandy isthmus that has connected Tyre to the mainland ever since.



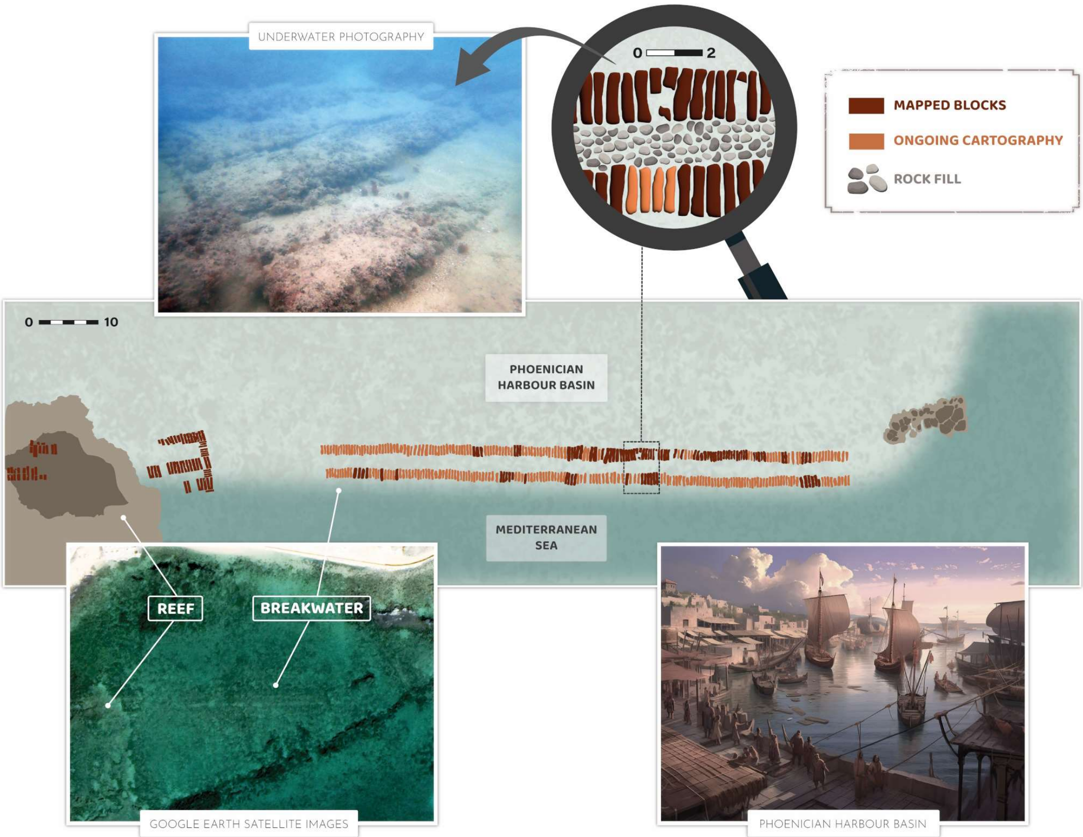
Location of Tyre in Lebanon.

Where was the "Egyptian harbour"?

The isthmus profoundly altered the layout of Tyre and its harbours. Ancient authors Strabo (16, 2) and Arrian (2, 7), living in the first and second centuries CE, report that the Phoenician city had two harbours, one opening towards the north (the so-called "Sidonian Harbour", or "Port of Astronoe"), and the other opening to the south (the so-called "Egyptian

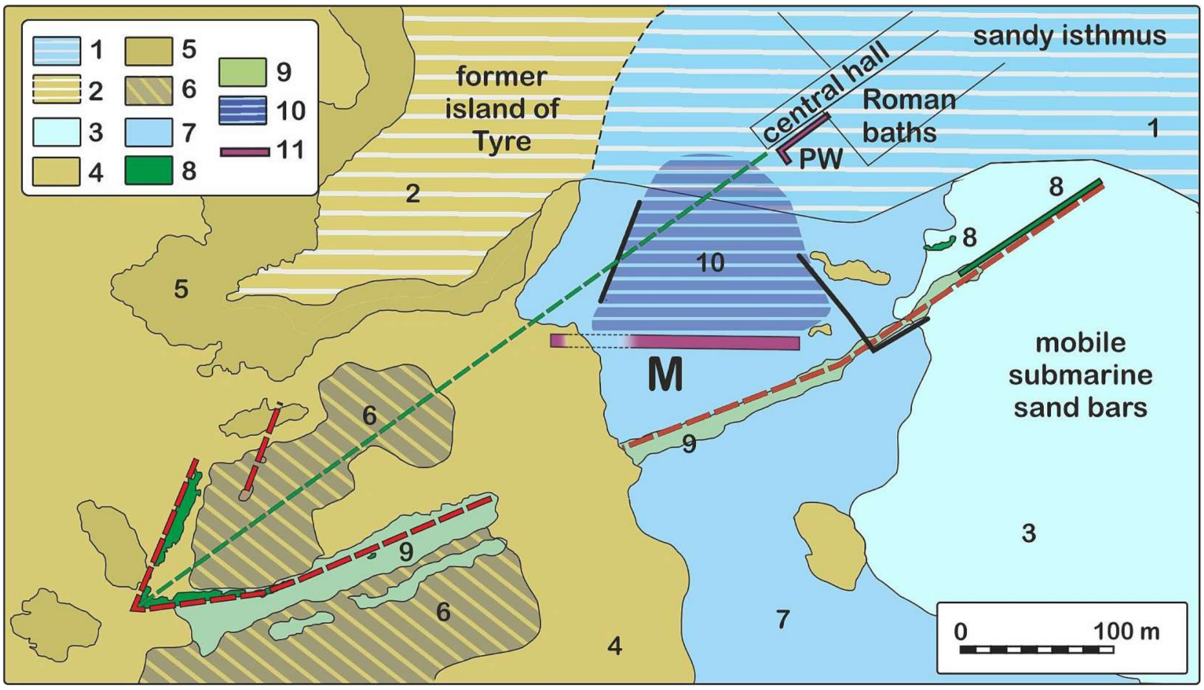
[75] ca. 750 m, acc. to Quintus Curtius, 4, 2 & Diodorus Siculus, 17, 7, however, Pliny, 5, 17 mentions 700 paces, i.e., nearly 1 km.
[76] ca. 60 m, acc. to Diodorus Siculus, 17, 7.
[77] 5.4 m, acc. to Arrian, Anabasis, 2, 18.

Harbour”). The ancient northern harbour is filled with Hellenistic to Byzantine sediments and is clearly documented below the modern harbour of Tyre (Marriner et al., 2005). The southern harbour no longer exists and several hypotheses for its location have been put forward over the past two centuries.



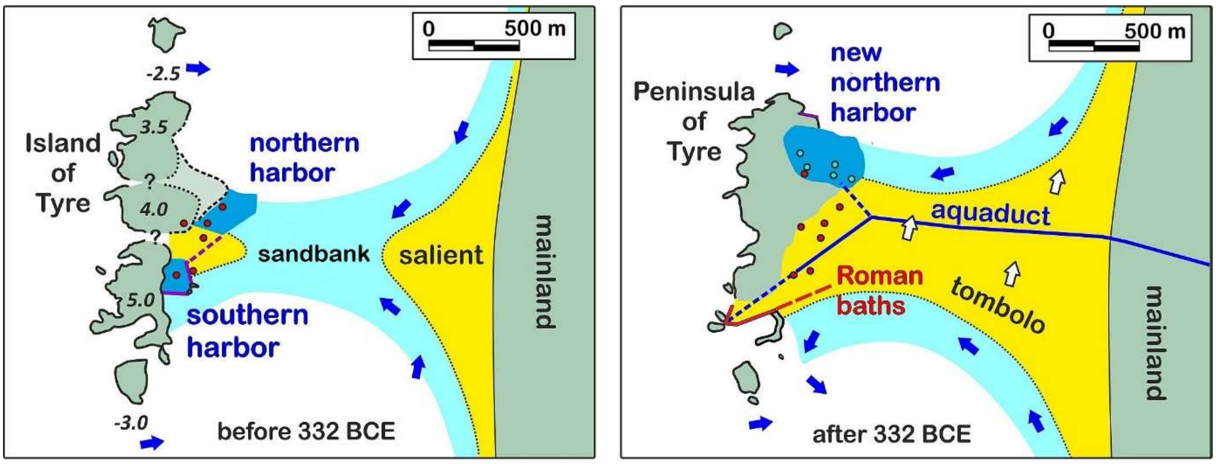
The east-west aligned, Phoenician-style breakwater discovered in 2019 extends over some 130 m. It displays a double alignment of oblong blocks (Figure by Sylvia Vinai, adapted from Goiran et al., 2021).

A breakwater, similar in style to the Phoenician breakwater built in the 6th-4th centuries BCE along the north coast (Nourredine, 2019), was discovered in 2019 along the south coast by a team of researchers led by the Archéorient Laboratory, Maison de l’Orient et de la Méditerrannée, at the University of Lyon 2, France (Goiran et al., 2021). Cores collected onshore by the team revealed the presence of sediments typically deposited inside a harbour basin, behind the offshore structure (Brocard et al., 2024). The newly identified breakwater is therefore regarded as protecting the Egyptian Harbour of Tyre (“M” on the figure below). Its basin (“10” on the figure below) would have covered an area of up to one hectare (100 x 100 m), south of the Roman baths complex. The port structures of the southern Phoenician harbour of Tyre appear to have been buried during the Hellenistic and Roman periods, allowing the south-east corner of the island to be used by the Romans for the development of monumental baths. The team suggests that the southern harbour had to be abandoned owing to the rapid growth of a massive sandy isthmus during the centuries which followed the erection of Alexander’s causeway. The area of this southern harbour was then repurposed, with the building of monumental baths, and the development of an urban district protected by Roman-style seawalls.



Distribution of man-made structures, bedrock, and sediments around the southern harbour of Tyre. Red dashed line: Poidebard (1939)'s southern harbour enclosure. Green dashed line: axis of the monumental Roman baths. Geology: 1: emerged part of the sandy isthmus, 2: emerged land over calcarenite bedrock (wherever bedrock is above -2.5 m), 3: submarine part of the sandy isthmus, 4: submerged outcrops of calcarenite, 5: shore platform cut into calcarenite (mostly man-made), 6: natural block pavement over calcarenite, 7: natural block pavement over marine sediments, 8: roman concrete (*opus caementicium*), 9: rubble mound dyke, 10: proposed southern harbour-basin, 11 (M): east-west Phoenician-like breakwater.

In addition, coring also revealed the presence of harbour sediments likely deposited in another basin, at an earlier location of the northern harbour of Tyre. This northern harbour would have been also abandoned to give way to the growing sandy isthmus, and relocated to its Hellenistic-Byzantine location, under the modern harbour of Tyre.



Schematic paleogeographic maps of Tyre highlighting the effect of the formation of the sandy isthmus on its two Phoenician harbours, the displacement of the northern harbour further north, and the repurposing of the southern harbour into a Roman baths area. Red & blue dots: corings. Arrows: net sand flux (blue: marine, white: terrestrial). Numbers on left panel refer to the minimum, currently constrained elevation of the calcarenitic bedrock relative to the ancient sea level at -2.5 m.

Tentative geomorphological chronology

The evolution of the marine landscape of Tyre was influenced by the development of the city well before Alexander's conquest. Tyre started as a small offshore outpost of the city of Ushu, or Palaeotyre (Old Tyre), which was founded on the stretch of coast facing the island. Urban and port development really started on the island after 1 500 BCE (Bikai, 1987). Various archives indicate that some islets were then probably interconnected, enlarging the original island, and improving shelter from sea waves to such an extent that by 1 350 BCE, the Tyrian king Abimilky reportedly stationed battleships in a proto harbour in the lee of Tyre Island (Amarna Letter EA 153). As sedimentation in the lee of Tyre Island further progressed, a submarine sand bank formed, built by the refraction and diffraction of waves around the island. A large harbour was still present in the lee of the island by around 1 200 BCE (Anastasi 1 papyrus) but the accumulation of sand over the sand bank had led to its partial emergence, creating a coastal "salient" attached to the lee of the island. Around 950 BCE, famous Tyrian king Hiram I, friend of King David and King Solomon, connected one more islet to the main island, and reclaimed the area in between, which was called "Eurychoros" (wide space, agora) by Menander, according to Josephus Flavius (Apion, 1, 17-18, see full text hereafter). Hiram I obviously used the naturally formed salient and extended it through additional land reclamation. By then, the initial single harbour in the lee of the island had probably been largely occupied by the sand bank, and a new layout with two harbours had to be implemented, with a northern Sidonian Harbour and a southern Egyptian Harbour, set astride the growing sandbank. We do not know who might have carried out the work, possibly Hiram I himself, or one of his successors, possibly Ethbaal I around 875 BCE (Katzenstein, 1973). At that time, the southern harbour could have been the main one, as a north-south reef aligned with Tyre Island better protected the whole southern bay, which therefore could have been used as a summer anchorage area.

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Both harbours were probably used for several centuries, while the city remained an island, as documented by the bronze bands of Balawat (858 BCE) and by Esarhaddon's Annals (671 BCE). During that time the city prospered and resisted several important sieges (Salmanazar V, from 726 to 722 BCE, Nebuchadnezzar II, from 585 to 573 BCE), weathering also earthquakes and tsunamis (760-750 BCE, 590 BCE, 525 BCE, 199-198 BCE, 148-130 BCE, 92 BCE, 19 CE, 303 CE, 502 CE, 551 CE and many more after that) (Gatier, 2011a).

After Alexander-the-Great built his causeway, the tombolo formed, and the harbours were once again threatened by sand accumulation. The northern harbour was moved away from the tombolo, at its current location, below the modern harbour. The southern harbour, on the other hand, was abandoned, possibly even before the Romans arrived in the area in 64 BCE (Gatier, 2011b). They probably used sand removed during the levelling of the tombolo for further land reclamation and built the monumental Roman baths and an urban district starting in the 1st century CE. The research team suggested that the structures described by Poidebard (1939) are the Roman seawalls that protected this urban area from sea waves.

An estimated 2.5 m relative sea level rise affected the site, submerging the southern harbour structures. The age of this submergence is still poorly constrained, but it most likely occurred quite late during Antiquity, possibly in Hellenistic and/or Roman-Byzantine times (between say 500 BCE and 500 CE). The sea then overtook the seawalls of the southern district, gutted the Roman landfill, and unearthed the Phoenician quay- and breakwater-structures that were beneath it, exposing them on the seafloor.

How long did it take?

The research team conducted sand flux and sand volume calculations to provide a rough estimate of the time required for coastal processes to accumulate the sand volume currently contained in the peninsula that connects the former island of Tyre to the mainland.

The influence of tidal currents is negligible because the tidal range oscillates between 30 cm (neap tides) and 50 cm (spring tides). Longshore sediment transport is therefore determined by winds and waves (Nir, 1996). The sandy isthmus of Tyre started to form during the Roman Climatic Optimum (200 BCE-100 CE), the climate of which is regarded as similar to the present-day (Murray, 1987). The team therefore used the present-day wind and wave climate at Tyre (fr.wisuki.com) to assess sand fluxes at Tyre. The strongest winds (> 50 km/h) come from the southwest, with weaker winds (0-20 km/h) tracking from northwest. Waves come from a narrow western sector, with some northwest storms.

Littoral drift is quantified by several more or less complex formulae. The simplest and most widely used one was proposed by CERC (US Army Corps of Engineers) in 1984:

$$Q = K.\ H^{2.5}.\ \sin(2\theta)$$

where Q is the littoral drift (in m^3/year), K is a coefficient determined by wave steepness and sand grain size, H is the wave height at breaking (in m), and θ is the angle (in °) of incidence of waves on the coastline at the breaker line. Littoral drift is nil for wave crests parallel to the coastline (θ = 0°), increases to a wave incidence up to 45° and diminishes at higher values.

At Haifa, to the south of Tyre, modern longshore drift moves 50 000-80 000 m^3/yr of sand northwards (Zviely, 2007) for a mean incidence angle of waves of θ = 10°. Assuming this sand transport capacity at Haifa, the decrease in the incidence angle to θ = 6° at Tyre implies that longshore transport capacity at Tyre is reduced by a factor 0.6 to 30-50 000 m^3/yr.

The total volume of sand accumulated behind Tyre Island was calculated as the difference between the elevation of the modern onshore and offshore surface of the sandy isthmus and the elevation of the substrate over which the sands were deposited. The resulting volume of sand accumulated behind Tyre Island before 332 BCE was estimated to 10 million m^3, and the volume accumulated after 332 BCE, to 30 million m^3 (Brocard et al. 2024).

This volume required 6 to 10 centuries to accumulate at a rate of 30 000 to 50 000 m^3/yr, which means that the isthmus would have been able to reach its current size between the 3rd and the 7th century CE.

Conclusion

The harbour history of Tyre, spanning a period of 3 500 years, is one of abandonment and relocation of infrastructures, resulting in a complex pattern of structures, often superimposed one on top of the other. The development of many ancient ports was hampered at some point by a geological process of some sort, such as tectonic uplift or subsidence, soil settlement in deltas and estuaries, and, most commonly, by coastal progradation, either by direct ingress of fluvial sediments in estuaries and deltas, or by coastal accretion down drift of river mouths. There, man-made structures affect longshore sediment transport. For example, sand accumulated updrift (south) of the Roman port of Caesarea Maritima (Israel), but Tyre, in southern Lebanon, constitutes a remarkable case by the large amplitude of changes imparted by man-built structures. The only other case of such an amplitude is Alexandria (Egypt), and in both cases, the most important changes have been caused by… Alexander-the-Great.

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Description of Phoenician Tyre by Josephus Flavius, Contra Apionem, 1, 17-18, dated after 94 CE (transl. W. Whiston, 1737, London).

17. […] This Dius therefore writes thus, in his histories of the Phoenicians: “Upon the death of Abibalus, his son Hiram [the first] took the Kingdom. This King raised banks at the eastern parts of the city and enlarged it. He also joined the temple of Jupiter Olympus, [Tyrian Baal] which stood before in an island by itself, to the city, by raising a causeway between them, and adorned that temple with donations of gold. He moreover went up to Libanus, and had timber cut down for the building of temples. […]
18. And now I shall add Menander the Ephesian, as an additional witness. This Menander wrote the acts that were done both by the Greeks and Barbarians, under every one of the Tyrian kings, and had taken much pain to learn their history out of their own records. Now when he was writing about those kings that had reigned at Tyre, he came to Hiram and says thus: “Upon the death of Abibalus, his son Hiram took the Kingdom. He lived fifty-three years and reigned thirty-four. He raised a bank on that called the broad place [Eurychoros] and dedicated that golden pillar which is in Jupiter’s temple. He also went and cut down timber from the mountain called Libanus and got timber of cedar for the roofs of the temples. He also pulled down the old temples and built new ones. Besides this he consecrated the temples of Hercules [Tyrian Melqart] and of Astarte.” [...]

Description of Phoenician Tyre by Herodotus, History, 2, 44, dated ca. 450 BCE (transl. A. D. Godley, 1920-25).

44. Moreover, wishing to get clear knowledge of this matter whence it was possible so to do, I took ship to Tyre in Phoenicia, where I heard that there was a very holy temple of Heracles [Tyrian Melqart]. There I saw it, richly equipped with many other offerings, besides that in it there were two pillars, one of refined gold, one of emerald, a great pillar that shone in the night-time [a lighthouse?]; and in converse with the priests, I asked how long it was since their temple was built. I found that neither did their account tally with the belief of the Greeks, for they said that the temple of the god was founded when Tyre first became a city, and that was two thousand three hundred years since.

Nabuchodonosor's ramp in A Prophecy Against Tyre by Ezekiel 26:8, dated 1st-3rd c. CE (transl. https://www.biblegateway.com).

7. For this is what the Sovereign Lord says: From the north I am going to bring against Tyre Nebuchadnezzar, king of Babylon, king of kings, with horses and chariots, with horsemen and a great army.
8. He will ravage your settlements on the mainland with the sword; he will set up siege works against you, build a ramp up to your walls[78] and raise his shields against you.
9. He will direct the blows of his battering rams against your walls and demolish your towers with his weapons. […]

Description of Alexander's causeway by Diodorus Siculus, Hist, 17, 7 (or 40-46), dated 49 BC (transl. Charles Henry Oldfather, 1933).

40.4. The king saw that the city could hardly be taken by sea because of the engines mounted along its walls and the fleet that it possessed, while from the land it was almost unassailable because it lay four stades [630-740 m] away from the coast. Nevertheless, he determined to run every risk and make every effort to save the Macedonian army from being held in contempt by a single undistinguished city.
40.5. Immediately he demolished what was called Palaeotyre [Old Tyre] and set many tens of thousands of men to work carrying stones to construct a mole two plethra in width [61 m]. He drafted into service the entire population of the neighbouring cities and the project advanced rapidly because the workers were numerous.
42.5. […] As his engines drew close to the city and its capture seemed imminent, a powerful north-west gale blew up ("ἀργέστης ἄνεμος μέγας" Argestes meaning a N300° wind direction) and damaged a large part of the mole.
42.6. Alexander was at a loss to deal with the harm done to his project by the forces of nature and thought of give up the siege attempt but driven by ambition he sent to the mountain and felling huge trees, he brought them branches and all and, placing them besides the mole, broke the force of the waves [note the trees are not used for the mole itself, but to protect the ongoing works].
42.7. It was not long before he had restored the collapsed parts of the mole, and pushing on with an ample labour force until he came within missiles' range, he moved his engines out to

[78] Translations for this structure differ, some use the word "ramp", others speak of a "mount". We could imagine a mount reaching the top of the wall (15 m high), like the one built by the Romans to seize the Massada fortress. However, on Tyre Island, such a mount would be on the beach and in shallow water near the foot of the wall. In addition, a causeway from the mainland would be needed to transport the materials required for the ramp. None of this has been substantiated by archaeology so far.

the end of the causeway, and attacked the walls with his stone throwers, while he employed his light catapults against the men stationed along the battlements. The archers and slingers joined in the barrage and wounded many in the city who rushed to the defence.
43.5. […] Now the causeway had reached the wall and made the city mainland, sharp fighting took place along the walls.
43.6. The Tyrians had the present danger before their eyes and easily imagined what a disaster the actual capture of the city would be, so that they spent themselves so freely in the contest as to despise mortal danger.
46.1. Alexander addressed the Macedonians, calling on them to dare no less than he. Fitting out his ships for fighting, he began a general assault upon the walls by land and sea and this was pressed furiously. He saw that the wall on the side of the naval base was weaker than elsewhere and brought up to that point his triremes lashed together and supporting his best siege engines.

Description of Alexander's causeway by Arrian, Anabasis of Alexander, 2, 18, dated 150 CE (transl. Edward James Chinnock, 1920).

18.1. […] he resolved to construct a mole from the mainland to the city. The place is a narrow strait full of pools; and the part of it near the mainland is shallow water and muddy, but the part near the city itself, where the channel was deepest, was about three fathoms [5.4 m]. in depth. But there was an abundant supply of stones and wood, which they put on the top of the stones. Stakes were easily fixed down firmly in the mud, which itself served as a cement to the stones to hold them firm. The zeal of the Macedonians in the work was great, and it was increased by the presence of Alexander himself, who took the lead in everything, now rousing the men to exertion by speech, and now by presents of money lightening the labour of those who were toiling more than their fellows from the desire of gaining praise for their exertions. As long as the mole was being constructed near the mainland, the work made easy and rapid progress, as the material was poured into a small depth of water, and there was no one to hinder them; but when they began to approach the deeper water, and at the same time came near the city itself, they suffered severely, being assailed with missiles from the walls, which were lofty, inasmuch as they had been expressly equipped for work rather than for fighting. Moreover, as the Tyrians still retained command of the sea, they kept on sailing with the triremes to various parts of the mole and made it impossible in many places for the Macedonians to pour in the material. […]

Description of Alexander's causeway by Quintus Curtius, History, 4, 2-3, dated ca. 50 CE (transl. J.C.Rolfe, Loeb, 1946).

2, 7. But the Tyrians, having plenty of confidence in their situation, had decided to sustain a siege; for a strait of four stadia separates the city from the mainland and was especially exposed to the Africa wind [SW wind], which rolls upon the shore wave on wave from the deep. And there was nothing which more than that wind stood in the way of receiving the work by which the Macedonians were preparing to join the island to the mainland. Even with a calm and mild sea foundations can only with difficulty be laid, while the Africa wind, by the blows of the sea as it dashes against them undermines all the first structures, and no mass is so firm that the waters do not eat it away, both by trickling through the joints of the works, and when a more violent wind rises, by pouring over the top of the entire structure. Besides this difficulty there was another equally great. The walls and towers of the city were surrounded by very deep sea; […]
2, 19. A great amount of rocks was available, supplied by Palaeotyre [Old Tyre], timber was

brought from Mount Libanus for making rafts and towers. And already the work had grown from the bottom of the sea to a moderate height, but nevertheless had not yet reached the surface of the waters, when the Tyrians, bringing up some small boats, mocked them with the taunt that those men famous in arms were carrying loads on their backs like beasts of burden; they also asked whether Alexander was greater than Neptune. These very insults inspired the soldiers to greater eagerness. And now the massive structure was rising a little above the water and at the same time the causeway was increasing in width and moving towards the city, when the Tyrians, seeing the size of the structure, whose increase had hitherto escaped their notice, began to encircle with light craft the work which did not yet form a juncture, and also to assail with missiles those who stood upon it. […]
3, 6. On that day a more furious wind stirred up the sea from its very depths and dashed it against the causeway, and the joints of the structure, lashed by surge after surge, loosened, so that the sea, flowing in between the blocks, broke right through the work. Therefore, when the heaps of stones which supported the earth that had been heaped upon them were demolished, the whole structure sank headlong into the deep, and Alexander, on returning from Arabia [Mont Liban], found hardly any traces of so great a causeway. Thereupon, as usually happens in disasters, they all put the blame on one another, although all might more reasonably have found fault with the fury of the sea. The king, on beginning to build a new causeway, made its front (instead of its side) face directly into the unfavourable wind [interpretation is difficult as the mole could not be built towards the NW or SW wind direction, as it would miss Tyre Island]. Thus, the front protected the rest of the works, which were hidden, as it were, behind it; he also made the causeway wider, in order that the towers erected on the middle of it might be far out of range of a weapon. Furthermore, they threw whole trees with their great branches into the deep, then loaded them with rocks, again threw other trees upon the pile of rocks, and finally heaped on earth; besides this, by piling up successive masses of rocks and trees they had joined together a continuous causeway, as if by a kind of bond. […]

3 POTENTIAL ANCIENT HARBOURS

Nearly 6000 ancient coastal settlements have been identified so far. It may be accepted that all of them had some kind of boat landing or shelter. From a nautical point of view, many of these sites are not considered very good for sheltering modern yachts, but were nevertheless used in ancient times. Conversely, *would you believe that a shelter that is considered today as “excellent” from a nautical point of view would not have been used in ancient times, at least as a bad-weather refuge shelter?*

If such a place, in addition, provided fresh water and food, it could become more than a simple refuge. If it also had some “hinterland” providing trade opportunities, it could become a bigger city with sufficient resources to build specific port structures like breakwaters and quays.

The aim of the present study is to list “Potential Ancient Harbours” defined as natural shelters that are considered ‘excellent’ by modern sailors but not (yet) listed as ancient harbours. The result is a list of ca. 150 places that might be further considered by historians and archaeologists to find out if they were indeed ancient settlements.

A few authors have been trying to define criteria for the location of ancient ports (Mauro, 2019[79]). Some authors used geographical criteria (headlands, islands, bays, rivers) and other authors more specific criteria (protection from wind and waves, seabed quality for anchoring, availability of water, salt and food). Nautical aspects were not often taken into consideration (except by Arnaud, 2005[80]) although they are vital for seafarers. The purpose of this paper is to compare shelters considered as ‘excellent’ by modern yachtsmen with ancient shelters known by archaeology, and to identify locations that might be accepted as ‘Potential Ancient Harbours’ where archaeologists might have a look around.

3.1 A Catalogue of ancient harbours

A ‘harbour’ is a place where ships can seek shelter. The concept of ‘shelter’ has to include i) anchorages, ii) landing places on beaches, and iii) ports with facilities for landing passengers and goods, including structures such as access channels, breakwaters, jetties, landing stages, quays, warehouses for storing commodities and equipment, shipsheds and slipways. Shelters of interest include all places which may have been used by seafarers sailing over long distances. Villae maritimae are also of interest, but shelters the likes of local fishermen, who may have landed their boats on the beach in front of their homes, are of less interest. In another limitation, only maritime harbours and some river ports that could be reached by deep-sea ships are considered.

This paper presents work done to collect, identify and locate ancient harbours and ports. It is based on a study of existing documentation, i.e., on the writings of nearly 100 ancient authors and hundreds of modern authors, incl. the Barrington Atlas.
The ancient authors are usually historians, philosophers or poets, but for this work the geographers retained most of our attention: Strabo, Pausanias, Pliny the Elder, Ptolemy, Avienus, Mela and others, some anonymous, who tell about their journeys like ‘Antonine’, ‘Scylax’, ‘Scymnos’, Pythias, Hanno, Odysseus, Aeneas, Jason, Arrian in the Black Sea. In addition to ports mentioned by ancient authors, some ports have been included as mentioned by modern authors: Karl Lehmann-Hartleben (1923), Honor Frost (1963), David Blackman (1982 & 2014), Talbert’s Barrington Atlas (2000), Nic Flemming (1986), Getzel Cohen (1995 & 2006), Micha Tiverios (2008), Helen Dawson (2013), Anton Gordieiev (2015) and some up to date web sites (http://pleiades.stoa.org/ and http://imperium.ahlfeldt.se/ and https://www.trismegistos.org and https://topostext.org/).

[79] MAURO, C., 2019 “Archaic and Classical Harbours of the Greek World - The Aegean and Eastern Ionian contexts”, Archaeopress Publishing Ltd, Oxford, (115 p).
[80] ARNAUD, P., 2005, “Les routes de la navigation antique”, éd. Errance, (248 p).

In a first stage, only ports were listed that are explicitly mentioned by each ancient author (portus, navale, statio). Cities where the presence of a port was known from other sources were not attributed to an author who mentions the city but does not mention the port. This limitation was certainly questionable as one cannot imagine coastal settlements without at least a minimal shelter for boats. It was therefore decided to include all sites mentioned by the authors of a Periplus such as Stadiasmus, Antonine, Arrian and Marcian who were sailing ships and for whom one might consider that all places they mention are harbours. Furthermore, it was considered that all coastal settlements mentioned in the Barrington Atlas must have had a shelter, and they were included too.
A list of ca. 6000 ancient ports and shelters was elaborated. They are scattered mainly around the Mediterranean Sea, but also in the North Sea, in the Atlantic Ocean, in the Red Sea and the Gulf and in the Indian Ocean. It can be viewed on: Catalogue of Ancient Ports.

3.2 A list of modern shelters

Modern yachtsmen use sailing guides, 'Pilots', for each area. These guides provide information on sailing routes, waypoints, services to be found in marinas, etc. They sometimes also rate the quality of the shelter:

- A: excellent,
- B: good with prevailing winds,
- C: reasonable shelter but uncomfortable and sometimes dangerous,
- O: in calm weather only.

Seafarers are intuitive people, they integrate all aspects to provide a judgment on the shelter quality. This judgment is of great value to us here. An excellent A-shelter provides all-round protection from wind, waves and currents, from all directions and at all times. This kind of protection from offshore waves is usually found inside bays with a narrow entrance and complex shape such as a 'dog-leg'. Protection from wind is important also and usually depends on the land topography surrounding the shelter. Note that shelters are defined for modern sailing ships with modern sails and some 'A-shelters' might prove not that good for ancient ships with square sails.
The work sequence was to list A-shelters and to check if each of them was or not recognised as one of the ancient harbours mentioned on the Catalogue of Ancient Ports. Therefore, the 14 modern nautical guides, or 'pilots' listed in the references hereafter have been searched. They contain over 4000 shelters, anchorages, marinas and commercial ports. Around 25% of them are excellent shelters. After comparing each of them with the Catalogue of Ancient Ports, the list hereafter was obtained for shelters that are not yet recognised as ancient harbours, but are good candidates from a nautical point of view.

3.3 Results

A list of ca.150 sites was obtained from the comparison of ancient and modern shelters. It is summarised in the figures and table below, grouping the numbers of Potential Ancient Harbours (PAH) for each area (a complete list is given at the end of this section).

COUNTRY	PAH
Belgium	1
Spain & Portugal	6
Baleares islands	17
France west & south & Corsica	4
Italy, Sicily, Sardinia, other islands and Malta	12
Adriatic Sea	29
Greece & Crete	20
Black Sea	2
Turkey west & south	7
Red Sea & Oman & Somalia	56
Levant, Cyprus & North Africa	2
Total	156

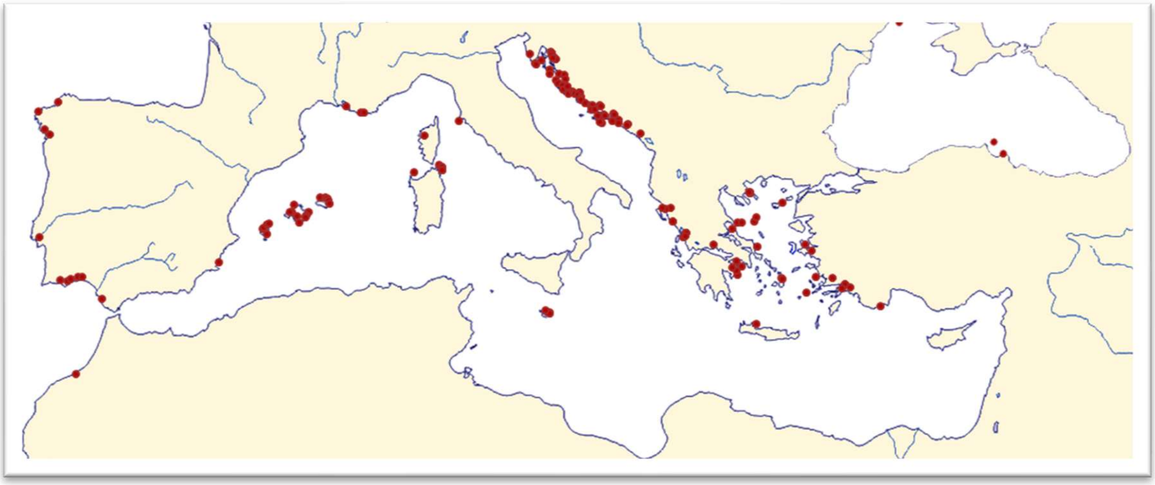


Figure 1. Potential Ancient Harbours in the Mediterranean area.

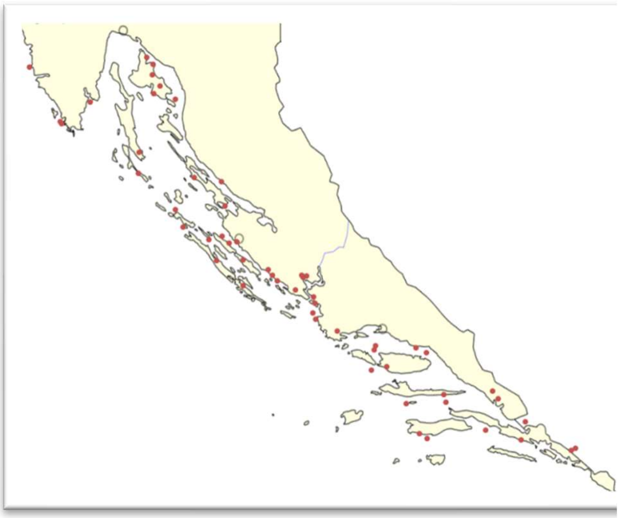


Figure 2. Potential Ancient Harbours in Croatia.

Figure 3. Potential Ancient Harbours on the Balearic Islands.

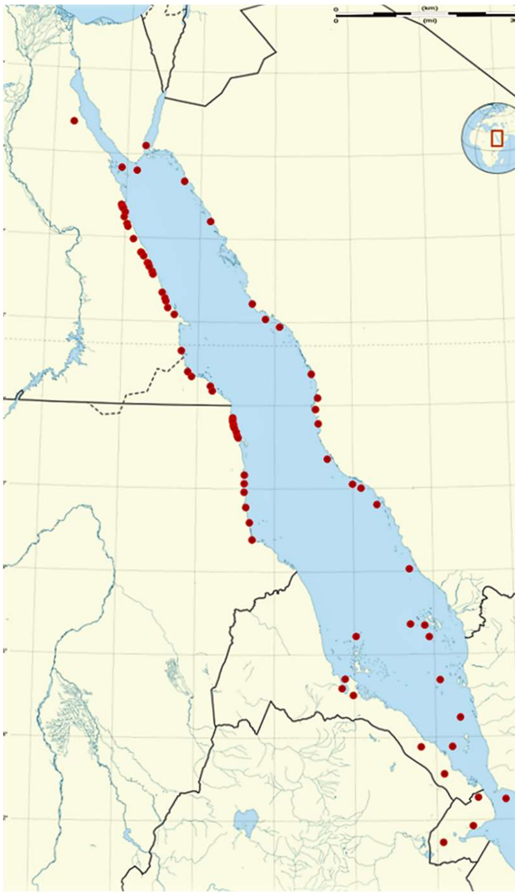


Figure 4. Potential Ancient Harbours in the Red Sea.

The maps shown here have no pretention of precision; they just intend to show concentrations of Potential Ancient Harbours; exact locations are available on Google Earth maps shown on:www.AncientPortsAntiques.com

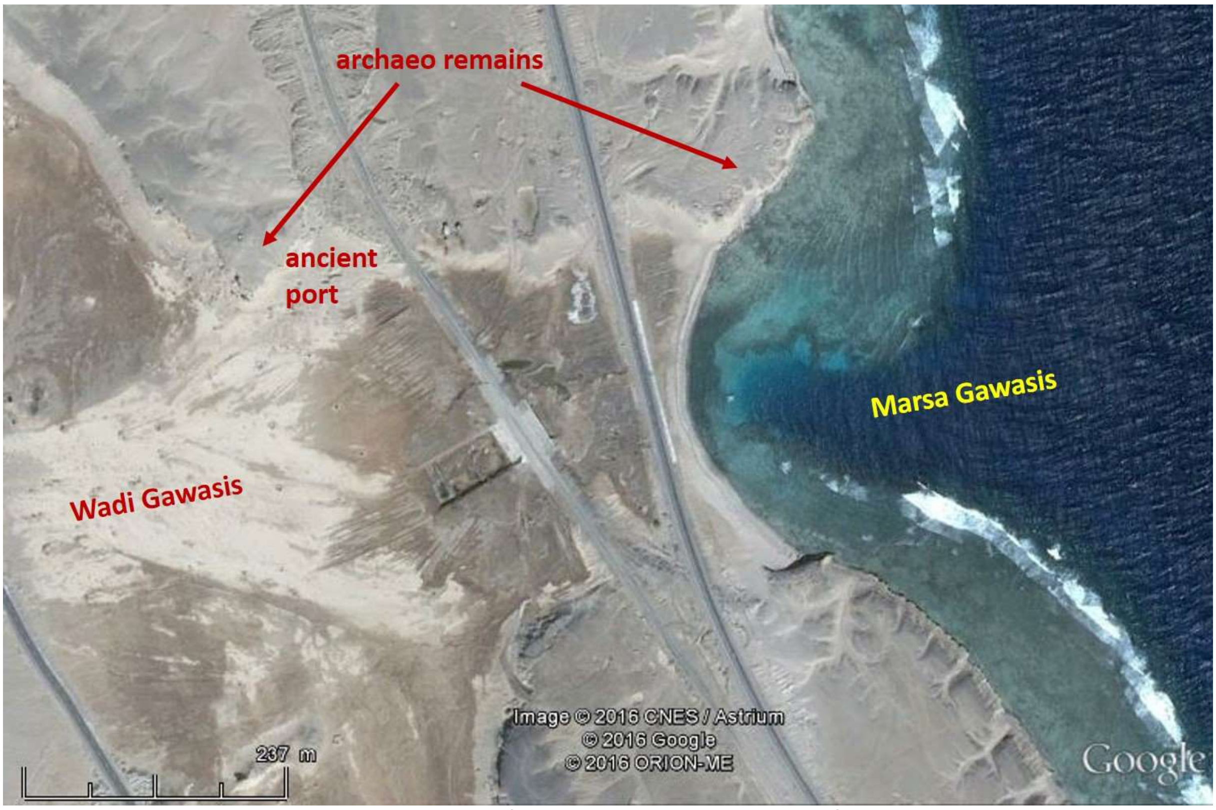
The data above show that quite a lot of Potential Ancient Harbours are found in Greece, scattered on the mainland and on the islands. Concentrations of Potential Ancient Harbours are found in Croatia, on the Baleares islands and NE Sardinia. The Red Sea provides the largest number of Potential Ancient Harbours, but they are scattered all over the area, with a concentration of 'marsas' in northern Sudan.

3.4 Some additional potential ancient ports

Everybody knows that a coral reef borders the Red Sea on almost its entire length. It is known also that the coral reef hates fresh water, polluted water and sediment and that it therefore is interrupted in places where large 'wadis' have their outlet into the sea. Such discontinuities of the reef provide deep-water coves that can be used as shelters for ships. As a matter of fact, water is very deep (over 10 m) and the reef features a kind of vertical underwater cliff. I had an opportunity to swim in such a place in the nineties with my friend Xavier Bohl from Port Grimaud when we were asked to design a marina in a place now called Port Ghalib, and I confirm that it is an impressive swim as one cannot see the seabed although the water is crystal clean. Such a deep-water cove is obviously not for anchorage, but the little beach inside the cove is suited for beaching.

The Google Earth view below shows the Marsa Gawasis cove as an interruption of the coral reef, and wadi Gawasis flowing into the sea.

Wadi Gawasis flowing into the sea at Marsa Gawasis, generating an interruption of the coral reef.



Archaeological remains and location of the ancient port about 300 m from the present coastline.
The wadi outlet was filled with sediment provided by the wadi.

The main point here is that:

this interruption of the reef and the resulting cove have been there for 4000 years.

Until recently, I thought wadis were wandering around and present coves were not ancient. However, I changed my mind when looking at Marsa Gawasis where recent archaeological finds show that this cove was used as a sea port in very ancient times 4000 years ago (Bard & Fattovich, 2007[81]; Tallet, 2015[82]).

Other similar places where this can be seen are wadi Safaga located 9 km north of wadi Gawasis, a place possibly called Quei located 26 km south of wadi Gawasis, Hamrawein port (possibly ancient Arsinoe Troglodytika), Quseir al-Qadim (ancient Myos Hormos), Marsa Dabr, Marsa Nakari (ancient Nechesia?).

This new insight may help to identify other 'Potential Ancient Harbours'. This does of course not mean that an ancient port will be found in each present cove on the Red Sea coast, but it may be worth listing them in order to have a closer look for archaeological remains in these places in the future. Note that many of these coves are used today for holiday resorts and diving centres which may be a sign of good shelter.
Here is the list for the stretch between Hurghada and Ras Banas (400 km). This stretch was chosen because it is the most likely area where ships would stop fighting against the northern wind when returning from their trip to the Land of Punt, and would unload their precious cargo to continue over land to the Nile river.

[81] BARD, K. & FATTOVICH, R., 2007, "Spatial Use of the Twelfth Dynasty Harbor at Mersa/wadiGawasis for the Seafaring Expeditions to Punt", Journal of Ancient Egyptian Interconnections, Vol. 2:3, 2010, (p 1-13).
[82] TALLET, P., 2015, "Les « ports intermittents » de la mer Rouge à l'époque pharaonique: caractéristiques et chronologie", Nehet 3, 2015, (p 31-72).

List of (19) Additional Potential Ancient Harbours
(Latitudes & longitudes are in decimal degrees, taken from Google Earth)

PLACE NAME*	COUNTRY	LATITUDE	LONGITUDE
Makadi Bay	Egypt	26.99200	33.90500
Al Nabila	Egypt	26.96630	33.92160
Unnamed cove	Egypt	26.94470	33.93370
Unnamed cove	Egypt	26.92910	33.94260
Coral Garden	Egypt	26.57180	34.03200
Kalawy Imperial	Egypt	26.50810	34.06890
Abu Sawatir Rocky Valley	Egypt	26.20550	34.22010
Sharm el-Bahari, Mangrove Bay	Egypt	25.86800	34.41800
Santido Resort	Egypt	25.83930	34.43750
Marsa Wizr	Egypt	25.78600	34.48930
Marsa Toronbi	Egypt	25.62070	34.58880
Coraya Bay	Egypt	25.60210	34.60600
Port Ghalib	Egypt	25.53090	34.63400
Marsa Mooray	Egypt	25.39600	34.70300
Marsa Abu Dabbab	Egypt	25.33900	34.74000
Marsa Fokairi	Egypt	24.75550	35.06760
Shams Alam Resort	Egypt	24.69000	35.08700
Unnamed cove	Egypt	24.51950	35.14100
Kala'an Gulf	Egypt	24.36000	35.29800

*: place names are taken from Google Earth and may contain some approximations

3.5 Analysis

Homeric seafarers often used beaches to land their ships on. It may be noted that a 30 m penteconter with 50 'strong' oarsmen could be hauled on the beach if the slope was mild enough, say no more than 1:10, or 10%, or 6° (the steepest man-made slipways had a slope of 1:6 acc. Blackman, 2013). This requires sand of a certain grain size (Komar, 1998): the very fine sands (or silts) found in large deltas yield a very flat slope which keeps ships far from land. Conversely, a shingle beach has a steep slope that is dangerous for landing ships on. With increasing ship sizes (and weights), beaching became unpractical, if not unfeasible, and places for safe anchorage were sought (see Greg Votruba, 2017).

During Athenian military expeditions, 200 people had to be fed on board triremes. It was impossible for masters to fill their ships with tons of food. In the absence of ports, ship pilots had to find places with a degree of shelter where drinking water could be found, and river estuaries could provide both. The Stadiasmus is an example of a collection of such knowledge and can be considered as the ancestor of medieval portolans and modern nautical instructions.

Commercial ships also preferred sheltered creeks and river estuaries, possibly with some kind of jetty, as their ships were too heavy to be pulled on the beach.

Seafarers obviously preferred sheltered creeks with clear landmarks on shore (such as a typical mountain). Many shelters were needed, as seafarers often followed the coast, using safe shelters to stop overnight and escape bad weather. Even though they could sail 50 to 100 nautical miles in a day, it was important to know where they could find safe shelter within two to three hours of navigation; i.e., only approx. 10 miles.

Many of these sheltered creeks still exist today, but large changes have occurred in some places:

- crustal movements which explain why some ancient ports are now submerged (Alexandria, Crete);
- a eustatic sea level rise of around 0.50 m over the past 2000 years which has sometimes completely changed the seascape (large deltas);
- seismic events inducing tsunamis which devastated adjacent coastal areas (Crete, Crane/Agrostoli);
- river estuaries usually tend to silt up, as rivers carry most of the materials that create beaches, and this explains why some ancient ports are now so far from the sea (Ephesus, Portus at Fiumicino) or have simply filled up with sand (Leptis Magna);
- in some large cities the ‘old port’ has been reclaimed to create a new waterfront area (Marseille, Beirut);
- beaches are subject to sedimentation and erosion by wave action, and the latter explains why some ancient ports were lost to the sea (Tunisia).

It should be noted also that ancient ports mentioned here have been collected from texts of various dates ranging from 1500 BC to 500 AD (with a few exceptions), that is 2000 years. The various authors have not seen the same things ... and some authors have just repeated what others wrote before them!

3.6 Conclusions

The aim of this study is not to provide a comprehensive list of yet unknown Potential Ancient Harbours based on rational and scientific deductions, but rather to list places that might be further investigated by historians and archaeologists. The somewhat intuitive methods used here do not give any proof, but just an indication of Potential Ancient Harbours.

Some areas show few Potential Ancient Harbours and this may be due to:

- ancient authors providing a comprehensive description of the coast (e.g., Arrian in the Black Sea);
- comprehensive modern archaeological surveys (e.g., in France, Italy, Spain, Tunisia); hence, many of today’s excellent shelters are recognised ancient harbours;
- many of today’s excellent shelters are modern marinas just added to a coastline without any good natural shelter and do not qualify as Potential Ancient Harbours (e.g., in France, Italy, Spain);
- some nautical guides did not survey the smaller anchorages (e.g., North Africa).

Without insult to the modern authors of the nautical guides, it can be said that the ancient Stadiasmus includes more places than the modern pilot of the North African coast between Carthage and Alexandria! The same holds for Arrian’s periplus of the Black Sea.

Conversely, some areas show many potential ancient harbours. This is probably due to a reversed combination of the above factors, e.g., in the Red Sea, Croatia where ancient sources are inaccurate, if any, and modern pilots are quite detailed.

The Catalogue of Ancient Coastal Settlements, Ports & Harbours tries to be exhaustive, but is most probably not. Hence, some Potential Ancient Harbours listed here may be recognised by some expert as ancient harbours already known to him and the present author will be delighted to hear about that in order to remove such places from the list of ‘potential’ ancient harbours. However, large parts of the listed Potential Ancient Harbours are probably real newcomers and will definitely require more attention from historians and archaeologists to find out if they were indeed ancient settlements.

Some of these places may not show a single sign of ancient presence at the anchorage or on land because erosion may have taken away all remains; they will therefore remain ‘potential’ ancient harbours. Hopefully, other places will provide more evidence of ancient human presence (amphorae, stone anchors, ballast stones, etc.) even if this evidence may be difficult to find as it may be under water and buried under thick layers of sediment.

Even more optimistic, the list of Potential Ancient Harbours might help historians re-interpreting ancient ‘Periploi’ and Ptolemy’s places in the Red Sea.

References

The following “pilots” were used:

- Spain & Portugal by Martin Walker & Henry Buchanan (IMRAY, 2010)
- Spain Mediterranean coast by John Marchment, (IMRAY, 2009)
- Baleares by Robin Brandon & Anne Hammick (IMRAY, 2000)
- France Western Mediterranean coast (SHOM, 2000)
- France Eastern Mediterranean coast (SHOM, 2001)
- Corsica & North Sardinia by Alain Rondeau (1997)
- Italy, Sicily, Sardinia, Malta by Rod Heikell (IMRAY, 2011)
- Adriatic Sea by Trevor Thompson (IMRAY, 2000)
- Ionian Sea, Peloponnese & Crete by Rod Heikell (IMRAY, 2001)
- Aegean Sea by Rod Heikell (IMRAY, 2001)
- Black Sea by Read Barker (IMRAY, 2012)
- Turkey, Black Sea & Cyprus by Rod Heikell (IMRAY, 2006)
- Red Sea, Egypt, Israel by Elaine Morgan & Stephen Davies (IMRAY, 2001)
- North Africa by Graham Hutt (IMRAY, 2012)

List of Potential Ancient Harbours
(Latitudes & longitudes are in decimal degrees, taken from Google Earth)

PLACE NAME	COUNTRY	LATITUDE	LONGITUDE
Nieuwpoort	Belgium	51.137000	2.749000
Camarinas	Spain north	43.132356	-9.172238
Isla Toxa Grande	Spain north	42.487487	-8.844113
Ensenada de San Simon	Spain north	42.303984	-8.63775
Isla Cristina	Spain south	37.206216	-7.327774
El Rompido	Spain south	37.214239	-7.125718
Sancti-Petri	Spain south	36.397146	-6.206802
Las Illetas	Spain Mallorca	39.531926	2.587282
Puerto de Soller	Spain Mallorca	39.796642	2.693481
Porto Cristo	Spain Mallorca	39.540520	3.336989
Porto Colom	Spain Mallorca	39.419308	3.265063
Puerto de Cala Llonga, Cala d'Or	Spain Mallorca	39.369239	3.224449
Porto Petro	Spain Mallorca	39.356874	3.212041
Puerto de Cabrera	Spain Cabrera	39.148226	2.933627
Cala Pi	Spain Mallorca	39.362034	2.834320
Puerto de Fornells	Spain Minorca	40.046405	4.130221
Puerto de Cala de Addaya	Spain Minorca	40.004438	4.199634
Cala Grao, Colom island	Spain Minorca	39.953126	4.273486
Cala Alcaufa	Spain Minorca	39.828192	4.294459
Cala Badella	Spain Ibiza	38.913538	1.222857
Port del Torrent	Spain Ibiza	38.967198	1.267691
Puerto de San Miguel	Spain Ibiza	39.084369	1.437616
Cala Portinatx	Spain Ibiza	39.114326	1.518128
Puerto de Sabina, Estanque Peix	Spain Formentera	38.730422	1.414050
Sausset les Pins	France south	43.330747	5.107255
Port St Pierre on Iles des Embiez	France south	43.079451	5.781492
Baie du Lazaret	France south	43.082920	5.905755
Porto	France Corsica	42.266501	8.693291
Stintino	Italy Sardinia	40.938117	8.225224
Cala Gavetta, on Isla La Maddalena	Italy Sardinia	41.212045	9.404022
Cala Bitta	Italy Sardinia	41.125616	9.470911
Poltu Quatu	Italy Sardinia	41.135830	9.495848
Porto Vecchio of Porto Cervo	Italy Sardinia	41.133359	9.536260
Bay of Cugnana-Portisco	Italy Sardinia	41.016495	9.523114
Porto Rotondo	Italy Sardinia	41.029277	9.546367
Edilnautica marina, on the isle of Elba	Italy west	42.806320	10.314434
Mellieha bay	Malta	35.974829	14.364465

Saint George's bay	Malta	35.926135	14.488961
Marsamxett, Msida creek	Malta	35.896406	14.494795
Blue Lagoon, on the isle of Comino	Malta	36.012741	14.323565
Uvala Tunarica, in Zaljev Rasa	Croatia	44.971613	14.097678
Kraljevica	Croatia	45.272957	14.566458
Zaton Soline, on the isle of Krk	Croatia	45.155990	14.608581
Vrbnik, on the isle of Krk	Croatia	45.078000	14.672386
Bay of Kosljun, Puntarska Draga, on the isle of Krk	Croatia	45.029639	14.619498
Punta Kriza, in Uvala Ul, on the isle of Cres	Croatia	44.641311	14.503273
Luka Krivica, on the isle of Losinj	Croatia	44.500672	14.495218
Uvala Lukovo-Sugarje	Croatia	44.443888	15.18564
Uvala Jasenova	Croatia	44.282389	15.210407
Uvala Soline, in Luka Soliscica on Dugi island	Croatia	44.141501	14.866483
Kukljica, on Ugljan island	Croatia	44.033868	15.24751
LukaTelascica, on Dugi island	Croatia	43.917810	15.142861
Uvala Soline, on Pasman island	Croatia	43.924342	15.360994
Uvala Vela Luka	Croatia	43.860591	15.572466
Betina, on Murter island	Croatia	43.821538	15.604590
Jezera, on Murter island	Croatia	43.784346	15.643490
Rasline	Croatia	43.807630	15.857736
Uvala Beretusa	Croatia	43.818403	15.886719
Jadrtovac	Croatia	43.675937	15.945718
Banovci, in Luka Grebastica	Croatia	43.636672	15.957561
Kremik Marina	Croatia	43.569867	15.940943
Uvala Rasotica, on the isle of Braç	Croatia	43.307747	16.885881
Bobovisca, on the isle of Braç	Croatia	43.352859	16.461513
Blace	Croatia	43.001627	17.481396
Mali Ston	Croatia	42.847606	17.704852
Uvala Luka, near Loviste	Croatia	43.029569	17.027106
Rijeka Dubrovacka	Croatia	42.670778	18.121156
Gruz	Croatia	42.653862	18.086801
Bigova	Montenegro	42.354278	18.704058
Pagania	GR: north-west	39.659491	20.098357
Vathi Vali	GR: north-west	38.758364	20.780577
Varko	GR: north-west	38.764219	20.805779
Nisis Trizonia	GR: north-west	38.368055	22.075595
Boufalo, Voufalo	GR: Evia	38.301918	24.11946
Ormos Vathikelon	GR: Evia	38.940900	22.940174
Ormos Mesopanayia	GR: north-east	40.202842	23.780868
Ormos Kriftos	GR: north-east	40.221810	23.782357

Ormos Dhimitriaki	GR: north-east	40.226768	23.753190
Ormos Panayia	GR: north-east	40.232231	23.737014
Khaidhari	GR: Peloponnese	37.533736	22.921406
Limin Gouvion, on Corfu	GR: Ionian Isl.	39.654110	19.849040
Palaiokastritsa, Limin Alipa, on Corfu	GR: Ionian Isl.	39.673427	19.709291
Sivota, on the isle of Lefkada	GR: Ionian Isl.	38.622712	20.683317
Ormos Abelike, on the isle of Meganisi	GR: Ionian Isl.	38.665943	20.790318
Ormos Langeri, inside Ormos Naousis on Paros	GR: Cyclades Isl.	37.138657	25.266262
Ormos Moudhrou, on the isle of Lemnos	GR: Eastern Isl.	39.870490	25.245694
Koukounaries, on the isle of Skiathos	GR: Eastern Isl.	39.150560	23.399511
Planitis, on the isle of Pelagos	GR: Eastern Isl.	39.347330	24.071967
Soudha	GR: Crete north	35.497358	24.079312
Yakakent Liman	TR: Black Sea	41.638876	35.501672
Hamsilos	TR: Black Sea	42.060269	35.042210
Dalyanköy	TR: West	38.353285	26.312599
Gökkovar Limani, Kokar	TR: West	38.137537	26.607011
Küyüçak	TR: West	37.153570	27.559237
Okluk Koyu, inside Degirmen Bükü	TR: West	36.920552	28.171595
Ingilizi Limani, inside Degirmen Bükü	TR: West	36.923470	28.156911
Büyük Cati	TR: West	36.790077	28.012561
Aksaz, in Karaagaç Limani	TR: South	36.840444	28.391038
Mersa Thelemet	Egypt: Red Sea	29.054510	32.635191
Merset el-Qad Yahya	Egypt: Red Sea	27.929551	33.893634
Marsa Abu Makhadiq	Egypt: Red Sea	27.041819	33.893311
Bodkin reef	Egypt: Red Sea	23.478978	35.493572
Sharm el Madfa, Marsa Hasa	Egypt: Red Sea	22.956168	35.668514
Marsa Shaab	Egypt: Red Sea	22.842591	35.777153
Marsa el Qad	Egypt: Red Sea	22.607727	36.260299
Marsa Abu Naam	Egypt: Red Sea	22.497571	36.309290
Marsa Gwilaib, Marsa Ribda	Sudan	21.790160	36.865975
Marsa Oseif, Khor Abu Asal	Sudan	21.759722	36.871819
Marsa Hamsiat	Sudan	21.686785	36.886603
Marsa Wasia	Sudan	21.643104	36.895915
Marsa Gafatir	Sudan	21.595219	36.919704
Marsa Halaka, near Abu Imama	Sudan	21.489421	36.954236
Marsa Shinab, Khor Abu Mishmish	Sudan	21.349183	37.010724
Marsa Fijja, Fijab, Bahia de Fuca	Sudan	20.035033	37.185976
Marsa Ata	Sudan	19.289287	37.328189
Harmil island	Eritrea	16.538714	40.153202
Melita bay near Ras Nasiracurra	Eritrea	15.264342	39.811446

Edd	Eritrea	13.933478	41.694754
Mersa Dudo	Eritrea	13.864934	41.907061
Ras Terma	Eritrea	13.214607	42.526752
Tongue island, near Monfreid's Zoukour, Zuqar	Yemen	13.881270	42.713690
As-Salif, near al-Qaryah	Yemen	15.320000	42.675000
Uqban island, Monfreid's Okban	Yemen	15.519620	42.378800
Dumsuq island, Monfreid's Dumsuk	Saudi Arab: Red S.	16.553170	42.060750
Saso, Sarso island	Saudi Arab: Red S.	16.871260	41.587620
Khor al-Birk	Saudi Arab: Red S.	18.214000	41.529000
Khor Nahud	Saudi Arab: Red S.	18.263000	41.504000
Marsa Qishran	Saudi Arab: Red S.	20.254630	40.011820
Abu Shauk	Saudi Arab: Red S.	20.876420	39.354980
Sharm Abhur, Bihar	Saudi Arab: Red S.	21.717350	39.098440
Al Jazeerah, near Ras Hatiba	Saudi Arab: Red S.	22.088060	39.030930
Al Qadimah	Saudi Arab: Red S.	22.353040	39.084470
Sharm Al Khawr	Saudi Arab: Red S.	24.273910	37.673650
Sharm Hasy	Saudi Arab: Red S.	24.625870	37.337310
Sharm Habban	Saudi Arab: Red S.	26.067420	36.572160
Sharm Antar	Saudi Arab: Red S.	26.592360	36.251000
Sharm Dumaygh	Saudi Arab: Red S.	26.642810	36.219320
Sharm Jubbah, industrial port of Duba	Saudi Arab: Red S.	27.559700	35.544000
Sharm Yahar, Al Harr	Saudi Arab: Red S.	27.621700	35.520980
Sharm el-Sheikh	Gulf of Aqaba	27.859350	34.291970
El-Kura	Gulf of Aqaba	28.475120	34.499530
Khor Shoreh, Shoora	Somalia	10.819660	45.859680
Guinni Koma, Monfreid's Gubet Karab	Djibouti	11.532760	42.523550
Tadjoura	Djibouti	11.782000	42.878000
Obock	Djibouti	11.966177	43.294719
Khor Omeira, Monfreid's Kor Omeira	Yemen	12.638344	44.137997
Ras Imran	Yemen	12.753677	44.724326
Bal Haf, Balihaf	Yemen	13.982719	48.173209
Khaisat, south of Ras Fartak	Yemen	15.610251	52.186919
Salalah, Raysut	Yemen	16.937126	53.999393
Sour	Oman	22.573202	59.536214
Bandar Khairan	Oman	23.519779	58.72588
Al Suwadi, Sawadi	Oman	23.785968	57.794247
Atalayoun, Marchica near Nador	Morocco	35.220721	-2.907731
Mohammedia-Fedala	Morocco	33.712125	-7.397729

4 ANCIENT PORT STRUCTURES

The main elements of a port are its *breakwater(s)* to reduce wave action inside a protected *basin*, where *quays* or jetties, with some mooring devices, are available for loading/unloading ships. Hence, a breakwater and a quay have to be built using available construction materials and methods, and a basin has to be dredged and maintained at adequate depth[83].

From our Catalogue (Volume I), we know that for nearly 6000 ancient coastal settlements, ports and harbours, we have around 650 ports (only 12%) with at least one of the structures listed below. The following port structures were found in ancient ports:

Abbr.	Type of structure	Nb
BW	Breakwater, sometimes also called mole	380
QU	Quay (masonry with berthing on one side), pier or jetty (masonry with berthing on two sides), and landing stage (jetty on piles)	375
PL	Pila, made of hydraulic concrete containing pumiceous volcanic ash (pozzolana)	51
MO	Mooring device (bollard, pierced block)	83
CN	Canal (for navigation or basin flushing and/or desiltation)	70
SL	Slipway to take ships in/out of the water	140
SH	Shipshed (always including a slipway)	86
SY	Shipyard (neoria, navalia) (incl. arsenals)	56
EX	Man-made basin excavated in the rock (e.g., Carthage's circular cothon)	36
LK	Limen Kleistos, "closable" harbour with a narrow entrance	88
PH	Lighthouse	174
HO	Warehouse	88

4.1 Brief historical overview

Many Paleolithic, Mesolithic and Neolithic sites have been identified in coastal areas, but they did not have any port structures[84]. A few examples are provided by logboat wrecks in northern Europe, Tarsos and Anchialeia (Turkey), Cape Andreas, Nissi Beach, River Aspros, Kyssonerga, Akanthou, Akrotiri (Cyprus), Tell Kabri, Shavei Zion, Megadim, Athlit -Yam, Neve-Yam (Israel), Gorham's cave (Gibraltar), Bouldnor Cliff (UK).

A submerged probable seawall dated ca. 5500-5000 BC was found at Hreiz (Israel)[85]. The **oldest known seaport structure** (in 2022) is the wadi al-Jarf breakwater in the Gulf of Suez (ca. 2570 BC, Khufu-Chéops). This structure is ca. 325 m long and ca. 6 m wide. It is made of

[83] DE GRAAUW, A., 2020, "Ancient Port Structures – An engineer's perspective", Portus Limen Project workshop, Rome, January 2019.
[84] DAWSON, H., 2013, "Mediterranean Voyages – The Archaeology of Island Colonisation and Abandonment", Left Coast Press, Walnut Creek, California, (324 p).
[85] GALILI, E., et al., 2019, "A submerged 7000-year-old village and seawall demonstrate earliest known coastal defence against sea-level rise", PLoS ONE 14(12): e0222560, https://doi.org/10.1371/journal.pone.0222560, (17 p).

cobbles and clay[86]. Extensive port facilities were built near Khufu's pyramid construction-site at Memphis for transport of large ashlars (Gizeh, Egypt). Further coastal settlements are found at Ayn Sukhna (Egypt), Malta, several Aegean islands, several places on the Bulgarian-Romanian coasts, Ictis insula (UK). The port of Byblos (Lebanon) is from the same period, but it is located inside natural coves with no known port structures[87]. Between 2400 and 2000 BC, a 4 m deep basin of 215 x 35 m was built with fired mudbrick at Lothal (India) near River Sabarmati, but this may have been a water reservoir. The smaller basins of Ur were probably also built in this period[88]. Further coastal settlements are found in the Gulf in at Susa, Uruk (Iraq), Rishir (Iran).

The very large port on Pharos island might also date from this period and its more than 2 km long main breakwater might be seen as an ancestor of the typical Phoenician breakwater structure with two ashlar vertical walls and interspace filled with rubble[89]. Many more places were found in the Nile delta, e.g., Avaris (dated 1700 BC) with a 450 x 400 m basin excavated near the Pelusiac Nile branch.

A series of Minoan ports were found on the north coast of Crete: Kydonia (Chania), Knossos and Amnissos (near Iraklio), Mallia, Ag. Nikolaos, Istron, Pachia Ammos, Tholos, Pseira, Mochlos, Kaloi Limenes, Lebena which are usually quite small[90].

Natural shelters were used in the 2nd millennium BC on the Turkish coast: Troy, Klazomenai, Miletos, Halicarnassus. Anchorages more or less sheltered by offshore ridges were used as natural shelters on the Levantine coast: Ugarit, Gibala, Shuksi, Siannu, Marathos, Simyra, Arca, Ibirta, Orthosia, Tripolis, Ampa, Botrys, Berytos, Akko, Ascalon, Gaza. In Yavne-Yam (Israel) a 100 m x 50 m stone rempart may have been built to improve the shelter[91].

Early Phoenicians gradually improved their natural shelters by adding breakwater structures on top of the offshore ridges, like at Sidon on the “Languette rocheuse” mentioned by Poidebard

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86 TALLET, P., 2015: http://www.orient-mediterranee.com/spip.php?article3017 : Khufu-Khéops is therefore a precursor, not only for his Great Pyramid, but also for his maritime works.

87 CARAYON, N., 2012a, “Geoarchaeology of Byblos, Tyre, Sidon and Beirut”, Rivista di Studi Fenici 1 2011_Impaginato 30/06/12 14:52, (p 45-55).

88 WOOLLEY, L., 1974, “Ur excavations, Volume VI, The buildings of the third dynasty”, Plate 61, The trustees of the two museums, London, Philadelphia, (184 p).
BLACKMAN, D., 1982, “Ancient harbours in the Mediterranean”, International Journal of Nautical Archaeology and Underwater Exploration, 11.2 (p 79-104) and 11.3, (p 185-211).
OLESON, J., 2015, “The Evolution of Harbour Engineering in the Ancient Mediterranean World”, Harbors and Harbor cities in the Eastern Mediterranean from Antiquity to the Byzantine Period, BYZAS 19 Conference, 30/5 – 1/6/2011, Istanbul, (p 509-522).

89 JONDET, G., 1916, ‘’Les ports submergés de l’ancienne île de Pharos’’, Mémoires présentés à l’institut égyptien, Tome IX, Le Caire, (121 p).
WEILL, R., 1916, “Les ports antéhelléniques de la côte d’Alexandrie et l’Empire crétois’’, Bulletin de l’Institut Français d’Archéologie Orientale, Tome XVI.
SAVILE, L., 1940, Presidential address of Sir Leopold Halliday Savile, K.C.B. on 6/11/1940, Journal of the institution of Civil Engineers 15, No 1, November 1940, (p 1-26).
BELOVA, G., et al., 2019, “Russian underwater archaeological mission to Alexandria, General report (2003-2015)”, Egypt and neighbouring countries 3, (p 1-31).

90 FROST, H., 1963, “Under the Mediterranean, Marine antiquities”, Routledge and Kegan Paul Ltd, London, (278 p).

91 GALILI, E., et al, 1993, “Underwater surveys and rescue excavations along the Israeli coast”, IJNA, 1993, 22.1, (p 61-77).

and Lauffray in 1951, and at other places (Arwad, Batroun, Zire)[92]. Corings show that Sidon's inner port was already existing in the 17-15th c. BC thanks to this artificially improved reef.[93]

At Kommos (Crete) a shipshed located near the coast, and including 6 galleries of 37 x 5.60 m, is dated Late Minoan (ca. 1400 BC)[94]. A possible Minoan slipway with two galleries of ca. 5 x 40 m is located at Nirou Khani (Crete). A slipway was also found at Sounion (Attica) and shipsheds were found at Kition (Cyprus). Mycenaean ports on the Peloponnesus[95] also date from this period: Epidauros, Egina, Hydra, Asini, Tiryns, Gytheion, Pylos[96].

Next are the following port structures, all located in ancient Phoenicia:

- Dor (Israel, ca. 1000 BC) with a 35 m shallow water quay made of large ca. 0.7 x 0.5 x 2 m ashlar headers facing the sea[97],
- Tabbat el-Hammam (Syria, ca. 900 BC) breakwater 200 x 15 m[98],
- Sidon (Lebanon, ca. 800-600 BC) north breakwater 230 m long, with headers up to 5 m[99],
- Tyre (Lebanon, ca. 800-600 BC) north breakwater 70 x 12 m, with 0.5 x 0.4 x 2 m headers [100],
- Athlit breakwater (Israel, ca. 800 BC) 130 x 10 m, with 0.65 x 0.65 x 1.8 m headers[101].

These vertical breakwaters all included ashlar headers ca. 0.5-1 x 0.5-1 x 1-5 m. These pioneering breakwaters consist of two ashlar vertical walls with interspace filled with rubble. Moreover, this type of structure was still built much later in the 3rd c. BC (Amathus in Cyprus 380 m, with 0.7 x 0.7 x 3 m headers) [102] and in the 2nd c. AD (Leptiminus and Acholla in Tunisia,

[92] VIRET, J., 2005, "Les « murs de mer » de la côte levantine", Méditerranée, N°104, (p 15-24). This paper is very informative, even if we do not completely agree with its conclusion.
[93] CARAYON, N., 2012b, "Les ports phéniciens du Liban - Milieux naturels, organisation spatiale et infrastructures", Archaeology and History in Lebanon, 36-37 (2012-2013), (p 1-137); and for further details on corings: MARRINER, N., 2009, "Géoarchéologie des ports antiques du Liban", edt. L'Harmattan, (262 p).
[94] BLACKMAN, D., & RANKOV, B., 2013, "Shipsheds of the Ancient Mediterranean", Cambridge University Press, p 10.
[95] Achaeans from the Peloponnesus were also called Danaans or Argives by Homer, and possibly Ahhiyawans by the Hittites and Tanaju by the Egyptians; today they are called 'Mycenaeans'.
[96] MAURO, C., 2019 "Archaic and Classical Harbours of the Greek World - The Aegean and Eastern Ionian contexts", Archaeopress Publishing Ltd, Oxford, (115 p). See also her http://www.ancientgreekharbours.com/ .
[97] ARKIN SHALEV, E., 2019, "The Iron Age Maritime Interface at the South Bay of Tel Dor: results from the 2016 and 2017 excavation seasons", International Journal of Nautical Archaeology, 48.2, (p 439-452).
Headers are long blocks placed with the smallest section towards the outer side of the wall. Stretchers are placed with their large side to the outer side.
[98] BRAIDWOOD, R., 1940, "Report on two sondages on the coast of Syria, south of Tartous ", In: Syria. Tome 21 fascicule 2, 1940. (p 183-226).
[99] CARAYON, N., 2012b, "Les ports phéniciens du Liban - Milieux naturels, organisation spatiale et infrastructures", Archaeology and History in Lebanon, 36-37 (2012-2013), (p 1-137).
[100] NOUREDDINE, I., 2010, "New Light on the Phoenician Harbor at Tyre", Near Eastern Archaeology 73:2–3 (2010). See also his 2018 publication: Archaeological Survey of the Phoenician Harbour at Tyre, Lebanon.
[101] HAGGI, A., 2005 , "Underwater excavation at the Phoenician harbor at Athlit, 2002 season", R.I.M.S. News, report N° 31, Haifa, 2005
[102] NAVIS II, 2002, The Navis II Database Project, European Commission Directorate General X: https://www2.rgzm.de/navis2/home/frames.htm (go to Harbours/Harbour Information/Israel/Caesarea). This RGZM site does not function presently and will be transferred to www.leiza.de: https://www2.leiza.de/navis/.

with 1 m headers) [103] and even in the 4th c. AD (Seleucia Pieria, 120 m, with 5 m headers[104]). They re-emerged in the 18th c. when international sea-borne trade asked for them again[105].

A major evolution was the introduction of 'Puteolanus pulvis' (‘pozzolana’) for hardening concrete under water. This enabled large blocks of hundreds of cubic meters of concrete to be constructed under water by pouring concrete into timber caissons, as described by Vitruvius around 20 BC (Coulon, 2020). The first known use for vertical concrete breakwaters is at Agrippa's naval base of Portus Iulius, near Pozzuoli, in 37 BC, and the most famous is at Caesarea Maritima (Israel) built between 21 and 10 BC[106]. The largest was probably built between 40 and 50 AD at Portus Claudius (Testaguzza, 1970, Noli, 2009, Oleson, 2014).

The first rubble mound breakwater was possibly built on Delos island in the 8th c. BC[107], but the Samos breakwater (ca. 530 BC) described by Herodotos (Hist, 3, 44-60) is more famous. This type of structure was widely used for breakwaters in water deeper than a few meters where dumping loose rock over-board barges was easier than positioning ashlar headers with divers. This construction method was described later on by Pliny the Younger at Centumcellae (103 AD). This construction method is still used very often nowadays (see chapter on Portus Augusti hereafter).

Some of these rubble-mound breakwaters have been luckily preserved and survived two millennia of wave attack, but most of the ancient breakwaters were destroyed by wave action and remains are found under water as “submerged breakwaters”. Careful examination of historical Google Earth images enables us to see quite a few breakwater remains in shallow waters (see section on “Remains of ancient breakwaters”).
As the process of destruction of breakwaters by waves was not all that clear, further analysis was undertaken by the author, focussed on the worst possible wave conditions, considering that they will eventually occur in the long term[108]. In other cases, an approach based on a ‘design wave’ must be used.

Breakwater destruction by wave action is not the only way for breakwaters to be submerged. Subsidence is another possibility because coastal structures were often built on layers of loose sand provided by longshore sand transport along the coast. Such layers might have been compacted by the overload and by wave-induced liquefaction due to repeated storms. Earthquake-generated liquefaction is another option for subsidence as it is likely to affect large areas covered with cohesionless water-saturated sand. Last but not least, tectonic subsidence involves crustal movements of the earth which may be horizontal, vertical or combined.

Vitruvius’ "de Architectura" dated around 20 BC, is the only ancient text left about marine works. Unfortunately, no drawings are available, so that his descriptions are not all that clear to us. The

[103] STONE, D., 2014, “Africa in the Roman Empire: Connectivity, the Economy and Artificial Port Structures”, American Journal of Archaeology,118(4), (p 565-600), and
STONE, D., 2016, “The Jetty with Platform: a distinctive port structure from North Africa”, Antiquités Africaines, 52-2016, CNRS éditions (p 125-139).
[104] PAMIR, H., 2014, “New Researches and New Discoveries in the Harbours of Seleucia Pieria”, Harbors and Harbor Cities in the Eastern Mediterranean, BYZAS 19, (p 177-198).
[105] ALLSOP, W., PIERSON, A., BRUCE, T., 2017, “Orphan breakwaters-what protection is given when they collapse?” ICE Coastal Structures and Breakwaters, Liverpool
[106] GALILI, E., et al., 2021, “Archaeological and Natural Indicators of Sea-Level and Coastal Changes: The Case Study of the Caesarea Roman Harbor”, Geosciences 2021, 11, 306, (26 p).
OLESON, J., BRANDON, C., HOHLFELDER, R., JACKSON, M., 2014, “Building for Eternity – The history and Technology of Roman Concrete Engineering in the Sea”, Oxbow Books, (327 p).
See also: http://www.romanconcrete.com/romanconcrete.htm
[107] FLEMMING, N., 1980, “Cities under the Mediterranean”, in: “Archaeology under Water”, edt. Keith Muckelroy, McGraw-Hill Book Co, (p 162-177).
See also: http://www.ancientportsantiques.com/a-few-ports/delos/
[108] DE GRAAUW, A., 2014, “The long-term failure of rubble mound breakwaters”, Journal Méditerranée. N° 123, online.

three of his methods are considered in some detail with help of various sketches prepared by previous architects and engineers.

A question might be asked why the ancient engineers did not invent reinforced concrete, e.g., by means of chains placed inside the mortar. As steel is subject to corrosion and therefore to increase of its volume, that induces cracking of the concrete, the ancients may not have found it such a good idea (NB: the oldest modern reinforced concrete structures are around one century old and are not in a good condition today, e.g., Tour Perret in Grenoble, France). Another part of the answer might be that as the ancients had vaults, they did not use overhanging structures that require reinforced concrete. However, massive structures like walls and towers needed to be reinforced at their base in order to provide internal cohesion. It appears that courses of bonding tiles were used for this purpose. It can be shown from available testing results that the initial shear strength of lime mortar on tiles and bricks is somewhat larger than on natural stones. Hence, each course of tiles placed inside the stone masonry acts like a modern tie beam made of reinforced concrete.

Pilae are massive piles (*opus pilarum*), which are made of stone or concrete (*opus caementicium*) which have been used as a base for arched structures like aqueducts and bridge piers. Many of them can still be seen on Google Earth pictures and some, like the one at Nisida, have been studied in detail. It is proposed here that several alignments of maritime pilae may have been the base of arched breakwaters.

Pierced stones can be used as mooring devices when the hole has a horizontal axis. Holes with a vertical axis are believed to be used for derricks like those used onboard ships.

Defensive chains strechting across a harbour entrance are mentioned by several ancient authors, including Vitruvius who explains that chains are suspended by means of machinery placed inside towers located on each side of the harbour entrance. Considering the forces involved, the length and the weight of the chain was obviously limited.

Silting-up of harbours was always a major concern and that is still the case for modern port engineers. One should remember that waves are the driving force of the so called “littoral drift” (longshore sand transport along the coast). As the aim of breakwaters is to reduce wave penetration into the port, sand will settle down. Hence structures including arches are not efficient to stop waves while letting sand passing through. That simply does not work!

4.2 Ancient documents on port structures

It might be considered that we would not be able to shed any new light on ancient texts that have already been studied so many times in the past centuries. It is nevertheless worth the effort of reading the complete corpus of ancient texts providing a description of ancient port structures (French translations are available in Appendix 1 hereafter).

- Centumcellae (Pliny the Younger, Letters, 6, 31)
- Portus Claudius (Suetonius, Claudius, 20)
- Portus Claudius (Dio Cassius, History, 60, 11)
- Portus Claudius (Pliny the Elder, Natural History, 16, 76 & 36, 14)
- Portus Iulius (Dio Cassius, History, 48, 50)
- Portus Iulius (Suetonius, Augustus, 16)
- Puteoli (Strabo, Geography, 5, 4)
- Brindes (Caesar, Civil War, 1, 25)
- Hereum Promontorium (Fenerbahce, Chalcedonia) (Procopius, Buildings, 1, 11)
- Hellespont crossing by Xerxes (Herodotus, History, 7, 34-37)
- Ephesus (Strabo, Geography, 14, 1)
- Samos (Herodotos, History, 3, 60)
- Tyre (Quintus Curtius, Stories, 4, 2)
- Caesarea Maritima (Flavius, Jewish War, 1, 21)
- Caesarea Maritima (Flavius, Jewish Antiquities, 15, 9)
- Alexandria (Strabo, Geography, 17, 1)
- Alexandria (Pliny the Elder, Natural History, 36, 18)
- Alexandria (Athenaeus, Philosophers' dinner, 5, 9)
- Carthage (Appian, Libyca, Book 8: The African Book, chap. 96)

And a few more general texts:

- Poliorcetica (Philo of Byzantion, chap. 3-4)
- Harbours (Vitruvius, de Architectura, 5, 12)
- Sand (Vitruvius, de Architectura, 2, 4)
- Lime (Vitruvius, de Architectura, 2, 5)
- Pozzolana (Vitruvius, de Architectura, 2, 6)
- Pozzolana (Pliny the Elder, Natural History, 35, 47)
- Mortar & lime (Pliny the Elder, Natural History, 36, 52-54)
- Iron (Pliny the Elder, Natural History, 34, 39-43)

In addition to this corpus of textual information, we also have an iconographic corpus consisting of over 260 depictions of ports during the Imperial period on coins, mosaics, paintings, ceramics, etc., as provided by Stéphanie Mailleur (2020)[109].

It appears from these documents that much is still unknown about ancient port structures and, more generally, about the "portscape".

4.3 Some ancient Greek terms

NB: the definitions provided below are no more than the most probable (and schematic) definitions. Note also that some small variations of the meaning may exist when translating from one language into another.

[109] MAILLEUR, S., 2020, "Imagining Roman ports. the contribution of iconography to the reconstruction of Roman Mediterranean portscapes of the Imperial Period", PhD Thesis, University of Southampton, (249 p). See also her 2019 presentation (in French).

4.3.1 Geographical descriptions

oikoumene (Latin: oecumene, mundus; FR: monde habité; GB: inhabited world): initially described as a circular island in the middle of an external ocean.
periêgêsis, periodos, periplous (Latin: periplus, descriptio; FR: périple; GB: round trip): designates a go-around tour with a detailed description, and 'periplous' being more devoted to sailing.
stadiasmos (Latin: stadiasmus; FR: stadiasme; GB: stadiasmus): description of the world based on an itinerary, usually along the coastline, on board a ship or on foot and mentioning distances (usually in stadia).

4.3.2 Harbours and mooring places

emporion (Latin: emporium, portus; FR: ville portuaire; GB: port of trade): maritime city with commercial port and trade facilities.
aigialos, aktè (Latin: acta, litus; FR: plage de halage; GB: beaching area) is a simple beach used for hauling ships on. Such a beach can be made of sand, shingle, or even rock. Thucydides (Pelop. War, 4, 26) used '**katarsis**' and '**prosbolè**' for a landing place. The Latin word '**ripa**' was used for what we might call a "beach market" where business was conducted on an urban beach without any port infrastructures (e.g., Vicus Lartidianus at Puteoli).
salos, episalos, ankyrobolion (Latin: statio navium; FR: mouillage peu profond sur rade ouverte; GB: shallow anchorage in open roadstead): shallow anchorage preferably on sandy bottom providing good holding for anchors, but with limited protection against waves and therefore of temporary use. The Latin word '**statio**' seems to designate a secondary maritime customs office, among many other meanings.
limên (Latin: portus, statio navium; FR: rade, havre, abri, port; GB: roadstead, harbour, port): sheltered area where ships can load and unload in most weather conditions, with or without port facilities like quays. A good port will enable operations independently of wave and current conditions. Strabo (Geogr. 16, 2) also used '**eulimenos**' for a good harbour at Laodicea and '**euphuei limeni**' for a good harbour at Sidon. The word '**panormos**' is used for a very good shelter and often used as a toponym. Strabo (Geogr. 14, 1 & 14, 6) also used '**hyphormos**' for a landing place sheltered from only one wind direction.
hormos, lekanion (Latin: navaculum?; FR: darse, bassin portuaire; GB: harbour basin): man-made harbour basin used for loading, unloading, building or repairing ships, with mooring facilities on a quay or on a mooring buoy. Procopius (Wars, 3, 20) first used the Late-Antique/Medieval term '**mandrakion**' for the port complex of Carthage in the 6th c. AD.
epineion (Latin: portus; FR: avant-port; GB: fore-port): port disconnected from the city and used for war ships (e.g., Piraeus/Athens and Ostia/Rome).
naustathmon (Latin: portus, castra navalia; FR: base navale; GB: naval base, naval station): harbour, or harbour section, used mainly for war ships.
neôrion (pl. neôria) (Latin: navale, navalia; FR: arsenal, chantier naval; GB: dockyard, shipyard): place for ship building and repair, including a slipway where a ship can be hauled out of the water, and possibly a dry-dock in which a ship can be dried-out.
neôsoikos (pl. neôsoikoi), epistion (Latin: navale, navalia; FR: loge, hangar à bateau; GB: shipshed, boathouse): shed for sheltering a boat, usually built partly over water.
limên kleistos (pl. limenes kleistoi) (Latin: portus; FR: port fermé; GB: closed port): port whose access was restrained by a closing device (**kleithron, pl. kleithra**) (Arnaud, 2023), usually with a narrow entrance closable by means of doors and/or a chain, sometimes intra-muros and connected to the city.
kôthôn (Latin: cothon, cothonum; FR: cothon; GB: cothon): used since antiquity to refer to the

circular port of Carthage. Elaborating on Festus' definition[110], today's specialists of harbour archaeology unduly associate this term to an excavated harbour-basin of any shape connected to the sea through a channel (Carayon, 2017). The term '**kibotos**' (chest, box), used in Alexandria, fits a quadrilateral shape. The Greek word for an excavated man-made harbour-basin is '**oryktos**'.
ichthyotrofeíon (Latin: piscina; FR: basin d'aquaculture; GB: artificial fish tank): used for breeding fish, usually a structure built out from the shoreline into the sea with hydraulic concrete, or cut into shoreline formations of soft bedrock (acc. to Oleson, 2014).
diorygma, diôrux cheiropoiêtos (Latin: fossa; FR: canal; GB: canal): man-made navigation canal.

4.3.3 Harbour structures

prokumia, prokymatia (Latin: moles, brachium; FR: brise-lames; GB: breakwater): massive structure built out into the sea to protect a port from wave attack: Flavius (Jewish War 1.412 & Jewish Ant. 15.334) describing the Caesarea mole, makes a distinction between the detached outer breakwater as a 'prokumia' and the main breakwater supporting the city wall, towers, warehouses and quays, as a '**teichos**' (wall). The Latin word '**munitio'** was found on an inscription (CIL X.1641 dated 139 AD) designating a embankment protecting the Puteoli arched breakwater. The Latin word '**brachium'** stands for 'arm' and is used in ancient port descriptions to designate a mole with a curved plan-shape (typically at Portus). The word '**mole'** is still used both in FR and GB by archaeologists for a massive structure separating two bodies of water, like a breakwater, a jetty or a causeway. A massive rubble mound built out into the sea is also called **chôma**. Appian (Libyca, 121) uses this word for Scipio's rubble embankment at Carthage. However, the same Appian (Libyca, 123-124) also mentions a quay as a 'chôma' - 'chômati', and Strabo (Geogr. 5.4.6) describes the Puteoli arched moles as a 'chômata'.
chôma, probolon, apobasis (Latin: crepido; FR: quai; GB: quay; US: dock): structure to load and unload ships that can be berthed and moored on only one side, usually made of blocks of stone or masonry. A tidal dock (FR: bassin à flot) is an enclosed basin where ships float at low water of the tide. A dry-dock (FR: forme de radoub) is an enclosed basin in which a ship can be dried-out for maintenance. To bring in a ship into the port to its allotted place for mooring, is to berth or to dock a ship (GB or US) (FR: accoster).
skala (Latin: scala; FR: appontement, débarcadère; GB: wharf, landing stage; US: pier, landing stage): structure to load and unload ships, usually on piles (e.g., finger pier).
sitônion (Latin: horreum (pl. horrea); FR: entrepôt; GB: warehouse): public warehouses used to store grain and many other types of consumables.
diolkos, olkos (Latin: clivus; FR: cale de halage; GB: slipway, ways): ramp sloping toward the water on which boats can be hauled in and out of the water with a windlass system ('**stropheion'**). The most famous one being the Diolkos of Corinth.

4.3.4 Harbour construction

symmagma? (Latin: caementa; FR: agrégats; GB: rubble aggregate): decimetre-sized chunks of rock (preferably Puteoli volcanic tuff, but possibly calcarenite) incorporated with mortar to form Roman concrete (Latin: rudus, opus caementicum).
telma (Latin: materia, arenatum, commixtione; FR: mortier de chaux; GB: lime mortar) is a mixture of lime (GR: **chalix**; Latin: calx; FR: chaux) and sand (GR: **ammos**; Latin: arena; FR: sable).
The Romans invented **hydraulic concrete** (FR: béton hydraulique, béton maritime) which is made by adding some activated aluminium silicates (pozzolana) to activate setting in wet condition, or *underwater,* and further protect hardened concrete from chemical attack, inducing

[110] Sextus Pompeius Festus (De verborum significatum, 3, 7) (2nd c. AD): "*Cothones appellantur portus in mari interiores arte et manu facti*" which does not refer to excavated basins but only to man-made basins. It is therefore suggested to use the word "kothon" only as a local nickname for the circular basin of Carthage.

an extraordinary longevity in seawater, not yet fully understood.
ammokonia, konis (Latin: puteolanus pulvis; FR: pouzzolane; GB: pozzolana) is a sandlike, pumiceous, incoherent volcanic ash, found in the Campi Flegrei volcanic district, near the city of Puteoli (modern Pozzuoli) (Oleson, 2014).
pila (Latin: pila; FR: bloc de béton; GB: block of concrete): large mass of concrete, often a cube or rectangular prism in shape which is poured into wooden formworks, possibly underwater.
kibôtion (Latin: arca; FR: coffrage, caisson; GB: formwork, caisson): structure, usually made of timber, into which concrete or similar materials are poured. The vertical piles placed on the outer walls of the caisson are called **stipites**, the piles placed inside the caisson are **destinae** and the horizontal tie-beams are **catenae.**
anachoma, gephyra? (Latin: arcae duplices, saeptio; FR: batardeau; GB: cofferdam): watertight structure, usually made of sheet piling, that encloses an area under water that can be pumped dry, in order to enable construction work to be carried out "in the dry".

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4.4 Beaching ships?

Homer repeatedly mentioned beaching ships. In Odysseus' time, the ships may have been of the eikosoros-type, with two files of 10 rowers. This oared ship is the ancestor of what would later be called a 'triaconter' (triakontoros) with two files of 15 rowers and a length of around 20 m. Such a ship may have weighted one or two tons.

It is worth comparing this to Senegalese traditional fishing boats ("pirogues"). Most of these boats are 10 to 20 m long with a 1 to 4 m beam. They are made from a single tree-trunk (monoxyle pirogues) which is enlarged by lateral planks. Considering the rather rough Atlantic wave climate, one of the questions is how fishermen operate to land on and to leave from the beach. Pictures from Franck Boyer (Kamikazz Photo agency, Dakar) give some clues:

Hauling of a large 20 m pirogue stern first …

… is a very heavy task …

… the bow is nearly on the beach.

Pictures by Franck Boyer (Kamikazz Photo agency, Dakar).

A nice time lapse of the hauling operation, which took around 3 hours, is shown on: https://www.youtube.com/watch?v=kXLDRCjTuBA

Rankov (2012) explains that it was possible to haul a 50-ton trireme on a slipway in a harbour with a team of 140 men, provided the slipway had the correct slope (say no more than 1:10, or 10%, or 6°) and was adequately greased. However, he considers that "it is hard to see that triremes would have been beached except from necessity". This can be understood because the friction on the beach is higher than on a greased slipway. In addition, the beach slope depends on its grain size (Komar, 1998): the very fine sands (or silts) found in large deltas yield a very flat slope which keeps ships far from land. Conversely, a shingle beach (e.g., Nice, France) has a steep slope that is dangerous for landing ships on.

Hence, with increasing ship sizes (and weights), beaching became unpractical, if not unfeasible, and places for safe anchorage were sought.

Greg Votruba (2017) provided convincing argumentation that cargo ships did not *habitually* beach and concluded that "from the Classical period at the latest, the standard practice was to remain afloat at anchor".

From our Catalogue (Vol. I) we know that for nearly 6000 ancient coastal settlements, ports and harbours, we have around 650 ports (only 12%) with some kind of ancient port structure such as breakwaters and quays.

Only three options were therefore available for loading and unloading ships outside of a port with heavy infrastructures:

1. **Stay offshore** at anchor and load/unload by means of small barges, as mentioned by Strabo for Ostia (Geogr. 5, 3, 5), by Pliny the Elder for Muziris (Natural History, 6, 26, 10) and by Isidore of Seville (Etymologiae, 19, 1, 19). This option may also have been chosen at Ashkelon (Galili, 2021).

Ship-to-ship transfer, mosaic at Statio 25 on Foro delle Corporazioni at Ostia (www.ostia-antica.org).

Ship-to-ship transfer of amphora content (Mus. Stockholm, N°3101456).

The left mosaic shows transfer of amphorae from a large sea-going ship to a smaller river ship.
The right mosaic shows a man on a smaller river ship transferring the content of an amphora into a barrel, perhaps a measuring module. The man on the larger sea-going ship waits for the next amphora to be transferred, and for taking back the empty amphora. This relief possibly shows an example of reuse of amphorae.

2. **Draft-beach** and load/unload by means of labourers wadding between the beach and the ship, as shown on a famous mosaic found at Sousse (Tunisia).

Unloading by wadding labourers, on 3rd c. mosaic found in Sousse.
Picture by A. de Graauw, 2018, Bardo Mus, Tunis.

The mosaic above shows a draft-beached ship, i.e., resting gently on the seabed at its bow, with its stern still afloat. This is the closest to the beach a ship can get without getting stuck (in a place without any tide).

A very similar operation is performed by Senegalese fishermen unloading their ship before hauling it on the beach.

Unloading fish by wadding labourers in Senegal.
Picture by Franck Boyer (Kamikazz, Dakar).

3. **Moor** at some kind of timber jetty built on the coastline, as shown on the famous Stabiae fresco.

Timber jetty on Stabia fresco (detail).

Remains of timber jetty at Yenikapi (Istanbul).

Ancient timber piled jetties have been built in many places, but few remains have been found. Recent archaeological excavations at Yenikapi (Istanbul) have uncovered a large piled timber jetty with three rows of piles. A similar timber piled jetty with three rows of large piles was also found in Marseille in front of the dolia horrea and in Bordeaux. Outside such large ports, much smaller timber jetties must have been built in many places.

Stevedores unloading a sea-going ship (Torlonia Mus.)
(see also Torlonia relief)

Stevedores loading a sea-going ship, 90x59 cm relief
(NarboVia Mus. N° 878.2.11 / 1310)

Stevedores loading the river boat Isis Giminiana, 3rd c. AD, ca. 0.70 x 0.35 m fresco
(Vatican Mus. N° 79638)

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VOTRUBA, G., (2017), “Did Vessels Beach in the Ancient Mediterranean? An assessment of the textual and visual evidence”, The Mariner’s Mirror, Vol 103:1, (p 7-29).

4.5 Vitruvius' methods

The oldest text about marine works we know of is Philon of Byzantium's text that is unfortunately lost (ca. 250 BC). Vitruvius' "de Architectura" dated around 20 BC, is the only ancient text left about marine works. In his time, 'Puteolanus pulvis' is already in use for hardening concrete in seawater, replacing crushed ceramics used by the Greeks in fresh water long before that. The resulting mass of 'hydraulic concrete' is "neither particularly hard nor strong" but provides an "extraordinary longevity in sea-water" (from Oleson et al., 2014)[111].

Roman hydraulic concrete ratios and properties are summarised below, from the extensive work of Marie Jackson (in Oleson et al., 2014).

Ratios and properties	Concrete with tuff	Concrete with carbonate rock
Lime (calx) (weight %)	15%	10%
Pozzolana (pulvis) (weight %)	40%	30%
Aggregates (caementa) (weight %)	45%	60%
Unit weight dry mix (kg/m^3)	1100 - 1250	1400 - 1550
Unit weight hardened concrete (kg/m^3)	1500 - 1600	1600 - 1700
Compressive strength (MPa)	5 - 8.5	2.5 - 5

This major innovation in river and coastal engineering was introduced around 200 BC for fish tanks (piscinae) (acc. to Oleson, 2014) and further developed in the 1st c. BC, when large blocks of hundreds of cubic meters of concrete were constructed under water under the name 'pila' (up to 1500 m^3 in Nisida). The oldest known applications for harbour works are at Agrippa's naval base of Portus Iulius, near Pozzuoli, in 37 BC, and at Cosa (Oleson et al., 2014). This technology (and Puteolanus pulvis that goes with it) was exported to several places around the Mediterranean Sea, such as Pompeiopolis (Turkey), Caesarea Palaestinae Sebastos (Israel), Alexandria (Egypt), Nora (Sardinia) and Iol Caesarea Mauretaniensis (Algeria). Clearly, as hydraulic concrete was discovered near Pozzuoli two centuries earlier, nobody would take the risk inventing another mixture without any certainty that it would provide the same *long-term* quality, especially as Vitruvius himself stated that Puteolanus pulvis was available only in Italy (de Architectura, 2.6.5). Hence, Roman engineers shipped it over long distances instead of looking for a local substitute.

Roman hydraulic concrete was never completely forgotten as it was found in Istanbul in 6th c. buildings (Yenikapi and Haghia Sophia), and in Budapest and Venice/Ravenna/Pisa in 16th c.

[111] OLESON, J., BRANDON, C., HOHLFELDER, R., JACKSON, M., 2014, "Building for Eternity – The history and Technology of Roman Concrete Engineering in the Sea", Oxbow Books, (327 p).
DILARIA, S., et al., 2023, "Volcanic Pozzolan from the Phlegraean Fields in the Structural Mortars of the Roman Temple of Nora (Sardinia)", Heritage 2023, 6, (p 567-587).

buildings[112], showing that the Byzantines inherited this technology (most probably with locally produced pozzolana) and that it was probably taken over by the Ottomans and the Venetians. It was finally reinvented by John Smeaton in 1756, followed by James Parker (1796), Louis Vicat (1818-1828) and Joseph Aspdin (1824) who named it 'Portland cement'.

Vitruvius described three methods for building port structures, but unfortunately, none of his sketches survived and this makes interpretation of his three methods quite hard[113].

The **first method** of Vitruvius consists of dumping pozzolana mortar with rubble inside an enclosure made of poles ("*stipites*") that are driven into the subsoil in order that these materials replace water by falling into the enclosure. This method is made possible by the use of hydraulic concrete (that hardens under water) which is made with pozzolana (provided materials are lowered with help of baskets and not just dumped into the water from the surface). This method supposes that piles can be driven into the subsoil and that they will resist the pressure of mortar before hardening (in the second method, Vitruvius mentions two months of hardening, while modern concrete would take less than one month). If needed, tie rods can be inserted between opposite faces of the enclosure. Such tie rods were made of wooden beams ("*catenae*"), supported by poles ("*destinae*"), which have disappeared with time, leaving transversal cavities inside the structure.
In any case, the enclosure height could not be much more than a few meters, but this was an acceptable water depth for ancient ships.

Note also that the pressure of hydraulic concrete is exerted from inside to outside the caisson-wall and that stipites are therefore placed *outside* the wall, thus leaving no cavities on the resulting concrete wall (see Brandon's sketch below).

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112 GINALIS, A., 2022, "The So-called "Küçük Liman" on the Firuzköy Peninsula:", International City and History Symposium on Avcilar, (p 143-161).
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113 OLESON, J., 1985, « Herod and Vitruvius: Preliminary Thoughts on Harbour Engineering at Sebastos; the Harbour of Caesarea Maritima », BAR International Series 257, (p 165-172).
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GIANFROTTA, P., 1996, "Harbor structures of the Augustan Age in Italy", in "Ceasarea Maritima, A Retrospective after Two Millennia", ed. A. Raban & K. Holum, Brill, Leiden, (p 65-76).
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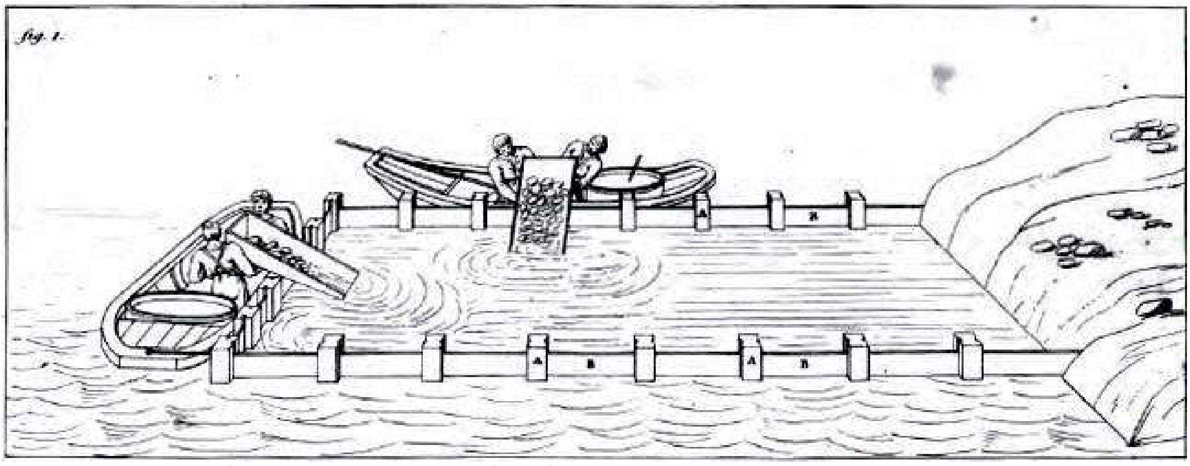
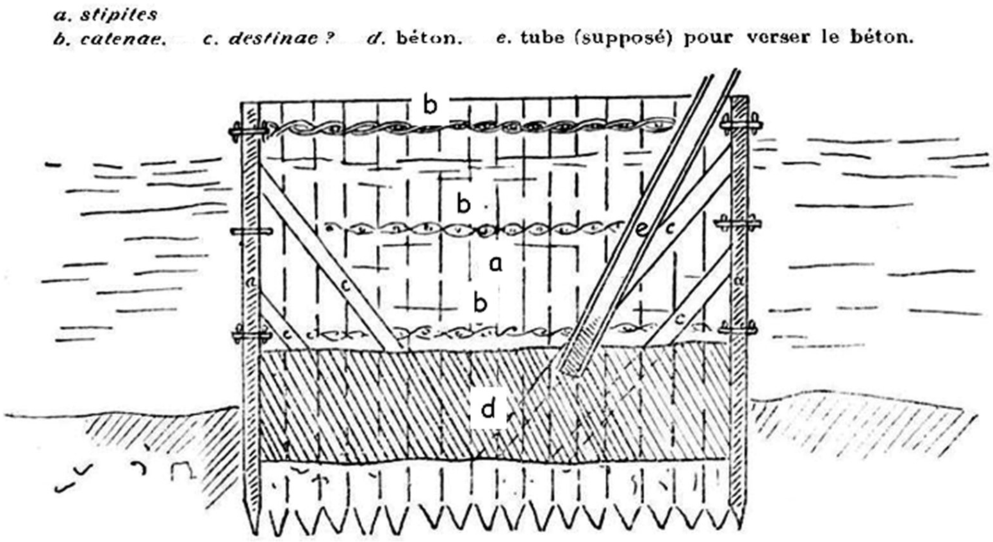
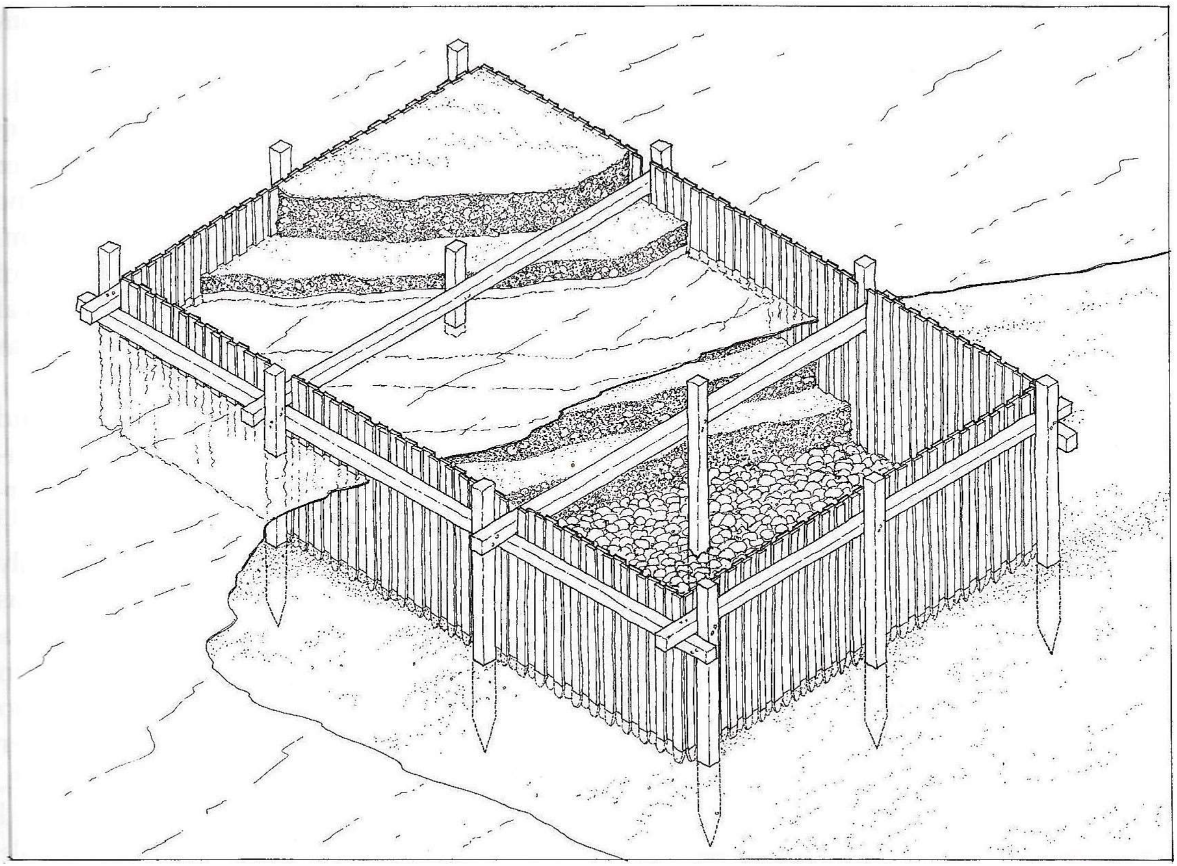


Claude Perrault's sketch (1673) with panels slid into grooves on poles, and labourers pouring concrete from the water surface which leads to segregation during the fall to the bottom.



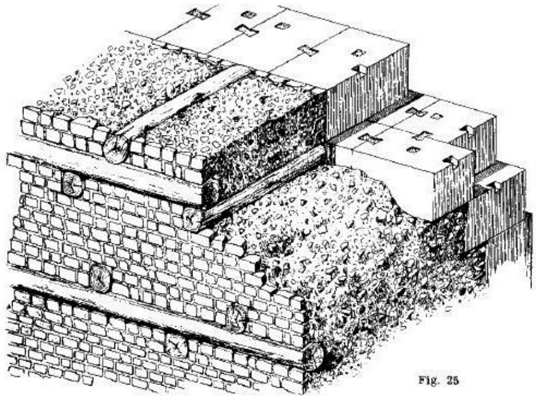
Ch. Dubois' sketch, "Observations sur un passage de Vitruve, Mélanges d'archéologie et d'histoire T. 22" (1902) with a system with adjacent poles (a) connected (or even engirdled) by chains (b). However, his system with chains and oblique tie rods does not seem realistic: the rods must be horizontal and connecting opposite caisson faces like Brandon suggested in 1996.



Christopher Brandon's sketch (1996)

Detail of the model of the Môle de la Marseillaise at La Nautique near Narbonne (model built by Jean Marie Falguera).
The piles are juxtaposed and tied by horizontal tie rods with a system of tenon and mortise that can still be seen.
(Photo A. de Graauw, 2011)

Portus' north breakwater (Fiumicino)
(Photo A. de Graauw, 2011)



Concrete reinforced with timber,
acc. to Bartoccini, 1958

According to C. Brandon (1996 & 2010) this method was widely used: Anzio, Astura, Cosa, Circeii, Egnazia, Sapri, Santa Severa, San Marco de Castellabate, Portus Claudius, Misenum and Baiae (Italy), Marseille (France), Side (Turkey), Caesarea (Israel), Thapsus (Tunisia) and probably the eastern jetty of Leptis Magna where large masses of concrete are still submerged.

It is sometimes suggested that some of the pilae remains found today might be the remains of arched breakwaters.

A similar method with an enclosure made of ashlar blocks instead of wooden piles was used, according to Brandon, at San Cataldo (Italy), and Pompeiopolis and Kyme (Turkey).

An alternative to this first method consists of prefabricating a rigid wooden enclosure, with or without a bottom, which is then floated to the desired location before being filled with hydraulic concrete or stones. Such a structure is now called a "floating caisson" (modern caissons are made of concrete and have a bottom in order to float). This alternative method is well suited for hard (rocky) seabeds where piles cannot be driven. This alternative seems to have been used for a stone wall at the Port des Laurons (Martigues, France)[114] and possibly for breakwaters at Hereum (Fenerbahce, Turkey)[115] and Lechaion (Corinth, Greece)[116] during Late Antiquity. It reached a technological summit at Caesarea Maritima (Israel).

In the latter case, Flavius' description mentions blocks of 50 x 18 (or 10?) x 9 feet (15 x 5.5 x 2.75 m), that is nearly 600 tons (archaeology has even revealed blocks of 14 x 7 x 4 m, or 1000 tons). Archaeological excavations showed imprints *inside and under* the concrete mound, proving that the structure consisted of wooden caissons used as lost formworks for concrete to be poured in situ. Such caissons with a bottom could be built on a nearby beach and be floated to their final position. This concept is similar to sinking an old ship to build a man-made island like the one of Portus Claudius.

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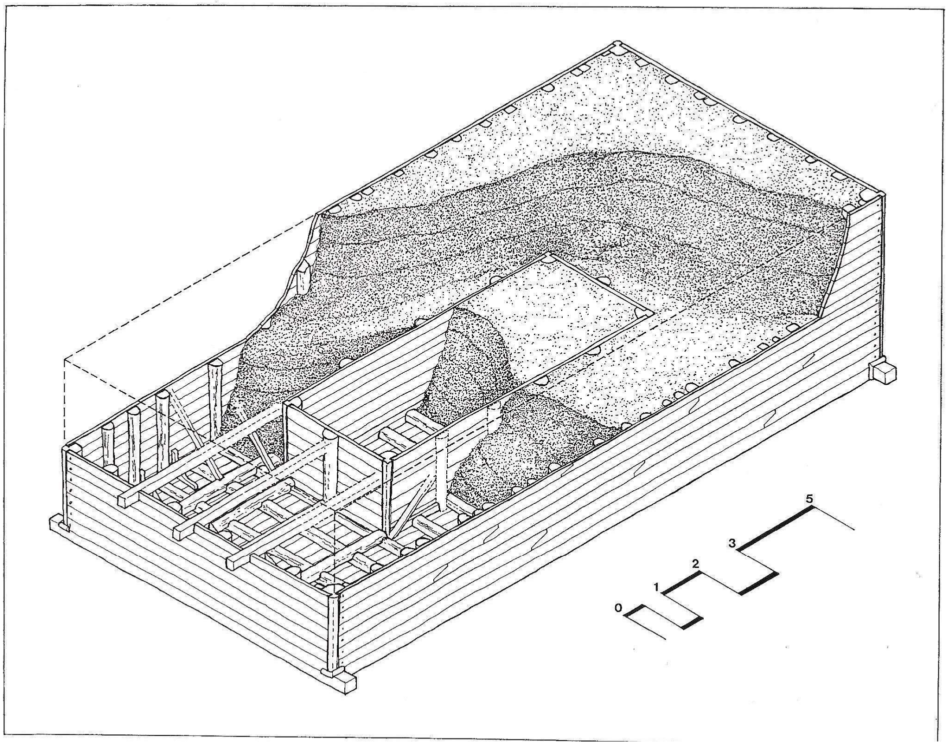
[114] MOERMAN, M., 1994 « Le port romain des Laurons, Martigues », Thèse de doctorat d'archéologie, Université de Provence, 2 vol., (297 p). This 22.9 x 2.2 m caisson is unique, as a stone wall was built in the dry on the wooden floor of the caisson. The caisson must have been sinking gradually during construction of the wall. The remains of the wall are around 1 m high and 1.8 m thick at the base, with a length of 22.5 m. However, the dating of the caisson timbers is still uncertain (possibly 18th c.).

[115] PROCOPIUS, "The buildings of Justinian", 1, 11.

[116] BARTHELEMY, P., 2018, "L'immense port antique de Corinthe sort de l'oubli", Le Monde, 30/5/2018.

A 40-cm thick layer of rounded cobbles (up to 35 cm diameter) was found underneath a large concrete block of the Caesarea western breakwater. This foundation method allows a strong flow within the foundation layer, e.g., with a wave having its crest outside and its trough inside the port. Such an alternate flow will erode sand underneath and thus undermine the whole structure[117].



Christopher Brandon's sketch of a floating caisson with bottom and central box (1996).

A particular refinement shown in the sketch above, is the central box of the floating caisson which is surrounded by hydraulic concrete and therefore absolutely dry, enabling the use of cheaper non-hydraulic concrete inside that box.

A variant of this method which was used only on the northern breakwater at Caesarea Maritima, consisted of a large *double-walled caisson without floor* constructed on shore and towed into position. Once on location, the space between the two walls was filled with mortar until the whole formwork sank to the bottom. Only then was it filled with hydraulic concrete. The size of the block recovered is 15 x 11.5 x 2.4 m, again, around 1000 tons.

Vitruvius may not have been informed about the *floating* caissons used at Caesarea as they were built between 21 and 10 BC., i.e., just after he wrote his book around 20 BC.

117 DE GRAAUW, A., 1984, "Design criteria for granular filters". J. Waterw., Port, Coast. and Ocean Eng., ASCE 110 (1984) 1. Delft Hydraulics Laboratory, Publication n° 287.
VOTRUBA, G., 2007, "Imported Building Materials of Sebastos Harbour, Israel", International Journal of Nautical Archaeology, 2007, 36.2, (p 325-335).
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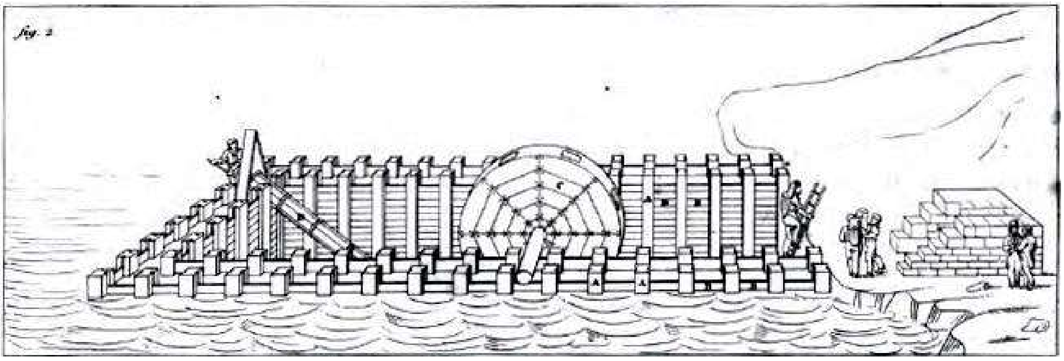
Double-walled floating caisson without bottom used at Caesarea Maritima (Israel)
(J. Robert Teringo, 1987)

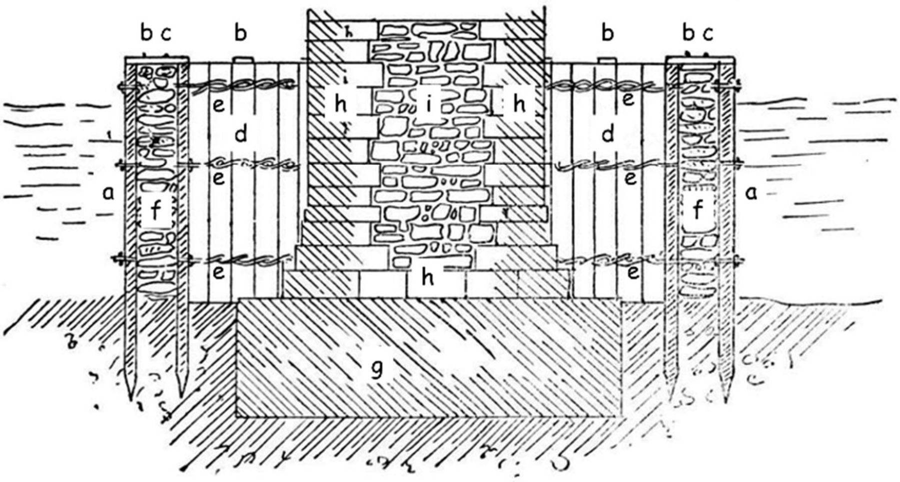
Vitruvius' **third method** is close to the first method as it also requires an enclosure, albeit a watertight one (we now call this a "cofferdam") allowing water to be pumped out in order to enable work in the dry. Hydraulic concrete and pozzolana are thus not needed in this method. However, the walls must resist the pressure of water and shoring may be needed, as, like in the first method, the height of the enclosure did not have to exceed a few meters which was a sufficient water depth for ancient ships. Moreover, large pumping capacity must be provided depending on the permeability of the subsoil. It would therefore be difficult to use this method on a sandy seabed as water would seep into the enclosed area through the bottom and Vitruvius rightly recommends digging out the area down to the rocky substratum[118]. He also indicates that the foundation must be wider than the planned structure. This foundation can be a slab of concrete placed on top of the rocky bottom or on a series of wooden stakes if the subsoil is unstable[119]. The jetty can then be completely built in the dry.
This method was mainly used to build bridge piers in rivers (and is still in use nowadays). Brandon nevertheless mentions some maritime applications: Marseille (Quays F.28 and F.120), Ponza and Nisida (Italy). The cofferdam of the Corne of the ancient port of Marseille may be mentioned also[120].

[118] Aachen University video on hydraulic heave of sand behind a cofferdam.
[119] The use of coal for filling the space between the stakes is somewhat unclear. Did they believe that as fire hardens wood, coal would preserve it in the long term?
[120] GUÉRY, R., 1992, "Le port antique de Marseille", Collection Etudes Massaliètes, 3, 1992, (p 109-121).



Claude Perrault's sketch (1673)

a. batardeaux. — *b. tabulae*, reliant les parois des batardeaux *(liernes)*. — *c.* catenae ou harts reliant les liernes dans la sens de la longueur des batardeaux ? — *d.* madriers *(stipites)*. — *e. catenae* ou harts reliant les madriers. — *f.* corbeilles d'argile remplissant les batardeaux *(creta in cronibus)*. — *g. fundamenta* en béton. — *h.* parement du mur en pierre de taille *(quadratum saxum)*. — *i.* béton ou construction mêlée *(ruderatio sive structura)*

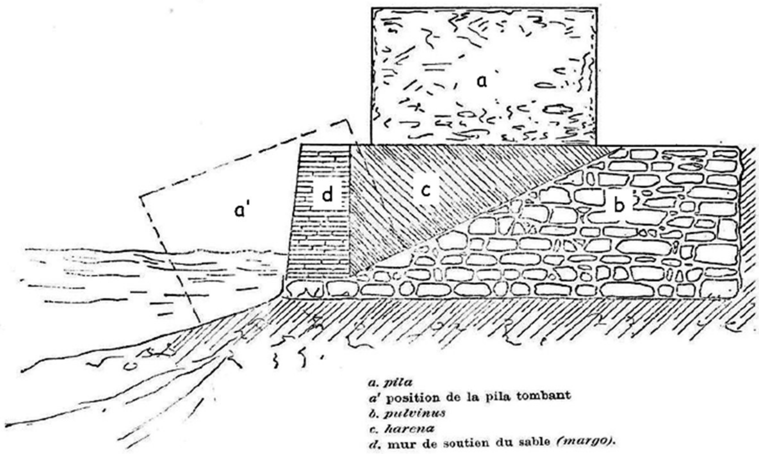


Ch. Dubois's sketch "Observations sur un passage de Vitruve, Mélanges d'archéologie et d'histoire T. 22" (1902)

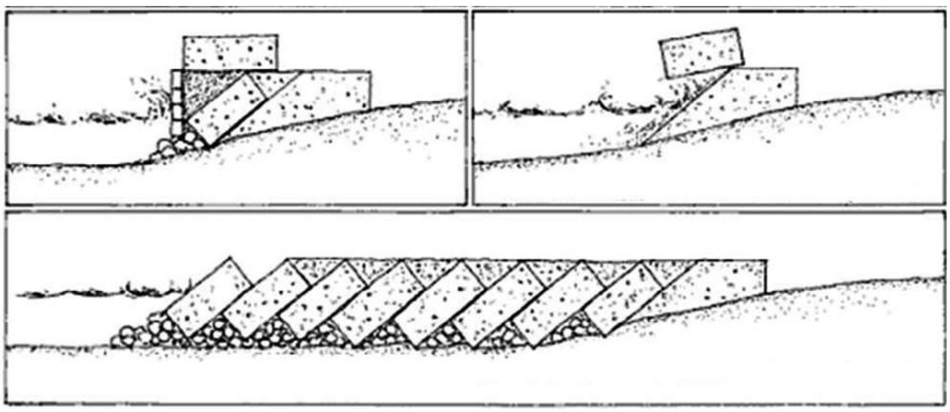
Vitruvius' **second method** consists of building the structure from the shoreline and progressing in offshore direction.

If stones are to be dumped into the sea, the stone size must be sufficient to resist wave attack. Stones of tens and hundreds of kilos must be used for the core and covered by an armour layer made of stones of several tons: no technical problem but tricky logistics. This method was used by Alexander when besieging Tyr (in 322 BC, well before Vitruvius).
Floating barges can be used to dump stones further out of the coastline, e.g., to build a man-made island, but barges are exposed to waves and increase risk of down time. This was done at Civitavecchia to build an island at the entrance of the port, as described by Pliny the Younger.

If concrete blocks are to be built into the sea, as Vitruvius seems to suggest, one can think of blocks of several tens of cubic meters built on the beach on top of a small mound made of sand and contained by a small wall (Vitruvius mentions a height of no more than 0.50 m). After hardening of the block, the small wall is removed and sand can be eroded by the sea. The block will then tumble into the sea and the process can be started again. One must be patient … and no application of this method is known. We may perhaps conjecture that Vitruvius deduced this method from what he knew about obelisk raising using a sand box that was gradually emptied through lateral portals (see Rick Brown's 1999 experiment on https://www.handshouse.org/obilisk and illustrative YouTube movie on https://www.youtube.com/watch?v=BgekJnMeNiY), but that he had no real experience with this method applied to a coastal structure.



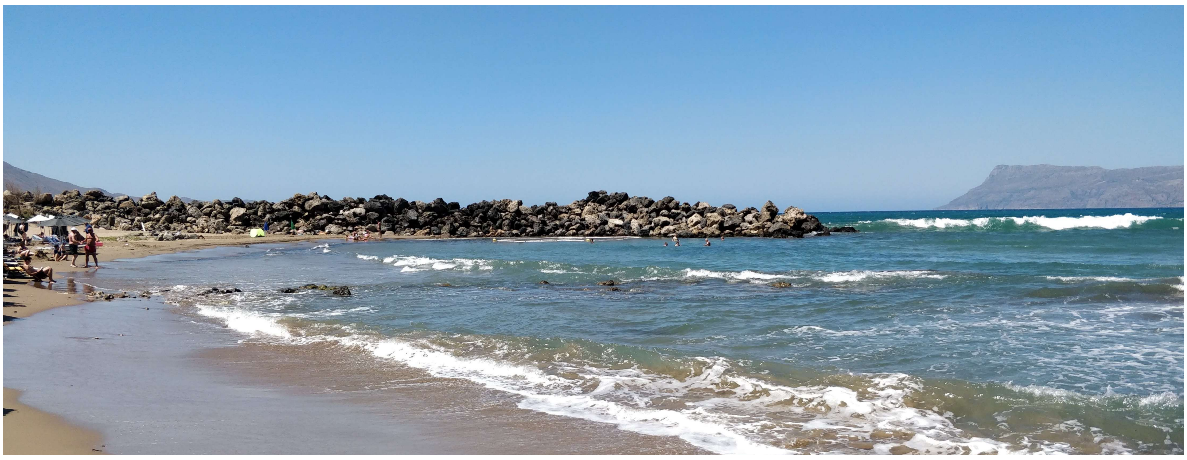
Ch. Dubois's sketch "Observations sur un passage de Vitruve, Mélanges d'archéologie et d'histoire T. 22" (1902)

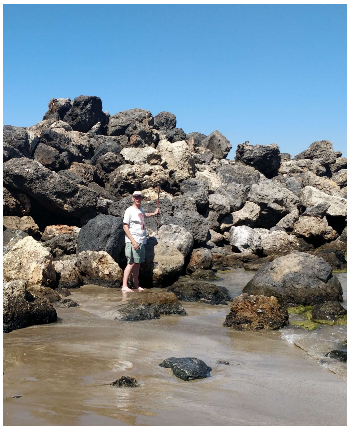


Christopher Brandon's sketch (1996)

4.6 Ancient rubble mound breakwaters

Rubble-mound breakwaters consist of piles of stones more or less sorted according to their unit weight: smaller stones for the core and larger stones as an armour layer protecting the core from wave attack.





Ancient rubble mound breakwater at Kissamos (Crete) (photos A. de Graauw, 2022).
The Kissamos breakwater is probably the only large rubble mound breakwater that is above the sea today as it was uplifted around 6 meters during the 365 AD earthquake and therefore protected from further wave attack. The armour layer consists of ca. 1 m rock boulders, or around 1 to 1.5 ton, reaching ca. 4 m above today's MSL. As far as can be seen on site without excavation, the whole structure was made of the 1 m rock still visible at its surface.

This kind of structure has been around for over 2500 years and modern coastal engineers still build them to create harbours sheltered from wave penetration. It was widely used for breakwaters in water deeper than a few meters where positioning of ashlar headers by divers was difficult. Ancient breakwaters may have been over- or undersized and the result is that only a few breakwaters have been luckily preserved, while many others are now found under water as "submerged breakwaters", as a consequence of 2000 years of storms.

Without going into the details of breakwater design, it can be understood easily that stability of a structure made of stones depends primarily on the stone size in relation to the strength of wave action: breakwaters in open waters exposed to storms acting on large areas and therefore inducing high waves, must consist of larger stones than breakwaters in sheltered areas.

A study was carried out to find some simple relation between the governing parameters (water depth, structure height, stone size) and the equilibrium position of the crest of rubble mound breakwaters subject to long term wave attack in breaking wave conditions (see section on "Failure of rubble mound breakwaters in the long term", hereafter).

It was concluded that undersized emerging rubble mound breakwaters reduce to submerged breakwaters and that, for a given stone size, submerged breakwaters stabilise to a predictable crest level after long term wave attack in breaking wave conditions.

For ancient breakwaters, this means that:

- We may find a few ancient breakwaters still in perfect condition: they were emerging and fulfilling modern design conditions (they were somewhat oversized!).
- If slightly undersized, we may find ancient breakwaters that were reshaped into an S-shape by 2000 years of storms: the seaward side is lowered to below Mean Sea Level (MSL) and the landward side may reach MSL (see section on “Sea Level Rise”).
- If more undersized, ancient breakwater will be lowered by wave action to a level depending on the stone size.

We must also remember that the MSL rose about 0.5 m since antiquity, so that breakwaters that were stable at that time in shallow water (a few meters water depth) may not be stable anymore because larger waves can reach them nowadays.

In tidal areas, the worst conditions for stability occur when the largest waves occur together with the highest water level. The probability of occurrence of this happening is smaller than for a fixed water level, but that may not change the final result for stability in the long term.

Careful examination of historical Google Earth images enables us to see quite a few breakwaters in shallow waters. A collection of such images is given in Appendix 2, together with some other pictures made on site.

Some remarkable ancient rubble mound breakwaters can be listed as follows:

- Portus (Fiumicino, Italy): deepest section of the 3200 m long breakwaters, now inland;
- Pharos (Alexandria, Egypt): over 2300 m long, submerged in open water;
- Thapsus (Bekalta, Tunisia): about 1100 m long, submerged in open water;
- Eretria (Eretria, Evia, Greece): at least 600 m long, submerged in sheltered water;
- Paphos (Kato Paphos, Cyprus): about 600 m long, with a parallel one 200 m long, submerged in open water;
- Leukas/Ligia (Lefkada island, Greece): about 540 m long, submerged in sheltered water;
- Pythagoreion (Samos island, Greece): about 480 m long, submerged in open water;
- Chersonesos (Cape Agami, Egypt): about 400 m long, submerged in open water;
- Eleusis (Vlychada, Santorini): about 360 m long, submerged in open water;
- Sullecthum (Salakta, Tunisia): about 350 m long, submerged in open water;
- Tieion (Filyos, Turkey): over 350 m long, submerged in open water;
- Mytlilini (Lesbos island, Greece): about 350 m long, submerged in sheltered water;
- Sabratha (Libya): about 320 m long, submerged in open water;
- Leptis Magna (Lebda, Libya): about 300 m long, berm breakwater in open water;
- Methone (Modon, Greece): about 250 m long, submerged in fairly open water;
- Neftina (Lemnos island, Greece): about 200 m long, submerged in open water;

and many others, smaller ones.

Obviously, questions remain on many of these structures, e.g., is the structure at Emporia (Spain) a breakwater or a city-wall falling into the sea? Was the Thapsus (Tunisia) structure a rubble mound breakwater or a vertical breakwater? Is the Kainopolis (Libya) feature a breakwater or just some beach rock? etc. etc.

An index of all breakwaters collected here is given hereafter (see pictures in Appendix 2).

Everybody is welcome to send me more information and pictures on ancient breakwater remains …

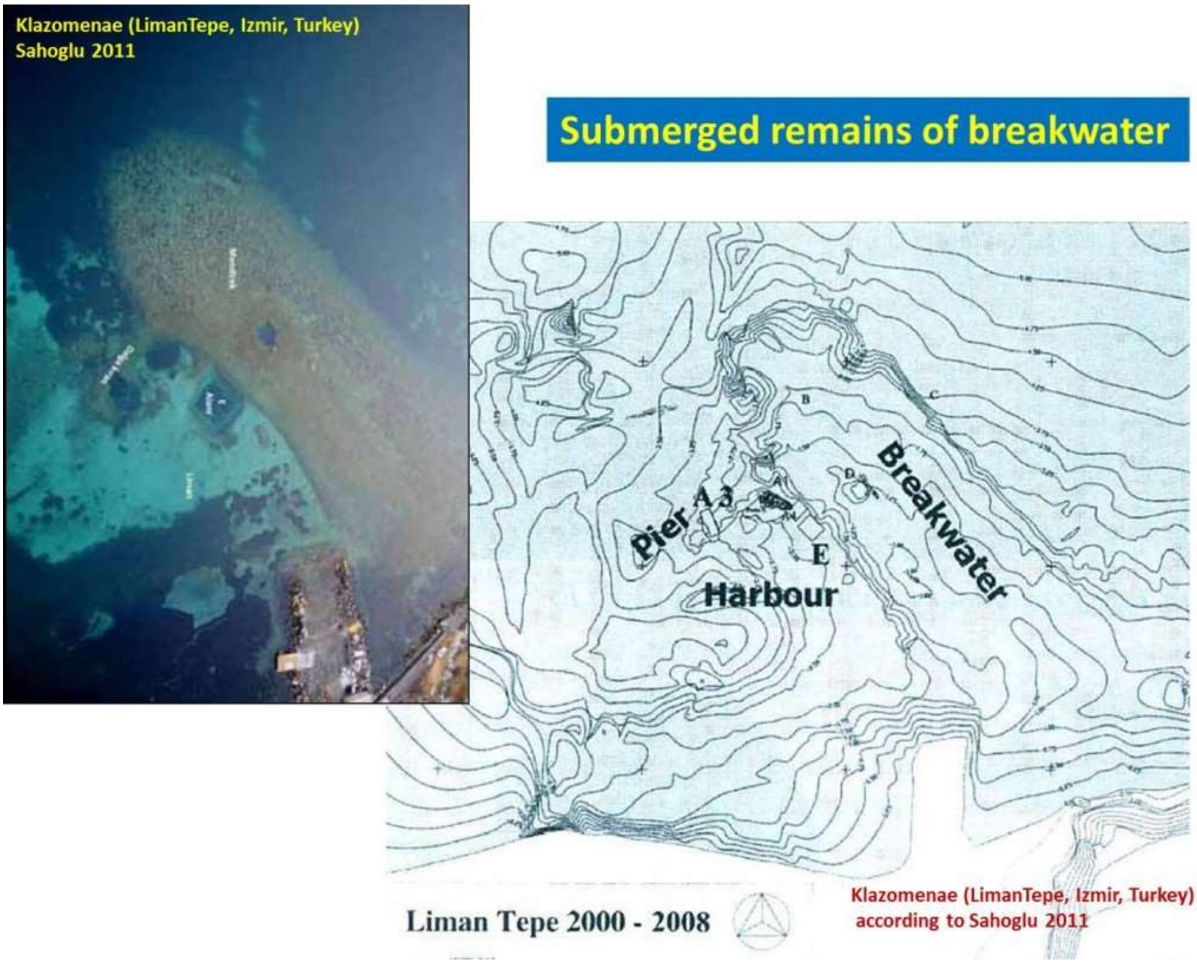
Index of places with remains of ancient breakwaters

4.7 Failure of rubble mound breakwaters in the long term

Kissamos ancient rubble mound breakwater (Crete)
(picture H. Hampsa, 2006)

Many rubble mound breakwaters have been built in antiquity to improve sheltering for ships. A typical example is shown above (Kissamos in Crete, from Hariclia Hampsa's PhD thesis in 2006). This particular structure has been luckily preserved as it survived 2000 years of wave attack ... as it was raised by tectonic movement. However, most of the ancient breakwaters were destroyed by wave action and remains are found under water as "submerged breakwaters". The process of destruction by waves was not all that clear and further analysis was undertaken by the author.

The present analysis of long-term stability concentrates on the worst possible wave conditions, considering that they will eventually occur in the long term. This means that we consider only cases with waves breaking between the toe and the crest of the submerged structure. Hence, the local wave climate must include waves large enough to break on the water depth in front of the submerged structure and breakwaters in very sheltered areas are not considered in this analysis. Similarly, breakwaters located in water depths larger than say 10 m are not likely to be subjected to breaking waves in the Mediterranean area and are therefore not considered here.



Klazomenae submerged ancient breakwater (Liman Tepe near Izmir, Turkey)

A typical example of a submerged breakwater is at Klazomenae, at Liman Tepe (near Izmir, Turkey). The remains are 140 m long and 45 m wide in a water depth of around 4 m at its seaward roundhead. The crest of the structure is now at 1 to 1.5 m below present seawater level. Due to tectonics, the ancient seabed was around 0.50 m higher, and the water level was about 0.50 m lower (according to N. Flemming, 1973[121]).

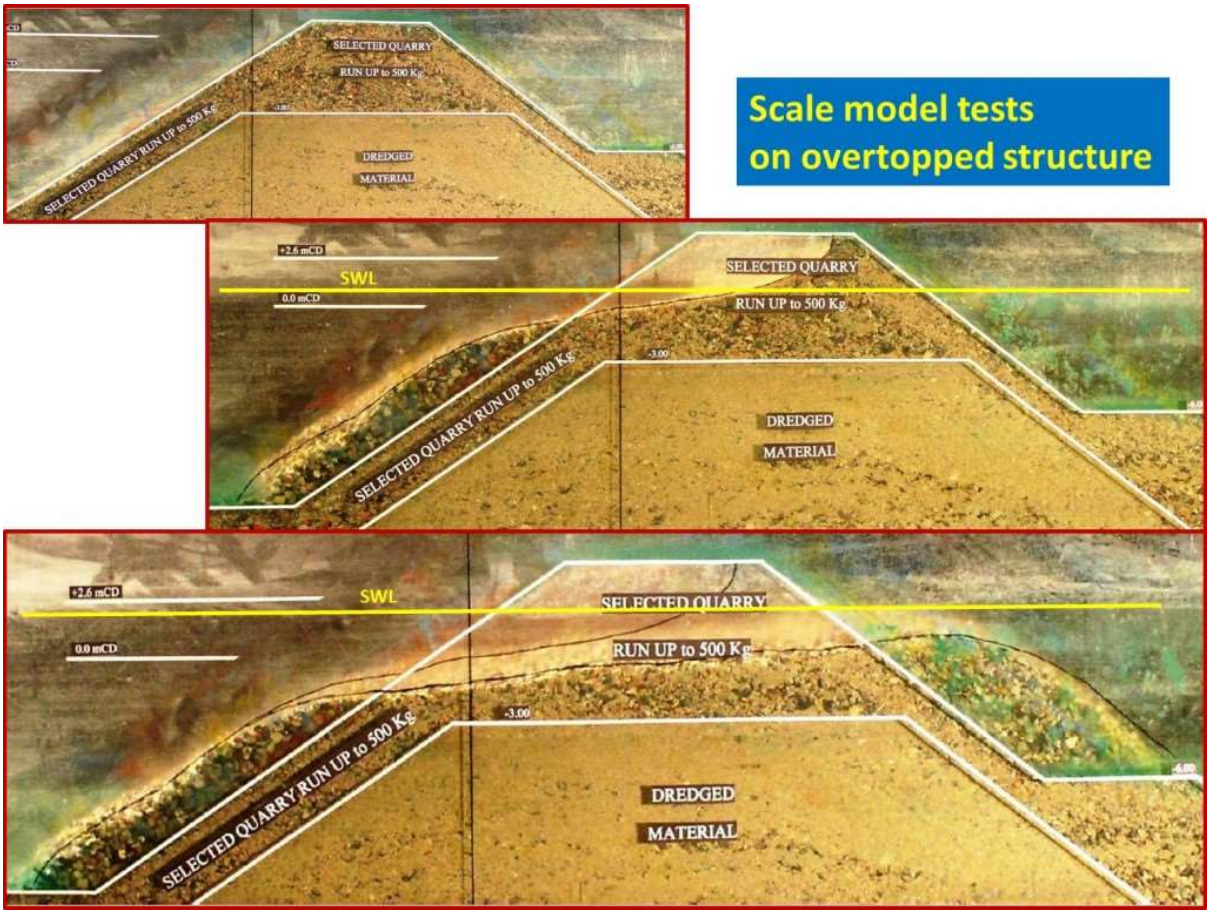
It must be noted that the location of this structure is rather sheltered from offshore waves and this may explain why this structure has survived so well in time.

This ancient harbour has been intensively studied by Vasif Sahoglu and his colleagues from the Ankara University Research Centre for Maritime Archaeology.

Many other examples are to be found in “Remains of ancient breakwaters” above.

[121] FLEMMING, N., et al., 1973, “Archaeological evidence for eustatic and tectonic components of relative sae level change in the South Aegean”, in “Marine Archaeology”, Proc. 23rd Symposium of the Colston Research Society, 1971, ed. D. Blackman, Bristol.

The following pictures show the process of reshaping of a low crested breakwater consisting of relatively small rubble at SOGREAH's Laboratory in 2006.



Reshaping of an overtopped rubble mound breakwater by wave action

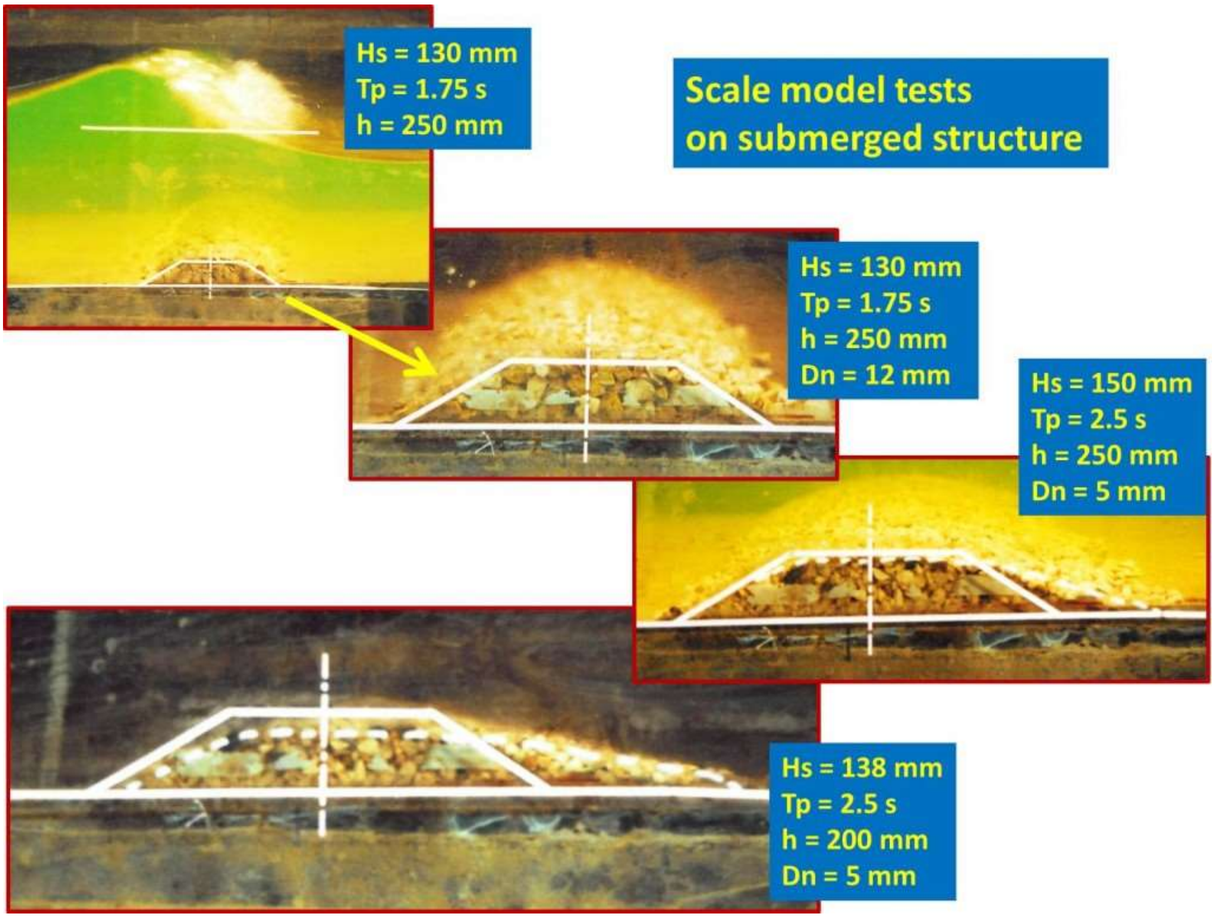
The initial structure is shown above at the top. Stone size on the model is nominal Dn = 7 mm. The structure is 545 mm high and placed in a water depth h = 450 and 480 mm.

The middle picture shows the structure after a sequence of around 1700 waves with significant height Hs = 60 mm and peak period Tp = 1.15 s. Waves were obviously not breaking before the seaward toe of the mound as Hs/h = 0.13 only, but broke on the structure front slope. This induced an erosion of the front slope, moving material from the crest down to the seaward toe.

The bottom picture shows the structure after a sequence of around 1500 waves with Hs = 80 mm and period Tp = 1.35 s. Waves were still breaking on the structure front slope. This induced further erosion of the crest, moving material from the crest to the rear side.

The main limitation of these tests is that they were performed with non breaking waves. Hence, wave attack on the structure was not the worst possible.
This structure was nevertheless changed from an emerging breakwater into a submerged breakwater.

Some unpublished scale model tests were performed in a 1 m wide wave flume at SOGREAH's Laboratory in April 1993 by the author.



Study of stability of a submerged rubble mound

The submerged rubble mound was given a very simple trapezoidal shape with 1:1.5 slopes, 40 mm high, and 100 mm long on the crest. The water depth h was 250 mm for most tests. The wave height was increased step by step during the test until full wave breaking occurred and no further increase of significant wave height could be obtained. The wave period was set at Tp = 1.75 s for most tests. Wave breaking was of the "spilling" type for all tests. The rubble mound was built with one single type of stone defined by its nominal Dn = 5.0 mm for the smallest size tested.

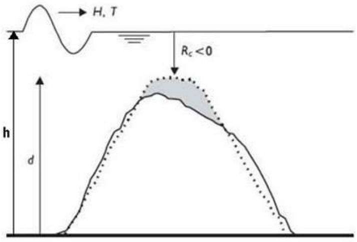
The structure was reshaped by wave attack and finally stabilised in a rounded shape featuring a steeper front slope and a milder rear slope. The crest was lowered somewhat (2 to 3 Dn) and the rear toe moved backwards (about 18 Dn).

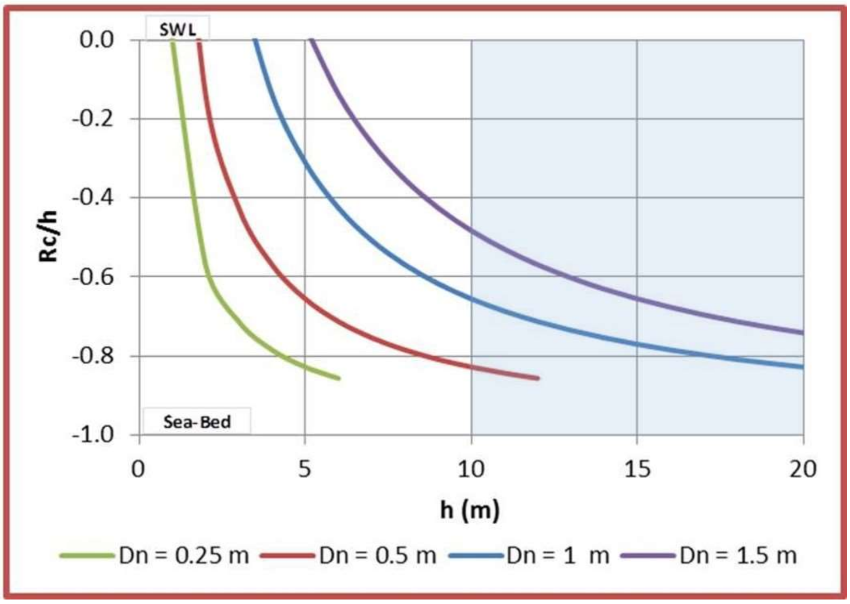
These tests are of course very limited and modest, but they yield most important results enabling a much wider perspective on the processes involved.

It is concluded that undersized emerging rubble mound breakwaters reduce to submerged breakwaters and that the crest can be located as follows:

Rc/h = 3.45 Dn/h – 1

For a given stone size, submerged breakwaters stabilize to the predicted crest level after long term wave attack in breaking wave conditions.





Stability of stones according to water depth
and rubble mound crest level

This result is obviously very useful for the design of breakwater construction phases, when the core of the structure may be exposed to storms inducing waves breaking on the structure. It is also useful to determine the long term equilibrium level of the crest of undersized breakwaters and near-bed rubble mounds protecting pipes.

For use in the Mediterranean Sea on ancient breakwaters, a water depth of around 10 m may be considered as a maximum in the figure above because ancient structures were not (often) built in larger water depths and because very large waves (say Hs > 6 m) are not frequent enough to induce significant damage in the long term.

Further scientific details and references are to be found in a more comprehensive pdf publication on “Stability of overtopped and submerged rubble mound breakwaters”. It was also published in Méditerranée, revues.org .

4.8 Subsidence

What are we talking about?

Before entering the subject of subsidence, we must distinguish it from breakwater destruction by wave action[122]. The latter yields spreading of materials on the sea floor resulting in a complete destruction of the breakwater superstructure which can then barely be recognised as such under water. This is not (or less) the case with subsidence yielding a vertical movement, possibly combined with tilting, of the structures.

Subsidence must also be distinguished from **wave-induced local scour** near the toe of the structure when breaking of waves coming in obliquely induce a longshore current that might yield erosion of the sandy bed in front of the structure. This may undermine the offshore toe of the structure and cause tumbling of the large capping blocks towards the sea, but not a uniform subsidence of the whole structure.

Repeated storms have sometimes been put forward as a possible explanation for the breakwater subsidence due to **wave-induced liquefaction**. From a hydraulic point of view, we must visualise a wave travelling towards the coast with a crest parallel to the breakwater. This wave is reflected by the offshore side of the breakwater, inducing a nearly double wave height in front of it. Large waves might indeed induce local liquefaction of the sandy seabed on the offshore side of the breakwater (Zen, 1990 & 1991). This induces a subsidence larger at that side than at the inner side of the breakwater and tumbling of large concrete blocks towards the offshore side would be observed rather than a uniform vertical subsidence.

A different mechanism is that of **wave-induced compaction** of the sub-soil underneath the structure. Before breakwaters are built, the seabed often consists of more or less loosely packed sand provided by longshore sediment transport. Adding the weight of the breakwaters and subjecting them to long-term vibrations due to wave action and to seismic action, will induce compaction of the sub-soil. In addition, **consolidation** of clayey materials (if any) and long-term deformation called **creep** may also play a role in coastal areas at a centennial or millennial time-scale. Modern engineers always dredge away these layers of loosely packed and clayey materials before building any structure, but ancient builders probably did not, because the required heavy-duty dredging equipment did not exist.

Because of the large waves acting on the outer side of the breakwater, a cyclic hydraulic gradient is generated between both sides of the breakwater. This induces a strong flow inside the rubble mound of the breakwater or at the interface between the large concrete blocks and the unprotected sandy seabed. In order to avoid irreversible problems with the foundation of large marine structures due to **piping and undermining**, a foundation layer consisting of a “granular filter” must be installed in accordance with strict requirements (de Graauw, 1984). As a matter of fact, foundation layers consisting of fine granular material (say 2 to 50 mm) placed underneath large blocks made of Roman concrete are an essential part of their foundation, but they have not been mentioned by excavators so far, except in Caesarea Maritima and Athlit, where a layer of cobbles (probably ship ballast) was found[123].

[122] See section on Failure of rubble mound breakwaters in the long term.
[123] VOTRUBA, G., 2007, “Imported Building Materials of Sebastos Harbour, Israel”, International Journal of Nautical Archaeology, 2007, 36.2, (p 325-335).

Only one other case has been recently noted in Fos where pillars made of ashlar were "laid on a level of coarse sand mixed with fragments of ceramics. Below this level, finer sand is largely mingled with dead posidonia" (Fontaine, 2021), but it is suspected that this perfect filter layer with Posidonia Oceanica was not entirely intentional … Another case is reported by Marty (2016)[124], also at Fos, where a layer of Posidonia was deliberately used as a filter.

Other explanations include earthquakes inducing **tsunamis**. The tsunami wave(s) first encounters the outer face of the breakwater, where part of its energy isreflected back to the open sea. At this stage, the tsunami might push large blocks of Roman concrete placed on top of the breakwater into the port, rather than generating a uniform vertical subsidence. Then, depending on the size of the tsunami, a substantial part of the energy would overflow the breakwater and submerge the whole harbour area, taking away all loose blocks, pavements, warehouses, ships, etc. The tsunami wave would then enter the city and would finally flow back to sea, taking much waste into the harbour, but it has been shown elsewhere that it can be really hard to distinguish ancient tsunami deposits from other deposits.

Earthquake-generated liquefaction is a convenient explanation for subsidence as it is likely to affect large areas covered with cohesionless water-saturated sand. It was probably mentioned by Aelius Aristides (Oration 19) who witnessed the 178 AD earthquake in Smyrna: "some of the temples have *fallen*, some *sunk* beneath the ground".
The potential for liquefaction depends on the sub-soil properties (Idriss & Boulanger, 2008 ; Hettler, 2014): sand must be loosely packed (less than 70% relative density) and may include a small fraction of fine silts or clay, so-called "silty sand" (less than 20% with a diameter below 74 microns). Longshore transport of sediment often provides this kind of sand in the nearshore area down to a water depth of ca. 10 m.
During an earthquake, sand with a large porosity (say 40% for a loose packing) will tend to re-arrange its packing and reduce its porosity (to say 30% for a dense packing). This will require some pore water to seep out of the sub-soil, but that flow may be delayed by low-permeability materials. Any load resting on this sub-soil would then be floating on water instead of resting on a solid skeleton of sand grains, and as water would gradually flow out, the load would gradually sink into the sub-soil until it would rest on the re-arranged sand skeleton (Aachen University video). This liquefaction process is a short term one occurring within minutes during and shortly after the earthquake. This is of course an idealised and simplified scenario, and many complications may occur in reality with superimposed layers of various materials, including impermeable layers, etc.
According to this process, liquefaction can only occur once in a given area.

Last but not least, we mention **tectonic subsidence**. This involves crustal movements of the earth which may be horizontal, vertical, or combined. This also involves faults along which such crustal movements appear during earthquakes. It must be reminded that a meters-high subsidence due to tectonic movements is a major and catastrophic event with many casualties that is usually reported even in ancient literature.

HAGGI, A., 2005, "Underwater excavation at the Phoenician harbor at Athlit, 2002 season", R.I.M.S. News, report N° 31, Haifa.
[124] MARTY, F., GUIBAL, F., HESNARD, A., "L'Estagnon : techniques de bonification d'une zone palustre au 1er s. ap. J.-C. à Fos-sur-Mer (Bouches-du-Rhône)", Colloque "Les ports dans l'espace méditerranéen antique", Montpellier 2014, (p 263-278).

Where did we observe subsidence of coastal structures?

Now we have a better understanding of the phenomena involved, let’s have a closer look at places where subsidence was observed (Flemming, 1978, Pavlopoulos, 2011, Kolaiti, 2023).

Let’s make a few preliminary notes on the available data:

- Subsidence (and uplift) may be a continuous process (e.g., consolidation) or a sudden process (e.g., liquefaction). Average rates of subsidence in mm/year make sense only in case of continuous processes.
- It is known from the eustatic Sea Level Rise (SLR) curve that its rate has been around 0.25 mm/year over the past 2000 years, and 0.7 mm/year over the 5000 years before that. Therefore, we selected data with an age of 1000 to 4000 years (1000 AD to 2000 BC). Hence, places that were submerged more 0.5 m over the past 2000 years must have been subject to some kind of subsidence (as Submergence = Subsidence + SLR).
- As the eustatic SLR amounted to ca. 0.5 m in the past 2000 years, any uplift larger than 0.5 m will be visible on land without underwater exploration.

Sites with more than 1 m submergence in 2000 years (0.50 mm/yr) were selected from our data base, yielding 265 sites (including Atlantis!).

Coastal sites submerged by more than 1 m in the last 2000 years.

Submerged sites are found in the Rhône delta, the Tyrrhenian coast, the bay of Naples, the Pô delta (Ravenna and Aquileia), several sites around the Peloponnesus and on Paros Island in the Cyclades, eastern Crete, many places on the SW Turkish coast between Izmir and Antalya, southern Cyprus, the Nile delta (Thonis-Herakleion, Alexandria), Cyrenaica (Apollonia), Sabratha, Carthage.

Port structures located on loosely packed sands provided by longshore sediment transport may be subject to liquefaction during earthquakes, inducing a general subsidence of the port. Sites in deltas are well-known for subsidence which is usually due to compaction of underlayers that are loaded with new sediment brought by the river(s). In addition, consolidation may occur if these underlayers contain clayey materials. Sites in rocky areas may be subjected to crustal movements linked to seismic activity, like around the Aegean Sea. The bay of Naples is a particular case subjected to so-called 'bradyseism' which induces alternatively uplift and subsidence.

A similar exercise showed 89 sites uplifted in the last 2000 years. Some of them are located in Calabria (Ferranti, 2017), northern Peloponnesus, Samos (Stiros, 2000), Rhodes (Triantafyllou, 2022), western Cilicia (Liberatore, 2023), northern Levant (Sivan, 2010), but most are located in western Crete as a result of the tilting of the island during the 365 AD earthquake.

Coastal sites uplifted by more than 1 m in the last 2000 years.

It is usually quite difficult to go into further detailed explanations of subsidence of coastal sites because many geological and geotechnical aspects are involved. An example is provided in this volume for Caesarea Maritima.

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4.9 Design waves for coastal structures on the Mediterranean coasts

The climate of the Roman period from 200 BC to 100 AD is considered fairly close to ours, with a cooler period before that and after that. William Murray (1987) compared ancient winds as described by Aristotle and Theoprastos with modern wind data, and found very good agreement. Hence, as waves are generated by winds, we usually suppose that the ancient wave climate is similar to the present one (see also “Ancient Climate”).

Hokusai, Under the wave off Kanagawa (1830) (Wikipedia).

Waves are generated offshore by friction of the wind on the sea surface (such waves are called ‘wind waves’). Waves travel on the sea surface over hundreds (even thousands) of kilometres after they were generated (such waves are called ‘swell’). When they reach the coastal shallow waters, they change in height and in direction due to shoaling, refraction and diffraction effects (a simplified computation is available on https://swellbeat.com/wave-calculator/).

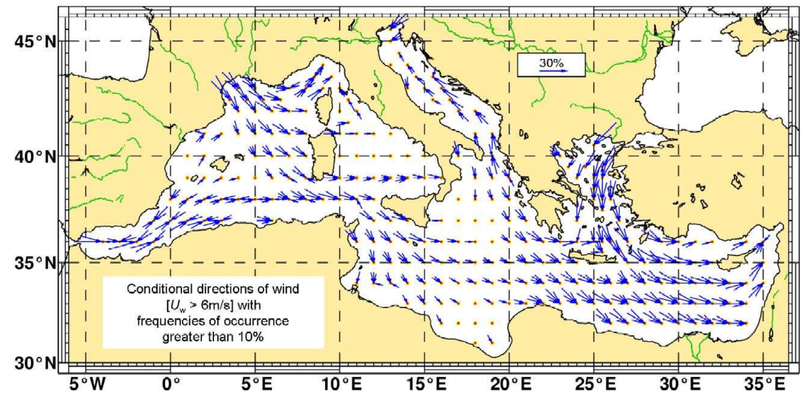
Modern design of coastal structures exposed to wave attack is based on a sound knowledge of the local wave climate. Wave generation and propagation are complex processes and statistics play an important role in the description of the wave climate in a given coastal location. A simple way to define a sea state is to mention its ‘significant wave height Hs’ which is defined as the average of the one third highest waves of that sea state. This Hs is considered to be close to the visual estimate which would be given by an experienced observer of the sea (see Holthuijsen, 2007).

Design of coastal structures is based on the principle of ‘accepting a certain level of damage to the structure, for a certain probability of occurrence of the waves’. One could indeed accept a lot of damage for a very rare event, or very little damage for a more frequent event. For modern coastal structures, it is usually accepted to have very little damage for a one in hundred years storm event. Hence, coastal engineers will speak about the ‘1 in 100 years Hs’ to define the design wave conditions. Assuming an average of 10 ‘big’ storms per year (which leads to 1000 storms over 100 years), this means that the design storm is the largest storm in this series of 1000 and therefore has a probability of occurrence of around 10^{-3}, that is 0.1%, in a given year … this seems not much ... However, the probability of occurrence of a ‘1 in 100 years’ super storm during your lifetime of say 75 years, is around 53% ... quite a high chance (nearly one in two) that you will witness this super storm, that is supposed to generate 'very little damage'.

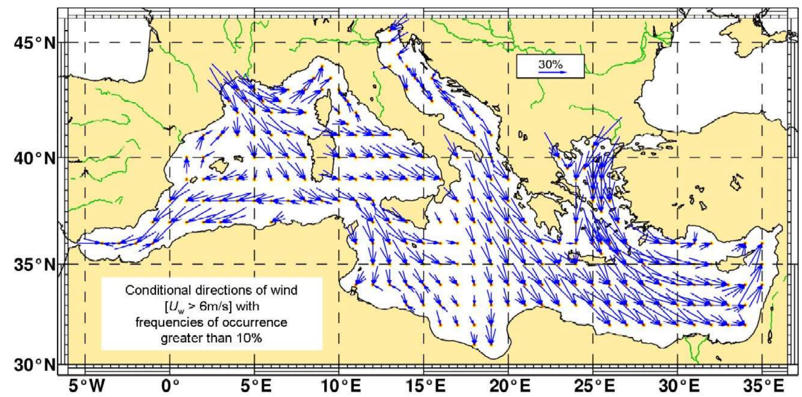
As they usually do not have wave measurements over 100 years, coastal engineers use a computational approach (called ‘hindcasting’) to generate wave data over a period of say 20-30 years, they perform a ‘Peaks Over Threshold’ analysis of the largest storms and they extrapolate this data to provide an estimate of the 100-year storm (see Mazas & Hamm, 2011).

Let us now go back to the Mediterranean Sea where we know that winds blow from north and NW most of the year. Data taken from the Wind and Waves Atlas of the Mediterranean Sea (2004) show this effect in more detail (local wind and wave statitics are provided by https://fr.wisuki.com and by https://fr.windfinder.com).

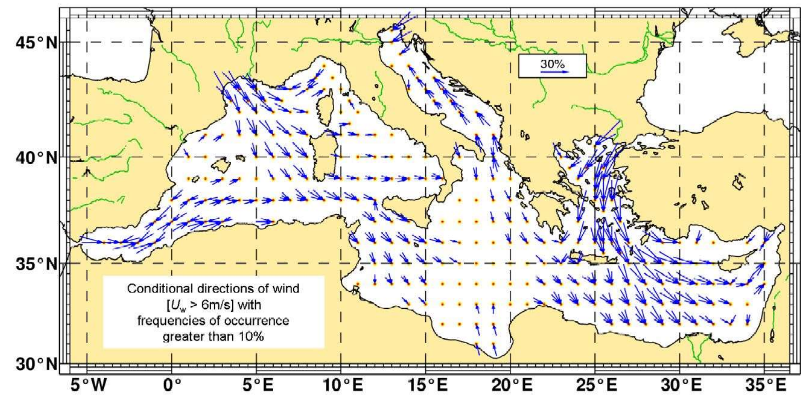
Spatial distribution of wind directionality. Spring



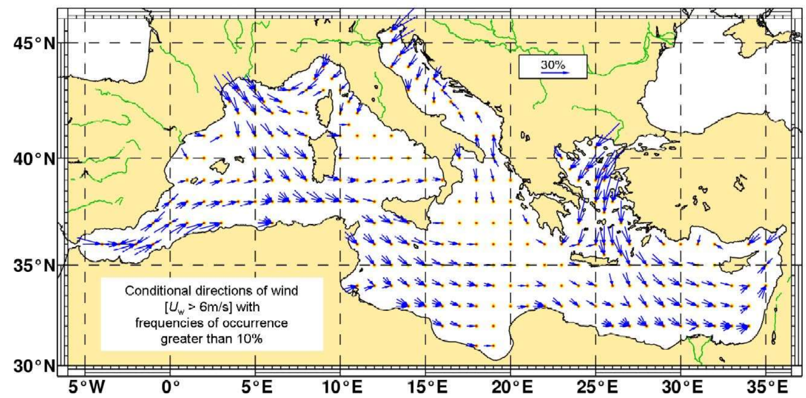
Spatial distribution of wind directionality. Summer



Spatial distribution of wind directionality. Autumn



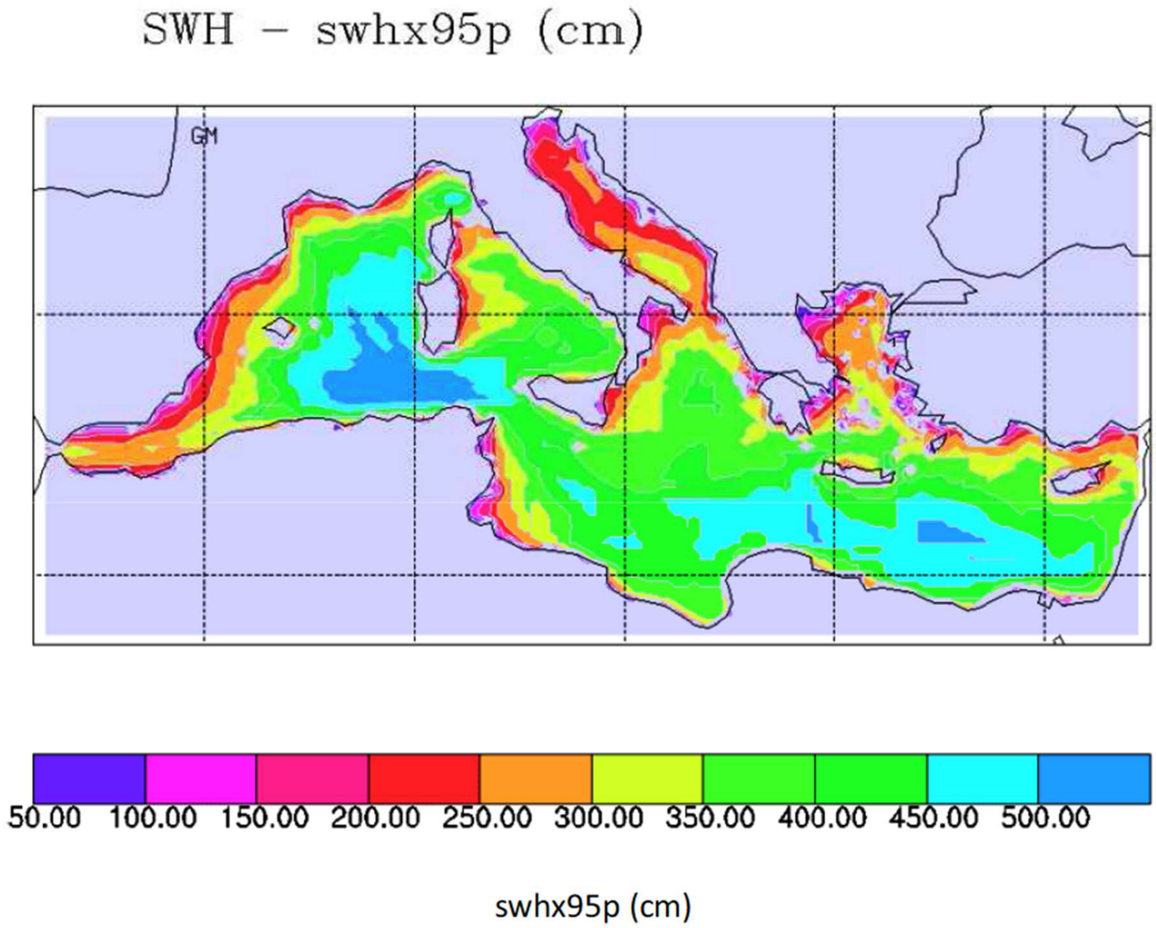
Spatial distribution of wind directionality. Winter



These pictures show the strong summer winds from NW: the Tramontane and Mistral in France, The Bora in the Adriatic and the Meltem in the Aegean. They reduce somewhat in autumn, but this would be more obvious on monthly charts instead of the above seasonal charts.

These winds induce waves travelling on the sea from NW to SE, towards the African coasts. For this reason the east coasts of Spain, Corsica-Sardinia, Italy-Sicily, Tunisia, and Greece are relatively less exposed to large waves than the north coasts of Algeria, Tunisia, Cyrenaica-Egypt.

Note that places with reduced exposure to waves are safe for coastal structures; these places may still be exposed to strong land winds, which is not safe at all for navigation as ships are taken away offshore by the wind where they will finally encounter large waves.



5% exceedance significant wave height which is exceeded during 5% of the time, acc. to Lionello (2011)

The results above are based on 30-year long simulations of the wind-wave field in the Mediterranean Sea carried out with the WAM model. The wave model has been forced by the wind field computed by the RegCM regional climate model at a 50 km resolution. The results are shown as a 5% exceedance significant wave height which is exceeded during 5% of the time, that is around 2 weeks/year. Depending on the area, the wave heights near the coastlines range from 1 to 4 m, with the highest values along the coasts of Algeria-Tunisia, Cyrenaica and the Levant.

The design wave heights for coastal structures are obviously larger. Depending on local wave statistics, the design wave height is a factor 2 to 2.5 times larger than the above mentioned 5% exceedance significant wave height, leading to Hs = 10 m in areas exposed to offshore waves.

The wave heights are shown for deep water (say over 100 m) and it must be stressed again that waves change in height and in direction from offshore up to the coastline where they will ultimately break due to the shoaling seabed. A first approach is to say that waves break when their height is around 0.6 times the local water depth, e.g., a wave with significant height Hs = 6 m will break on a water depth h = 10 m. Hence, if an ancient breakwater was built in 5 m water depth, the largest Hs reaching the structure would have been 3 m. Storms with Hs = 3 m are numerous. For a modern breakwater built in 20 m water depth, the largest Hs reaching the structure is 12 m which is a fairly large value that corresponds to exceptional storms in the Mediterranean Sea (less exceptional in the Atlantic).

So do not use the map above for the design of your next breakwater! Just use it to realise that some areas are more subject to severe wave attack than others.

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4.10 Reinforced concrete?!

4.10.1 Unreinforced Roman Concrete

According to Vitruvius (De Arch., 2, 6) and Pliny (Nat. Hist., 35, 47 & 36, 52-54) Roman mortar consists of lime and pozzolana, and Roman concrete is the mixture of this mortar with aggregates (more details in section on Vitruvius' methods). The resulting structure was called opus caementicium.

Although the compressive strength of Roman concrete is smaller than that of modern concrete, its longevity, especially in marine conditions, is still a matter of surprise and debate for modern civil engineers. A major innovation was performed by replacing river sand by sand from the Phlegraean Fields near Pozzuoli, allowing mortar to cure under water. It is therefore often called 'hydraulic concrete'. Longevity of Roman hydraulic concrete has long been attributed to this mixture. However, recent research indicates that the presence of lime clasts generates a process of long-term self-healing of micro cracks by filling them with calcite[125].

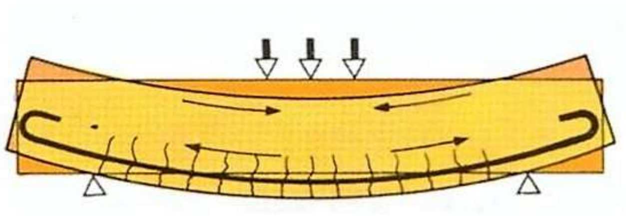
Large masses of concrete are useful for massive structures like ramparts and thick walls, towers, harbour breakwaters, the like. However, unreinforced concrete cannot withstand tensile forces such as those generated by flexion.

4.10.2 Reinforced Concrete

Reinforced Concrete (RCC) was invented at the end of the 19th c. and is now much used for marine structures. It consists of a combined use of concrete and steel. The first has high resistance to compressive forces but none to tension forces, and the second has just the opposite if we consider slender steel bars.

This is a major innovation because RCC structures can resist flexion with its associated compressive and tensile forces. Before this innovation was made, large spans had to be covered by arches acting with compression only, while after that, they could be covered by simple beams acting with flexure.

How does this work?



Beam placed on two lateral supports.
The vertical load induces compression in the upper layer of the beam and tension in the lower layer.
The steel rebar is thus placed in the lower layer,
but it can take over the tensile forces only after the concrete has cracked (micro-cracks!).

In a certain way the vertical load on the beam is taken over by the lower steel rebar like a wash line supports clothes. Obviously, a rusting wash line is not acceptable!

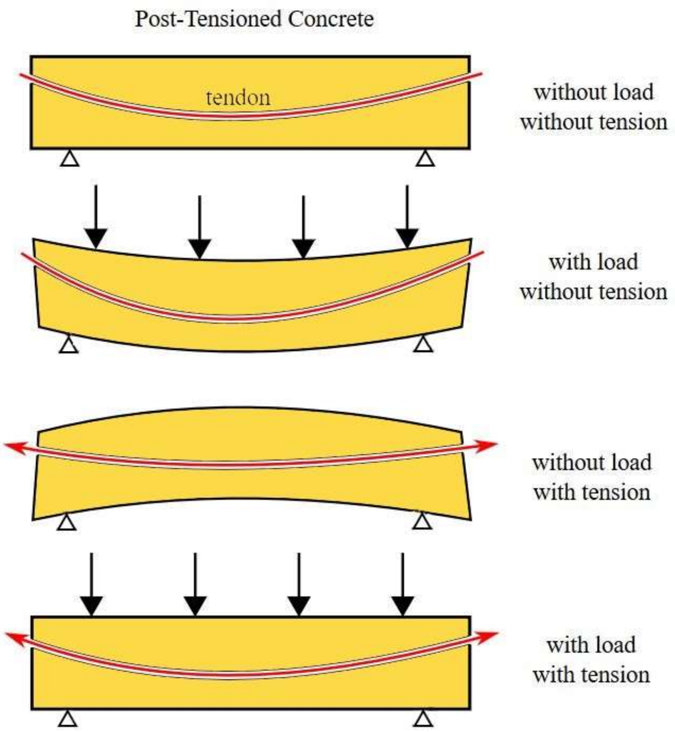
[125] SEYMOUR, L., et al., 2023, "Hot mixing: Mechanistic insights into the durability of ancient Roman concrete", Science Advances, 9, eadd1602, New York, (13 p), https://www.science.org/doi/10.1126/sciadv.add1602

In a marine environment, salt water and associated chlorides (Cl^- ions), sulphates (SO_4^{--} ions), carbon dioxide (CO_2), oxygen (O_2), water (H_2O) and other chemicals penetrate into the concrete by capillarity and diffusion and by convection through the micro cracks. These micro cracks are a problem because they allow the environment inside the concrete, eventually reaching the steel rebar. Obviously, the compaction quality and thickness of the cover layer located between the lower rebar and the under face of the beam (around 50 mm) is important, but *micro cracks must exist* in order to have the steel rebar working.

The result is that quite some RCC marine structures built in the past decades are already in really bad condition and needing very expansive repair works. Some coastal structures were supposed to last many decades, but are showing serious deficiencies after only 10-15 years! This is usually visible by traces of corrosion of the steel rebars embedded in the RCC structure.

This is inherent to the very concept of RCC and to the need for micro cracks in order to have steel bars taking over tensile forces. Some modern solutions like water repellents, additives with pore-blocking ingredients, cathodic protection, stainless steel rebars provide some relief.

This problem with RCC micro cracks does not exist with prestressed concrete (PCC). Instead of having a simple rebar as shown on the figure above, a steel cable (called “tendon”) is encapsulated and a prestress is applied to it. This induces compression inside the whole beam, as well in its upper layer as in its under layer. The vertical load on the beam thus induces additional compression in the upper layer (but concrete can resist that) and a tension counteracting the prestress in the under layer, but the latter remains under compression at all times.



Beam placed on two lateral supports.
The vertical load induces tension in the lower layer of the beam.
The prestressed tendon induces compression in the lower layer
which counteracts the tension induced by the vertical load.
(picture Wikipedia)

In this way no micro cracks occur and the beam is much more resistant to the environmental intrusions of chlorides and other chemicals, but the quality of the prestressing tendons is obviously of paramount importance: plastic ducting, grouting, cathodic protection, yield- and ultimate strength, stress relaxation. Further research on stainless steel tendons is ongoing.

The concept of flexure and cantilever can be applied only to structures able to absorb traction (tensile) forces that are induced by flexure. It was seen with Vitruvius' methods that wooden tie rods could be used, but wood does not resist in the long term (except when preserved in sediment). A similar system with granite columns can be seen at Ashkelon (Israel). Granite is weaker than wood for traction, but resists in time as can be seen at Ashkelon in the remains of the crusaders' bulwark built around 1150.


Concrete reinforced with granite columns (Ashkelon beach, Israel)

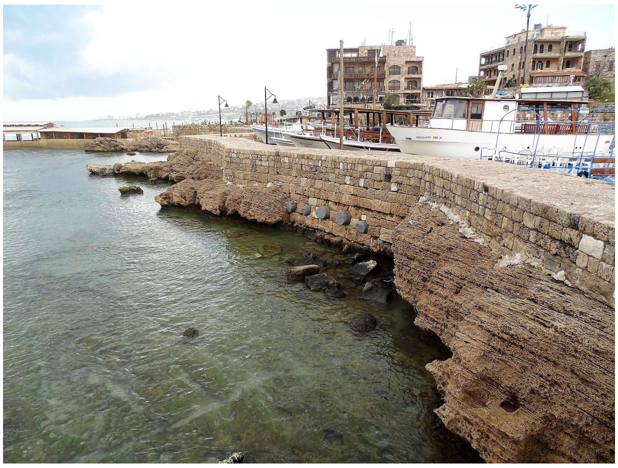
In figures: hard loaf wood can yield a tensile strength of around 100 MPa (10 kgf/mm^2) (in the fibre direction!) while granite does not exceed 20 MPa. For compression strength, everything is reversed: wood yields around 30 to 40 MPa, but granite is at 200 MPa.

It is sound to apply traction on wood and compression on granite.

According to Marie Jackson in John Oleson's "Building for Eternity" (Oxbow Books, 2014), the compression strength of Roman hydraulic concrete (i.e., with Puteolanis pulvis, or 'pozzolana') ranges between 2.5 and 8.5 MPa (modern concrete reaches 50 MPa and even up to 150 MPa for modern ultra-high-performance concrete). The tensile strength is reduced to about 1/10 of the compression strength. The latter being notably increased by steel reinforcement (steel has a tensile strength of around 200-300 MPa at the elasticity limit state), (see also: http://www.romanconcrete.com/romanconcrete.htm).

Iron chains could have been used as reinforcement in Roman concrete … but the invention of the arch helped to overcome the problem of flexure for several millennia and corrosion of steel would soon become a problem.

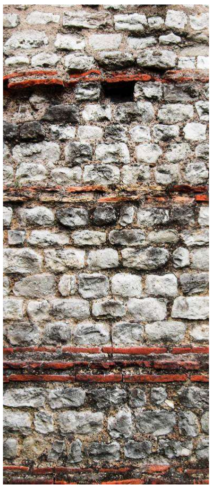
17th c. arch of the Ermita de Santa Barbara at Alicante, Spain (photo A. de Graauw, 2015)



Quaywall reinforced with granite columns at Byblos, Lebanon (photo MarcBE Panoramio-78716173)

4.10.3 Horizontal chaining

The horizontal columns of Ashkelon and Byblos remind the ashlar headers aiming at connecting two faces of a wall. For Opus Vittatum Mixtum walls, Jean-Pierre Adam (La Construction Romaine, 1995) speaks of "horizontal chaining" consisting of 2 or 3 layers of terracotta tiles (courses of bonding tiles) as can be seen on the London Wall behind the statue of Trajan.



Statue of Trajan in front of London Wall.

It needs to be proven that these courses of tiles really act as bonding tiles, i.e., a structural element able to take over tensile strengths (todays' chaining is steel reinforced).

It must therefore be demonstrated that terracotta not only resists at least as well to traction as the natural stone used in concrete, but also that the adherence of mortar on terracotta is better than on natural stone.

As far as **tensile strength** is concerned, we have mentioned granite above with a tensile strength of around 20 MPa, but sandstone and limestone are weaker with around 5 MPa. With a strength of 5 to 10 MPa, terracotta is in the same order of magnitude (but optimists would say "double").

Concerning adherence, or **bond strength**, of lime mortars on terracotta and natural stone, we must go into some details, as this subject has not been much studied …
Measuring the bond strength of a stone or a brick on a layer of mortar is similar to measuring a shear stress. The unit of this stress is N/mm^2 (MPa) like for traction and compression stresses. According to Pierre Nicot (PhD thesis "Interactions mortier-support", Toulouse, 2008) "bond strength can be defined as the force required to separate two constituents" and he explains that bond strength between mortar and a support can be chemical and mechanical. The latter involves porosity of the support, its water absorption capacity, etc. Dare we make an analogy with welding of metals?

These comments lead us to consider the tests defining these parameters. Some tests are normalised under masonry test procedures (EN 1052):

- Part 1: Determination of compressive strength, (BS, CSTC),
- Part 2: Determination of flexural strength, (CSTC),
- Part 3: Determination of initial shear strength, (CSTC, BS),
- Part 5: Determination of bond strength by the bond wrench method, (CSTC).

It can be noted that the 'pull-off test' and 'crossed couplet test' are missing to obtain the tensile bond strength, but according to Wikipedia on its Mohr's circles page "the force required to tear off atoms from each other is much larger than the force required to make them slide over each other", which means that resistance to initial shear stress (also called 'cohesion') is lower than the resistance to pure tensile strength. The test of interest here is thus the one described in Part 3 of the norm EN 1052. This test is conducted by pushing out a brick pinched between two others ('shear triplet test') with an interpretation using Mohr's circles which is well known in the field of soil and rock mechanics.

Thomas Zimmermann & Alfred Strauss from the University of Wien[126] provide initial shear strengths of only 0.03 MPa for lime mortar without cement, and 0.21 MPa for mortar with cement.

Adrian Costigan & Sara Pavia from the Trinity College Dublin[127] say that bond strength is very important for the compressive strength of the whole masonry structure. Their results can be summarised by a bond strength ranging between 0.1 and 0.4 MPa (depending on the tested types of lime mortar), and a compressive strength ranging between 2 and 8 MPa (that is 20 times more than for bond strength).

Today's mortars (e.g., Beamix 341 or Weber.mix MM319) also claim bond strengths on brick in the order of 0.1 to 0.2 MPa, and even 0.3 MPa. These values can be increased (by a factor 10!) with special adjuvants.

So far for bond strength between mortar and brick. But how about bond strength between mortar and natural stone?

At the beginning of the 19^{th} c., Louis Charles Boistard conducted tests on the bond strength of natural stones on lime and sand mortar with the following conclusion: "bond strength of lime and sand mortar can be estimated at at least 1500 pounds/sq feet" that is around 7000 kgf/m^2, or 0.07 MPa after 18 months of hardening.

G. Vasconcelos & P.B. Lourenço from the University of Minho[128] performed tests on wall sections of 1.0 x 1.2 m^2 and found a diagonal shear stress of 0.05 MPa for masonry with

[126] ZIMMERMANN, T. & STRAUSS, A., 2011, "Variation of shear strength of masonry with different mortar properties", North American Masonry Conference, Minneapolis, 2011.
[127] COSTIGAN, A. & PAVIA, S., 2010, "Influence of Mechanical Properties of Lime Mortar on the Strength of Masonry", Historic Mortars Conference, Prag, 2010.
[128] VASCONCELOS, G. & LOURENÇO, P.B., 2006, "Assessment of the in-plane shear strength of stone masonry walls by simplified models", Structural Analysis of Historical Constructions, New Delhi, 2006.

ashlar and 0.11 MPa for masonry with natural rock; the first having more linear joint planes than the latter, which may perhaps explain the different test results.

M. Corradi & al. from the University of Perugia[129] performed similar tests for various types of wall and found shear stresses around 0.08 MPa.

These figures tend to prove that bond strength on bricks (0.10 to 0.40 MPa) is indeed higher than on natural stones (0.05 to 0.10 MPa).

It seems that we may carefully validate the hypothesis that courses of bonding tiles located in the lower sections of massive structures like bulwarks and donjons increase the internal cohesion of the lower part of the structure.

[129] CORRADI, M., et al., 2003, “Experimental study on the determination of strength of masonry walls”, Construction and Building Materials, 17, Elsevier, 2003.

4.11 Pilae & arched breakwaters

Pilae are massive piles (*opus pilarum*), which are made of stone or concrete (*opus caementicium*). According to Oleson et al. (2014), the Latin word *pila* designates a “large mass of concrete, generally square in plan, and often a cube or upright rectangular prism in shape” [130].

Pilae have been used as a base for arched structures like aqueducts.

Pont de Gard aqueduct

The ratio of opening between adjacent piers over pier width is as follows on the Pont du Gard:

- Upper level: opening = 1.4 pile widths
- Lower levels: opening = 4.1 pile widths

An arched breakwater looks like an aqueduct with a single tier. “Maritime pilae” seem to be more “closed” than aqueducts, i.e., they have a smaller opening over pila-width ratio. This might be explained by their completely different aim which is not to support some kind of road or canal, but to stop wave penetration into the port while providing limited opening for water circulation inside the port, also supposed to reduce sedimentation in the port, or at least in its entrance channel.

The method of construction of the submerged part of pilae with hydraulic concrete was described by Vitruvius and tested by Oleson et al. (2014) in Brindisi (see also Coulon & Golvin, 2020). The aerial part of pilae was made of traditional masonry or concrete without pozzolana.

Except in Civitavecchia, no ancient arched breakwater can be seen today. Remains of concrete pilae have been found in many places and a list is presented below, along with pictures of those that can be seen under water on Google Earth, some of which may be remains of arched breakwaters.

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[130] OLESON, J., BRANDON, C., HOHLFELDER, R., JACKSON, M., 2014, “Building for Eternity – The history and Technology of Roman Concrete Engineering in the Sea”, Oxbow Books, (327 p).
BRANDON, C., 2010, “How did the Romans form concrete underwater?”, Historic Mortars Conference, Prague.
BRANDON, C., 1996 « Cements, Concrete, and Settling Barges at Sebastos: Comparisons with Other Roman Harbor Exemples and the Descriptions of Vitruvius », in « Ceasarea Maritima, A Retrospective after Two Millennia », ed. A. Raban & K. Holum, Brill, Leiden, (p 25-40).
and also:
COULON, G., and GOLVIN, J-C., 2020, “Le Génie maritime romain”, Actes Sud/Errance, (201 p).
GIANFROTTA, P., 1996, "Harbor structures of the Augustan Age in Italy", in "Ceasarea Maritima, A Retrospective after Two Millennia", ed. A. Raban & K. Holum, Brill, Leiden, (p 65-76).
FELICI, E., 1998, "La Ricerca sui porti romani in cementizio: metodi a obiettivi", Archeologia subacquea, (p 275-340).
FELICI, E., 2000, "Modern development and ancient maritime sites along the Tyrrhenian coast", Coastal Management Sourcebooks, (p 81-88).

The following conclusions can be drawn:

- Most sites with one or more pilae are in Italy (35 out of 50), especially around Naples (25 sites from Caieta to Sapri), which is no wonder as the pozzolana required for under water pila construction originates from the area of Campi Flegrei.
- The average dimensions of the measured pilae are 9 m x 7 m: nearly square. The average horizontal surface is 68 m^2. The height cannot be determined on Google Earth.
- The largest pila is the one found at Nesis: 14.5 x 14.5 x 8 m[131].

Various types of alignments can be distinguished from the pictures below:

- single isolated structures (e.g., Punta Fuenti, Fréjus, Caesarea Maritima, Alexandria-Antirhodos), possibly a foundation for some heavy structure such as a tower or lighthouse,
- rather continuous structures in the open sea, probably part of a vertical breakwater (e.g., Castellabate, Scidrus, Gnathia, Side, Psamathos, Caesarea Maritima),
- rather continuous structures in a sheltered area, perhaps forming a massive jetty or quay platform inside a harbour basin protected by a breakwater (e.g., Cosa, Horrea Caelia),
- pilae spaced with regular intervals (say 0.5 to 1.0 pila-width), perhaps the base of arched breakwaters or timber decks, or intervals meant to be filled with rubble dumped into timber formworks placed between the pilae (e.g., Caieta, Misenum, Baia, Portus Iulius, Nesis, Pausylipon, Civitavecchia, Alexandria-Qait Bey).

The pictures show that the distance between adjacent pilae is usually less than their width:

- Caieta: opening = 0.3 to 0.4 pila width
- Portus Iulius: opening = 0.7 pila width
- Misenum: opening = 1 to 1.5 pila widths

Several alignments of pilae have been claimed to be remains of arched breakwaters, including the Roman breakwaters at Tarragona[132] and Izmit[133], but little evidence was provided, except for Puteoli where many pictures are available, and Nisida with a picture from 1635 (see section on Puteoli and Nisida), and Civitavecchia, which is still visible at Molo del Lazzaretto where arches seem to have been placed on top of a rocky shoal with an opening ratio is ca. 0.7.

Molo del Lazzaretto at Civitavecchia (de Graauw, 2022).

131 MATTEI, G., TROISI, S., AUCELLI, P., PAPPONE, G., PELUSO, F., STEFANILE, M., 2018, “Sensing the Submerged Landscape of Nisida Roman Harbour in the Gulf of Naples from Integrated Measurements on a USV”, Water 2018, 10, 1686, (31 p).

132 TERRADO, P., 2019, “El Puerto de Tarraco en Epoca Romana, (siglos II aC – III dC). Fuentes, historiografía y arqueología”, Autoritat Portuària de Tarragona y Arola Editors, (362 p), citing (p 177) Sanahuja (1859) telling about masses of hydraulic concrete, and citing (p 178) Echanove about arches. This ancient Roman breakwater was partly removed in 1843 and is now on land in a reclaimed area.

133 TEXIER, C., 1839, “Description de l’Asie Mineure”, Nicomédie, (p 17-28), ed. Firmin Didot, Paris.

The most famous ancient arched breakwater is at Puteoli (Pozzuoli). Some arches were still in place in the early 19th c., but the structure was gradually destroyed after that. Paolo Antonio PAOLI produced a detailed drawing in 1768 showing 15 *pilae* (including 2 supposed *pilae*, but the inscription CIL X 1641 dated 139 AD, mentions 20 *pilae,* Oleson, 2014, p 24). In his Book of Phtomyris (1, 53) Chaeremon (ca. 85 AD) even speaks of “around 30 arches” The largest *pilae* of ca. 15 x 15 m were at the offshore end of the structure. The nearshore *pila* was somewhat smaller: ca. 8 x 12 m. The opening ratio between adjacent *pilae* varied from 0.5 to 0.9, which is close to the values found for Portus Iulius and Misenum (more in section on Puteoli).

Concerning Portus Claudius’ north mole, Nero’s coins might point towards an arched breakwater as the water flow between piers is clearly indicated on the right side of the coin (more in section on Portus Augusti).

One last note on arched breakwaters concerns the "Mosaico parietale con scena di porto"[134] which was found at Palazzo Rospigliosi on the Quirinal Hill in Rome. It is supposed to show the Alexandria lighthouse:

Mosaic of a port scene found at Palazzo dei Conservatori, Roma (end 2nd - early 3rd c.) (Musei Capitolini, N° AC 32360).

The arched structure shown at the lower side of the mosaic clearly is a quite massive arched structure which looks like an arched breakwater, rather than a portico. As it was found in Rome, one might ask whether this is not the north breakwater of Portus rather than a structure in Alexandria ...

[134] https://mostre.museogalileo.it/archimede/oggetto/MosaicoParietaleScenaPorto.html

List of known pilae

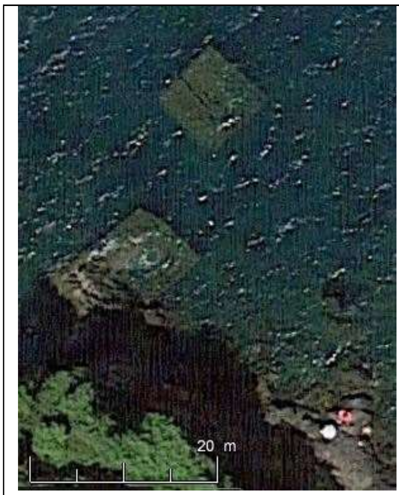
Note that piles made of ashlar (e.g., Fossae Marianae piles) and made of masses of hydraulic concrete that are not nearly-cubic (e.g., breakwaters of Portus, Antium & Terracina, the wall at Les Laurons and numerous fish tanks-*piscinae*) are not listed hereunder.

N°	Ancient name	Modern name	Country	Length (m)	Width (m)
428.1	Tarraco, Tarrakon	Tarragona, Roman breakwater demolished in 1843	Spain		
666	Massalia Graecorum, Lacydon	Marseille, Vieux Port, place Jules Verne	France south		
704	Forum Julii, Forum Julium	Roman naval base at Frejus, with a pila near the Lanterne d'Auguste	France south	6.75	6.2
881	Domitiana positio, Portus Domitianus	Roman villa at Santa Liberata, on the peninsula of Argentario	Italy west	9-10	8
891	Cosa, Cossae, Portus Herculis Cosanus, Etruscan Cusi, Cuthi	Ansedonia	Italy west	6.5	6
900	Centumcellae	Civitavecchia, Molo del Lazzaretto	Italy west	5.3	11
949	Astura, Storas	Torre Astura	Italy west		
953	Port of Circei, Circe	inside Lago di Paola, with access via canal and breakwaters	Italy west	6.5	6
962	Caiete, Caieta, Caeatas, Etruscan Caithi	Spiaggia di Fontania, at Gaeta	Italy west	6	5.5
981	Misenos, Misenum, Misene	Punta Terrone, pilae of the southern breakwater	Italy west	8-9	6-7
982	Misenos, Misenum, Misene	Punta di Pennata, pilae of the northern breakwater	Italy west	12	10
984	Misenos, Misenum, Misene	Punta di Pennata, pilae within the harbour	Italy west		
Oleson		Castello Aragonese di Baia	Italy west	8.5-10.5	7-7.5
Oleson		Cantieri di Baia	Italy west	ca. 8	ca. 7
986	Baiae, Baïes, Portus Baianus, with connection to Lacus Baianus	Baia, two concrete moles over 200 m long	Italy west		
Oleson		Villa dei Pisoni	Italy west		
Oleson		Secca Fumosa is not a port but some kind of platform, with opus reticulatum facing	Italy west	8	8

987	Portus Iulius, Julius, port of Julien, with connection to Lacus Lucrinus	Lucrino, two concrete moles over 200 m long	Italy west	8	8
Oleson	Portus Iulius, Julius, port of Julien, with connection to Lacus Lucrinus	East of eastern breakwater	Italy west	5.5	5
991	Puteoli, Dikaiarcheia, Dicearque, in the Campi Phlegraei volcano district	Pozzuoli, Pouzzoles, Puteoles, in the Campi Flegrei volcano district, pilae of arched mole are under modern breakwater	Italy west	12-15	8-15
Oleson	Puteoli, Dikaiarcheia, Dicearque, in the Campi Phlegraei volcano district	Pozzuoli, Pouzzoles, Puteoles, east of modern breakwater; possibly, the largest known concentration of pilae	Italy west	10	10
993	Nesis	Nisida, very large pila of over 1500 m^3, with opus reticulatum facing	Italy west	14	14
Oleson	Imperial Villa of Pausilypon	Gaiola	Italy west		
994	Imperial Villa of Pausilypon	Imperial villa at Posillipo	Italy west	10	7
994.1	Imperial Villa of Pausilypon	Palazzo degli Spiriti	Italy west	7.5	6
995	Imperial Villa of Pausilypon	Pollion's villa at Porto Marechiaro	Italy west	14	5
Oleson	Imperial Villa of Pausilypon	Villa Rosebery	Italy west		
997	Neapolis	Naples, Piazza Municipio, offshore Roman quay made with wooden caissons	Italy west		
1009	Capraria, Capreae insula	Bagni di Tiberio, near Marina Grande on the isle of Capri	Italy west	7	4
1010	Capraria, Capreae insula	Palazzo a Mare, near Marina Grande on the isle of Capri	Italy west	11	8
1011	Capraria, Capreae insula	Scoglio del Monacone, near the isle of Capri	Italy west		
1013.1	Seirenoussai nesoi, Anthemoessa insulae, Anthemuse, possible Siren islands, no stopover for Odysseus	Isola di Gallo Lungo	Italy west		
1017	Vietri	Punta Fuenti, near Vietri sul Mare	Italy west	12	10
1023		San Marco di Castellabate	Italy west	?	4.5
1028	Scidrus	Roman villa at Cammerelle, near Sapri	Italy west	8	5.5

1246	Hadrianou Hormos, port of Lupiae, Miltopiae?	Porto Adriano, at San Cataldo near Lecce; concrete poured into ashlar cells	Italy Adriatic	?	12
1252	Gnathia	Egnazia, with several pilae, one with opus reticulatum facing	Italy Adriatic	5	3.5
1295	Port of Hatria, Adria	Torre del Cerrano, with several pilae	Italy Adriatic		
3173	Ephesos, Roman port	West side of Panayirdag hill, near Selcuk	TR: West		
3328	Side, Sida	Selimiye, with possible ancient lighthouse	TR: South	?	7.5
3377	Soles, Soli, Soloi, Pompeiopolis	Mezitli, west of Mersin; concrete poured into ashlar cells	TR: South	?	15
3492	Caesarea Palaestinae, Cesaree, Ace, Sebastos	Qesaria, Caesarea Maritima, Roman port of Herod, built from 21 to 10 BC, with Drusion lighthouse; concrete poured into timber caissons	Israel		
3498	Apollonia, Sozousa	Arsuf, crusader castle	Israel		
3934	Alexandria, Portus Magnus and its Pharos	Alexandria, Antirhodos: concrete poured into timber caissons	Egypt: Med Sea	15	8
Oleson	Alexandria	Alexandria, SE of Fort Qait Bey, dock Ball Trap	Egypt: Med Sea		
4076	Leptis Magna, Lepcis Magna, Lepcitani Septimiani	Leptis Magna, Lepcis Magna, eastern outer breakwater	Libya		
4137	Thapsus	Ras Dimass, near Bekalta, south of Monastir, large breakwater of the south port, with concrete poured into timber caissons & possible lighthouse	Tunisia		
4146	Horrea Caelia, Heraklea	Hergla	Tunisia	3	3
Oleson	Carthago, Carthagine, Punic Qart Hadasht, Knyn, port of Salammbo	Carthago, commercial port, Neptune block	Tunisia	18	9
4237	Thapsa, Tipasa	Tipaza, sheltered by two islets	Algeria	10	3
4244	Psamathos	isle of Joinville in front of Cherchel, with ancient lighthouse	Algeria	8	6

Pilae seen on Google Earth



Santa Liberata

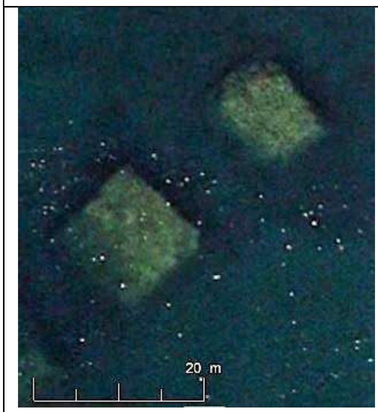
Santa Liberata

Cosa

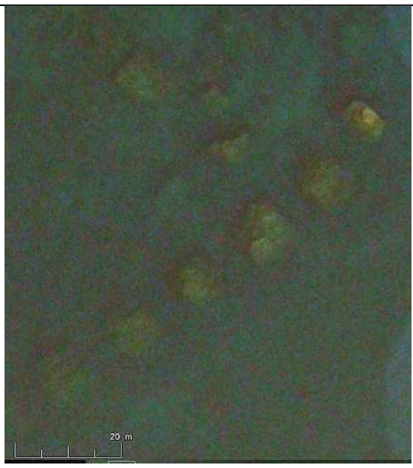
Circei

Caieta

Misenum, Punta Terrone

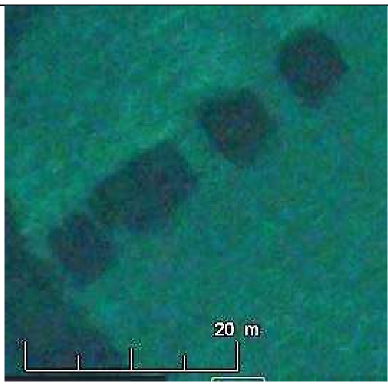


Misenum, Punta di Pennata

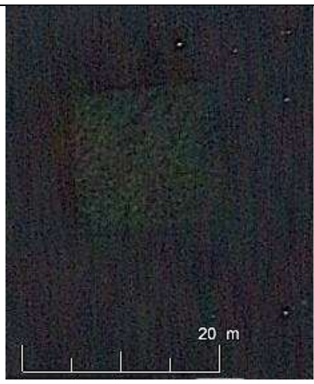

Secca Fumosa

Castello Aragonese di Baia

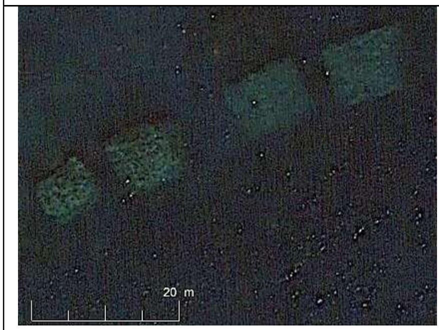
Portus Iulius



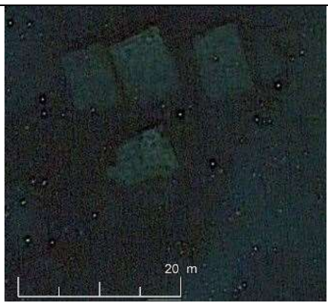
Portus Iulius



Nesis



Pausylipon, Imperial villa

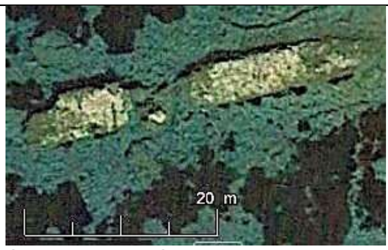


Pausylipon, Palazzo degli Spiriti

Pausylipon, Porto Marechiano

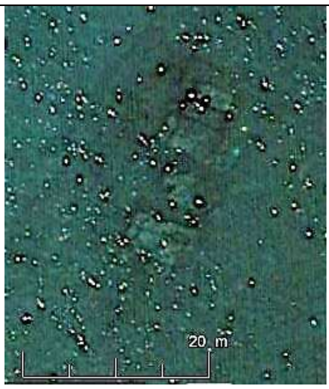
Capri, Palazzo a Mare east

Capri, Palazzo a Mare west



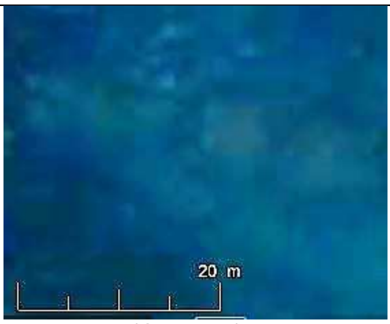
San Marco di Castellabate

Scidrus (Sapri)



Gnathia (Egnazia)

Side (Selimiye)

 Horrea Caelia (Hergla)	 Psamathos (Cherchel)	

4.12 Lighthouses and beacons

As several very good reviews of ancient lighthouses and navigational aids have been provided in the past, our aim is not to add another review here, but just to supply a few pictures made by the author[135].

Except for Alexandria and Rome, lighthouses and beacons are rarely mentioned in ancient literature. The possibly earliest mention of a lighthouse is by Homer (Iliad, 19, 401):

> "Like the gleam that sailors catch at sea from a fire burning on a lonely upland farm, when the winds drive them unwillingly from home over the teeming seas, such was the gleam that went up into the sky from Achilles' ornamented shield." (transl. Jones, 2003).

The light is thus provided by Achilles' large and beautiful shield, which is symbolically located today at his tomb near Cape Sigeum.

Homer mentions Pharos Island, but obviously without any lighthouse at that time, as the famous Pharos lighthouse was built much later, around 280 BC.

Also Herodotus seems to tell about a light-emitting-column (Hist. 2, 44):

> "I took a ship for Tyre in Phoenicia, where I had learned by inquiry that there was a holy temple of Herakles. There I saw it, richly equipped with many other offerings, besides two pillars, one of refined gold, one of emerald: a great pillar that shone at night;" (transl. Godley, 1920).

Later on, Strabo mentions a watchtower on the Nile delta (Geog. 17, 1, 18):

> "After the Bolbitine mouth there runs out to a great distance a low and sandy promontory. It is called Agnu-ceras (or Willow Point). Then follows the watch-tower of Perseus, and the fortress of the Milesians." (transl. Bell, 1903).

Strabo does not mention any light emitted by this watchtower.

In addition, Josephus Flavius mentions two towers at the entrance of the port of Caesarea Maritima (Israel) which may have been lit (Jewish Wars, 1, 21 & Jewish Antiquities, 15, 9).

Lighthouses are most emblematic landmarks, but many smaller beacons guided seafarers at the entrance of harbours and estuaries, as described by Strabo in the Rhône delta (France) (Geog. 1, 4, 8) and by Rutilius Namatianus at Vado Ligure (Italy) in 417 AD (De reditu suo, 1, 453):

> "Nevertheless, the mouths [of the Rhodanus] still remain difficult of entrance for ships, not only on account of the impetuosity of the river and the silting up, but also of the lowness of the country, so that in foul weather one cannot descry the land even when close to it. Wherefore the Massiliotes set up towers as beacons, because they were in every way making the country their own". (Loeb Classical Library, 1923).

> "Entering on the region of Volaterra, appropriately called "The Shallows," I thread my way through the deep part of the treacherous channel. At the bow the look-out watches the water beneath and gives directions to the helm beyond, guiding the stern with warning shouts. A boundary on each side marks puzzling narrows by a pair of

[135] The major web site on this subject is: https://www.pharology.eu/ by Ken Trethewey: TRETHEWEY, K. (2018) "Ancient Lighthouses, and other lighted aids to navigation", Jazz-Fusion Books, Cornwall, UK.
CHRISTIANSEN, J. (2011) "Les phares et la signalisation maritime à l'époque romaine", Université Lumière (Lyon II), Mémoire de Master 2, (269 p).
KOUNTOURA GALAKI, E. (2021) "A Light in the Darkness: Monastery Lighthouses in the Aegean Sea and Surrounding Coastal Regions", in Seasides of Byzantium, Harbours and Anchorages of a Mediterranean Empire, Byzanz zwischen Orient und Okzident 21, Mainz 2021, (p 131-142).
A brief overview is given on: https://en.wikipedia.org/wiki/History_of_lighthouses

> trees and presents a line of piles hammered in there: to these it is the custom to fix tall laurels easy to see because of their branches and bushy foliage, so that, although the shifting bank of thick mud shows its mass of sea-weed, a clear passage may keep the guiding-signs unstruck." (Loeb Classical Library, 1934).

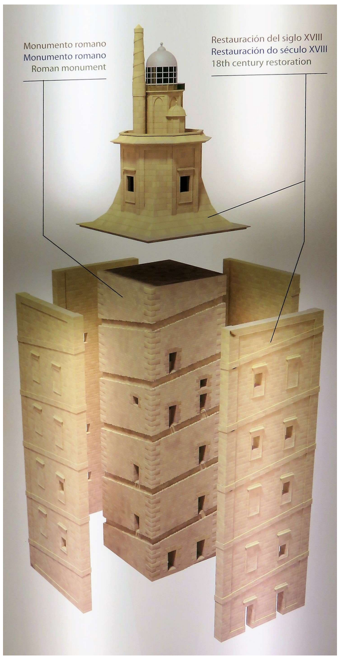
Despite the limited number of ancient texts, many pictures were found on coins, reliefs, and mosaics, and around 150 towers found by archaeology are proven or potential lighthouses.

Pictures made by this author concern Leptis Magna (2000), Brigantium (2017), Fréjus (2018) and Cadiz (2023).

The Leptis Magna lighthouse (Libya) is at the eastern end of the northern coastal protection. It was built around 200 AD.

Leptis Magna, remains of ancient lighthouse
(A. de Graauw, 2000).

The Tower of Hercules is the ancient Farum Brigantium near A Coruna (Spain). It dates from the 1st c. AD and was renovated in the 18th c. by adding a new external wall as shown on the picture below taken on site. The ancient foundations are still visible underneath the new construction.



Tower of Hercules (A Coruna, Spain) showing reconstructed outer wall and ancient foundation level (A. de Graauw, 2017).

Fréjus (France) had at least three navigation beacons: one outside the port on the Ile du Lion de Mer, one at the Triton Monument on the northern side of the port entrance, possibly a lighthouse, and one near the Lanterne d'Auguste on the southern side of the port entrance. These structures date from the 1st c. AD.

Fréjus (France), the Lanterne d'Auguste is not a lighthouse but an unlit beacon located near a larger structure 'M7' that may have supported a lighthouse (A. de Graauw, 2018).

[Cadiz](#) (Spain) is home of the ancient Phoenician harbour of Gadir, later called Gades. Its foundation dates to at least the 9th c. BC. The first settlement was on an island called Erytheia, now connected to the south part of the city and to the long sandy spit called Kotinoussa.

Cadiz, Gadir (Spain) with Ponce Canal between Erytheia island and Kotinoussa mainland
NB: top is East
(A. de Graauw, 2023).

The Cadiz Archaeological Museum features a remarkable graffito of a lighthouse. It seems to be dated from the 4th to the 5th c. AD[136]. However, it is not known where this lighthouse stood and when it was erected. Considering the many shipwrecks on the reefs near the northern side of the Ponce Canal, it should be envisaged that such a lighthouse would be most useful at today's Castillo de San Sebastian on the south side of La Caleta.

Cadiz, Gadir, Gades (Spain), 4th – 5th c. graffito of a lighthouse,
approx. size 40 x 30 cm
(A. de Graauw, 2023).

[136] BERNAL CASASOLA, D., 2009, "El faro romano de Gades y el papel de los Thynnoskopeia en el Fretum Gaditanum", in ARIAS, F., FERNÁNDEZ OCHOA, C. and MORILLO, A. (eds.), Torre de Hércules. Finis Terrae Lux. Simposio sobre os Faros Romanos e a Navegación Occidental na Antigüidade (A Coruña, Brigantium 20), (p 85-108).

4.13 Pierced stones

"Pierced stones" (τρητοῖο λίθοις, tretoi lithois) are found on ancient quays. The piercing may be horizontal or vertical. These stones have sometimes all be taken as mooring devices, but it might be of interest to have a closer look.

If you are interested in anchors, please refer to the chapter on ancient ships.

The Torlonia relief clearly shows a mooring ring with horizontal piercing and a mooring line. The unloading bridge with a man carrying an amphora is also clearly pictured.

Detail of the Torlonia relief

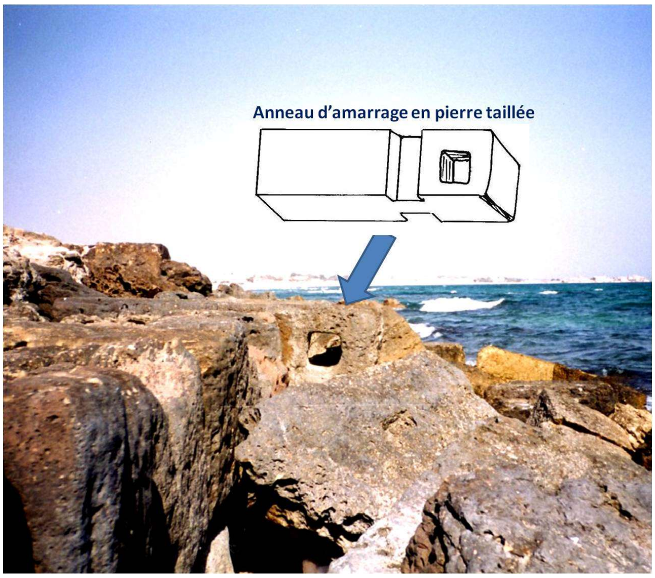
Large mooring stones were found on the quays of the hexagonal Portus Trajanus:
2.20 x 1.10 x 0.70 m with a hole of 0.45 m.

Mooring ring at Portus Trajanus, Roma (Testaguzza, 1970, p 170).

Pompei's Porta Marina hosts a wall with many similar pierced mooring stones, but its use as a quay is uncertain.

Mooring rings at Porta Marina, Pompei (ARTE, 2018).

Another mooring ring with horizontal piercing can be seen on the north coast of Leptis Magna (which proves, by the way, that ships came on this side, perhaps before construction of the port inside the estuary). Note also the tenon and mortise system to attach the block inside the quay.



Mooring ring, north coast of Leptis Magna
(Photo A. de Graauw, 2000)

Mooring stones with vertical piercing are found also, e.g., on the west quay of Leptis Magna and recently at Boca do Rio (Algarve). These are fairly light structures.

Mooring stone at Boca do Rio (Algarve, Portugal)
(archaeologynewsnetwork.blogspot.com)

Mooring stone at Leptis Magna
(Photo A. de Graauw, 2000)

Only two cases of bollards were found, one located on the isle of Delos[137] and one in Carthago[138].

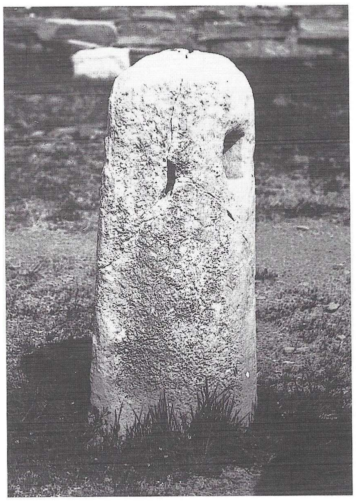


Fig. 2. — Borne d'amarrage
devant le Portique de Philippe.

Mooring bollard on the quay of the Delos Sacred Port (Duchêne, 2001).

Fig. 9 – Mooring stone in grey granite from the S mole near Roman harbour entrance. The hole marks the probable setting of a timber crossbar and the unweathered lower part would have been embedded in the quayside.

Mooring bollard found at Carthago (Hurst, 2010)

Belova's team in Alexandria[139], reported a ca. 0.10 m hole near the edge of many large breakwater blocks (2 x 2 x 1 m).
These holes have probably been used for ropes, either during construction of the structure, and/or for mooring ships later on.

A similar case was found at Phalasarna (Crete) where a ca. 0.10 m hole was found on the edge of a quaywall block.

(Photo A. de Graauw, 2022)

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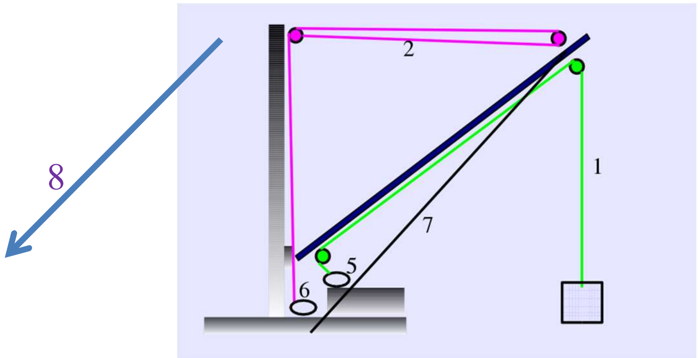
[137] DUCHENE, H., and FRAISSE, P., 2001, "Le Paysage portuaire de la Délos antique", Ecole Française d'Athènes, (192 p).

[138] HURST, H., 2010, "Understanding Carthage as a Roman Port", Bollettino di Archeologia on line I, Volume speciale B/B7/6, ROMA 2008 International Congress of Classical Archeaology, (p 49-68).

[139] BELOVA, G., et al., 2019, "Russian underwater archaeological mission to Alexandria, General report (2003-2015)", Egypt and neighbouring countries 3, (p 1-31).

However, heavier structures are found also ... Most goods had to be loaded/unloaded on men's back. The heavier goods (e.g., wild animals in cages that transited through Leptis Magna on their way to Rome's arenas) would perhaps require some kind of machinery.

According to Wikipedia "A derrick is a lifting device composed of one tower, or guyed mast (guy lines 8 on the sketch below), such as a pole which is hinged freely at the bottom. It is controlled by lines (2 & 7) powered by some means such as man-hauling or motors (6), so that the pole can move in all four directions. A line runs down and over its bottom with a hook on the end, like with a crane (1 & 5). It is commonly used in docks and on-board ships".



Derrick

This typically marine lifting device is not mentioned by Vitruvius who was more interested in lifting devices used for construction of buildings (Vitruvius, de Architectura, 10, 2): "All devices described above can also be used for loading and unloading ships, some upright, others laid down on pieces of timber that are easy to move. One may also place the same cables and the same pulleys on the ground in order to pull ships out of the water"[140]
The derrick is nevertheless an obvious concept for any sailor used to handle mast, boom and topping lift.

The main interest of a derrick is that it can turn the load laterally by means of the lateral lines (7 on the sketch above). The vertical force is taken over by the vertical mast resting on a strong support. The horizontal force induced by the cantilever is taken over by two guy lines (8) placed on the land side behind the mast in order not to hinder the lateral movement of the load.

We suggest that the heavy-duty pierced stones found in Aquileia and in Leptis Magna might host the foot of a derrick mast.

Possible foot-hole of a derrick mast at Aquileia
(Photo A. de Graauw, 2010)

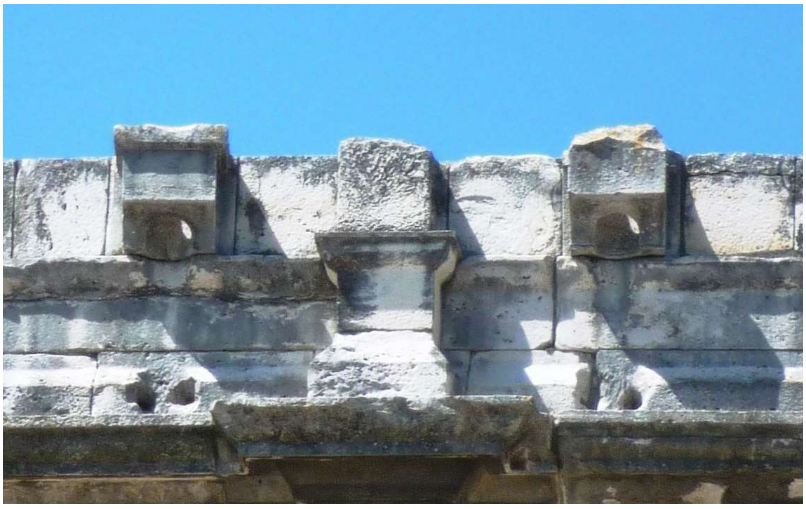
[140] http://www.unicaen.fr/recherche/mrsh/erlis/3078

https://journals.openedition.org/etudesanciennes/310

Possible foot-holes of derrick masts
at Leptis Magna
(Photo A. de Graauw, 2000)

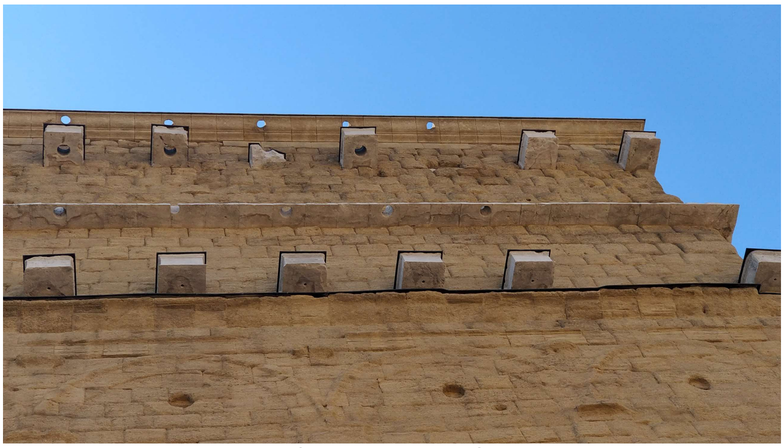
It is interesting to compare these derricks to the poles used to support the “velum” in theaters and amphitheatres[141]. They can be seen in Rome and in Nimes (France):

- 240 poles of 450 x 550 mm for Rome’s Colosseum[142],
- 120 poles with diameter 300 mm Nimes’ arena.



Feet of velum poles at Nimes.
Note the mark of the poles on the wall and the clamp holes.
(Photo A. de Graauw, 2011).

A similar, even more sophisticated, velum-pole system can be seen at the Orange theatre:



Feet of velum poles at Orange.
Note the three superposed holes above the pedestal stone.
(Photo A. de Graauw, 2020).

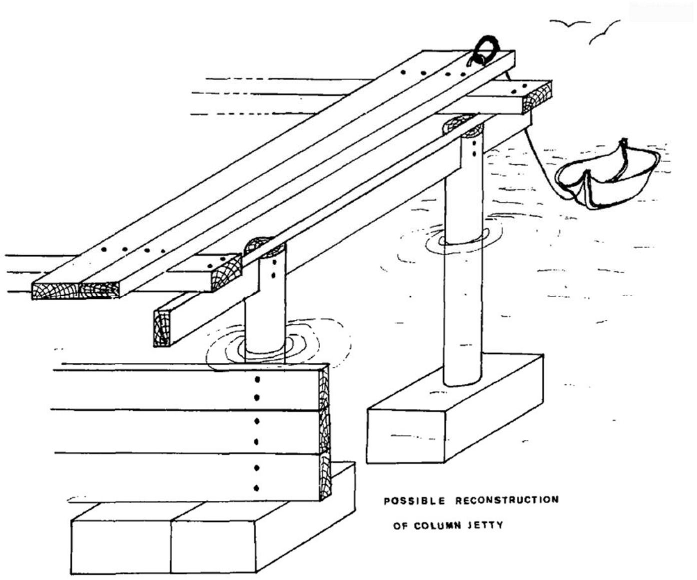
The semi-circular shape at Leptis Magna is still a bit mysterious …

These pierced stones are after all perhaps just meant for some kind of timber mooring pole, but be careful not to get your fingers and mooring lines caught between the pole and the wall …

[141] MADELEINE, S., 2010, "La restitution d’un vélum sur le théâtre de Pompée", La technologie gréco-romaine entre restitution et reconstitution, Lire entre les lignes, mettre en les mains, Mar 2010, Caen, France, (p 43-68). MADELEINE, S., 2015, "Essai de typologie du vélum sur les théâtres romains", Autour des machines de Vitruve, L’ingénierie romaine : textes, archéologie et restitution, Jun 2015, Caen, France, (p 65-82).

[142] https://en.wikipedia.org/wiki/Colosseum

A last group of pierced stones was found at the south anchorage of Caesarea (Sdot Yam, Israel) where two rows of 0.5 x 0.6 x 1.3 m stones, each with one 0.20-0.25 m hole, were found. This alignment is 75 m long and 5 m wide, looking very much like a jetty from the beach to some nearshore reefs. The author (Galili, 1993) assumes that the stones were used as a base for timber piles supporting a jetty[143]. Similar stones were found near Saintes Maries de la Mer (0.7-0.8 m stones with hole of 0.22-0.25 m diameter) (Long, 2016)[144] and a similar stone (1.15 x 0.83 m with twin holes of 0.27 m) was found at Myndos[145].



Pierced stones as a base for piles of a timber jetty at Sdot Yam (Israel), acc. to Galili (1993).

Fig. 8 : Les Saintes-Maries-de-la-Mer : vues des blocs de calcaire percés d'un orifice central (clichés : K. Boscolo).

Pierced stones as a base for piles of a timber jetty at Saintes Maries de la Mer (France), acc. to Long (2016).

143 GALILI, E., et al, 1993, "Underwater surveys and rescue excavations along the Israeli coast", IJNA, 1993, 22.1, (p 61-77).

144 LONG, L., and DUPERRON, G., 2016, "Navigation et commerce dans le delta du Rhône durant l'Antiquité : bilan des recherches sur le port fluvial d'Arles et ses avant-ports maritimes", Revue archéologique de Narbonnaise, Suppl. 44, Actes du colloque international tenu à Montpellier du 22 au 24 mai 2014, (p 199-217).

145 DUMANKAYA, O., 2015, "East-harbour mole at Myndos", TINA, Sayi, N°3, (p 12-45).

Pierced stones have been used at all times.
Here is a case of “mooring stone” probably meant for the horse of a knight of Malta.
(Photo A. de Graauw, 2022).

4.14 Defensive harbour chains

A "limen kleistos" is a port whose access was restrained by a closing device, usually with a narrow entrance[146]. This closing device, consisting of a gate system (kleithron, kleithra) or a chain system (alyseis), could be used both to stop the enemy from entering the port and to trap the enemy once inside the port, as mentioned by Dio Cassius (Hist, 51, 9) at Paraetonium (Egypt):

“Gallus, it seems, caused chains to be stretched at night across the mouth of the harbour under water, and then took no measures openly to guard against his opponents but contemptuously allowed them to sail in with perfect immunity. When they were inside, however, he drew up the chains by means of machines, and encompassing their ships on all sides - from the land, from the houses, and from the sea - he burned some and sank others.” (translation Lacus Curtius).

Another story is also told by Dio Cassius (Hist, 12, Frag.) at the port of Hippo Diarrhytos:

“The natives put chains across the mouth of the harbour, and the invaders found themselves in an awkward situation, but escaped by cleverness and good fortune. They made a quick dash at the chains, and just as the beaks of the ships were about to catch in them, the members of the crews moved back to the stern, and so the prows were lightened and cleared the chains; and again, when all rushed into the prows, the sterns of the vessels were lifted high into the air. Thus, they effected their escape […]”. Note that as they "escaped", they were trapped inside the port.

Ancient authors mention least 8 harbours with chains at the entrance:

- Syracusa, Sicily, in the 3rd c. BC (Frontinus, Strategemata, 1, 5),
- Byzantion-Bosphorion, in the 2nd c. AD (Dio Cassius, Hist, 75, 10, and Zonaras, Constantin, 120, citing Dio Cassius),
- Byzantion-Kynegoi, in the 2nd c. AD (Dio Cassius, Hist, 75, 10, and Zonaras, Constantin, 120, citing Dio Cassius),
- Andriake, near Antalya, in the 1st c. BC (Appian, Civil wars, 4, 10, 82),
- Alexandria Portus Magnus (3 ports), in the 1st c. AD (Lucan, Pharsale, 10, 57),
- Paretonium, Marsa Matruh in Egypt, in the 1st c. BC (Dio Cassius, Hist., 51, 9),
- Carthage, in the 2nd c. BC (Appian, Libyca, 96) and in the 6th c. AD (Procopius, War against Vandals, 1, 20),
- Hippo Diarrhytos, Bizerte in Tunisia, in the 3rd c. BC (Dio Cassius, Hist., 12, fragments reported by Zonaras, 8, 16).

In the particular case of Chalkedon, near Istanbul, in the 1st c. BC (Appian, Mithridatic, 10, 71), the bronze chain was used only to close a gate system. Another particular use of a chain was made by Polycrates when he symbolically linked Delos island to Rhenea island with a chain (Thucydides, Pelop. wars, 3, 104). Using Remmatia island located between Delos and Rheneia, the length of this chain must have been at least 425 m (250 + 175 m) and it must have been placed on the seabed as it seems unlikely that it could be tense because of the large force this would require.

A system closing a harbour entrance (“phragmata”) is mentioned by Aeneas Tacticus in the 4th c. BC (Siege Defense, 8) and by Philo of Byzantion in the 3rd c. BC (Poliorcetica, 3, 29), but they do not explicitely mention chains and the surviving text of Philo is incomplete and its translation is debated[147]. Aeneas Tacticus (Siege Defense, 11) mentions the harbour of Chios where it is possible “to draw the barrier (“kleithron”) of the harbour up on land for

[146] Lehmann-Hartleben, 1923, p 65-74, Blackman, 2013, Mauro, 2020 & 2022, and Arnaud, 2023.

[147] τὰ δὲ στόματα τῶν λιμένων φράττειν τμητοῖς κλείθροις, ἐν οἷς εἰσι ἀνφιδέαι περιτρέχουσαι καὶ στρογγύλαι, σιδηροῦς κόλπους ἐχούσαι, "to fence the passes of harbours with kleithra in which are round female hinges, with iron eyes", acc. to Arnaud, 2023.

drying and caulking" (translation Lacus Curtius) which points at a timber structure like a gate. In addition, Halieis may have been a "limen kleistos" with gates that could be closed (Jameson, 1969, contradicted by Frank Frost in 1985).

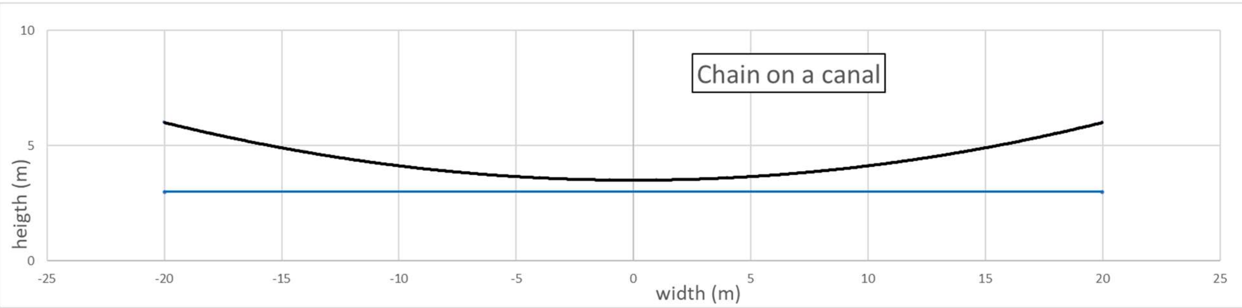
Chains stretching across a harbour entrance are mentioned by Vitruvius (Arch, 5, 12): "erect a tower on each side, wherefrom chains ("catenae") may be suspended across by means of machinery" (translation Lacus Curtius). Archaeology has shown that chains were most probably also installed at the entrance of Phalasarna (Hadjidaki, 2019) and possibly at Myndos (Dumankaya, 2015). Many harbours (listed below) are known or suspected to have been "kleistos" but it is usually not known if chains (or gates) were used.

In order to install a chain (or gates) to close the entrance of a harbour, the width has to be limited. Except for Motya with an entrance width of 5 m (but this place is not considered any more as a military harbour), the smallest entrance width known is at Phalasarna (around 10 m). Other narrow entrances range between 10 and 30 m (Naupaktos, Lechaion, Salamis, Aegina, Halieis, Amathus, Andros, Methymne, Miletos, Knidos, Phaselis, Leuke Akte, Apollonia, Gummi, Carthage, Caesarea Mauretaniae) and up to 75 m, as far as we can see from today's remains (Kantharos, Munychia, Larymna, Thasos, Chalkedon, Elaia, Kos, Rhodos, Patara, Kydonia, Paphos, Seleucia Pieria). Remains seen on Google Earth seem to show some entrances around 100 m wide (Corcyra, Anaktorion, Oiniadae, Zea, Mytilene, Kaunos, Kyrenia). Larger entrances may possibly also have had a closing chain (Myndos: 117 m acc. to Dumankaya, 2015; Golden Horn: 650 m acc. to Kastenellos, 2017[148], and even nearly 1100 m between both Hieron's on the Bosphorus acc. to Aydingün, 2022).

Considering a unit weight of 25 kg per meter for a chain with 10 cm shackles, a length of 10 m (250 kg) is not a problem to be lifted by capstans. A 40 m-chain weights around one ton and can also be lifted, but a sag will be generated and it is interesting to know how much this sag is depending on the traction force.

The mathematical formulation was written down by Leibniz in 1691, after some discussions between people like Galileo, Bernoulli and Huygens, just to say here that it is not an easy matter. Anyhow, this formulation can now be used to compute the horizontal force required on a chain stretching between the lateral banks of a canal. If the chain is fastened 3 m above the water level with a sag of 2.5 m, it will hang at least half a meter above water, meaning that a trireme cannot pass over or under it.

On a canal 40 m wide and 3 m deep, the chain looks as follows according to Leibniz's famous "catenary equation":



Chain on a 40 m wide canal, fastened at 3 m above the water level and with a 2.5 m sag.

The computation shows that the required chain length is 40.4 m, just a little more than the canal width. The required horizontal traction force is about 2 tons, i.e., about twice the mass of the chain, on each side of the canal. This should not be a problem with Roman capstans located on both lateral quays of the canal at 3 m above the water level.

148 A chain of around 650 m seems to have been installed in the 5th c. near Yeralti mosque at the Golden Horn entrance.

A smaller traction force of 1 ton would induce a longer chain with a larger sag. With a sag of 5 m, the height of fastening the chain on the banks would increase from 3 m to 5.5 m, requiring towers on both lateral quays of the canal. A wider canal, e.g., 150 m, would require a heavier chain (3.75 tons) and more traction from both banks (14 tons) in order to have a 5 m sag.

Such towers are perhaps among those meant by Vitruvius (Arch., 10, 1) when he writes about “innumerable different machines, which it is unnecessary here to discuss, since they are so well known from our daily use of them, such as wheels generally, the blacksmith's bellows, chariots, calêches, lathes, and other things which our habits constantly require.” (translation Lacus Curtius), which implies that machines were frequently installed in/on towers/lathes.

Our computations show that a chain can be stretched between both sides of a canal by means of a traction force not exceeding 10-15 tons, which may be considered feasible with Roman equipment like capstans and treadwheels.

It has been suggested that the chain closing a harbour entrance would need to be supported by floating pontoons (Diels, 1920). Although so-called “booms” have been used in the Middle Ages with wider entrances of 300 m and more, our computations do not confirm the need for such an arrangement for entrances smaller than 100 to 150 m.

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List of "limenes kleistoi" (LK)

Lehmann-Hartleben was the first to provide a list of (42) "limenes kleistoi" in 1923. We now have around 90 of them (known "X" or suspected "X?", some with a chain "C" or gate(s) "G") and with varying entrance-channel widths ranging from 5 m to 120 m.

NAME	NAME_MOD	COUNTRY	LATITUDE	LONGITUDE	LK	CH	Width
Centumcellae	Darsena Romana in the port of Civitavecchia	Italy West	42.09506	11.78781	X?	?	?
Lokroi Epizephyrioi	Locri	Italy West	38.20770	16.23680	X?	?	?
Syracuse, Syrakus, « Small Port », Lakkios, Achradina	Porto Lachio, near Via Diaz at Syracuse	Italy Sicily	37.06930	15.29000	X	G	?
Motye, Motya	Mozia	Italy Sicily	37.86350	12.46600	X?	?	5
unnamed	Marsaxlokk	Malta	35.83941	14.54805	X?		
Port of Ambrakia	Phidokastro, near Arta on R Arachthos	GR: North-West	39.04100	20.95300	X	?	?
Anaktorion	near Nea Kamarina	GR: North-West	38.92200	20.84330	X?	?	100?
Oiniadae	Katoxi, Trikardo, now inland	GR: North-West	38.41143	21.19364	X?	?	100?
Naupaktos	Lepanto	GR: North-West	38.39220	21.82900	X?	?	30?
Nisa, Nisaea	Roman fort at Agios Nicolas, near Megara	GR: Attica +	37.97850	23.35450	X?	?	?
Salamis, Salamine, inner port	Bay of Ambelaki, on the isle of Salamis	GR: Attica +	37.950162	23.538702	X?	?	15
Piraeus, Kantharos	The Piraeus	GR: Attica +	37.94200	23.63775	X	?	50
Zea	The Piraeus	GR: Attica +	37.93678	23.64859	X	?	96
Munychia, Munychie	Mounikhias	GR: Attica +	37.93718	23.66039	X		54
Larymna	Larimna	GR: Attica +	38.56608	23.28780	X?	?	45?
Potidaia	Nea Poteidaia, on Halkidiki, Chalcidique peninsula	GR: North-East	40.19641	23.33897	X?	?	?
Aigina, Aegina	Roman naval base South of Kolonna hill, on Isle of Egina	GR: Peloponnese	37.74765	23.42464	X?	?	30
Halai, Halieis, Halia	Portocheli	GR: Peloponnese	37.31600	23.15186	X?	G	20
Gytheion	Githio	GR: Peloponnese	36.76190	22.5688	X?	?	?

Lechaion, Lecheum	Lechion	GR: Peloponnese	37.93213	22.88619	X	?	20
Heraion	Perachora, near Limni Vouliagmenis	GR: Peloponnese	38.02787	22.85268	X?	?	?
port of the Pheacians, naval base of Alkinoos, Corcyra	Ormos Garitsa, Kokotou district on Corfu	GR: Ionian Isl.	39.60890	19.92325	X?	?	100?
Palaiopolis	Paleopolis, on the isle of Andros	GR: Cyclades Isl.	37.81434	24.82498	X?	?	20?
Paros, Minois	Paros, Paroikia Bay, on the isle of Paros, Bara	GR: Cyclades Isl.	37.08810	25.15162	X	?	?
Thasos naval base	Thassos, Limenas	GR: Eastern Isl.	40.78130	24.71220	X	?	55
Samothraca insula	Paleopoli, on the isle of Samothrace	GR: Eastern Isl.	40.50100	25.53000	X?	?	?
Methymne	Mithimna, on north coast of the isle of Lesbos	GR: Eastern Isl.	39.368928	26.167595	X?	C?	12
Mytilene, naval base	on south side of Mytilini, on the isle of Lesbos	GR: Eastern Isl.	39.10571	26.55778	X	?	100?
Chios, Berenice de Chios	Chio, with Roman quarry at Latomi, on the isle of Chios	GR: Eastern Isl.	38.371887	26.139368	X	?	?
Pythagoreion, Samos	Pythagoreio, on the isle of Samos	GR: Eastern Isl.	37.68932	26.94356	X	G?	?
Kos, Cos	Naval base at Mandraki harbour, on the isle of Kos	GR: Eastern Isl.	36.89477	27.28650	X	?	75?
Rhodos, Small port	Naval base at Port Mandraki	GR: Eastern Isl.	36.45097	28.22624	X	?	50
Byzantion, Prosphorion, Bosphorion	Marmaray Sirkeci railway station, in the Golden Horn	TR: Bosphorus N	41.01570	28.97840	X	C	?
Byzantion, Kynegoi	Balat, Fener district, near Ferruh mosque, in the Golden Horn	TR: Bosphorus N	41.03440	28.94570	X	C	?
Genesintis, Boona	Persembe in the bay of Vona	TR: Black Sea	41.06030	37.78400	X	?	?
Chalkedon	Kadiköy in front of Istanbul, on R Kurbagalidere	TR: Marmara S	40.98290	29.03420	X	G	50?
Cyzicos	on the isthmus of the peninsula of Erdek	TR: Marmara S	40.38130	27.88500	X	?	?
Falasarna, Phalasarna	Falasarna, Phalasarna.	GR: Crete North	35.51075	23.56944	X	C?	10?
Cydonie, Kydonia	Khania, Chania	GR: Crete North	35.51900	24.02150	X	?	75?
Salamis, Salamine	7 km North of Famagousta, on R Pedieos, R Gialias	Cyprus	35.17509	33.91162	X	?	?
Kition	Larnaca, slipways at Bamboula	Cyprus	34.92042	33.63290	X	?	?
Amathus, Amathonte	10 km East of Limassol	Cyprus	34.70958	33.14389	X?	?	20

Nea-Paphos	Kato Paphos	Cyprus	34.75411	32.41060	X	?	55
Soloi, Soli	Potamos tou Kambou, West of Gemikonagi	Cyprus	35.14060	32.81220	X	?	?
Keryneia	Kyrenia	Cyprus	35.343834	33.3233	X	C	100
Canae, Kanai, Kane Prom.	Karadag, near Bademli, island now connected to mainland	TR: West	39.03950	26.81210	X	?	?
Elea, Elaia, Elee, port of Pergamon	Naval base and commercial port at Kazikbaglar	TR: West	38.94270	27.03870	X?	?	60?
Palaia Smyrna, Naulochon	Bayrakli, Izmir	TR: West	38.46510	27.17100	X	?	?
Smyrna, Eurydikeia	Konak, Izmir	TR: West	38.4198	27.1336	X?	?	?
Klazomenai	Liman Tepe, near Urla Iskele	TR: West	38.36431	26.77518	X?	?	?
Erythrai	Ildir, in front of Chios	TR: West	38.38080	26.48110	X?	?	?
Hellenistic port of Ephesos, Arsinoe	West side of Panayirdag hill, near Selcuk	TR: West	37.94100	27.34080	X	?	?
Priene	Güllübahce	TR: West	37.65915	27.29666	X	?	?
Miletos main port, Dokimos Harbour	Milet, Lion Harbour	TR: West	37.53170	27.27950	X?	?	30?
Myndos, Neaoplis	Gümüslük "East Harbour", Dogu Limani	TR: West	37.05476	27.23331	X?	?	117
Halicarnassus, port of Pedasa, Zephyrion	Bodrum, small naval base inside modern marina?	TR: West	37.03395	27.42900	X	?	?
Halicarnassus, Portus Secretus?	Bodrum, South of fort	TR: West	37.03030	27.42850	X?	?	?
Knidos, Cnidus, naval base, ancient Triopion	Cnide West, former isle of Triopion now connected to mainland, Cape Kriou	TR: West	36.68629	27.37182	X	?	25
Kaunos (between towers T4 & T5)	Sülüklü Gölü, near Dalyan on R Dalyan	TR: South	36.82405	28.61893	X	?	110
Patara, Arsinoe, port of Xanthos, on R Xanthos	Gelemis, with ancient lighthouse	TR: South	36.26360	29.30813	X	?	40?
Andriake, port of Myra	Andraki, near Demre	TR: South	36.22647	29.95618	X	C	?
Phaselis, Phaselide	near Tekirova	TR: South	36.52510	30.55310	X?	?	18
Attaleia, port of Perge	Antalya	TR: South	36.88440	30.70230	X?	?	?
Seleucia Pieria, home port of Classis Syriaca fleet	Cevlik, port of Antioch of Daphne, inner harbour at the toe of the hill	TR: South	36.11640	35.92920	X	?	60
Laodicea	Lattaquie, Lattakieh, at Ras Ziaret	Syria	35.51317	35.76989	X?	?	?
Siduna, Sidon	Saïda, Saida	Lebanon	33.56450	35.36828	X	?	?

Tyre, "Sidonian port"	Sour, North port	Lebanon	33.27602	35.19534	X	?	?
Port of Aksaph, port of Megiddo	Tell abu Hawam, Haifa	Israel	32.80140	35.01940	X?	?	?
Stratonos Pyrgos	Caesarea Maritima, pre-Herodian port	Israel	32.50630	34.89210	X	?	20?
Ezion Geber? Gasion Gabel?	Geziret Faraun, Pharaoh's island, Coral island	Gulf of Aqaba	29.46240	34.85884	X?	?	?
Asabon	Jazirat al-Ghanam, Cape Musandam, Mussendom	Gulf	26.41300	56.55500	X?	?	?
Girsu	Tell Telloh	Gulf	31.56200	46.17700	X?	?	?
Ur, Uri, Sumerian Urim, North Port	Tell el-Muqayyar	Gulf	30.96250	46.10306	X	?	?
Alexandria, Portus Magnus, home port of Classis Alexandrina fleet	Royal port: near Palace	Egypt: Med Sea	31.20557	29.89443	X	C	100?
Kibotos	port located inside the Port of Eunostos	Egypt: Med Sea	31.18860	29.88205	X?	?	?
Leuce, Leuke Akte	Ras el-Kanayis, Ras Kanaïs	Egypt: Med Sea	31.23780	27.86690	X?	?	15
Paretonius, Paraetonium, Ammonia	Marsa Matrouh, Matruh, Bates' island, Geziret el-Yehudiyeh	Egypt: Med Sea	31.36102	27.26687	X?	C	?
Chersis, Xherson, Aphrodisias insula	el-Kerchi, Kersa, Chersa islets 15 km NW of Derna	Libya	32.83871	22.50011	X?	?	?
Apollonia, port of Cyrene	Susah, Soussa	Libya	32.90409	21.96733	X?	?	20
Gummi	Mahdia	Tunisia	35.50562	11.07931	X	?	15
Ruspina	Monastir, islet La Tonnara (el-Ghedamsi islet)	Tunisia	35.78247	10.83257	X?	?	?
Hadrumete	Sousse	Tunisia	35.82832	10.64029	X?	?	?
Carthage	Carthago, rectangular commercial port	Tunisia	36.84150	10.32500	X	C	21
Carthage	Cothon of Carthage: circular naval base	Tunisia	36.84150	10.32500	X	?	?
Hippo Diarrhytos	Bizerte	Tunisia	37.27618	9.89406	X	C	?
Caesarea Mauretaniae, Iol	Cherchel, western basin	Algeria	36.61010	2.18758	X?	?	15

4.15 Harbour silting-up

Around 50% of the known ancient Mediterranean harbour-locations are not used anymore today (within a radius of 1500 m around the location of the ancient harbour). Around 15% of the ancient Mediterranean harbours are now silted-up, of which ca. 75% are not used anymore today. This shows that when siltation occurs, ports are often finally abandoned, which does not mean that many dredging efforts have not been spent for years before giving the place back to Nature.

The ancients often looked for estuaries to shelter from the sea (and also to find fresh water). In this way they solved the problem of exposure to waves but fell into another problem: the silting-up of harbours by fluvial sediment (case of Ephesus and many other ports like Leptis Magna, etc.).
Sediment brought by rivers is usually transported *by waves* along the coastline on both sides of the estuary (this is called littoral drift or longshore sand transport). The direction and volume of this littoral drift is determined by the angle of incidence of waves arriving on the coastline. If a port is built in such an area, sedimentation must be expected on one side of the port, with erosion of an equal volume on the other side (Portus Claudius, Caesarea Maritima).
A partial opening of the breakwater (e.g., arched breakwater at Puteoli) does not change much to the problem of silting-up as the actuator of littoral drift is wave action. But the purpose of a breakwater is exactly to protect from wave action; hence, sand will settle down. However, a canal through the breakwater at the average wave-breaking line where a current is generated by wave set-up may help to flush the port basin and the port entrance channel (e.g., El Hanieh (Libya), Centumcellae (Italy), Caesarea Maritima (Israel), Sidon (Lebanon)).
Oblique waves generate an oblique coastline that tends to be oriented parallel to the wave crests, e.g., a tombolo is created behind an obstacle because of wave diffraction, like at the Giens, and Argentario-Orbetello peninsulas. Ancient places like Tyr, Pharos, Peniscola (Spain) and Peniche (Portugal) are also the result of large-scale tombolo development. This is also true for so-called "detached breakwaters" (located at a small distance and parallel to the coastline). Sooner or later, a tombolo will develop behind such structures.

This problem of littoral drift is still met by modern coastal engineers on almost every coastal project. Let’s see this in more detail.

Littoral drift is quantified by several more or less complex formulae. We mention here the most popular and simple one, as proposed by CERC in 1984 (American Coastal Engineering Research Center):

$$Q = K \cdot H^{2.5} \cdot \sin(2\theta)$$

where Q is the littoral drift (in m^3/year), K is a coefficient (depending on parameters like wave steepness, sand grain sizes, etc.), H is the wave height at breaking (in m) and θ is the angle of incidence of waves on the coastline at the breaker line (in degrees). This formula shows the importance of the wave height, as anyone would suspect. It also shows the importance of wave incidence: littoral drift is nil with frontal waves (when wave crests are parallel to the coastline, θ = 0°), it increases with wave incidence up to 45° and reduces beyond that. The average wave direction thus determines the volume of sediment transported along the coastline and a sound knowledge of the wave climate and of wave propagation to the coast is required.

The main difficulty of computation of the coastline evolution is that waves reshape the sandy seabed. This leads to an “iterative” computation of wave refraction and diffraction: the larger the wave incidence, the larger the littoral drift and the more the seabed is reshaped, which in turn changes the wave propagation pattern and requires a new computation, etc.

Without going into further details, it can be understood that river sediment supply will be distributed on both sides of the estuary, generating a curved coastline in order to reduce the wave incidence with increasing distance from the estuary (a nice example is Ostia). It can also be understood that oblique waves generate an oblique coastline that tends to be oriented parallel to the wave crests (e.g., a tombolo is created behind an obstacle).

Similarly, for a bay between two rocky promontories: the shape of the bay will be curved (close to logarithmic spiral) corresponding to wave spreading due to refraction on the seabed and to diffraction around the promontories (e.g., bays of Cavalaire, Pampelone, Alexandria's Magnus Portus and so many others).

For wave incidence larger than 45° with respect to the coastline, a sand spit develops, e.g., Flèche de La Gracieuse near Fos where the modern port of Marseille has located its largest container and oil terminals. The sand spit usually ends with a hook due to wave diffraction. Sometimes, successive hooks can be seen as a result of long-term evolution. A sand spit is often very narrow (say 20-50 m) and much effort is devoted to avoid its break-through during storms if it protects major infrastructures like at Fos. This author suggests a similar sand spit may have protected the entrance of Marius' canal.

Our aim is not to summarise here one year of hydraulic courses for coastal engineers within one page, but

to stress the importance of wave action
and to note that this knowledge is available only since the 1950's.

Empories' ancient city wall acting as a detached breakwater.

4.16 Tombolos & salients

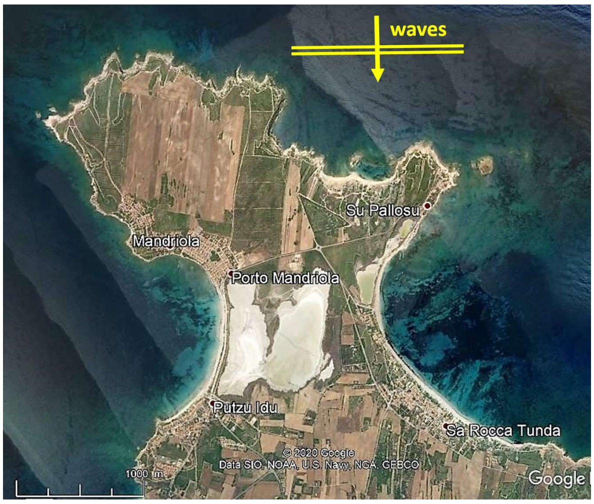
Our aim in this section is to describe some parameters defining the existence and the size of tombolos and salients. Much research on this subject has been done in the past 50 years because of its interest for coastal protection works like detached breakwaters, which are man-made structures placed parallel to the existing initial shoreline (see some references hereafter).

Islands connected to the mainland by an isthmus have been inhabited by people since prehistoric times and around 65% of those found on the Mediterranean coasts are ancient settlements.

Definitions

Strictly speaking, a tombolo is a sand spit connecting the mainland at a right angle to an offshore island or obstacle. A sand spit is often generated from the mainland to each side of the island. In the lee of a small island, both sand spits, or tombolos, will join as a single sandy isthmus, possibly leaving a triangular marsh area near the initial coastline. A large island may generate two separate tombolos and a large marsh area.
Note that some people call "tombolo" the whole mushroom-like feature including the sandy isthmus and the island, but geographers do not.

Small single isthmus
Cap Serrat, Tunisia (Google Earth, 2019)



Large double isthmus
Mandriola, Sardinia (Google Earth, 2017)

The Cap Serrat isthmus is small with a 160 m island, and the Mandriola isthmus with a 3600 m island, is over 20-times larger, but the general geomorphological shapes are similar.

A rocky cape is obviously not a tombolo, even with a beach, as it does not have a sandy isthmus.

Coastal sands are moved along shores by waves with an oblique incidence. Wave crests nearing the coast are often more or less parallel to the initial shoreline (say with an angle smaller than 10°), and wave diffraction generates the typical symmetrical shape of the tombolos shown in the pictures above where waves come in from the top of the pictures. We might we call this "tombologenic wave-diffraction".

Note that sand on each side of the isthmus usually has different origins, e.g., a river outlet on each side, and different wave directions move sand on each side towards the isthmus.

The famous Orbetello (Italy) and Giens (France) tombolo beaches are considered as independent beaches on each side of the island, generated by two different wave climates from west and from east.

In the case of Giens (France), the eastern beach is fed by sand from the Gapeau river, but the western beach is barely fed by any coastal sediment and is therefore much thinner and moving eastward.

Independent beaches showing very limited wave-diffraction effects, Giens, France (Google Earth, 2018)

If wave crests approach the island laterally, the isthmus has an asymmetrical shape with limited diffraction on the remote side, and such an isthmus is better thought of as a headland (e.g., Point Reyes, north of San Francisco, USA). We will not consider such cases in our study.

Large headland, Point Reyes, CA-USA (Google Earth, 2018)

Similarly, in case wave crests approach the beach at an angle of 45° or more, a sand spit is generated. A true sand spit has a free end, usually turning around like a hook. However, in a few cases, such a sand spit may encounter an island (Cadiz in Spain, Chesil Beach in UK). As no wave diffraction is involved in that process, we will not consider such cases in our study.

This sand spit is not part of a tombolo because waves approach from the right of the picture and involve no diffraction at all, Cadiz, Spain (Google Earth, 2019)

Last, but not least, a bell-shaped salient occurs when the offshore island is smaller, or further away from the initial coastline, than in the case of an isthmus.

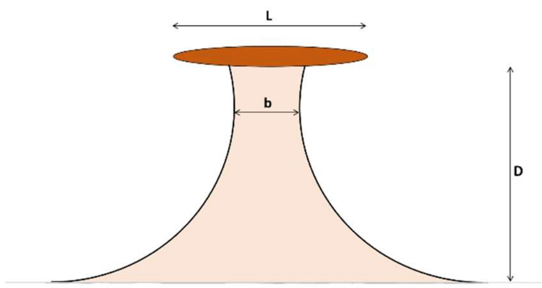
In the case of oblique wave crests, the salient will be asymmetrical with its apex pointing away from the incoming waves.

Salient, Cirella, Iraly (Google Earth, 2018)

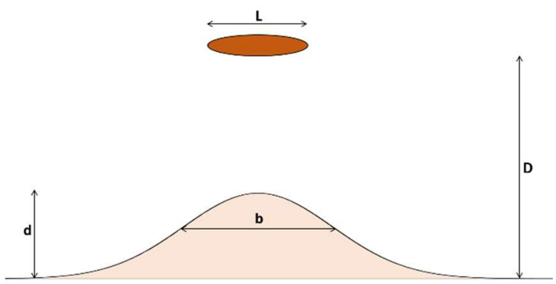
It must be noted also that some alluvial fans (fluvial sediment deposit at the river outlet) may have the aspect of a salient, but they usually have no offshore island and no wave diffraction.

In our study hereafter, we shall concentrate on isthmuses and salients perpendicular to the coast and generated by wave diffraction. They can only exist if:

- the initial coastline is a sandy beach (or shingle),
- an island (or obstacle) yields an area sheltered from waves and generating wave diffraction,
- wave crests approach the initial coastline with an angle smaller than say 10°,
- no currents flow between the island and the initial coastline.



Isthmus with two tombolos



Salient

L is the length of the island and D is the distance from the initial shoreline. For isthmuses, we define b as the smallest width of the isthmus, and for salients, b is the width at the inflexion point, and d is the distance from the tip of the salient to the initial shoreline.
An isthmus is thus geometrically defined by *L/D which is a constant in time*, as long as the sea level is constant.

Formation

When offshore wave-crests approach the coast with a small angle (usually less than 10°, but in any case, less than 45°), they are subjected to refraction which tends to align the wave crest parallel to the coastline. If wave crests encounter an obstacle like a small island, they are subjected to diffraction which tends to turn the waves around the island.
When breaking on a sloping coastline, waves release their energy in turbulence and in longshore currents which may transport sediment (usually fine sand with a median diameter

D_{50} of 0.2 mm to one or more millimetres). Shoreline forms are thus created by wave refraction and diffraction and longshore sand transport. The combination of these physical phenomena is complex but now well modelled in some physical scale models and in numerical so-called “one-line models” reproducing the shoreline.

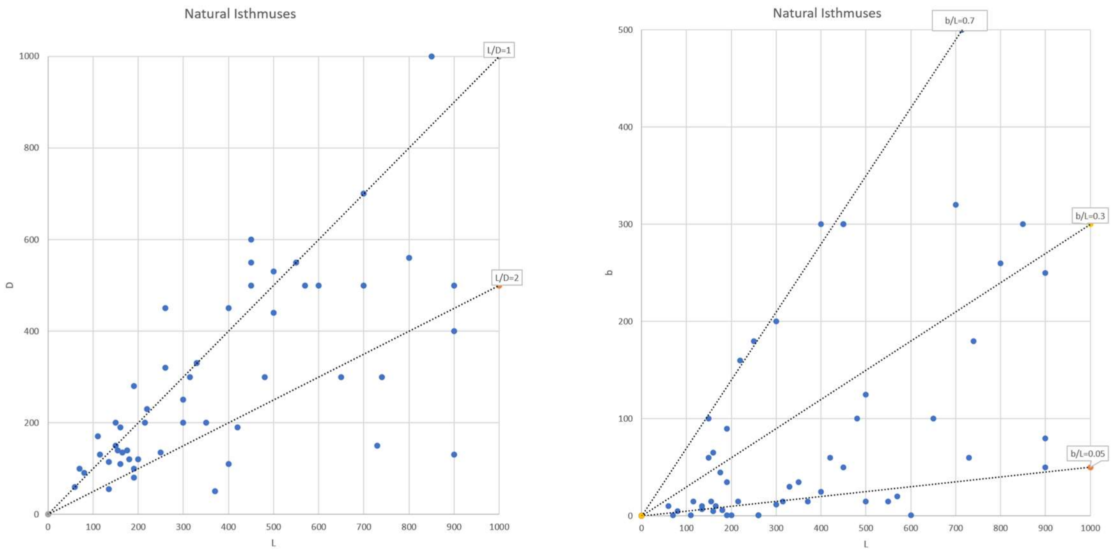
Wave diffraction pattern behind a detached breakwater
Xilxes, Spain (Google Earth, 2015)

The diffraction pattern is clearly shown on the picture above where breaking wave crests are always at a small angle with the shoreline. This implies that some longshore sand transport is ongoing from right to left, towards the isthmus. If you would walk from right to left on the beach shown on this picture, you would first see waves refracting during their approach to the shore (bottom right of the picture), then you would enter the curved shoreline where wave refraction and diffraction are combined (the shoreline shape is close to that of a logarithmic spiral). Finally, you would arrive in the lee of the detached breakwater and enjoy maximum shelter from offshore waves. It has been shown that a current system exists which forms a circulation cell turning in clockwise direction in the particular case shown on the picture above (Mory & Hamm, 1997).

Mediterranean isthmuses

Using Google Earth, we searched the 45 000 km of the Mediterranean Sea coasts to detect salients and isthmuses with two tombolos, and over 120 sites were listed. This list includes around 75 natural isthmuses and around 20 natural salients generated by offshore islands, islets or reefs. In addition, a few sites with man-made single or multiple detached breakwaters were listed (a comprehensive list is provided in Appendix 3).

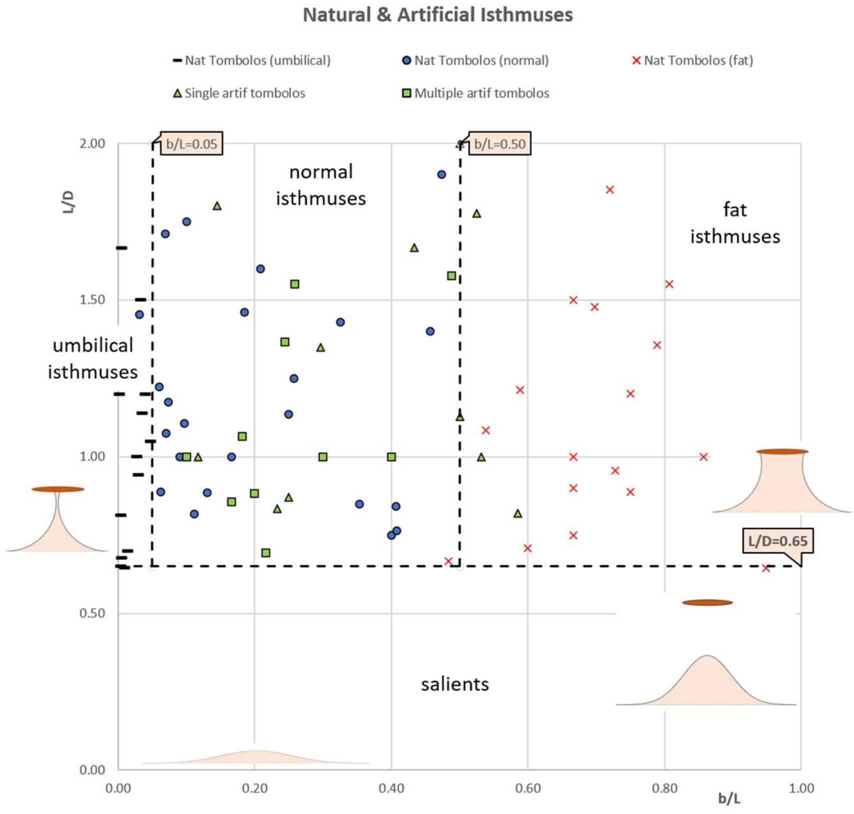
Let's first have a look at the relationships between L and D, and b and D for natural tombolos:



D versus L and b versus L for natural isthmuses with two tombolos (for L < 1000 m)

Both figures show much scatter.
For D versus L, it may be seen that, very schematically, L/D = 1 to 2, with many exceptions.
For b versus L, it may be seen that b/L = 0.05 to 0.7 with much scatter. A kind of average at b/L = 0.3 corresponds very well to results given by Rosen (1982, fig. 8) who gives: a = 0.33 L, with a = (L-b)/2.

Let's now have a look at a relationship between the dimensionless parameters L/D and b/L:



L/D for isthmuses with tombolos and for salients,
including both natural and artificial man-made structures (for L/D < 2)

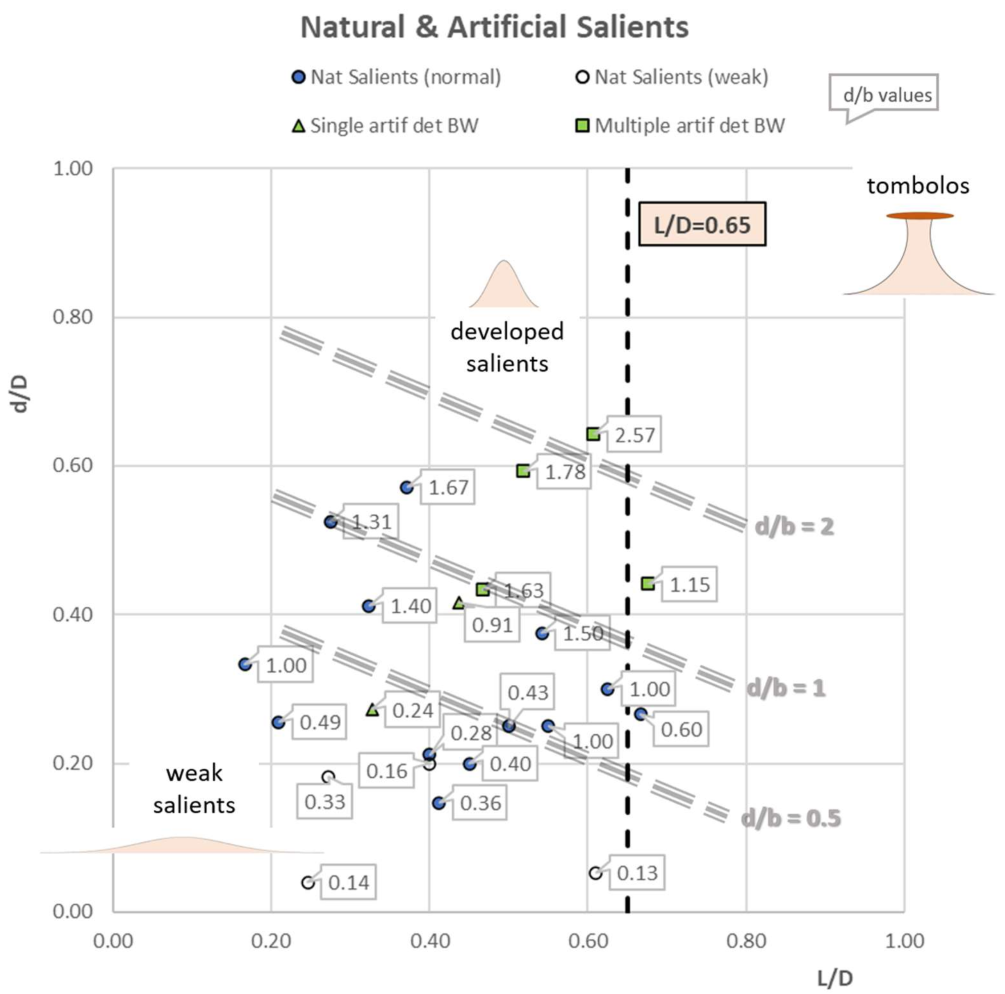
Again, much scatter is found.
We can distinguish "fat" isthmuses with b/L = 0.5 to 1, and "umbilical" isthmuses with b/L < 0.05. Between these extremes, a wide area is covered by “normal” isthmuses, where artificial isthmuses nicely mix-up with natural ones, without any visible difference between single and multiple detached breakwaters.
The demarcation line between isthmuses and salients is L/D = 0.65. This result is in full agreement with several other researchers (Mangor, 2020 and Sunamura, 1987) and in line with other researchers who give wider ranges (van Rijn, 2013, Bricio, 2008, Ming, 2000).

Isthmus:	L/D > 0.65
Salient:	L/D < 0.65

but beware !!
Isthmuses may connect and disconnect the island or detached breakwater (i.e., become a salient) depending on wave conditions., e.g., storm waves may change an isthmus into a salient, not only due to waves turning around the breakwater’s roundheads, but also due to waves overtopping the breakwater and/or wave energy passing through the porous breakwater. This is particularly true for umbilical isthmuses with small b/L < 0.05 where the demarcation line between isthmuses and salients may range between 0.65 and 1.5.

Mediterranean salients

As mentioned above, salients are found for L/D smaller than 0.65, and we may have a look at the relationship between the dimensionless parameters L/D and d/D:



L/D for salients, including both natural and artificial man-made structures (for L/D < 0.65)

Strictly speaking, isthmuses are formed when d/D = 1 and L/D > 0.65, that is in the upper right of the figure above. We can distinguish "weak" salients with small d/D, and "developed" salients with larger d/D. The tags show the values of d/b and a trend is visible as shown by the oblique lines.

It may be observed from the figure above that salients located behind multiple artificial detached breakwaters have d/b values ranging between 1 and 2. Both salients located behind a single artificial detached breakwater have lower d/b values of 0.24 (Salou, Spain) and 0.91 (Altafulla, Spain). Natural salients have d/b values ranging between 0.14 (Mar Menor, Spain) and 1.50 (Corfu) and even 1.67 (Maaten al-Uqla, Libya).

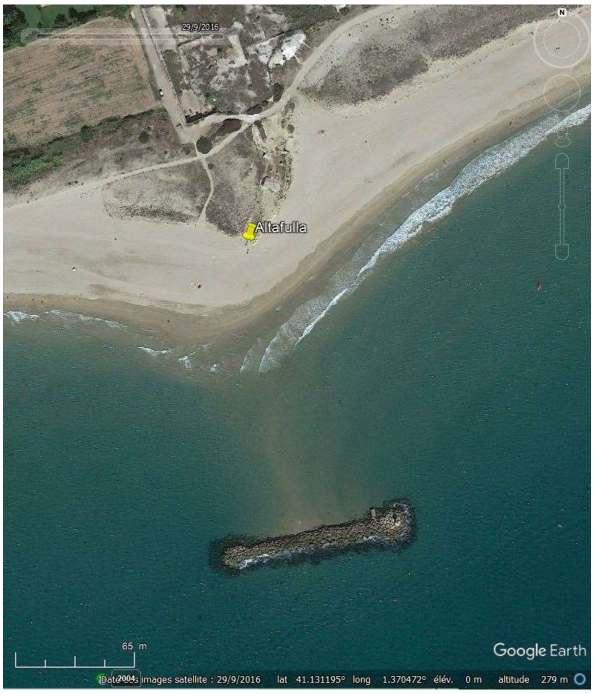
Effects of wave climate

The large scatter found in the above results is a bit frustrating and we might ask if the wave climate has some effects on the shape of isthmuses and salients, e.g., one third of the umbilical isthmuses are located in areas sheltered from offshore waves … but two thirds are not!

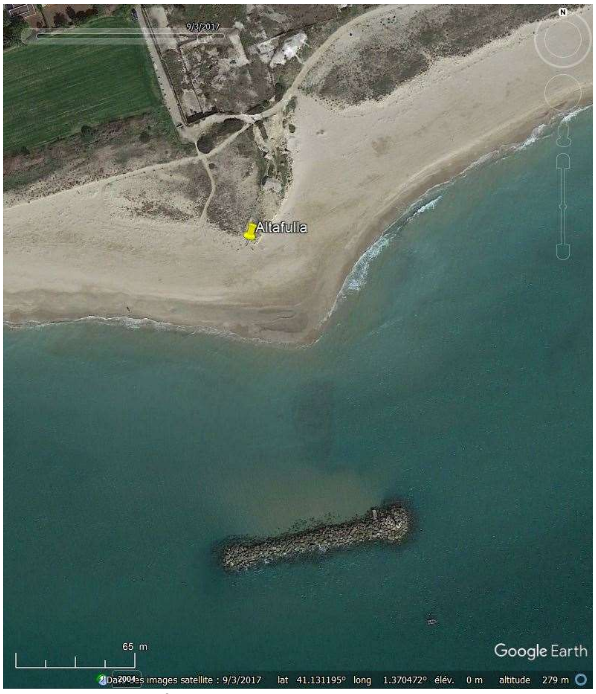
Umbilical isthmus,
Çiçek island, Turkey (Google Earth, 2019)

Umbilical isthmus,
Porto Pollo, Sardinia (Google Earth, 2019)

The isthmus shape-changes due to periodical storms make any assessment of a Google Earth picture somewhat tricky because we do not know if it was taken just before or just after a storm. However, Google Earth usually provides at least half a dozen pictures taken at different times over the past 20 years and we are able to estimate some movements of isthmuses and salients.



Salient moved SW,
Altafulla, Spain (Google Earth, 29/9/2016)



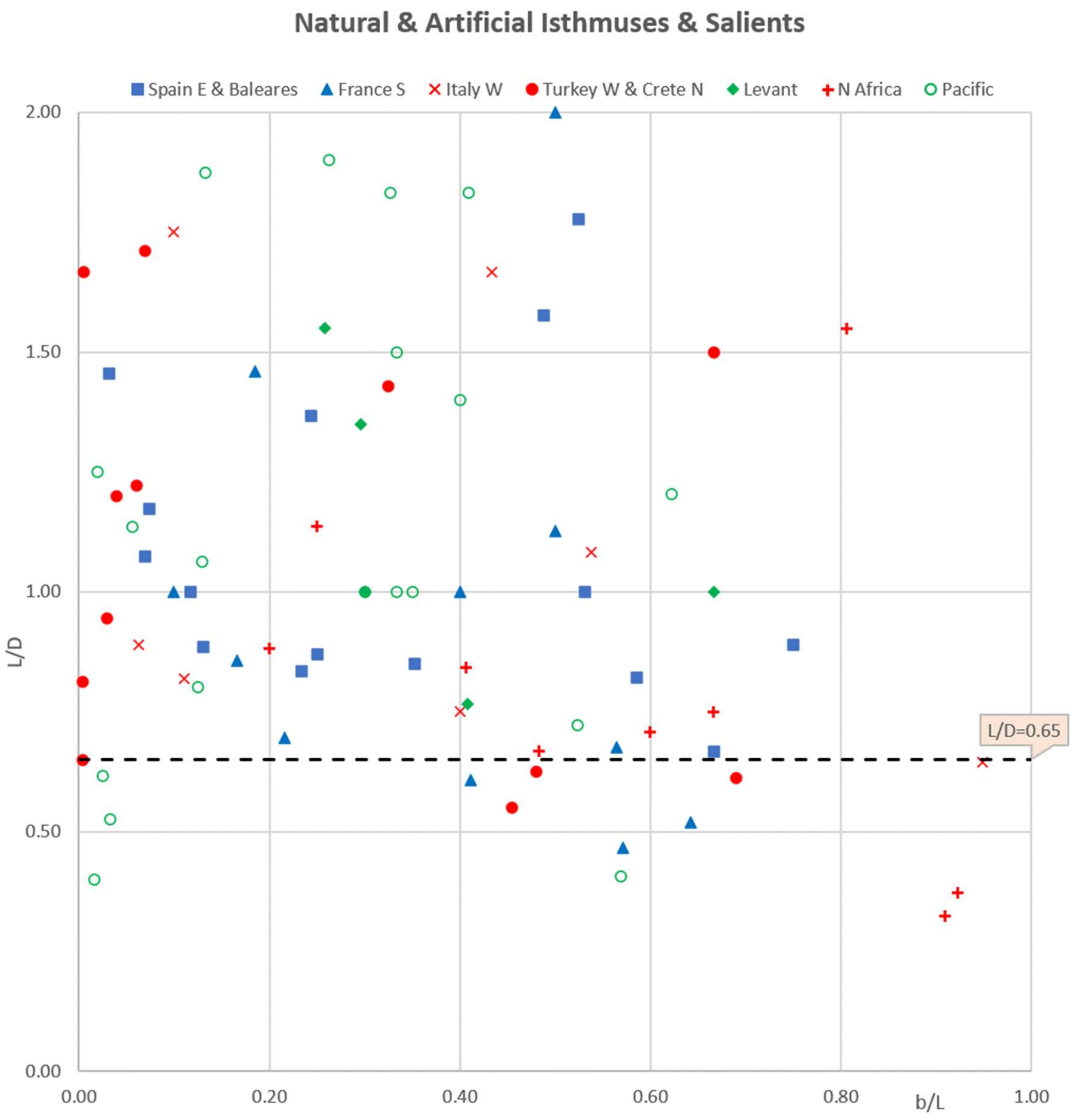
Same salient moved NE,
Altafulla, Spain (Google Earth, 9/3/2017)

Altafulla is located around 10 km NE of Tarragona (Spain) and features a beautiful salient with L/D = 0.44 and b/L = 1.05, sheltered by a 105 m detached breakwater. It seems that during the winter 2016-2017 the tip of the salient moved ca. 40 m from SW to NE, showing that the waves came mainly from SE in September 2016 and from SW in March 2017.

Although the tip of the Altafulla salient moved during a winter season, and although it is observed also that b varied from 85 m to twice this value during a period of 5 years, the overall shape did not change much and we may consider that all isthmuses and salients found on Google Earth are in a state of long-term dynamic equilibrium.

A first step to find out how the wave climate interacts with the isthmus- and salient shapes, would be to measure the "Dean number" for each site [De = $H_0/V_f/T$, with H_0: offshore wave height (m), T: wave period (s), V_f: fall velocity of sediment in water (m/s)] or possibly even better, the "Dalrymple number" [Da = $gH_0^2/V_f^3/T$]. These parameters are dimensionless and include the effect of both waves and coastal sediment.

As we do not have their value for each site, we used a more regional approach, comparing shapes of isthmuses and salients located in various parts of the Mediterranean area (eastern Spain, southern France, western Italy, south Aegean, Levant, North Africa) and on the Pacific Ocean between Vancouver and Cape Horn.



All isthmuses and salients for various specific areas.

The figure above does not show any groups of isthmus-shapes (in terms of L/D versus b/L) for the selected areas, and we have to conclude that local wave climate differences seem to have no effect.

Moreover, Sunamura's model-test results (their fig. 3 & 4) can be re-interpreted as showing no influence at all of their "K" parameter including wave effects.

In other words, the wave climate (and perhaps even the sediment grain size) does not seem to affect the final equilibrium shape of tombolos and salients. It might then be considered that waves affect only the speed of shape evolutions, and not the final equilibrium state, but this does not sound very realistic as we know that wave parameters (e.g., wave steepness) and sediment grain size both have an influence on beach slopes.

In any case, a much finer approach is probably needed and the last word has certainly not yet been said …

One of the threads might to make a better distinction between isthmuses grown out from a salient with wave crests parallel to the initial coastline, and isthmuses made of two separated spits generated by different wave climates on each side of the final isthmus.

References

MANGOR, K., 2020, “Detached breakwaters - MarineSpecies Introduced Traits”, Wiki, http://www.marinespecies.org/introduced/wiki/Detached_breakwaters
For single detached breakwaters:

Isthmus: L/D > 0.9 to 1.0

Salient: L/D < 0.6 to 0.7

VAN RIJN, L., 2013, “Design of hard coastal structures against erosion”, www.leovanrijn-sediment.com
For multiple detached breakwaters:

Isthmus: L/D > 2

Salient: L/D = 0.5 to 2

Weak salient: L/D = 0.2 to 0.5

no effect: L/D < 0.2

BRICIO et al., 2008, “Geometric Detached Breakwater Indicators on the Spanish Northeast Coastline”, Journal of Coastal Research, Vol. 24, N° 5, (p 1289-1303).
For 27 multiple detached breakwaters on the Catalan coast:

Isthmus: L/D > 1.3

Salient: L/D = 0.5 to 1.3

Limited response: L/D < 0.5

MING , D., & CHIEW, Y., 2000, “Shoreline Changes behind Detached Breakwater”, Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, (p 63-70).
From scale model tests, with interesting result on salient area.

Isthmus: L/D > 1.25

DALRYMPLE, R., 1992, “Prediction of storm/normal beach profiles”, Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, 118 (2), (p 193-200).

“Dalrymple Nb”: $gH_o^2/V_f^3/T$ (H_o, T of waves, V_f is fall velocity of sediment).

MORY, M. & HAMM, L., 1997, “Wave height, setup and currents around a detached breakwater submitted to regular or random wave forcing”, Coastal Engineering, Vol. 31, (p 77-96).

ROSATI, J., 1990, “Functional Design of Breakwaters for Shore Protection: Empirical Methods”, Technical Report CERC-90-15, US Army Corps of Engineers, (49 p).
Nice overview of all formulations, but no final answers.

SUNAMURA, T. & MIZUNO , O., 1987, “A study on depositional shoreline forms behind an island”, Ann. Rep., Inst. Geosci., Univ. Tsukuba, N° 13, (p 71-73).
For 23 natural islands in Japan:

Isthmus: L/D > 0.67

Salient: L/D = 0.3 to 0.67

Limited response: L/D < 0.3

SUH, K. & DALRYMPLE, R., 1987, “Offshore Breakwaters in Laboratory and Field”, Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, (p 105-121).
Scale model tests and some field data.

ROSEN, D. & VAJDA, M., 1982, “Sedimentological Influences of Detached Breakwaters”, Coastal Engineering Conference, (p 1930-1949), (fig 8).
For single detached breakwaters:

Isthmus a/D = 0.33 L/D (a is sand-free distance along inner side of BW).

DALRYMPLE, R., 1976, “Study of equilibrium beach profiles”, Coastal Engineering Conference, (p 1277-1296).

"Dean Nb": $H_o/V_f/T$ (H_o, T of waves, V_f is fall velocity of sediment).

5 ANCIENT SHIPS

If you are interested in ancient anchors, you might start with Peta Knott[149] and with Greg Votruba[150].

Let's distinguish galleys (navis longis, longboats, warships)
and merchant ships (navis oneraria, strongyla ploia, round ships).

Let's start by saying that ancient ships were the most elaborate technology of the ancient world. Let's note also that all galleys were not exclusively warships, as many early merchant ships were oared, and that most galleys had sails on board. But, generally speaking, oared (war)ships were long and narrow (length/beam ratio of ca. 7:1) and sailing merchant ships were bulkier (length/beam ratio of 3 to 4:1).

We badly miss pictures of ancient ships and we have to rely solely on reliefs, mosaics and ceramics and on modern artwork based on what we think we understand about ancient ships. A number of wrecks of merchant ships have been found, but very few ancient texts to describe them (one noteworthy exception: the Isis, by Lucian of Samosate). The reverse is true for war ships as only one wreck was found so far (the Marsala Punic ship, found in 1969), and some bronze rams described by Murray, including the 465 kg Athlit ram found in 1980. An explanation may be that merchant ships sunk with their cargo so that at least the bottom of the ship was preserved, while war ships were destroyed and their wooden structure was scattered around, except the rams.

One of the best modern "images" is the reconstruction of an Athenian Trireme at scale one in the Olympias Project of J.S. Morrison, J.F. Coates et N.B. Rankov between 1987 and 1994[151]. The project still survives on internet thanks to the "Trireme Trust".

The Kyrenia II experiment (1986-87) reproducing a small 30 ton merchant freighter of 14.5 x 4.5 m showed that she could resist a Force 9-10 Bft storm, see the Kyrenia Restoration Program.

[149] KNOTT, P., 2003, "Weighing Down the Trade Routes", School of Archaeology, University of Sydney.
[150] VOTRUBA, G., 2019, "Building upon Honor Frost's Anchor-Stone Foundations", in: "In the Footsteps of Honor Frost. The life and legacy of a pioneer in maritime archaeology", Blue, L. (ed.), Sidestone Press, Leiden, p 213-244.
[151] MORRISON, J.S.; COATES, J.F.; RANKOV, N.B., (2000), "The Athenian Trireme", Cambridge University Press, 2000.

For further details on ancient ships, refer to the major contributions of Lionel Casson and William Murray:
CASSON, L., 1995, “Ships and seamanship in the ancient world”, Johns Hopkins University Press, (470 p).
MURRAY, W. M., 2012, “The Age of Titans, the rise and fall of the great Hellenistic navies”, Oxford University Press, (356 p).

5.1 Brief historical overview

Humans have been sailing the seas for at least 50 000 years, progressively migrating to all of the world’s islands, but no archaeological remains of Prehistoric navigation before 8000 BC have been found so far[152].

If you are not an expert historian, this brief historical overview of ancient seafaring in the “western world” may help you to start …

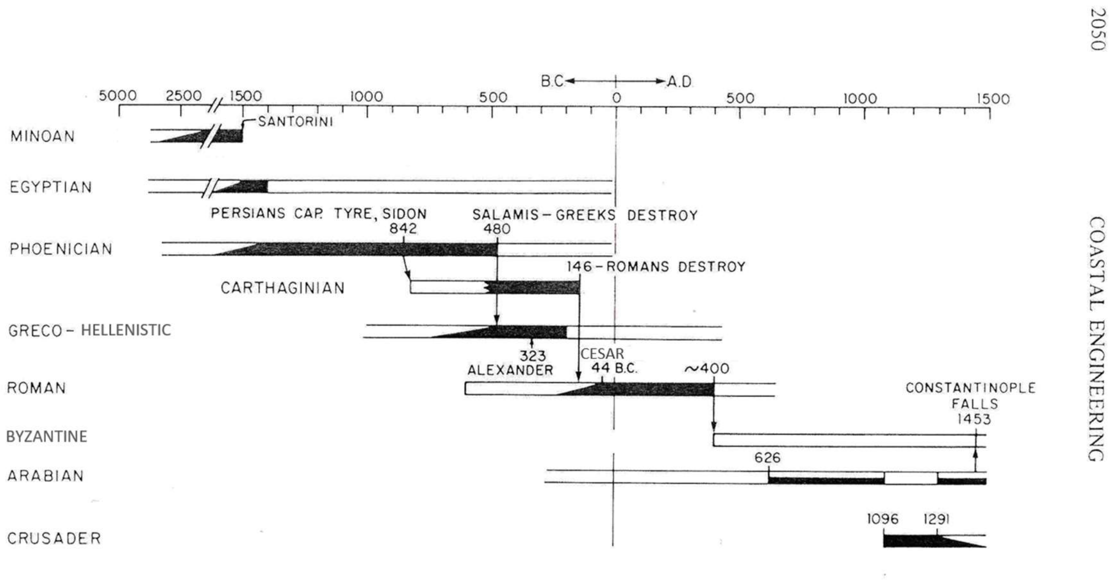


Figure 1. Chronology of civilizations' influence on Mediterranean harbors and ships.

Chronology of civilisations adapted from Inman[153].

The Mediterranean Sea has been sailed for millennia since Prehistoric times, the Bronze Age, Greek and Roman times, with a climax in the first centuries of the Common Era.
As far as archaic seagoing shipping is concerned, Egyptian rulers have been sailing during the

[152] PHILIPPE, M., 2018, “Un état des connaissances sur la navigation préhistorique en Europe atlantique”, Bulletin de la Société préhistorique française, 115, 3, (p 567-597).
[153] INMAN, D., 1974, in “Ancient and modern harbors: a repeating phylogeny”, 15th Coastal Engineering Conference, New York, (p 2049-2067).

Early Bronze Age (ca. 3300-2100 BC)[154]. In the Gulf, Mesopotanians were sailing to the Indus valley and to East Africa via Dilmun (Bahrain) and Magan (Oman)[155].

Minoans from Crete were probably the first “professional” seafarers sailing internationally in the Mediterranean area. This spanned, in round figures, the period between 2000 BC and 1500 BC.

From 1500 BC to 1200 BC, the Mycenaeans ruled the Aegean Sea and eastern Mediterranean as illustrated by Homer’s later epic on Achaeans fighting the Trojan War[156] while the Egyptians were still sailing on the Nile and on the Red Sea, and we know of Hatshepsut’s sailing from Myos Hormos on the Red Sea to the Land of Punt (ca. 1450 BC) and of Rameses III’s naval battle near Pelusion on the Nile against foreign invaders (1178 BC).

The Bronze Age ended around 1200 BC, when the Iron Age started with long “Greek Dark Ages” in Greece (1200-800 BC) corresponding to a Phoenician climax (Carthage was founded in 814 BC, but Byblos was already a trade port in the 3rd millenium BC). This was followed by a Greek revival called “Greek Archaic Period” (800-500 BC) and by the beter known “Greek Classical Period” (500-323 BC), the “Hellenistic Period” (323-31 BC) and the Roman period[157].

At the end of the Roman Empire (476 AD), it was western Europe that had its “Dark Ages”, for say five centuries, during which everything had to be rebuilt in the western Mediterranean … while the Arabs were over-active in the Indian Ocean.

And after that, came the Vikings …

Finally, if you would like to read a recently published overview on ancient ports, I recommend Arnaud (2016)[158] “Les infrastructures portuaires antiques”, Marriner (2017)[159] “Harbors and ports”, and Morhange (2016)[160] “The eco-history of ancient Mediterranean harbours”. For a complete overview on ancient seafaring, see Danny Lee Davis (2009)[161]. For a history of the ancient Mediterranean, see David Abulafia (2014)[162].

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[154] MARCUS, E. 2002, “Early Seafaring and Maritime Activity in the southern Levant from Prehistory through the Third Millenium BCE”, *in* van den Brink & Levy eds, *Egypt and the Levant, interrelations from the 4th through the Early 3rd millenium BCE*, New approaches to Anthropological Archaeology, (p 403-417).
See also Wikipedia: https://en.wikipedia.org/wiki/Sahure

[155] POTTS, D., 2016, "Cultural, economic and political relations between Mesopotamia, the Gulf region and India before Alexander", in Megasthenes and His Time, Harrassowitz Verlag, Wiesbaden, (p109-118).

[156] Achaeans were also called Argives (or Danaans) by Homer, and Ahhiyawans by the Hittites and Ekwesh (or Denyen or Tanaju) by the Egyptians; today they are called ‘Mycenaeans’.

[157] For a superb overview of the Roman history, have a look at: BADEL, C. & INGLEBERT, H. , 2014, “Grand Atlas de l’Antiquité romaine – Construction, apogée et fin d’un empire”, éd. Autrement, Paris, (191 p).

[158] ARNAUD, P., 2016, “Les infrastructures portuaires antiques”, in The Sea in History: The Ancient World – La Mer dans l’Histoire: L’Antiquité, General editor Christian Buchet, Woodbridge, The Boydell Press.

[159] Marriner N., MORHANGE C., FLAUX, C., CARAYON, N., 2017, “Harbors and ports, ancient”, A. S. Gilbert (ed.), Encyclopedia of geoarchaeology, Springer Science+Business Media, Dordrecht, (p 382-403).

[160] MORHANGE, C., MARRINER N., CARAYON N., 2016, “The eco-history of ancient Mediterranean harbours”, in The Inland Seas, Towards an Ecohistory of the Mediterranean and the Black Sea, T. Bekker-Nielsen et R. Gertwagen (eds.), Verlag, (p 85-106).

[161] Danny Lee DAVIS, 2009 "Commercial Navigation in the Greek and Roman World", PhD thesis, University of Texas, Austin, (359 p).

[162] ABULAFIA, D., 2014, “The Great Sea: A Human History of the Mediterranean”, Penguin Books, (943p).

5.2 Ancient galleys

The oldest pictures of rowing ships, galleys, are found on Cycladic so-called “frying pans”, from Syros Island and dated from 2800 to 2300 BC. As they feature around 2 x 15 oars, they might be considered as ancestors of the later ‘triaconter’. The stempost (on the left) is high-rising and decorated with a fish motive, much like the later Gurob ship.

Galley with around 2 x 15 oars on a Cycladic “frying pan”, Syros Island, 2800-2300 BC (Athens National Archaeological Mus.)

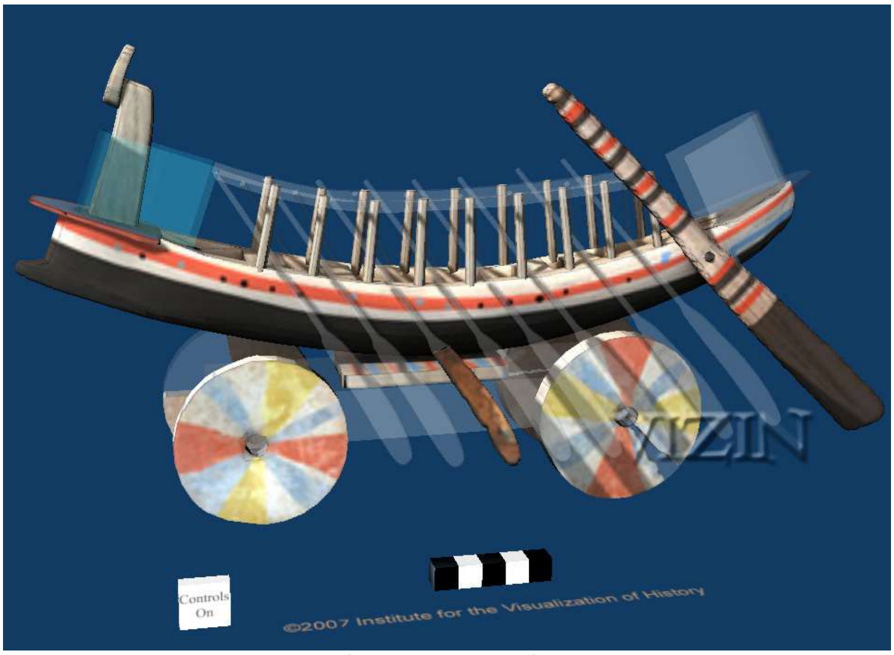
Minoans have been sailing the Aegean Sea between 2500 BC and 1500 BC, and from 1500 BC to 1200 BC, the Mycenaeans ruled the Aegean Sea and eastern Mediterranean.

The Gurob model ship is a Helladic oared galley found by Flinders Petrie in 1920 (Tomb 611 at Gurob, Egypt), and dated 1250-1050 BC[163]. It was re-discovered and analysed by S. Wachsmann[164] in 2012.

[163] EMANUEL, J., 2012, “Cretan Lie and Historical Truth: Examining Odysseus' Raid on Egypt in its Late Bronze Age Context”, In V. Bers, D. Elmer, D. Frame, & L. Muellner (Ed.), *Donum Natalicium Digitaliter Confectum Gregorio Nagy Septuagenario a Discipulis Collegis Familiaribus Oblatum* (p 1-41). Washington, DC, Center for Hellenic Studies.

[164] WACHSMANN, S., 2013, “The Gurob Ship-Cart Model and Its Mediterranean Context”, Ed Rachal Foundation Nautical Archaeology Series, Texas A&M University Press.

Port-side view of the 1920 Gurob ship model (Petrie Museum of Egyptian Archaeology; p.5 negatives, no. 904).
The nearly 40 cm long ship is placed on a cart, probably for transportation over land.
NB: the stern rudder was misplaced on this picture.
(Source : http://www.vizin.org/Gurob/Gurob_final_4PC/Gurob_VRML_html-pgs/Gurob_photo-catalogue_home.html)



Port-side view of 2007 3D digital Gurob ship model.
(Source : http://www.vizin.org/projects/gurob/solution.html)

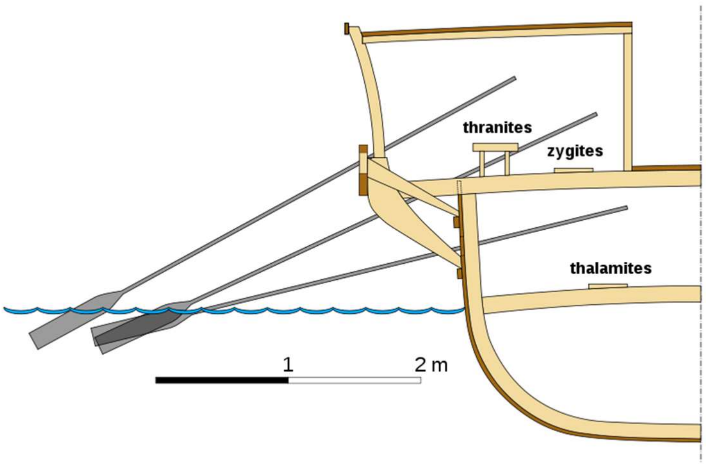
This ship may have been a model of the Homeric eikosoros with two files of 10 rowers. It is believed that Odysseus was possibly sailing on this kind of ship and that he and his bunch of Mycenaean sailors were raiding the eastern Mediterranean coasts as far as Egypt where they may have been defeated by Ramsses II around 1278 BC, a few years before the Trojan War[165]. This oared ship is an ancestor of what would later be called a 'triakonter' (triakontoros) with two files of 15 rowers, and a 'pentekonter' (pentekontoros) with two files of 25 rowers. These ships were respectively around 20 m and 30 m long, with a beam around 3 m and a draught around 0.5 m. The black hull (pitch/asphalt covered) induced the Homeric word "black ship"[166].

[165] EMANUEL, J., 2014, "Odysseus' Boat? New Mycenaean Evidence from the Egyptian New Kingdom". In Discovery of the Classical World: An Interdisciplinary Workshop on Ancient Societies, a lecture series presented by the department of The Classics at Harvard University. Cambridge, MA.
[166] For further reading on ancient galleys, see nicely illustrated work of Adrian WOOD, 2012, "Warships of the Ancient World – 3000-500 BC", Osprey Publishing, Oxford, UK, (48 p).

The Phoenicians would later on include two levels of oarsmen (see Sennacherib relief below) and the Greeks would include a third level in the famous "trireme".

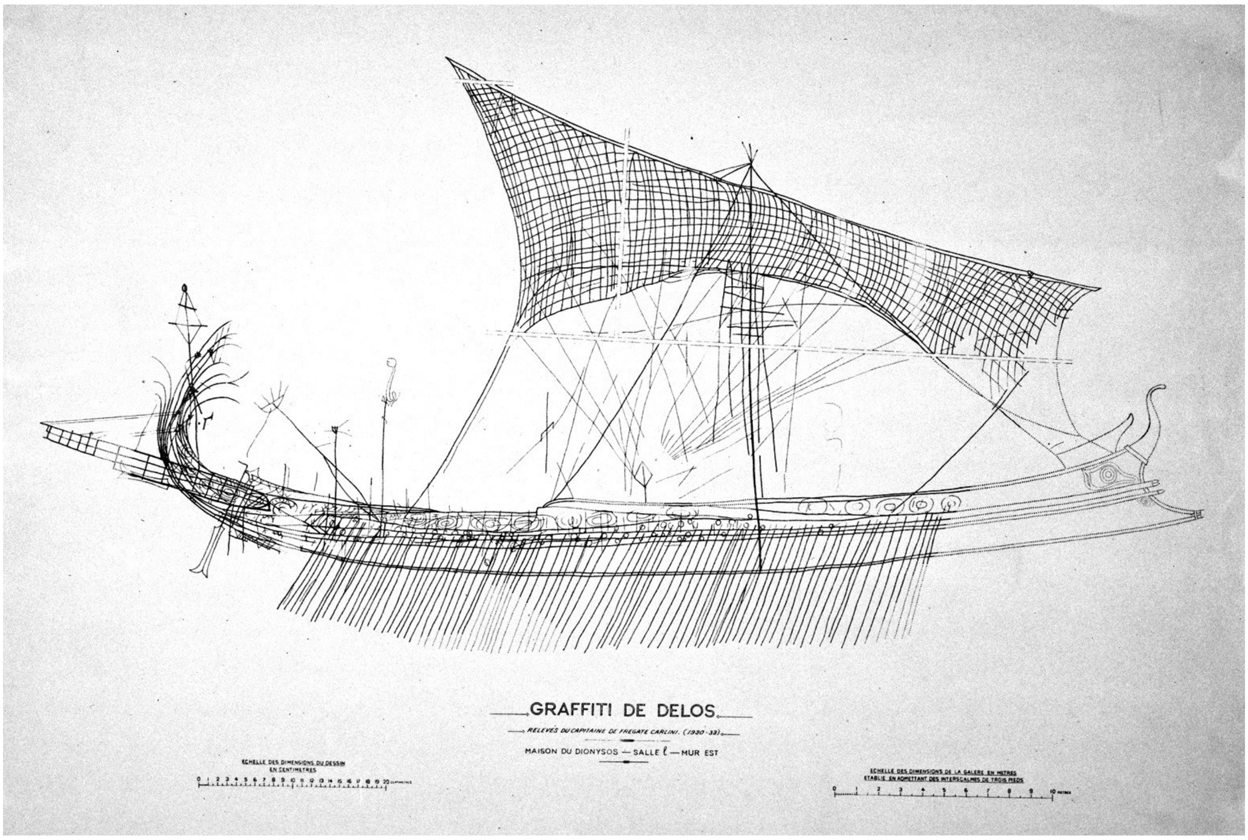
While older galleys were meant for transport of 'rowing warriors', the trireme was a true battle-ship with ramming capacity.
Triremes first appear in Ionia and soon become the main type of battle ship in the Mediterranean area from the end of the 6th until the 4th c. BC, then again with the Romans until the 4th c. AD because of their efficiency. The trireme is considered as a major Greek ancient invention because of its speed, manoeuvrability, strength and its ease of construction. It is most certainly Athens' main instrument of conquest at sea in the 5th c. BC. The length of the ship is 35 to 40 m, the width is less than 6 m and the draught is around around 1 m, for a total water displacement of 48 tons. 170 oarsmen sit on three levels (or 'rows') with 85 oars per ship side. The ship is light and agile and enables the ramming manoeuvre by means of a bronze ram which is placed on the bow; this leads to the first really 'naval' battles. Its cruising speed under oar is around 5 to 7 knots (one knot = one nautical mile/hour = 1.8 km/h) and its top speed is 8 to 10 knots.

Oars are around 4.2 m long. Oarsmen sit with their back to the bow, like modern oarsmen. The upper oar rests on an outrigger located in the oarbox, the middle oar rests on the topwale and the lower oar passes through an oarport.
Each oar rests against a pin (called 'rowlock' or 'thole') and is attached to it with a strap (called 'thong'). Each oarsman owns his oar, his thong and his cushion.
An open ship without an upper deck is called an 'aphractos' and a decked ship is called a 'kataphractos'.

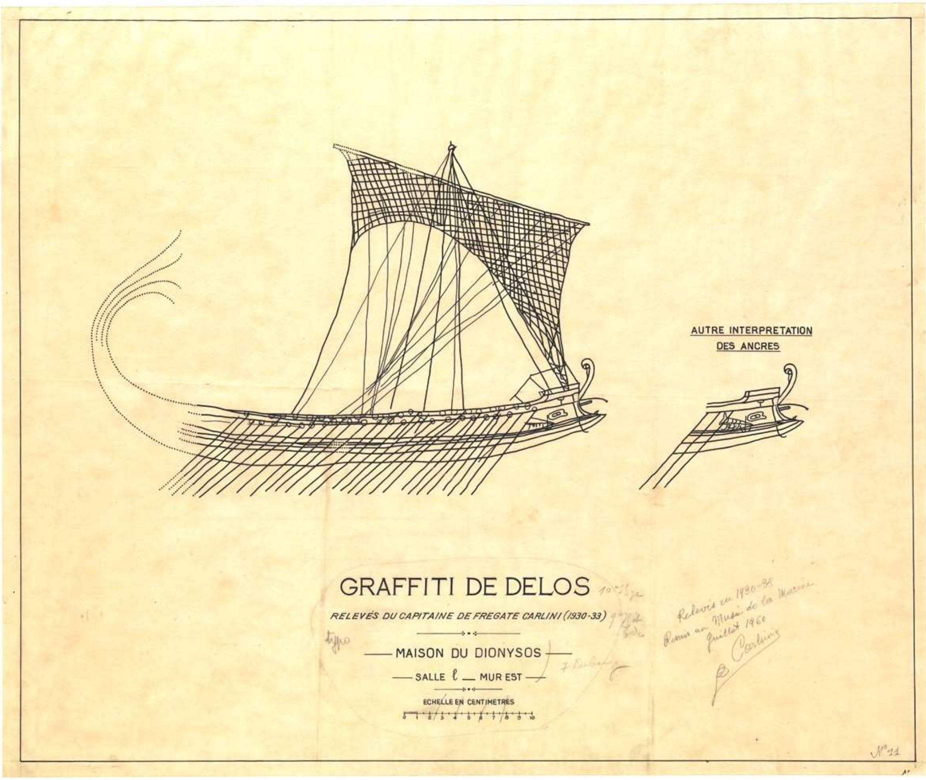


See further details in the excellent works of Morrisson, 2000 and of Rankov, 2012[167].

[167] MORRISON, J.S.; COATES, J.F.; RANKOV, N.B., 2000, "The Athenian Trireme", Cambridge University Press, 2000, (319 p).
RANKOV, B., 2012, "Trireme Olympias, The Final Report", Oxbow Books, Oxford, (243 p).



Trireme showing 85 oars copied by Capt. Carlini from the graffito of the House of Dionysos on Delos Island in 1930-33. The graffito was over 1 m long and surely is one of the finest pictures of a trireme (Musée de la Marine, Paris)



Galley showing 28 oars copied by Capt. Carlini from the graffito of the House of Dionysos on Delos Island in 1930-33. If each sketched oar represents 3 levels of one oarsman, then this ship is a trireme (Musée de la Marine, Paris).

This is all what remains from the graffito copied by Capt. Carlini in the House of Dionysos on Delos Island in 1930-33.
(photo : A. de Graauw at Delos Mus. 2015)

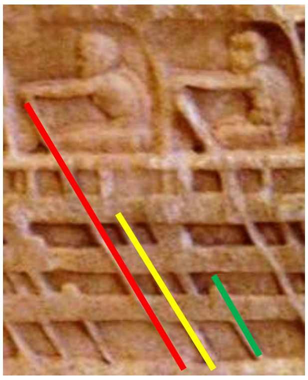
Later on, the Romans built “quinqueremes” of 40 to 45 m length and around 100 ton displacement, with ca 300 oars, each activated by one or two oarsmen.

The number 5 is related to the number of oarsmen per cell (interscalmium) on one side of the galley:

Trireme: 1+1+1 oarsmen on 3 levels

Quadrireme: 2+2 oarsmen on 2 levels

Quinquereme: 3+2 oarsmen on 2 levels, or 2+2+1 oarsmen on 3 levels



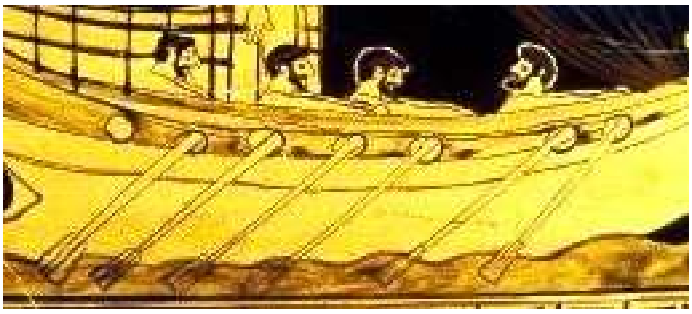
These descriptions are mainly based on an interpretation of reliefs called “Lenormant” (left, dated 410 BC) and “Pozzuoli” (right, dated 1st c. BC to 1st C. AD) where three levels of oarsmen can be distinguished:

- red on top (thranites),
- yellow in the middle (zygites),
- green below (thalamites).

The relief of the tomb of Caius Cartilius Poplicola, 25-20 BC (Ostia Antica) also explicitly shows three levels of oars.

This approach is most widely accepted at the end of the 20th c.[168].

However, Alec Tilley[169] suggests another approach that is also of interest.



This approach is mainly based on an interpretation of the so-called “Siren vase” (left, dated ca 480 BC) where only one level of oarsmen is seen.

Note that the port hole of the central oarsman must be somewhat below the port hole of the lateral oarsman in order not to hinder him (e.g., 10 cm?).

This might be seen on the “Samothrace Victory” (below).

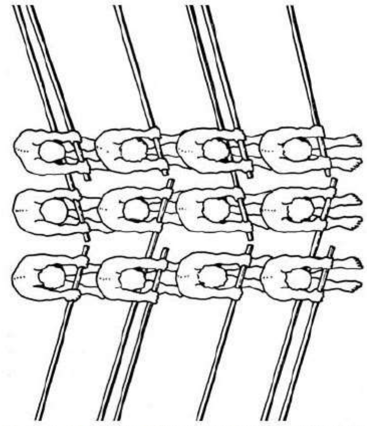
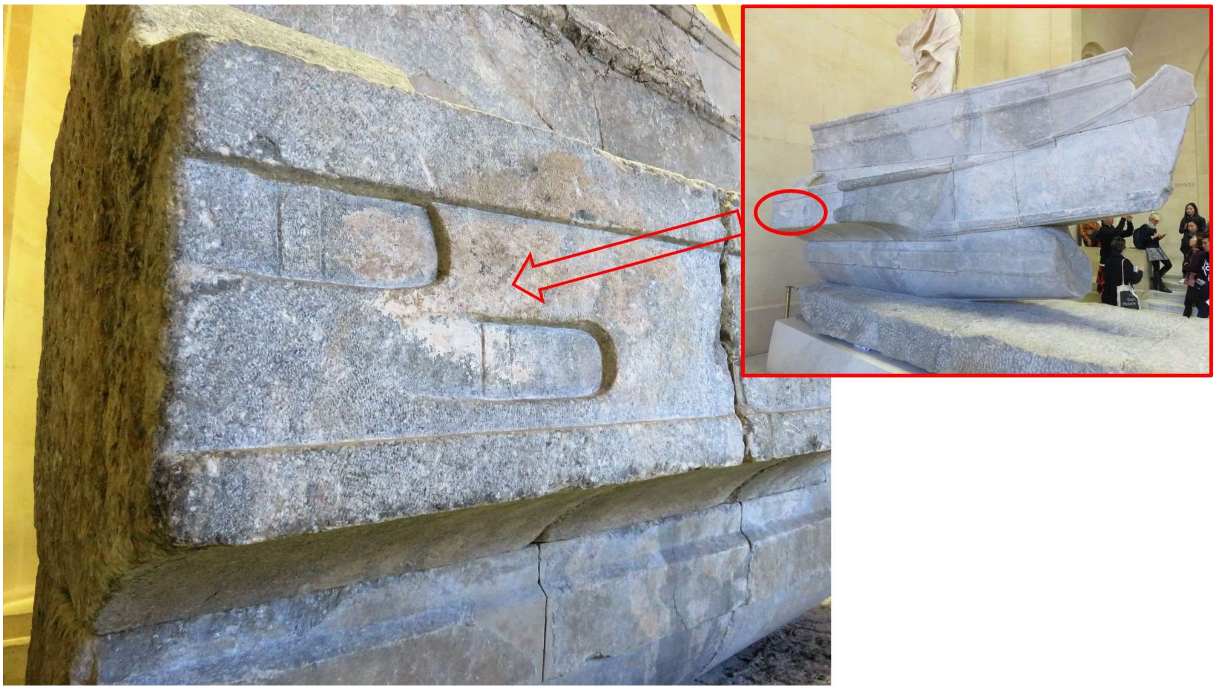


Figure 4. The ship on the Siren Vase ‘decoded’. (Tilley, 1970, fig. 1, reproduced courtesy of Antiquity Publications Ltd)

The question may then be asked if this ship may be called trireme as it has groups of three oarsmen per cell (or room, Latin ‘interscalmium’, is the distance between two successive thole-pins, 0.88 to 1.05 m acc. to Rankov). Those supporting the ‘Lenormant approach’ (Morrisson, Casson, Murray, etc.) reply that the ship of the Siren vase is not a trireme but just a ship with three oarsmen on one single level.

Representations of ships with two levels are known also, without excluding the possibility of having three oarsmen (two on top and one below, which makes it a trireme) or even four (two on top and two below, which makes it a quadrireme):

[168] MORRISON, J.S., 1941, “The Greek trireme”, Mariner's Mirror 27, (p 14-44).
[169] TILLEY, A., 1970, “The ship of Odysseus”, Antiquity 44, (p 100-104).



Pedestal of Samothrace Victory, starboard side (photo: A. de Graauw at Louvre Mus. 2016)

The pedestal of the statue ‘Samothrace Victory’, probably a trihemiolia dated 190 BC, (above) shows two levels of port holes. The thole pin in each port hole seems to be shown also.

On this relief of ‘Praeneste’ of the second half of 1st c. BC (left) two levels of oars can be seen with their leather sealing sleeves. Can we ascertain that oarsmen are on different levels (Casson does it) or on the same level with slightly shifted port holes like in Tiley’s interpretation of the Siren vase?

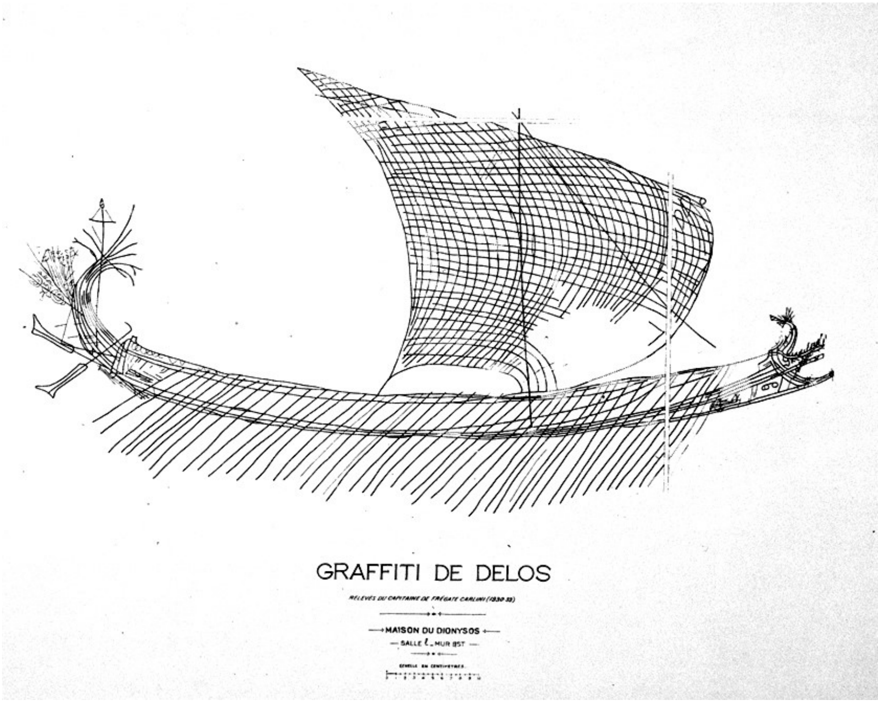
The Assyrian so-called ‘Sennacherib’ relief of the 7th c. BC (left) shows a Phoenician ship with two levels of oarsmen (according to Casson).

A model of a terracotta Punic bireme (left, dated ca 300 BC) to be seen in Alicante's Museo Arqueologico also shows two levels of oarsmen (length 208 mm) (photo: A. de Graauw at Alicante Mus. 2015).

This somewhat confusing situation is also due to an evolution of definitions in ancient texts. The older texts mention the Greek word 'pentecontore' to designate a ship with 50 oarsmen on two longitudinal files, that is 25 oarsmen on each side of the ship. Later texts mention the Latin word 'trireme' to designate a ship with 3 oarsmen per cell on each side. In the old definition, one would have said '170' to designate a trireme, according to the total number of oarsmen on board. Conversely, a pentecontore with one line of oarsmen per side would be called a 'monoreme' or a 'one' in the later definition. This change of definition was probably made necessary by the increasing complexity of the oar systems.

Subsequent larger galleys are therefore designated by their number of oarsmen per cell on each side of the ship: the 'six', 'seven', 'eight', 'ten', etc. until 'eighteen', considering that the 'twenty', 'thirty' and 'forty' may have been double hull ships (see tables hereafter).

Large galleys with up to 9 men per oar will be built, but these monsters will not survive the battle of Actium (31 BC).



Galley showing 50 oars copied by Capt. Carlini from the graffito of the House of Dionysos on Delos Island in 1930-33. If each sketched oar represents 2 levels of 9 oarsmen, then this ship would be called an '18' and could be Antigonos' flagship. (Musée de la Marine, Paris).

This is all what remains from the graffito copied by Capt. Carlini in the House of Dionysos on Delos Island in 1930-33. (photo: A. de Graauw at Delos Mus. 2015)

Some believe that Caligula made a replica of this ship (ca. 40 AD) which is known as the 'Nemi II' because it was used for naval games on Lake Nemi, north of Rome. This ship, and a second one, were found buried in the mud on the bottom of the lake, they were recovered and studied in 1927-32, but unfortunately disappeared during a fire in 1944[170].

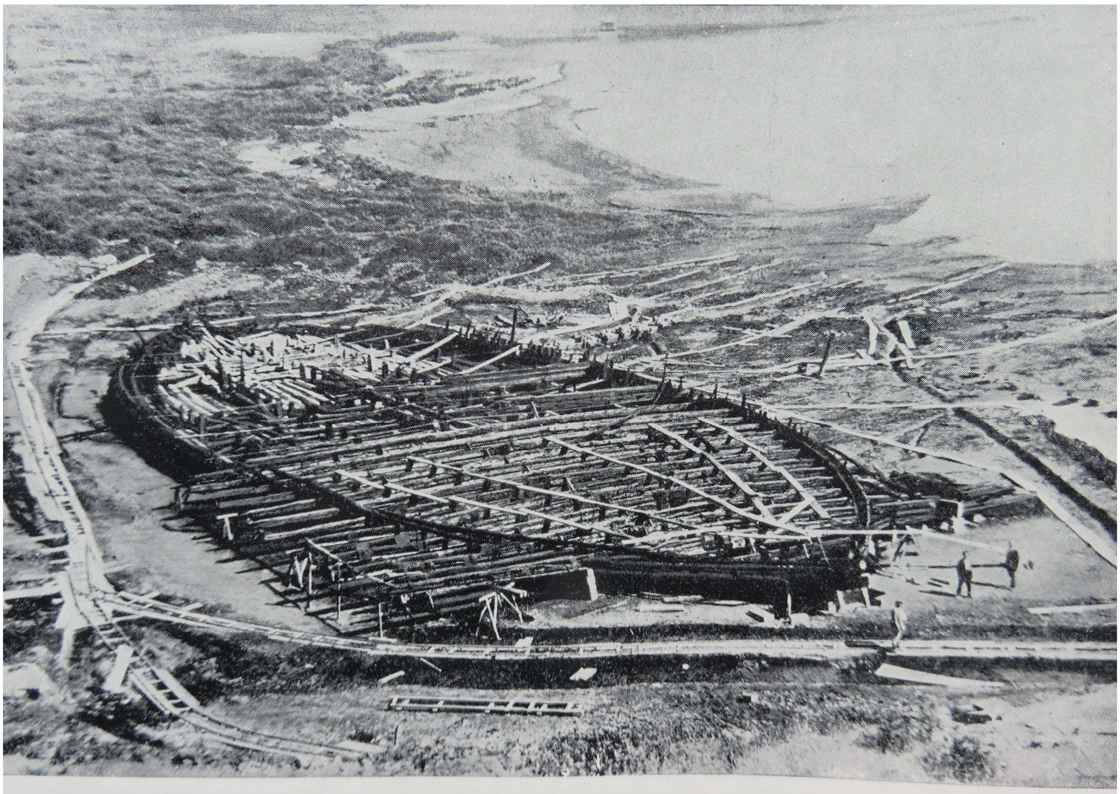


FIG. 91 – LA SECONDA NAVE COMPLETAMENTE EMERSA

Caligula's Nemi II ship on Lake Nemi (picture 1930).
Ship size 73 x 24 m, note the size of the persons standing in front of the ship.

The following ships are presented in the 3 tables hereafter:

- known ancient maxi-ships
- other ancient ships
- pm: the Maltese galley

[170] UCELLI, G., 1950, "Le Navi di Nemi", Libreria dello Stato, Roma, (386 p).

ANCIENT MAXI - SHIPS

Length (m)	Width (m)	Nb levels	Nb oarsmen Per side	Nb of ships	Owner	Date of construction	Observations	Source (see Biblio)
?	?	?	13	4 or 5	Demetrios Poliorcetes & Ptolemy II	ca 300 BC	Demetrios' flagship, also used for marriage of his daughter Stratonice at Rhosos (Pieria Antioch)	[6] p121
110?	10	1	« 8 » (or 16?)	1	Lysimachus of Thrace	ca 300 BC	« Leontophoros »: Double-hull (?) with 1600 oarsmen + 1200 soldiers.	[4] p39 [6] p171
70	20	2	15	1	Demetrios Poliorcetes of Macedonia	ca 290 BC	Captured by Ptolemy I, and destroyed.	[4] p41 [6] p280
70	20	2	16	1	Demetrios Poliorcetes of Macedonia	ca 290 BC	Demetrios' flagship against Lysimachus. Seen in Rome in 149 BC by Polybius.	[4] p40 [6] p280
70	20	2	18	1	Antigonus Gonatas of Macedonia	ca 258 BC	« Isthmia »: Antigonus Gonatas' flagship against Ptolemy II. Ship « of Delos ». Double-hull?	[4] p41 [6] p185
?	20?	3	20	1	Ptolemy II of Alexandria	ca 255 BC?	Double-hull?	[3] p107 [6] p178
?	20?	3 or 4 ?	30	2	Ptolemy II of Alexandria	ca 255 BC?	Largest seagoing galleys ever built. Double-hull?	[3] p107 [6] p178
?	?	?	20	1	Hieron II of Syracuse	ca 240 BC	« Syracusia » did only one trip from Syracuse to Alexandria. First cruise ship?! Payload 2000 t	[4] p98 [3] p185
130	45?	3?	40	1	Ptolemy IV of Alexandria	ca 220 BC	Double-hull with 2 (or 4?) coupled « 20 ». 4000 oarsmen + 3250 soldiers & sailors. Mainly a deterrent?	[2] p289 [3] p108 [4] p40 [6] p178
130	45?	-	-	1	Ptolemy IV of Alexandria	ca 220 BC	« Thalamegus », floating royal palace. Probably never out of her home port.	[2] p289
75? 104?	11? 20?	3 or 4?	30	1	Caligula	ca 40 AD	Used for transporting the Vatican obelisk. Payload: 1300 t.	[3] p189 [4] p46 [8] p104
73	24	2	18	2	Caligula	ca 40 AD	« Nemi II », replica of the « 18 » of Delos. Used for naval games on the Lake of Nemi.	[4] p43
55	>14	-	-	1	?	2nd century	« Isis », for transporting grain between Alexandria and Rome. Payload: 1 200 t (or 20 to 30 000 amphorae).	[3] p186

OTHER ANCIENT SHIPS

Length (m)	Width (m)	Nb levels	Nb oarsmen Per side	Nb of ships	Owner	Date of construction	Observations	Source (see Biblio)
30	5	1	1	many	Greeks	ca 1100 BC	Pentecontore (50 oarsmen)	Wikipedia
20	2,6	2	2	many	Greeks Phoenicians	ca 700 BC	Bireme (140 oarsmen)	[4] p63
35 to 40	4,8	3	3	many	Greeks Phoenicians	ca 500 BC	Famous Greek trireme of the Medic Wars (170 oarsmen + 30 sailors)	[4] p22 & 63
35	5	3	5	many	Romans Carthaginians	ca 400 BC	Famous quinquereme of the Punic Wars (270 oarsmen + 120 soldiers)	[4] p108 [2] p337
35 to 40	9 to 10	-	-	many	Romans	ca 0	Cargo « 10 000 amphorae » transporting wine and oil. Typical wreck at La Madrague de Giens	[3] p173

PM: OTHER GALLEYS

Length (m)	Width (m)	Nb levels	Nb oarsmen Per side	Nb of ships	Owner	Date of construction	Observations	Source
45	9	1	5	many	Maltese galley	ca 1450 AD	250 oarsmen + 350 soldiers & sailors	Petiet (1992) p109...
23	3 to 4	1	1	many?	Viking	ca 320 AD	Nydam ship with 30 oarsmen	Wikipedia

Length is overall, Width is excluding outriggers.

Number of levels: Nb of superimposed levels of oars/oarsmen (max of 3 to 4 levels) ([11] p38)

Number of oarsmen per side: Nb of oarsmen on all levels (max of 9 oarsmen per oar, [11] p39), e.g.:

- a trireme had 1 oarsman per oar and 3 levels of superimposed oars (slightly shifted) ([12] p161)
- a quinquereme had 2 oarsmen per oar on 2 upper levels and 1 oarsman on the lower level ([11] p32)
- a Maltese galley had 5 oarsmen per oar on one single level (cf. C. PETIET)
- Acc. to L. Casson, all ships with more than 16 oarsmen per side are double-hull ships ([10] p107)
- Acc. to W. Murray, the Leontophorus is a double-hull ship with two coupled « 8 », hence an erroneous name designating a « 16 » ([13] p178)
- Acc. to W. Murray, the 20, 30 et 40 are double-hull platforms designed for besieging port cities ([13])

Amphora: a full amphora weighted 35 to 55 kg

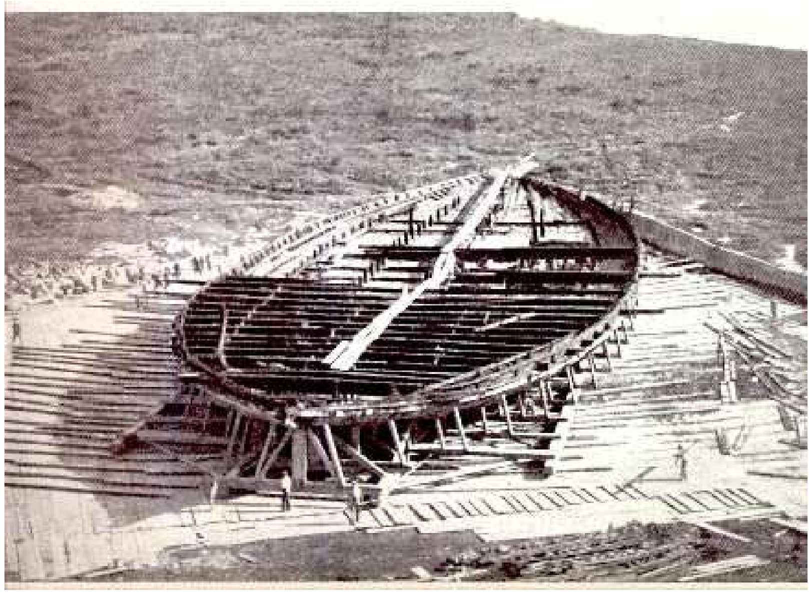
PM: dead-weight includes payload, passengers and consumables (water, food, etc.).

Biblio on Ancient Ships

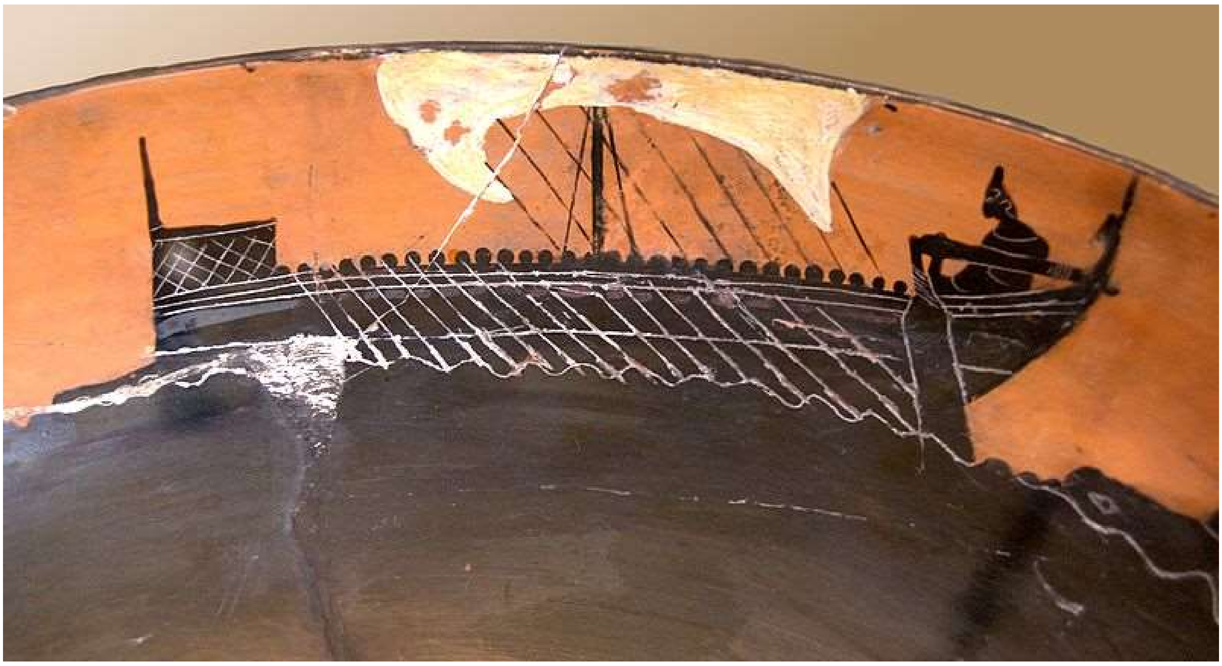
1. ARNAUD, P., 2005, “Les routes de la navigation antique”, éd. Errance.
2. BASCH, L., 1987, “Le musée imaginaire de la marine antique”, Institut hellénique pour la préservation de la tradition nautique, Athènes.
3. CASSON, L., 1995, "Ships and seamanship in the ancient world", Johns Hopkins University Press, (470 p).
4. GUILLERM, A., 1995, “La marine dans l’antiquité”, Que sais-je ? N°2995, éd. Presses Universitaires de France.
5. MORRISON, J.S.; COATES J.F.; RANKOV, N.B., 2000, “The Athenian Trireme”, Cambridge University Press.
6. MURRAY, W. M., 2012, “The Age of Titans, the rise and fall of the great Hellenistic navies”, Oxford University Press, (356 p).
7. RANKOV, B., 2012, “Trireme Olympias, the final report”, Oxbow Books.
8. REDDE, M., 2005, “Voyages sur la Méditerranée romaine”, Actes Sud/Errances.

The initial ancient references are the following:

- the ‘13’ of Demetrios Poliorcetes and of Ptolemy II: Plutarque, Démétrius, 31 & 32 ; Athénée citing Callixène, Banquet des Savants, 5, 9
- the Leontophorus of Lysimachus : described by Memnon, cited by Jacobus Palmerius (that is Jacques Le Paulmier, 1678)
- the ‘15’ of Demetrios Poliorcetes: Plutarque, Démétrius, 20 & 43
- the ‘16’ of Demetrios Poliorcetes: Pline l’Ancien, Histoire Naturelle, 16, 76 ; Diodore, Histoire, 20, 92 ; Plutarque, Démétrius, 20 & 43 ; Polybe, Histoire, 36, 5 ; Tite Live, Histoire Romaine, 45, 42
- the ‘18’ of Antigonus Gonatas, son of Demetrios Poliorcetes, offers his flagship to the temple of Apollo at Delos around 255 BC: Athénée, Banquet des Savants, 5, 12 ; Pausanias, Grèce, 1, 29
- the ‘20’ and the ‘30’ of Ptolemy II: Athénée citing Callixène, Banquet des Savants, 5, 9
- the Syracusia of Hieron II of Syracuse offered to Ptolemy II : Athénée citing Moschion, Banquet des Savants, 5, 10
- the ‘40’ of Ptolemy IV : Athénée citing Callixène, Banquet des Savants, 5, 9 ; Plutarque, Démétrius, 43
- the Thalamegus of Ptolemy IV : Athénée, Banquet des Savants, 5, 9
- the ship of Caligula for transporting the obelisk : Pline l’Ancien, Histoire Naturelle, 15, 76 & 36, 14 ; Suétone, Vie des douze Césars, Claude, 20 ; Ammien Marcellin, Histoire de Rome, 17, 4
- the Nemi I & II of Caligula : no ancient reference, but two wrecks found by archaeologists in 1927-32 and unfortunately destroyed in 1944 by fire (photo of 1930 right)
- the Isis : Lucien de Samosate, Le navire ou les souhaits



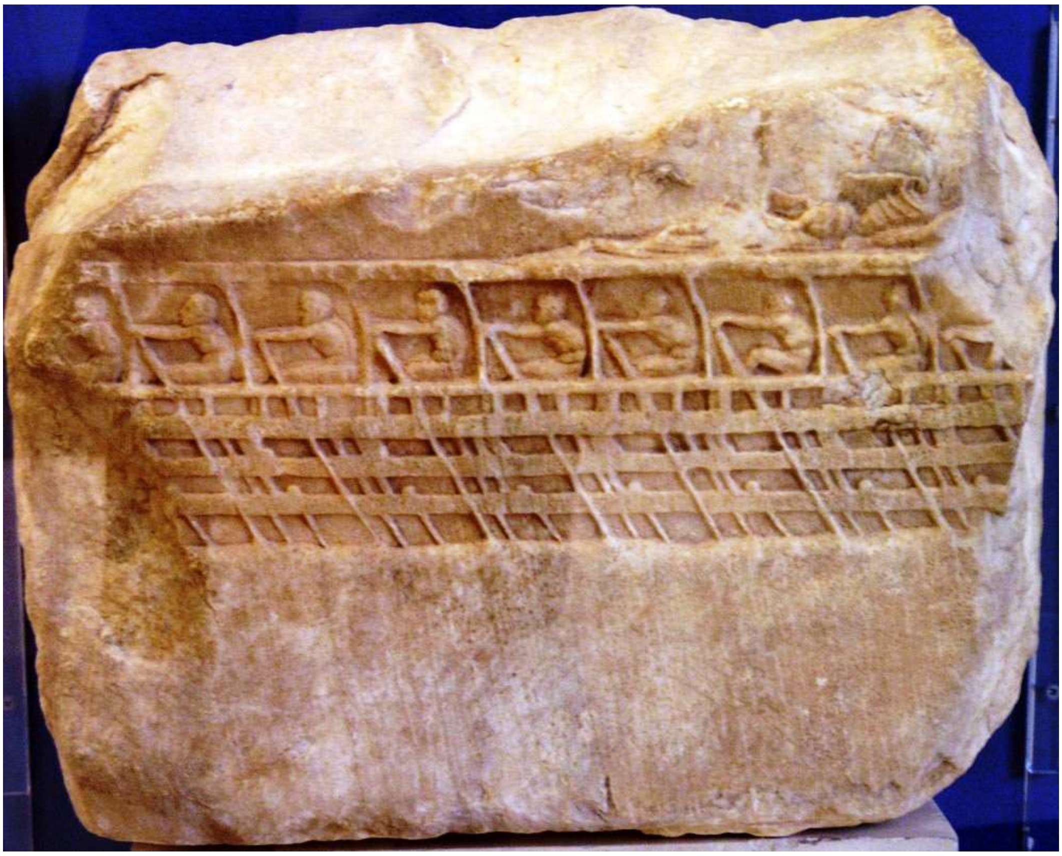
Caligula’s Nemi II ship on Lake Nemi (picture 1930).



Greek pentecontore, black & red Attic cup, around 520 BC (BNF, Paris)
Source : http://fr.wikipedia.org/wiki/Fichier:Boat_Cdm_Paris_322_n1.jpg

Phoenician galley, relief from Sennacherib Palace at Ninive, around 700 BC (British Mus.)
Source : http://en.wikipedia.org/wiki/File:AssyrianWarship.jpg

Roman galley, relief from Fortuna temple at Praeneste, second half of 1st c. BC (Vatican Mus.)
Source: http://luna.cas.usf.edu/~murray/actian-ram/actian_ram_project02.htm



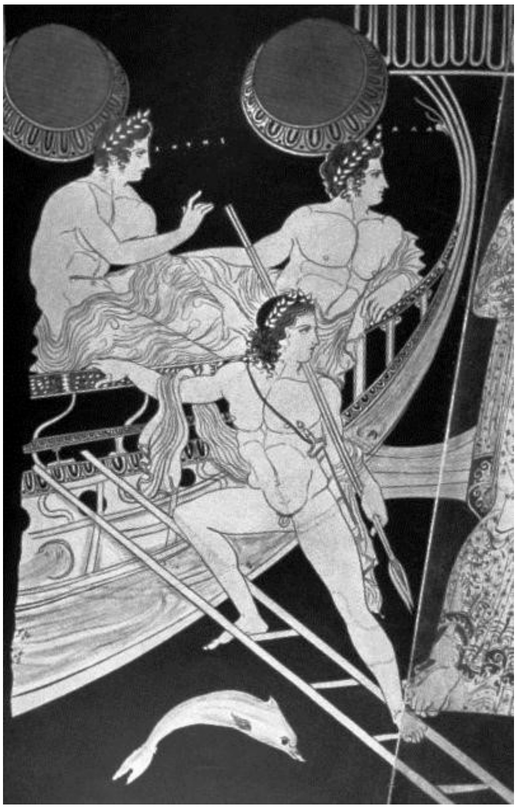
Greek trireme, Lenormant relief, Athens' Acropolis, around 410 BC (Acropolis Mus.)
Source : http://en.wikipedia.org/wiki/File:ACMA_Relief_Lenormant.jpg

Relief of the tomb of Caius Cartilius Poplicola, 25-20 BC (Ostia Antica)

http://www.romeartlover.it/Newosti5.html

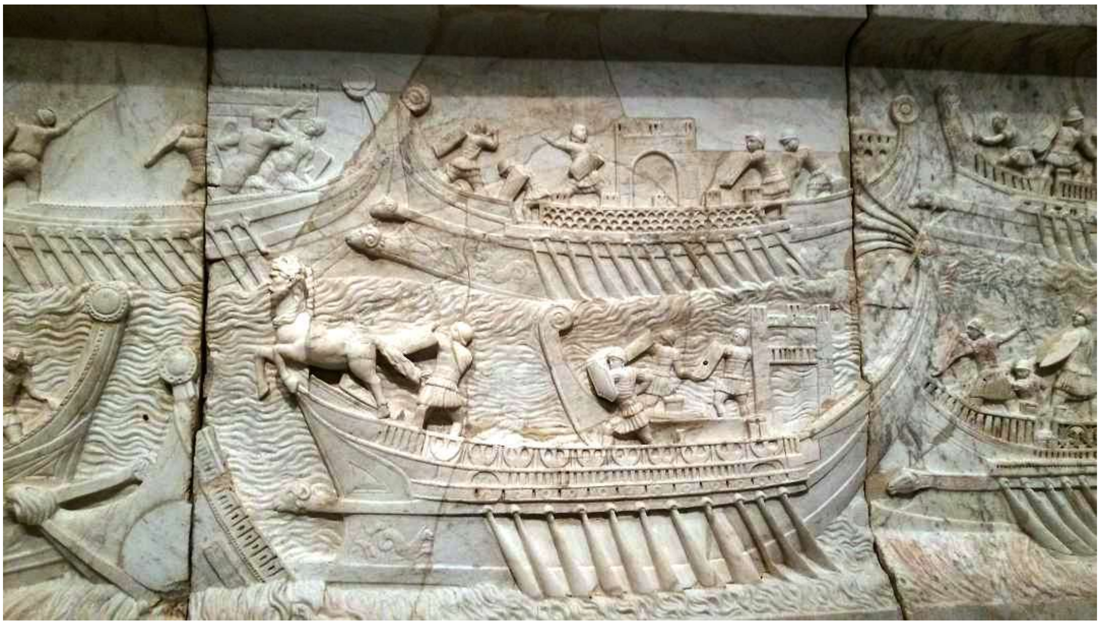
Pozzuoli relief, 1st c. BC to 1st C. AD (Naples Mus.)
Source : DEA / A DAGLI ORTI. Collection De Agostini Editore
http://www.agefotostock.com/en/Stock-Images/Rights-Managed/DAE-10327036

Siren vase, around 480 BC (British Mus.)
Source : http://www.britishmuseum.org/research/search_the_collection_database/search_object_details.aspx?objectid=399666



Talos vase, around 400 BC (Jatta Museo à Ruvo di Puglia, photo Simon & Hirmer, 1976)
Source : http://www.perseus.tufts.edu/hopper/image?img=Perseus:image:1993.01.0247

Galley on Isola Tiberina in Rome: probably a 100 BC quinquereme (photo: A. de Graauw, 2015)



Actium relief (Medinaceli collection, Cordoba).
Top ship is a Roman liburnian with ram-shaped embolion (waterline ram used as a weapon) and proembolion (upper-ram used either as a weapon or as a bumper) (photo: Miriam Pinagel)

Galleys in shipsheds on mosaic (detail) found at Anse (France) in 1843
dated 2nd or 3rd c. AD (photo: J-C. Béal, 2017).

5.3 Merchant ships

Surprisingly, the oldest pictures of ships are found in Scandinavia as stone carvings and paintings (Alta and over 300 other places in Norway, Sweden and Finland)[171]. Although dating petroglyphs is difficult, the Norwegian pictures are as old as 5000 BC, and perhaps even 8000 BC at Efjorden[172].
These ships may have been 'dugout' canoes like the one found in Pesse (Netherlands), also called logboats or monoxyle or pirogue[173].

Petroglyph featuring Neolithic Fishermen
(Alta, Hjemmeluft, Bergbukten3A, Norway, ca 4000 BC)

Egyptian rulers have been sailing during the Early Bronze Age (ca. 3300-2100 BC), i.a. Pharaoh Khufu-Cheops' port at wadi al-Jarf importing stones from the Sinaï (ca. 2550 BC), Sneferu (ca. 2575 BC) and Sahure (ca. 2450 BC) of the 4th and 5th dynasties sending ships to Byblos for wood and to Puntland for exotic goods[174].

Note that over time, the ships that initially set sail for Puntland from Ayn Sukhna near Suez, gradually moved southwards to Wadi al-Jarf, Marsa Gawasis, Myos Hormos and Berenike. This is due to the wind climate on the Red Sea and to improved roads leading to Nile valley via the Eastern Desert.

Note also that the great pyramid builders of the 4th - 5th - 12th dynasties have also been great seafarers.

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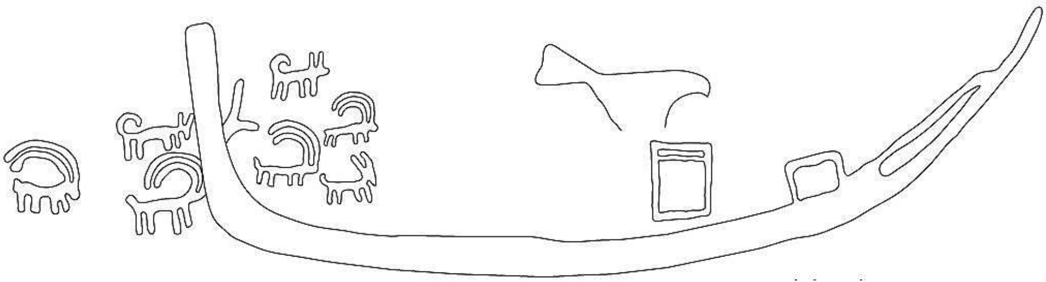
[171] GJERDE, J.M., 2019, "An overview of Stone Age rock art in northernmost Europe – what, where and when?", in Rock Art of the White Sea, Cambridge, (p 204-224), and
GJERDE, J.M., 2019, "Alta (Norway), Rock Art of", in Encyclopedia of Global Archaeology, C. Smith (ed.), (10 p).
[172] https://archaeologynewsnetwork.blogspot.com/2017/09/discovery-of-10000-year-old-petroglyph.html#gsWuGlr4SSsf9xG8.97
[173] PHILIPPE, M., 2023, "L'arbre qui cache la forêt: Métaphore de la pirogue monoxyle dans l'enregistrement archéologique des premières navigations européennes, une approche méthodologique", in: Actes du 29e Congrès préhistorique de France, 31 mai-4 juin 2021, Toulouse, (p 111-127).
[174] MARCUS, E. 2002, "Early Seafaring and Maritime Activity in the southern Levant from Prehistory through the Third Millenium BCE", in van den Brink & Levy eds, Egypt and the Levant, interrelations from the 4th through the Early 3rd millenium BCE, New approaches to Anthropological Archaeology, (p 403-417).
See also Wikipedia: https://en.wikipedia.org/wiki/Sahure



One of the oldest pictures of a ship (Egyptian Protodynastic, 3200 BC acc. to P. Tallet, 2012[175])

Pierre Tallet's explanations : « A l'extrémité droite du rocher inscrit, au sein d'un panneau rocheux assez érodé, sont représentées deux embarcations superposées. La gravure la mieux conservée, dans la partie supérieure, est longue de 130 cm. Il s'agit d'un grand bateau, à la coque faiblernent incurvée. Le dessin coupe une inscription rupestre antérieure - une scène de chasse néolithique ou figurent cinq bouquetins et deux chiens - ce qui permet une datation relative de ces gravures. L'embarcation présente à l'avant une sorte de petite cabine et vers le centre, un motif de *serekh*, de petite dimension, à moins qu'il ne s'agisse d'un habitacle associé au bateau, ou de tout autre élément d'architecture. L'espace à l'intérieur est assez érodé, mais il est certain qu'aucune inscription n'y a jamais figuré. Il est surmonté d'un faucon de grande taille (long. 14 cm), dont la silhouette a été obtenue par percussion sur le rocher. L'oiseau est représenté à l'horizontale, d'une façon relativement inhabituelle. Le style général de la représentation semble correspondre à une période très ancienne de l'histoire égyptienne : les dessins de faucons penchés vers l'avant, tout a fait comparables à celui-ci, apparaissent en effet à plusieurs reprises dans le matériel inscrit de la tombe U-j d'Abydos (Nagada IIIA, c. 3200 av.]-C), vraisemblablement destinée a un roi « Scorpion I ». Il s'agit des plus anciennes representations du signe hiéroglyphique G5, qui prend dans la documentation inscrite postérieure un aspect différent, le faucon ayant tendance à être redressé dès les attestations datées de Iry-Hor et Sekhen/Ka. Des représentations très proches de faucons à l'horizontale sont également présentes dans l'inscription I du Gebel Tjaouti, dont la première pourrait commémorer la victoire de ce roi abydénien sur un rival résidant a Nagada. Au terme de l'analyse de son riche mobilier funéraire, le propriétaire de la tombe U-j d'Abydos est maintenant considéré par de nombreux chercheurs comme un souverain dont l'influence a pu s'exercer sur l'ensemble du territoire égyptien. Nous sommes conscients que les elements permettant de dater la representation du Ouadi 'Ameyra restent ténus, et que celle-ci ne peut en aucun cas permettre à elle seule d'affirmer qu'une expédition minière avait déja été organisée en direction du Sud-Sinai à une époque aussi ancienne de l'histoire. Cette éventualité mérite cependant, selon nous, d'être gardée en mémoire, en attendant la découverte de nouveaux éléments permettant de préciser cette chronologie. »

Similar petroglyphs are found at Rod el-Air near near Serabit el-Khadim[176], and in the Egyptian Eastern Desert (Lankester, 2012[177]) and other examples are shown on vases of the same Gerzean period (e.g., British Museum N°35324, 35502 & 36326) and on the handle of the so-called Gebel el-Arak knife.

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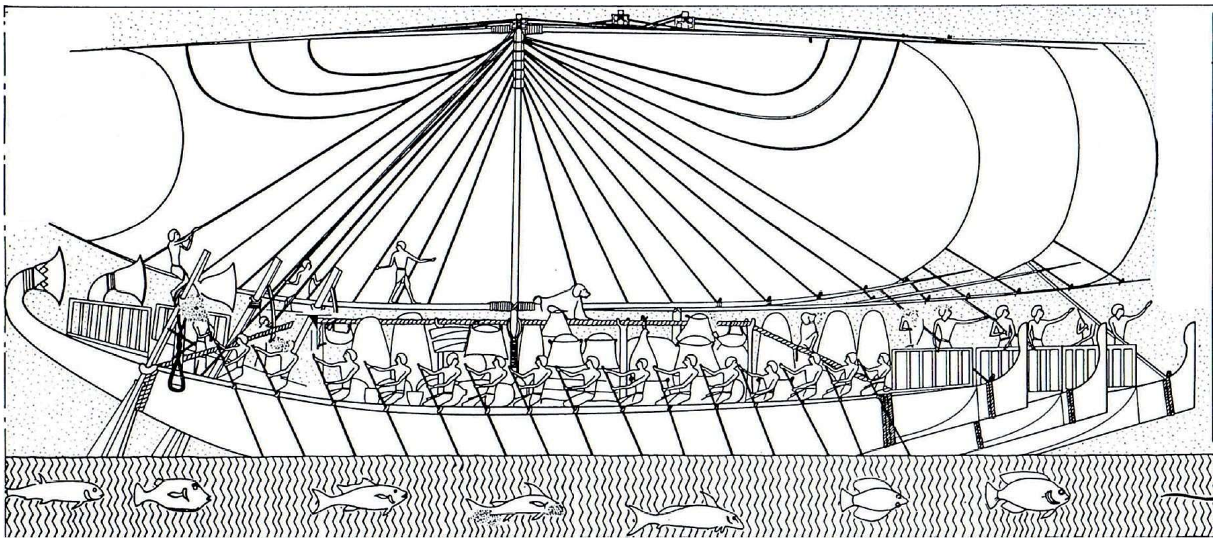
[175] TALLET, P. & LAISNEY, D., 2012, "Iry-Hor et Narmer au Sud-Sinaï (Ouadi 'Ameyra) – Un complément à la chronologie des expéditions minières égyptiennes", Bulletin de l'Institut Français d'Archéologie Orientale, Tome 112, Le Caire, 2012, (p 381-398). Location near 29.198°N, 33.233°E.

[176] POMEY, P., 2012, "Pharaonic Ship Remains of Ayn Sukhna", Proceedings of the Twelfth Symposium on Boat and Ship Archaeology, Istanbul 2009, (p 7-15).

[177] LANKESTER, F., 2012, "Rock Art in Egypt's Eastern Desert", University of Durham, UK, (43 p).

Minoans from Crete were probably the first “professional” merchant seafarers sailing internationally in the Mediterranean area. This spanned, in round figures, the period between 2000 BC and 1500 BC.

Egyptians developed river and sea ships for 2000 years during the 3rd and 2nd millennia BC[178]. Between 2000 and 1800 BC, several pharaohs of the 12th dynasty sent expeditions on the Red Sea from Marsa Gawasis to the Land of Punt, to bring back exotic goods. Around 1450 BC, Queen Hatshepsut also sent a fleet to the Land of Punt, this time from Myos Hormos (Quseir).



Hatshepsut’s fleet sailing back from Puntland (ca. 1450 BC), relief found in Deir el-Bahari temple.

Later on, Ramesses II won a famous battle against the Sea Peoples ca. 1278 BC and provided shipbuilding assistance to the Hittites in ca. 1259 BC (Tablet KUB III 82 found at Boghazkoy/Hattusa[179] [180]).

Ramesses III's war ships are shown on the Medinet Habou relief (ca. 1180 BC) where it can be noted that the lower yard has been removed so that the sail has a lose foot[181]. This development can perhaps be seen as opening the way to the lateen sail concept that will emerge around 1400 years later.

After this, Egyptian seafarers seem to vanish from the scene while Phoenician seafarers appear. Between 1200 and 600 BC, Phoenicians were involved mainly in (fairly) peaceful maritime trade, sailing all over the Mediterranean Sea and beyond, but very few written or iconographic documents of this period came down to us[182]. The Bible mentions “Tarshish ships” and “Byblos ships” several times, probably meaning large ships sailing respectively for metals to Tartessos in the south of Spain and for timber to Byblos in Lebanon. As the name

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[178] POMEY, P., 2015, “Navires et construction navale dans l’Égypte ancienne”, in *Entre Nil et mers, la navigation en égypte ancienne* », edt B. Argémi & P. Tallet, Actes des rencontres de Provence Égyptologie, Musée Départemental Arles Antique, le 12 avril 2014.

[179] POMEY, P., 2006, “Le rôle du dessin dans la conception des navires antiques. À propos de deux textes akkadiens”, in *L’Apport de l’Égypte à l’histoire des techniques.* Edt B. Mathieu, D. Meeks, M. Wissa*,* Méthodes, chronnologie et comparaisons, BdE 142, Cairo.
See also discussion POMEY, 2009 and BASH, 2009.

[180] EMANUEL, J., 2014, “Sea Peoples, Egypt, and the Aegean: The Transference of Maritime Technology in the Late Bronze–Early Iron Transition (LH III B–C)”, Aegean Studies, No. 1, 2014, (p 21-56).

[181] See note above.

[182] VAN ALFEN, P., 2015, “Phoenician Trade: An Overview”, Working Paper v.31.3.2015.

"Tarshish ship" was also used in other areas like the Red Sea, we can assume that it refers to a type of ship rather than to a destination.

In this period, the Egyptian pharaoh Necho II sent an expedition to circumnavigate Africa (ca. 600 BC).

Sargon II's Palace relief showing log transport (ca. 715 BC),
found at Dur Sharrukin (Khorsabad in Iraq).

This period was followed by the better known "Greek Classical Period" (500-323 BC), the "Hellenistic Period" (323-31 BC) and the Roman period[183].

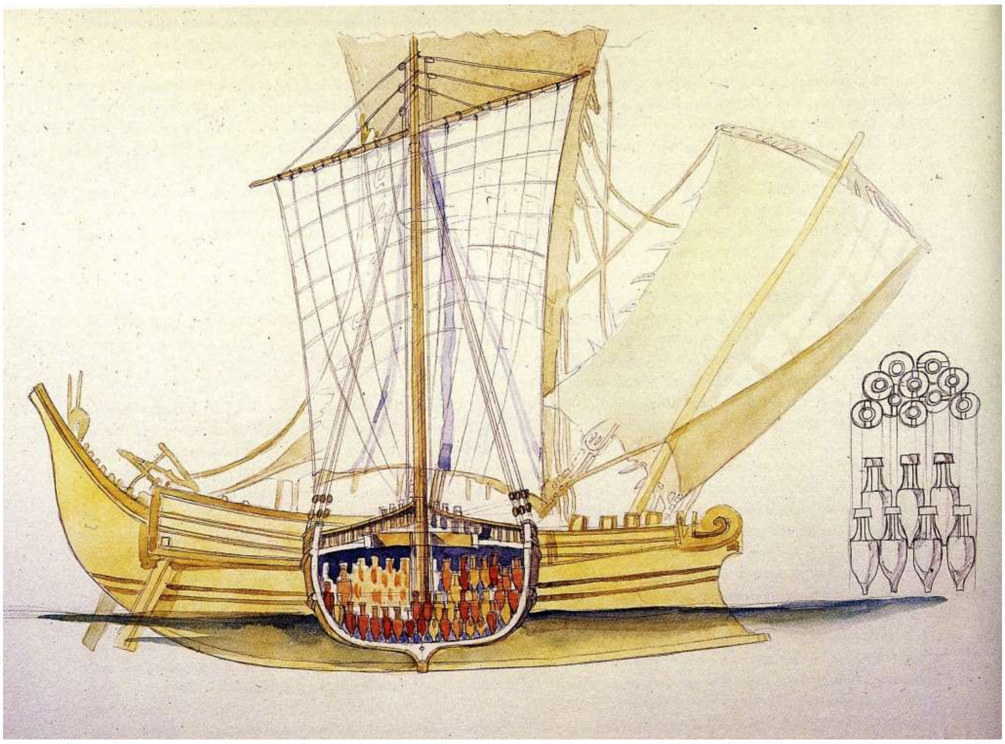
Early large Greek merchant ships of the Kerkouros type with combined rowing and sailing capacity, seem to have been in use between 500 BC and 100 BC[184]. They could carry an average of 250 tons of cargo, up to 500 tons. Their average dimensions may have been 21 x 3 m, with 1:7 beam over length ratio, up to 50 x 7 m for the larger ones.

Kerkouros relief, 1st c. AD, possibly a bireme (7 oars below & 6 oars on top)
with cargo near the stern, behind the gubernator
(source: Antike Denkmäler, Band III, Tafel 31A, DAI, 1926, now in Torlonia Mus.).

[183] For a superb overview of the Roman history, have a look at: BADEL, C. & INGLEBERT, H., 2014, "Grand Atlas de l'Antiquité romaine – Construction, apogée et fin d'un empire", éd. Autrement, Paris, (191 p).
[184] ARNAUD, P., 2012, "La mer, vecteur des mobilités grecques", in "Mobilités grecques", Capdetrey & Zurbach (edt.), Scripta Antiqua 46, Ausonius, Bordeaux, (p 89-135).

It may be noted also that Kerkouros ships usually docked stern first, while later ships also docked bow first as shown on the Torlonia relief. Alongside docking was required if heavy cargo (live animals, barrels) was to be lifted by cranes.

Later ships were more bulky and had no significant rowing capacity anymore, like the Roman Corbita type with 1:4 beam over length ratio. Exceptional ships like the Isis, 55 x 14 m, could carry 1200 tons with around 4.5 m draught, but normal ships ranged between 20 and 50 m for 100 to 500 tons of cargo with up to 3.5 m draught. Both concave bows (sharp bulbous bow, also called 'cutwater') and convex (rounded) bows were in use (see Foro delle Corporazioni at Ostia mosaïcs). The stern was quite high as these ships could easily be overtaken by waves travelling at 10 to 20 knots during a storm.



Roman ship showing stowed amphorae, after the Madrague de Giens shipwreck, dated 75 to 60 BC, estimated dimensions 40 x 9 m and 3.5 m draught for 375 ton of cargo (by Jean-Marie Gassend, 2005)

The Muziris Papyrus (ca. 150 AD) is a fragmentary document found in 1985[185]. On its verso side, it provides a list of cargo which has been reconstructed as follows: 544 tons of pepper, 76 tons of malabathron (cinnamomum tamala leaves), 3 tons of ivory tusks and 0.5 ton of ivory fragments, 2 tons of tortoise shell, and 80 boxes of Gangetic nard (possibly 1 or 2 tons)[186]. That is a payload of ca. 628 tons, requiring a very large Roman ship (this one was called the Hermapollon). The total value of this cargo reaches a stunning amount of 9.2 million Roman sesterces, which is around 90 million modern Euros[187].

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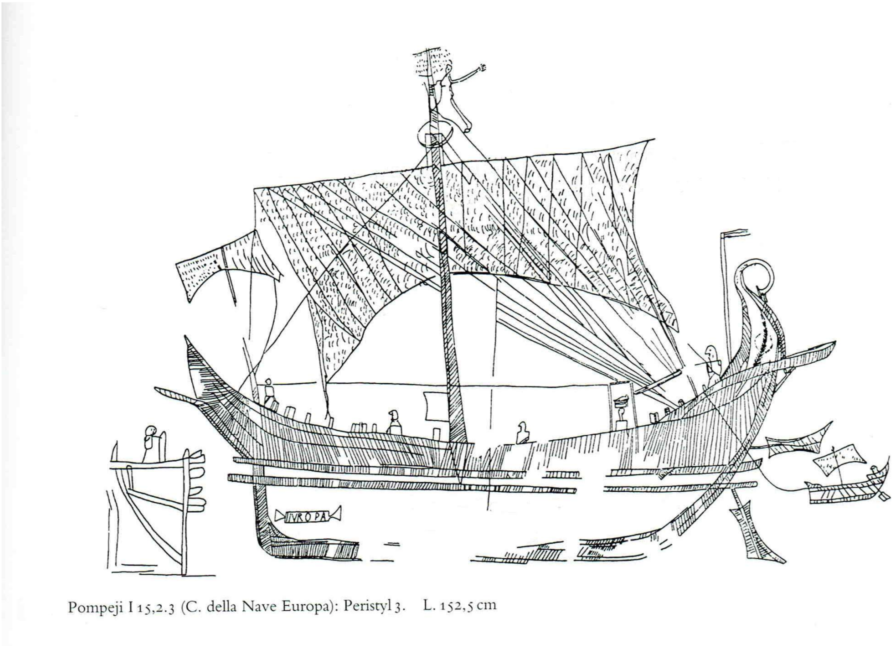
185 Casson, L., 1990, "New Light on Maritime Loans: P.Vindob. G 40822", in Zeitschrift für Papyrologie und Epigraphik 84, (pp 195-206), gives a complete translation into English. The papyrus is presently housed in the Austrian National Library in Vienna. It is one of the very few surviving maritime contracts presently available to us (see also: http://papyri.info/ddbdp/sb;3;7169).

186 De Romanis, F., (2012), "Playing Sudoku on the Verso of the 'Muziris Papyrus': Pepper, Malabathron and Tortoise Shell in the Cargo of the Hermapollon", Journal of Ancient Indian History, 27, (pp 75-101), gives a brilliant reconstruction of the cargo on board the Hermapollon. See also his 2014 conference: http://www.college-de-france.fr/site/jean-pierre-brun/seminar-2014-12-09-10h00.htm

187 1 Roman sesterce = 6.5 €, based on the fairly low annual salary of a 1st century soldier or worker of 1000 sesterces/year (i.e. one denarius = 4 sesterces = 16 asses per day, acc. to Tacitus, Annals, I, 17, and on 250 days/year), compared to the French lowest revenue (RSA) of 6 420 €/year in 2016 for a single man. See also: https://web.archive.org/web/20130210071801/http://dougsmith.ancients.info/worth.html



Large merchant ship from a graffito in Pompei
(source: M. Langner, 2001, "Antike Graffitizeichnungen").

Most of our knowledge is taken from shipwrecks that tell us about the ships and about their content. Amphorae were stowed vertically, protected by bales of straw and secured with ropes. Copper and tin ingots were placed at the bottom of the hold, acting as ballast. It is believed that wheat was carried in sacks of one artaba (ca. 30kg) for easy loading/unloading. The port(s) of origin can often be guessed from the content of the ship, but the port of destination is usually more difficult to identify. It may be said that large ships (and a few smaller ones) were sailing on the long haul between major hubs, but that local redistribution was conducted by small ships only[188]. See section on "Ancient maritime trade" hereafter.

Many web sites provide further information, e.g., Navis, Navistory, Navigation dans l'Antiquité.

5.4 Who is the « Gubernator »? the helmsman … and/or the pilot?

« Gubernator » in Latin, and « Kybernetes » in Greek.

Greek Pentecontore, detail on Attic Cup,
ca 520 AD (BNF, Paris)

[188] BOETTO, G., 2012, "Les épaves comme sources pour l'étude de la navigation et des routes commerciales: une approche méthodologique", in: "Rome, Portus and the Mediterranean", edt. S. Keay, British School at Rome, Oxbow Books.

He was the captain acting both as the helmsman and as the pilot who knew the location of safe shelters and how to handle the ship to enter them.

This can be deduced from the famous last voyage of Paul where the *kybernetes* and the *naukleros* are the obvious decision-making sailors on board, together with the centurion who is a distinguished ‘client’:

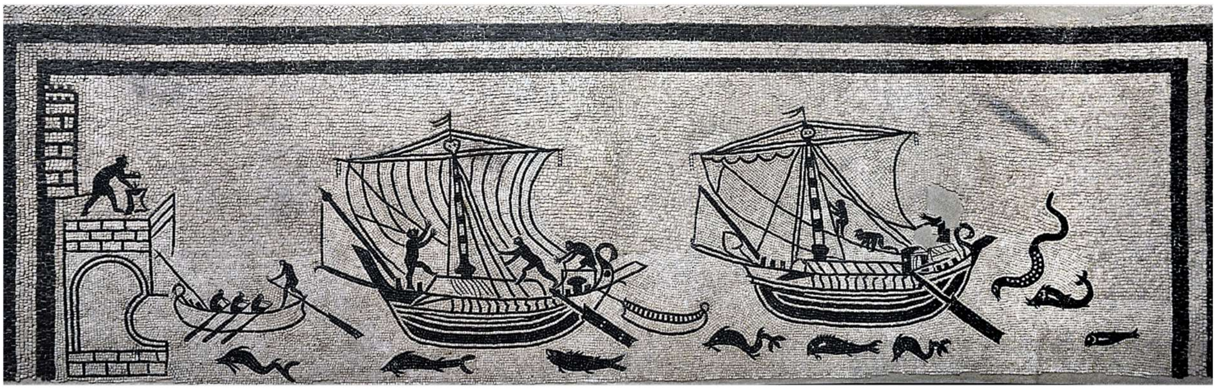
“Nevertheless, the centurion believed the master [κυβερνήτης, kybernetes] and the owner of the ship [ναύκληρος, naukleros], more than those things which were spoken by Paul.” (Luke’s Acts (27. 11), probably 80 to 90 AD)[189].

However, Virgil (Aeneïd, 5, 176-177) makes a clear distinction between master and pilot during the famous race between four navy ships at Drepana-Trapani (Sicily)[190]: “*ipse gubernaclo rector subit, ipse magister hortaturque uiros clavumque ad litora torquet.*” (he [Gyas] replaced the pilot, and as a master, he urges his men while steering shoreward, transl. Joseph Farrell, 2014). This is still the case on modern navy ships where the captain’s job is to conduct war more than to steer the ship by himself.

Some pilots were based in a given port and had detailed knowledge of local sea ways in addition to a vast experience in ship handling (similar to modern maritime pilots).

Let’s look at the oldest text describing a pilot job in the dangerous area of the Gulf of Khambhat (India) with extremely large tidal ranges (up-to over 10 m):

“Because of this, native fishermen in the king’s service, stationed at the very entrance in well-manned large boats called trappaga and cotymba, go up the coast as far as Syrastrene, from which they pilot vessels to Barygaza. And they steer them straight from the mouth of the bay between the shoals with their crews; and they tow them to fixed stations, going up with the beginning of the flood, and lying through the ebb at anchorages and in basins.” (Periplous Maris Erythraei, 1st c. AD).



Ships entering the port of Ariminum (Rimini) following a pilot boat, while the crew is busy reducing sail, 2nd c. AD mosaic found in Palazzo Diotallevi (Luigi Tonini Mus.)

A very illustrative ancient text of a pilot job on the Libyan coast reads as follows:

“Now when day appeared, a man in rustic garb signalled and pointed out which were the places of danger, and those that we might approach in safety. Finally, he came out to us in a boat with two oars, and this he made fast to our vessel. Then he took over the helm, and our Syrian [captain] [i.e., Amarantus] gladly relinquished to him the conduct of the ship. So, after proceeding not more than fifty stadia [five miles], he brought her to anchor in a delightful little harbour, which I believe is called Azarium [probably somewhere near Derna in Libya] and there disembarked us on the beach. We acclaimed him as our saviour and good angel. A little while later, he brought in another ship, and then again another, and before evening had

189 http://www.ellopos.net/elpenor/greek-texts/new-testament/acts/27.asp
190 https://books.google.fr/books?id=kCZICgAAQBAJ&lpg=PP1&hl=fr&pg=PA43#v=onepage&q&f=false

fallen, we were in all five vessels saved by this godsent old man, the very reverse of Nauplius who received the shipwrecked in a vastly different manner [he deliberately misled sailors to ground them onto the rocks]. On the following day, other ships arrived, some of which had put out from Alexandria the day before we set sail. So now we are quite a fleet in a small harbour." (Letter from Synesius of Cyrene (370 – 414 AD) to his brother in Alexandria, May 397 AD).

This description fits a modern pilot (except for the "rustic garb"!) where the "boat with two oars" is now replaced by a modern pilot launch or helicopter.

Another ancient text reads as follows:

"If the captain entered the ship in a river without a pilot, and if he was not able to control the ship and lost her when a storm occured, the charterer may undertake legal action against him." (Justinian's Digest, 19.2.13.1, Ulpianus, book 32, Ad Edictum, ca 530 AD).

This text shows that a pilot could be mandatory in some areas with higher risk for shipping. This is still the case today.

A much older text available on the so-called ''Pithom stela'' (dated 264 BC) probably also mentions a pilot at the entrance of Ptolemais Theron on the Red Sea[191].

It is fairly certain that ancient pilots did not rely on any written documents such as the known Periploi and Stadiasmoi, because they do not provide sufficient information for a pilot (these documents were probably compiled by merchants and other people sailing on ships). Even today, maritime pilots do not write down their experience, as they still consider it as an art that cannot be expressed by words ('ars gubernatoris'). Some scientific knowledge on ship handling has been gathered and written down, but local knowledge, e.g., near port areas is only in the pilot's head and transmitted oraly from one generation to the next.

Concluding: the *gubernator* was the true captain of the ship and acted both as the helmsman and as the pilot who knew the location of safe shelters and how to handle the ship to enter them. However, on navy ships, the helmsman/pilot and the master were two different individuals.
Sometimes, the ancient pilot worked similarly to a modern maritime pilot who is usually based in a given port and has detailed knowledge of local sea ways in addition to a vast experience in ship handling (he therefore trains extensively on digital simulators, and on manned models like Port Revel).

5.5 Some more definitions of ancient Greek terms

NB: the definitions provided below are no more than the most probable (and schematic) definitions. Note also that some small variations of the meaning may exist when translating from one language into another.

Commercial shipping:
naukleros has several meanings**:**
1. (Latin: naucler(ic)us, navicularius, dominus navis; FR: armateur; GB: ship owner): the meaning of this word seems to have changed over time (ship owner, ship master, maritime trader) and in space (Italy, Egypt), acc. to Arnaud (2016). He was a member of his city's professional guild who could negotiate privileges and shipping prices with the emperor's Annona and therefore belonged to the Roman elite. He could also act as a *negotiator* for his own business, acc. to Arnaud (2015).

[191] THIERS, C., 2007, « Ptolémée Philadelphe et les prêtres d'Atoum de Tjékou. Nouvelle édition commentée de la "stèle de Pithom" (CGC 22183) », Université Paul Valéry-Montpellier III.

2. (Latin: magister navis; FR: subrécargue; GB: supercargo): trader travelling on board the ship and representing the owner of the cargo who empowered him to buy and sell cargo.
phortegos (Latin: naucler(ic)us, navicularius; FR: cabotage; GB: coastal trade): ship owner sailing his own ship and acting as a seaborne trader, which may *perhaps* be assimilated with a person conducting coastal trade.
emporos (Latin: emporus, mercator; FR: marchand; GB: trader): maritime trader sailing on another man's ship.
cheimon (Latin: mare clausum; FR: mer fermée; GB: closed sea): season with unstable weather, from early November to end of March, during which large-scale shipping was avoided, at least in the western Mediterranean area.
annona (Latin: annona; FR: annone; GB: annona): organisation for state-owned grain supply from Sicily, North Africa and Egypt via shipping lanes connecting them with Ostia and other important ports.

Military shipping:
trierarkhos (Latin: trierarchus; FR: triérarque; GB: trierach): person operating a kind of one-year leasing of a war ship (e.g., trireme) owned by the state. This is one of the wealthiest citizens' duties ('leitourgia').
nauarkhos: in ancient Greece (Latin: nauarchus; FR: commandant; GB: commander): commander of a war ship; in ancient Rome (Latin: nauarchus; FR: amiral; GB: admiral): commander of a fleet (fleet captain).

Further reading:

- KOWALSKI, JM., 2012, "Navigation et Géographie dans l'antiquité Gréco-Romaine - La terre vue de la mer", éd. Picard, Paris.
- ARNAUD, P., 2016, "Entre mer et rivière : les ports fluvio-maritimes de Méditerranée ancienne", Colloque 'Les ports dans l'espace méditerranéen antique. Narbonne et les systèmes portuaires fluvio-lagunaires', Espace Capdeville, Montpellier 22/23 mai 2014.
- ARNAUD, P., 2016, "Cities and Maritime Trade under the Roman Empire", in "Connecting the Ancient World - Mediterranean Shipping, Maritime Networks and their Impact", Christoph Schäfer (ed.), Pharos Studien zur griechisch-römischen Antike, Band 35, (p 117-173).
- ARNAUD, P., 2015, "Inscriptions and port societies: evidence, "Analyse du discours", silences, portscape ...", International Conference on Roman Port Societies through the evidence of inscriptions, organized by Pascal Arnaud and Simon Keay as part of the ERC Advanced Grant funded Rome's Mediterranean Ports Project in conjunction with the British School at Rome, 29-30 January 2015.
- BONNIER, A., 2008, "Epineia kai limenes: the relationship between harbours and cities in ancient greek texts", Opuscula, 1, 2008, Stockholm.

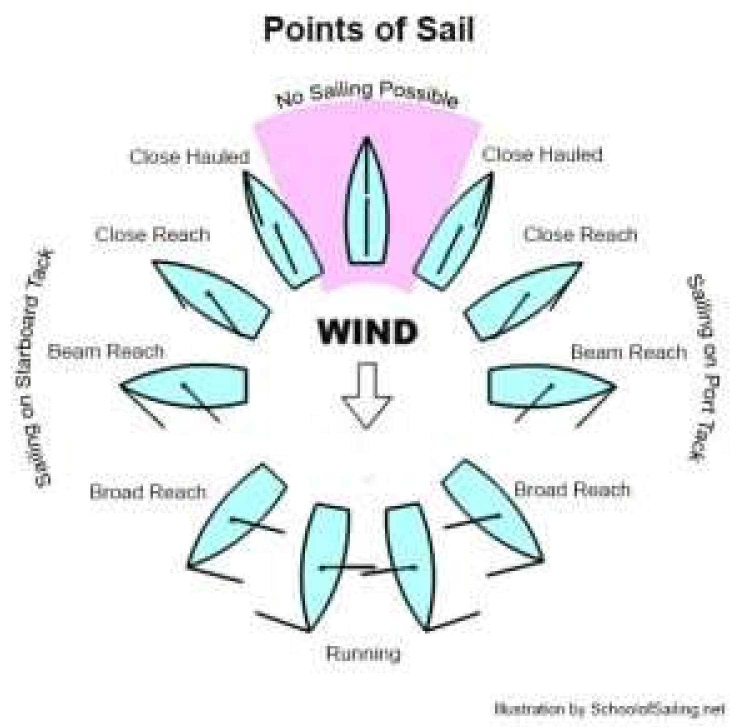
6 ANCIENT SAILING

6.1 How about the wind?

Wind force. Sailing was (and still is) considered comfortable with winds of Beaufort force 3-4 (up to 15 knots wind), it becomes quite 'sportive' with force 5-6 Bft and critical above force 7 Bft (over 30 knots wind).
According to Pascal Arnaud (2005, p 22[192]), as long as a sea state (wind and waves) does not exceed say force 4 Bft (15 knots wind), the sailor is free to manoeuvre his ship in various directions, but for higher sea states he loses this freedom and has to sail downwind[193]. As, during storms, waves may be travelling at 10 to 20 knots, they can overtake the ship and thus require a high stern to avoid flooding the aft deck.
The 1986 Kyrenia II experiment (small 30-ton freighter of 14.5 x 4.5 m) has shown that an ancient merchant ship could resist well in a force 9-10 Bft storm (45-50 knots wind). Surely much better than any ancient battleship that would probably not resist more than force 6 Bft (25 knots wind) and 1 m waves, as shown during the Olympias sea trials (50-ton trireme of 37 x 5.5 m) in 1992 (Morrison et al., 2000). A similar experience was performed in 2017-2019 with the Ma'agan Mikhael II (small 20-ton freighter of 16.6 x 4.3 m) showing results similar to those obtained with the Kyrenia II (Palzur, 2021[194]).

Wind direction. It was mentioned above that, provided the wind force does not exceed 15 knots, the sailor has some freedom as to his direction of sailing. Ships were normally sailing from wind astern (180°) to wind abeam (90°), but it was possible to sail into the wind up to around 60° (see Arnaud, 2005, and Morrison et al., 2000). However, such a close-hauled course was very uncomfortable[195] and not very efficient because of the leeway (lateral drift) ranging between 10° and 20°: with a mild wind of 5 to 10 knots, the course with respect to the ("true") wind direction was therefore around 70° to 80° (60° + 10° to 20° leeway), meaning that only 20° to 10° headway was really made with respect to the 'no headway' direction of 90°. This close-hauled sailing meant a lot of effort for small progress in the desired direction (of 0°) and both Casson (1995) and Whitewright (2011) concluded that the average speed in the desired direction was less than 2 to 2.5 knots. It may therefore be expected that few sailors would choose close-hauled sailing on a long distance, unless they were forced to do so by unexpected wind conditions or other compelling reasons[196].

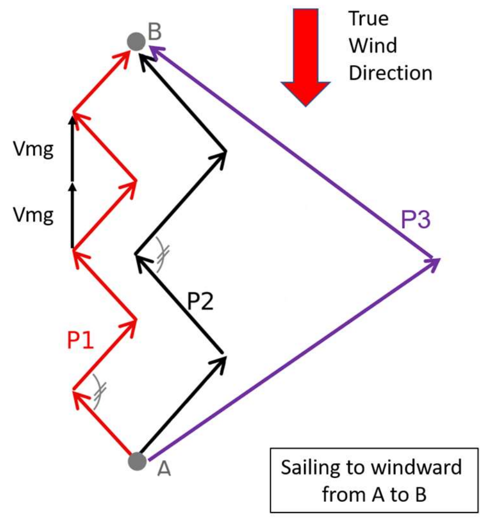
[192] ARNAUD, P., 2005, "Les routes de la navigation antique", éd. Errance.
[193] Virgil (Eneid, 5, 8-25) explains what any sailor would still do today with unfavourable winds, i.e., try tacking, but bear away to downwind if the wind is too strong.
[194] MORRISON, J.S.; COATES, J.F.; RANKOV, N.B., 2000, "The Athenian Trireme", Cambridge University Press, (350 p).
PALZUR, Y. & CVIKEL, D., "Sailing Ma'agan Mikhael II", Archaeonautica [Online], 21 | 2021, (p 277-282).
See also: http://kyrenia-collection.org/styled-4/styled-7/index.html
[195] Achilles TATIUS (Leucippe and Clitophon, 3, 1) describes windward sailing with multiple tacking.
[196] WHITEWRIGHT, J., 2011, "The Potential Performance of Ancient Mediterranean Sailing Rigs", IJNA International Journal of Nautical Archaeology (2011), **40** .1: 2–17. See also his 2008 PhD thesis (Vol. I & Vol. II) at Southampton University.
GAL, D., SAARONI, H., CVIKEL, D., 2023, "Windward Sailing in Antiquity: The Elephant in the Room", IJNA International Journal of Nautical Archaeology, DOI : 10.1080/10572414.2023.2186688.
PALMER, C., 2009, "Windward Sailing Capabilities of Ancient Vessels", IJNA International Journal of Nautical Archaeology, 38:2, (p 314-330), DOI: 10.1111/j.1095-9270.2008.00208.x.
CASSON, L., 1995, "Ships and seamanship in the ancient world", Johns Hopkins University Press, (470 p).



Points of sail of modern sailing boats.

The points of sail shown above are valid for modern 'Bermuda' rigs with a large genoa sail, but ancient ships had square sail(s) or a lateen or settee sail. Modern sailing boats may reach 20-30° as shown above, but they are designed for racing more than for transporting cargo.

If the ship's destination requires sailing upwind, 'beating to windward', then periodic 'changing tack' is needed. It consists in zig-zaging on close-hauled courses. The ship's speed in the desired direction (Vmg, 'Velocity made good' [197]) is obviously reduced.



Changing tack strategy:
Close-hauled sailing course: P1 requires more turns, thus more time, but the total distance is the same as P2.
Close-reach sailing course: P3 requires more distance, but this may be faster as the speed is higher.

[197] https://en.wikipedia.org/wiki/Velocity_made_good: rectilinear speed resulting from the much longer distance sailed while tacking.

With a square sail or a lateen sail including a top yard, the preferred method for changing tack was by 'wearing'[198] : turn the ship to running downwind, then turn her back to a close-hauled course on the other tack (the word 'gybing' is used on modern yachts with triangular ‘fore-and-aft- rig’).

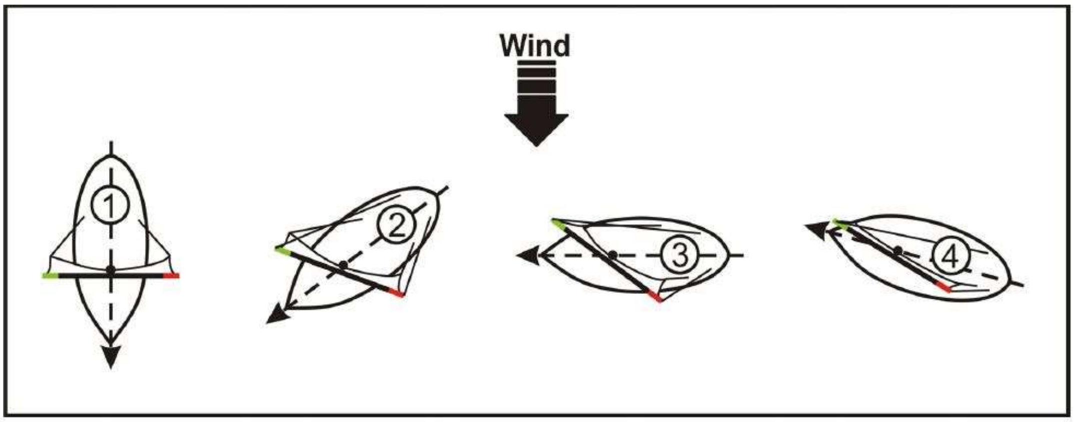


Figure 2-12. The changing position of yard and sail, tack and clew, sheets and braces when altering course, on a starboard tack. 1) Dead run: yard and sail are set across the vessel and both sheets and braces are used to control the sail. 2) Broad run/reach: Port yardarm is braced aft and the port clew is sheeted aft, starboard brace and sheet are loosened. 3) Beam reach: Port yardarm is braced further aft and port clew is sheeted in further, starboard clew is secured forwards of the mast is becomes the starboard tack. 4) Close-hauled: The sail is set as close to the centreline of the vessel as possible, port clew is sheeted in as far as possible and port yardarm is braced around as much as possible. Starboard tack is secured further forward and the starboard lifts (if fitted) may be tensioned to help maintain the tension in the luff of the sail. Bowlines (if fitted) would also be set up on this course.

Points of sail with a square rig (J. Whitewright, 2008).

[198] https://thetidesofhistory.com/2021/02/21/tacking-and-wearing-jibing/ ,

Kyrenia II sailing at close reach on the Aegean Sea in 1987.

A merchant sailing ship will show the best performance when sailing at broad reach, but it also needs to show acceptable performance in sailing to windward at close reach with a simple easy-to-build sailing rig[199].

Modern sailing boat under spinnaker at broad reach … rather sportive!

[199] https://en.wikipedia.org/wiki/Category:Sailing_rigs_and_rigging

6.2 How about the sailing rigs?

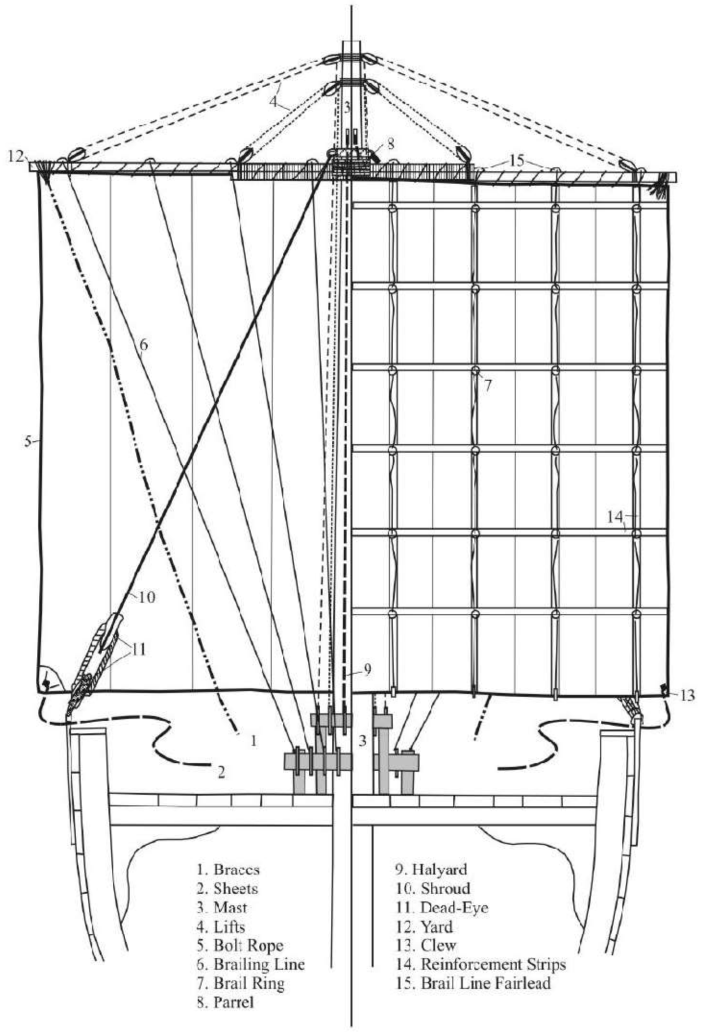
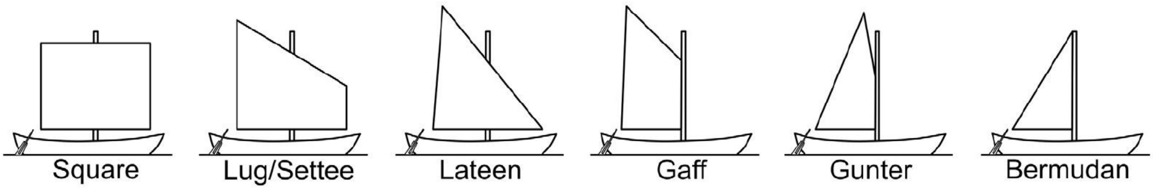


Figure 2-6. Simplified locational diagram of rigging-components on the Mediterranean square-sail rig. The right-handside illustrates a view of the sail from the front, while the left-handside illustrates a view from the stern of the vessel (J.Whitewright).

Square sailing rig (J. Whitewright, 2008).



Sailing rigs (J. Whitewright, 2008).

The lateen/settee rig was probably invented in the 2nd c. AD and was widely adopted in the 5th c. AD. This does not mean that square sails were abandoned, as they were still in use on windjammers at the end of merchant sailing in the early 20th c.. Several concepts thus coexisted over very long periods of time (Julian Whitewright (2011), Pascal Arnaud (2005), Rod Heikell [200]).

[200] HEIKELL, R., 2015, “Sailing Ancient Seas”, Taniwha Press, UK.

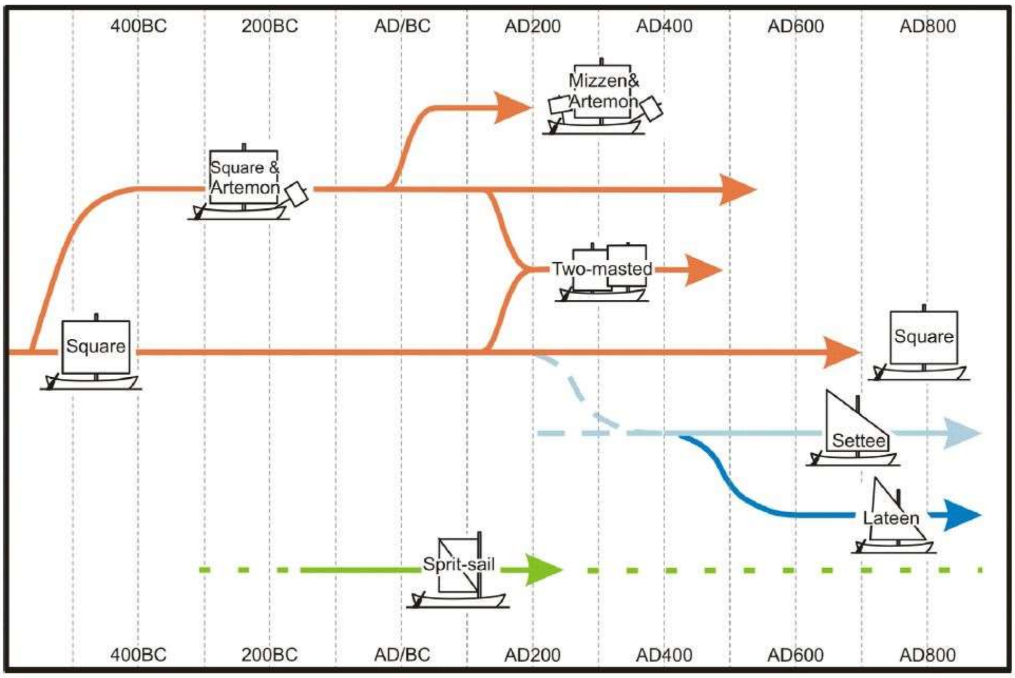


Figure 3-11. Multilinear development of ancient Mediterranean sailing rigs. Solid lines indicate definite, identifiable evidence, dashed lines indicate conjectural pathways.

Development of Mediterranean sailing rigs (J. Whitewright, 2008).

The various sailing rigs obviously had pros and cons and mariners made their own choices. Note that modern sailors are biased by the modern triangular Bermuda rig designed for sailing-boat racing in the 19th c.[201] .

From the point of view of a sailor sailing a square-rigged ship at close reach, it was worth trying to reduce the length of sail-cloth susceptible of sagging on the luff side by pulling down the windward end of the yard. This would probably leave too much sail abaft the mast so that the ship would easily luff[202], but it opened the way to the triangular shape of the lateen rig pointing into the wind. Furthermore, the lateen sail consisted of less components than the square sail, but it required more crew to be handled. A drawback of the lateen sail is that it is difficult (impossible with strong wind) to take the yard from one side of the mast to the other side, thus leading to a favoured tack when the yard is downwind of the mast and an unfavourable tack when the yard is upwind of the mast (so-called "bad tack").

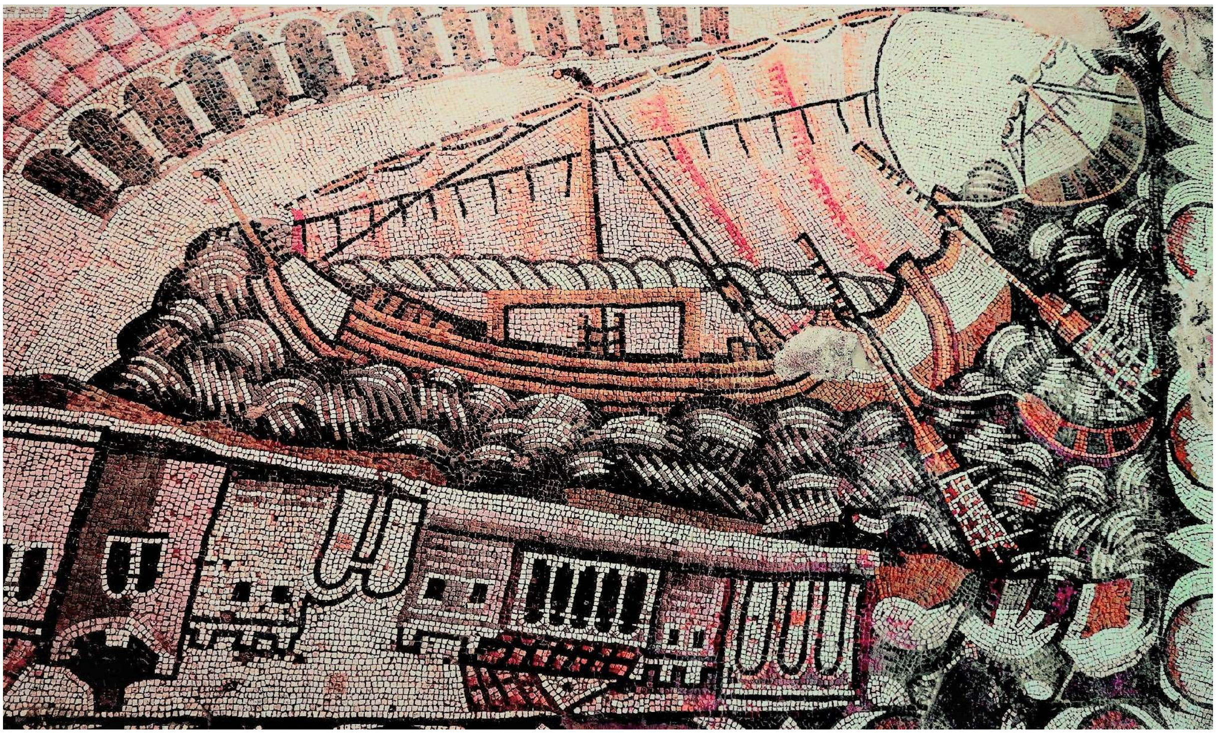
Good tack (left) and bad tack (right) with a lateen sail
(source: https://www.youtube.com/watch?v=tdQDpJ8OQWE)

[201] https://en.wikipedia.org/wiki/Bermuda_rig

[202] Aristotle, Mechanica, 851-b, already pointed this out, see POMEY, P., 1997, "La Navigation dans l'Antiquité".

Whitewright (2011) shows that the lateen and settee rigs performed only very slightly better to windward than square sails as it allowed sailing 55 to 65° off the wind direction, while a square sail would allow 60 to 65°. The 'velocity made good' was only 1 to 2 knots in both cases (with moderate wind and calm sea). Hence, there is very little difference in the overall performance of both rigs and *this explains why both coexisted for many centuries*.

The 5th c. Kelenderis mosaic below shows a ship with reefed trapezoidal settee sail close to a lateen rig[203].



Kelenderis 5th c. AD mosaic (3 x 3 m) discovered by Levent Zoroglu in 1992, showing a harbour scene with a ship in full action in a rough sea. (source: http://www.cka.org.tr/dosyalar/bir_bakista_mersin.pdf)

Note that although the harbour city is depicted, the ship is sailing at close reach with a reefed sail in rough seas with many waves. Such a picture of a sailing ship in full action is very rare as artists never had an opportunity to see this from the shore.

Sailors are not conservative at all when it comes to sail settings and they may very well have used the triangular setting of the square sail for many centuries before the Kelenderis mosaic picture.

6.3 Sailing on the Mediterranean Sea

The main sailing routes have been deduced from ancient texts (Arnaud, 2005) and from modern 'Pilots' used by yachtsmen. Indeed, the meteorological sailing conditions are considered to be fairly unchanged over the past few millennia (see section on "Ancient climate"). Wind speed and direction are of paramount importance for sailing, as Mediterranean currents play a secondary role and high waves are avoided as much as possible.

203 POMEY, P., 2017, "À propos de la voile latine : la mosaïque de Kelenderis et les *Stereometrica* (II, 48-49) d'Héron d'Alexandrie", Archaeonautica, 19, 2017, (p 9-25).
WHITEWRIGHT, J., 2009, "The Mediterranean Lateen Sail in Late Antiquity", The International Journal of Nautical Archaeology (2009), 38.1: 97–104.

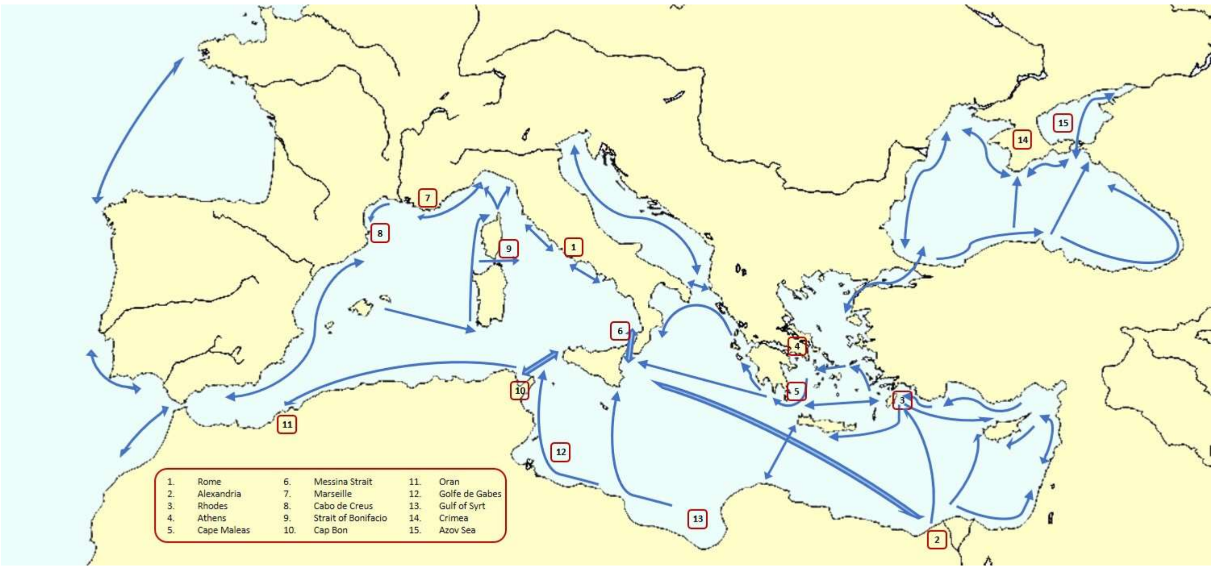
The prevailing wind direction almost everywhere on the Mediterranean Sea is NW.

Note that 'prevailing' usually means 'over 50% of time', but not 100%!
In addition, a *constant* wind direction is required for long-haul offshore sailing. This is typically the case from Sicily to Alexandria in summer time, but other prevailing wind directions may exist locally, e.g., north on the Aegean Sea, north and NE on the Black Sea and east along the coasts of Algeria. Obviously, some finer analysis is needed to find a way back to Rome from Alexandria. This trip is achieved by using sea breezes blowing in the afternoon from the sea to the land[204]. These winds are best felt within a few miles off the coast. They blow more or less perpendicular to the coast, but may locally reach an angle of 45° or even be parallel to the coast. So here is the conclusion:

Going east can be achieved by long-haul offshore sailing, and going west has to be done with more coastal navigation.

The trip to Rome is therefore much longer than the trip to Alexandria as it not only is longer in distance, but it also involves much waiting for favourable wind conditions: one or two weeks sailing to Alexandria, but at least double when sailing back to Rome.

[204] Sea breezes blow from sea to shore in the afternoon, easing the arrival to harbours. Land breezes blow during the night and early morning easing departure from the harbour.
Acc. To Rod Heikell in "The Adlard Coles Book of Mediterranean Cruising", 2012, Chap 6, p 312-313:
"**1.** The relatively high temperatures of the Mediterranean mean that sea breezes are not the gentle zephyrs encountered in more temperate climes. In many places, the temperature differences generate winds up to Force 5–6 and can reach up to 50 miles off the coast.
2. There is a fairly accurate wind clock for the sea breeze. As the land warms up in the morning the sea breeze will begin to blow at 1100–1200 local time at around Force 2–3. Usually within an hour the wind will get up to Force 4–6 and will blow through the afternoon until early evening. The wind will die off fairly quickly around 1900–2000 local time. The abruptness of the change is linked to the air temperatures and geography of a region. In general, the higher the temperature, the more abrupt the transition between morning calm and the onset of the full force of the sea breeze. The terrain affects the sea breeze according to altitude: low-lying plains or gentle S-facing slopes will heat up more quickly than mountain ranges with valleys in shadow for much of the day and so generate greater pressure differences and stronger winds.
3. The direction the coast faces will affect the sea breeze clock. In general S-facing coasts will have an earlier sea breeze than N-facing coasts. Likewise, E-facing coasts will have an earlier sea breeze than W-facing coasts."
It may be added here that coastal effects modify the wind direction and strength, e.g., around a headland with high land where the wind will follow the shore and curve around the headland with an increased speed.



Main ancient Mediterranean sailing routes

The trip from Alexandria to Rome goes north directly to Rhodes, or along the Levantine coast and then west along the southern Cypriot coast, but some will make a direct route to Cyprus using the westerlies. In any case, sailing from Cyprus to Rhodes is difficult due to adverse winds[205]. The Aegean Sea is famous for its northern wind called Meltemi[206] which makes its east-west crossing a subtle operation using local winds around the islands. The route through the Aegean Sea is still a matter of debate, some favour the northern route, but those not going to Athens prefer the southern route avoiding the dangerous Cape Maleas. West of the Peloponnesus, the Ionian Sea with prevailing NW winds has to be crossed, either directly to the Messina Strait, or by following the Greek coast before crossing over to Calabria. An alternative to this Aegean route is the Libyan route along the coasts of Cyrenaica, Libya and Malta or Tunisia (mainly in May and in October, in order to avoid the northwestern "etesian winds", see statistics in chapter "Alexandria Magnus Portus, Winds").

The western Mediterranean is subjected to low pressures travelling from west to east and inducing a counter-clockwise wind pattern. Hence, on the French south coast, the wind will

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[205] Lucian of Samosata (2nd c. AD) tells the fascinating story of a very large grain freighter caught in a storm off Cyprus:
"I had it from the master, a nice intelligent fellow to talk to. They set sail with a moderate wind from Pharos, and sighted Acamas on the seventh day. Then a west wind got up, and they were carried as far east as Sidon. On their way thence, they came in for a heavy gale, and the tenth day brought them through the Straits to the Chelidon Isles; and there they very nearly went to the bottom. I have sailed past the Chelidons myself, and I know the sort of seas you get there, especially if the wind is SW.
It is just there, of course, that the division takes place between the Lycian and Pamphylian waters; and the surge caused by the numerous currents gets broken at the headland, whose rocks have been sharpened by the action of the water till they are like razors; the result is a stupendous crash of waters, the waves often rising to the very top of the crags.
This was the kind of thing they found themselves in for, according to the master, and on a pitch-dark night! However, the Gods were moved by their distress, and showed them a fire that enabled them to identify the Lycian coast; and a bright star–either Castor or Pollux–appeared at the masthead, and guided the ship into the open sea on their left; just in time, for she was making straight for the cliff. Having once lost their proper course, they sailed on through the Aegean, bearing up against the Etesian winds, until they came to anchor in Piraeus yesterday, being the seventieth day of the voyage; you see how far they had been carried out of their way; whereas if they had taken Crete on their right, they would have doubled Malea, and been at Rome by this time."

[206] Acc. to Rod Heikell in "The Adlard Coles Book of Mediterranean Cruising", 2012, Chap 6, p 313: "From the Dardanelles it blows from the NE, curving down through the Aegean to blow from the N and NW before curving to blow from the W around Rhodes."

blow from south to east first, then turn to north to NW, generating the famous Mistral and Tramontana. This explains that it can be difficult to sail from Marseille to Cabo de Creus and that this has to be done close to the coast to avoid high offshore waves induced by the Tramontana. The trip back may lead through the Baleares and Sardinia, where the westerlies will prevail, then along the western coasts of Sardinia and Corsica where a southern wind may blow. Those going to Rome will take the dangerous Strait of Bonifacio between Sardinia and Corsica.

The coast of North Africa is prone to summer easterlies between Cap Bon and Oran, but lack of wind between Oran and Gibraltar … in addition to adverse east going surface currents of Atlantic water compensating the Mediterranean evaporation.

The Tunisian Golfe de Gabes and Libyan Gulf of Syrt have a tidal range up to 1 m inducing tidal currents that can be used by sailors in both directions. The summer winds may blow from north to east.

The access to the Black Sea is very difficult because of the strong southward surface current of fresh water flowing towards the Mediterranean Sea, in addition to NE winds. Inside the Black Sea, currents flow counter clockwise and favour a trip to the east along the Turkish coast, before crossing over to Crimea against prevailing winds. Nevertheless, ancient seafarers are known to have sailed massively along the western Black Sea coast to Crimea and to the Azov Sea, possibly because this trip was free of pirates.

The need for a large number of shelters follows from the fact that sailors may need to wait for proper wind conditions or may try to escape bad weather conditions. Even though they can sail 50 to 100 nautical miles in a day (see "Ancient Measures"), it is important to know where they can find a safe shelter within two to three hours of navigation, i.e., only approx. 10 miles.

It has hopefully been made clear in this (very) brief survey of Mediterranean sailing that it is a vast and complicated subject that requires a lot of experience. History shows that Mycenaeans (ca. 1500-1200 BC), Phoenicians (ca 1200-150 BC) and Greeks (ca. 800-300 BC) were very good at that. Mycenaean sailors had a very difficult playground in the Aegean Sea. Perhaps their experience was later taken over by Phoenicians who used it to travel all over the Mediterranean Sea and beyond.

6.4 Modelling Mediterranean sailing routes

Our aim in this section is to compute travel times between various ancient ports (hubs discussed in the section on "Ancient maritime trade") and to compare different alternative routes between two ports, e.g., Alexandria and Portus, compare both ways to and from each place, and compare seasonal influences.

Ancient sea routes have been described by several ancient authors such as Strabo and Pliny, and by an anonymous author who wrote a document known as the "Stadiasmus". Pascal Arnaud produced a monumental work in 2005 summarising these ancient navigation routes[207]. Apart from a collection of 127 Mediterranean navigation routes, he was able to define the main units of distance. This is not as trivial as it would appear at first sight, as each distance at sea was defined by sailing days and was converted by the ancient scholars

[207] ARNAUD, P., 2005, "Les routes de la navigation antique", edt. Errance, (248 p), & ARNAUD, P., 2012, "La mer, vecteur des mobilités grecques", in "Mobilités grecques", Capdetrey & Zurbach (edt.), Scripta Antiqua 46, Ausonius, Bordeaux, (p 89-135).
Note that Pascal Arnaud not only is a famous professor in Roman History, but also an experienced sailor who has been sailing the Med himself for decades.

into distances in stadia[208]. Pascal Arnaud was able to distinguish the following basic units of distance: 1000 stadia, 700, 600 and 500 stadia. He was able to correlate these distances with travel times as follows:

- one-day + one-night sailing (24 h) yields a 1000 stades travelled distance,
- half a day & night (12 h) yields 500 stades,
- one daylight sailing, "daytime" (15-17 h) yields 600-700 stades.

With one stadium equalling 1/10th of a nautical mile, the average ship velocity therefore was around 4 nautical miles per hour, i.e., 4 knots[209]. It may be argued that this definition of distances based on travel times depends on the meteorological conditions (winds and waves, assuming that currents are usually negligible in the Med). This is true, but ancient sailors had no accurate instrumentation for measuring positions expressed in latitudes and longitudes[210]. Ancient authors reporting distances at sea obviously took the meteorological conditions of each trip into account and provided some kind of averaged value. We may thus consider at this point that we have a reliable data set for distances between ports reported by ancient authors. This data set was carefully analysed and validated by Pascal Arnaud.

Let's now turn to a computational model of these Mediterranean navigation routes. A major attempt was conducted in the ORBIS Project by Stanford University in 2011-2014 (http://orbis.stanford.edu/#). This model is a superb tool that seems to be still operational online, but:

- it works with a coarse 5 x 5° grid for wind stats,
- the choice of the "fastest" track is not explained (black box effect),
- it is "relying on a modest number of segmented routes" and "roughly approximates the preferred routes of sailors in the Roman period" and it is therefore not open to choosing other routes.

Based on the ORBIS approach, I decided to build my own model based on a 1 x 1° grid for wind stats, and allowing any route to be chosen on that grid. This approach is clearly using averaged values for winds (based on long term statistics) and averaged values of ship speeds for each relative wind direction, including parameters such as high waves and low visibility. Hence, computed travel times are also averaged values.

[208] One Roman stadium is 185 m long, which equals 1/10th of a modern nautical mile of 1852 m. However, ancient authors often used other definitions of the stadium (Greek, Egyptian, etc. which are somewhat different (say from 150 to 200 m, see section on "Ancient measures").

[209] WHITEWRIGHT, J., 2011, "The Potential Performance of Ancient Mediterranean Sailing Rigs", The International Journal of Nautical Archaeology (2011), 40.1: 2–17. According to ancient reports, ancient ships sailed at 1 to 2 knots in adverse wind conditions and 4 to 6 knots with favourable winds.

[210] This concept was introduced by Ptolemy in the 2nd c. AD, see also sections on "Ancient maps" and "Measuring latitudes".

MedAtlas grid of points for wind statistics.

In a first stage, the detailed MedAtlas[211] data was taken over for each point on a 1 x 1° grid for the whole area of the eastern and central Mediterranean Sea, say from Tyre to Portus. This encompasses 147 grid points with wind data for annual and four seasonal conditions.

Secondly, the ship model was taken over from Arcenas[212]. This ship model is a ship-speed rose providing a 'Velocity made good' (Vmg) for each relative wind direction. Vmg is the resulting velocity of the ship in the desired direction, which may result from various sailing techniques such as tacking and gybing, including the ship's leeway (see section "How about the wind?").

Third, the wind statistics were combined with the ship model to provide resulting ship speeds for each heading at each grid point.

Fourth, this result is used in a navigation model, where a track passing through a number of grid points is chosen from one place to another (e.g., harbour or promontory). The distance between each point is computed by means of spherical trigonometry and the travel time is deduced from the ship speeds at each grid point.

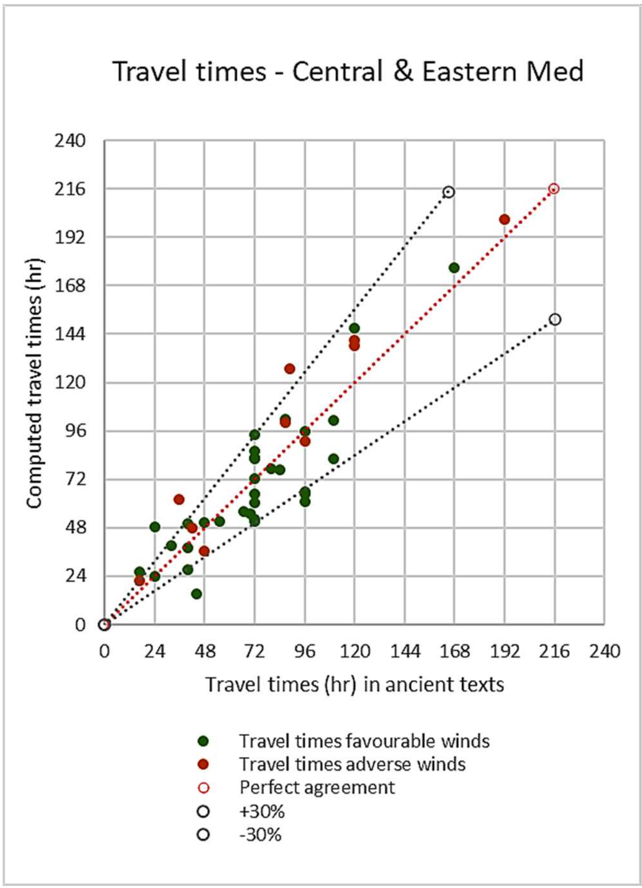
In order to validate this 'MedNav' model, around 40 trips which had been identified by Pascal Arnaud were used. The result is shown below in a comparison of computed travel times with travel times reported in ancient texts.

The red dotted line is the line of perfect agreement when computed and reported travel times are exactly equal. Both grey dotted lines show +30% and -30% values and it can be seen that most of the points lay within the +/-30% range (that is nearly a factor one in two). It may be noted here that this range corresponds to the meteorological uncertainties you might take into account when planning any trip at sea with a sailing boat.

Globally, the data points show a nice agreement with a correlation coefficient of 0.91. This result also shows that the Arcenas ship is quite good.

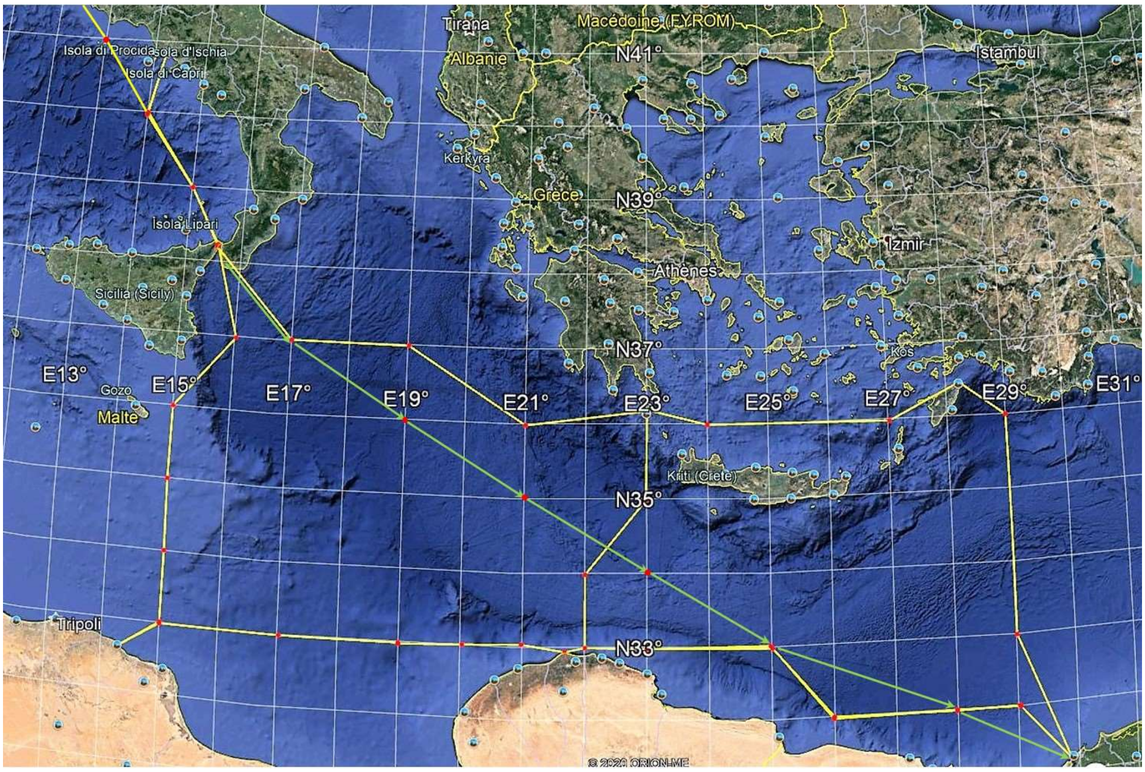
A distinction was made between trips with favourable winds and trips with adverse winds (e.g., travelling from east to west in the eastern Med or from south to north in the Aegean). This result shows that little impact of wind conditions is felt and proves that ancient authors have taken this cleverly into account in their distance estimates.

[211] MEDATLAS, 2004, "Wind and Wave Atlas of the Mediterranean Sea", Scientific Report RTP10.10, Western European Armaments Organisation.
[212] ARCENAS, S., 2015, "ORBIS and the Sea: a model for maritime transportation under the Roman Empire", ORBIS Project, Stanford Univ., (6 p), (http://orbis.stanford.edu/#). We chose his "fast ship".



Validation of the MedNav navigation model.

We are now ready to go one step further in using the MedNav model for computing the famous Alexandria-Portus routes, including seasonal effects.



Various routes between Alexandria and Portus.

The route from Portus to Alexandria enjoys favourable NW winds all along. From Portus, we sail down to the strait of Messina (ancient Zankle) and from there to Alexandria in a direct SE track (green arrowed line in figure above). This trip reputedly takes one to two weeks. This direct track, as the crow flies, is 1084 nautical miles (2007 km) and is sailed at an average speed of 4.5 knots in 244 sailing hours (ca. 10 days). Taking the same way back would mean beating the adverse wind all the way and it would be very uncomfortable. We have therefore been looking for other routes:

- Alexandria-Rhodos-Kythera-Zankle-Portus, the north route via the southern Aegean and Ionian seas.
- Alexandria-Paphos-Rhodos-Kythera-Zankle-Portus, the same as above, but via Cyprus.
- Alexandria-Phycus-Leptis Magna-Zankle-Portus, the south route via Cyrenaica.

The computations show that the fastest route is the north route via Rhodos, with 452 sailing hours (2.8 kt average speed). The next fastest is the uncomfortable direct track beating the wind, with 462 hr (2.4 kt average speed). Another route leads to Rhodos via Paphos (Cyprus), but is slower with 482 hr. The south route requires beating the wind between Alexandria and Phycus (Cyrenaica) and yields 490 hr. Summarising, it may be stated that the trip from Alexandria to Portus takes 450 to 500 sailing hours depending on the chosen route. That is around 20 sailing days, plus or minus one day, and twice the time required to sail with favourable winds from Portus to Alexandria.

It seems that these results nicely fit the general feeling of scholars interested in this subject, who agree that ancient vessels averaged between 4 and 6 knots with favourable winds, and less than 2 knots to 2.5 knots with unfavourable winds[213].

With this renewed trust in our model, we can investigate further and check the seasonal influence. Let’s take the same trip between Alexandria and Portus, both ways, and compute the travel times in each of the four seasons.

Route	Spring	Summer	Fall	Winter
Portus > Alex direct track	266	244	267	253
Alex > Rhodos > Portus	402	452	381	360
Alex > Leptis Magna > Portus	440	490	420	435

Travel times (hours) between Portus and Alexandria depending on seasons.

On the way to Alexandria, seasons do not matter much as the travel time is around 240-270 hours (10-11 days). However, on the way to Portus, seasons do matter a lot. Summer is obviously the worst period to sail in this direction, as the trips in fall and winter are clearly faster. Note that the south route via Leptis Magna is always somewhat slower than the north

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213 CASSON, L., 1995, "Ships and seamanship in the ancient world", Johns Hopkins University Press, (p 282-291).
GAL, D., SAARONI, H., CVIKEL, D., 2021, “A new method for examining maritime mobility of direct crossings with contrary prevailing winds in the Mediterranean during antiquity”, Journal of Archaeological Science, 129, (16 p).
GAL, D., SAARONI, H., CVIKEL, D., 2022, “Mappings of Potential Sailing Mobility in the Mediterranean During Antiquity”, Journal of Archaeological Method and Theory, Springer, (52 p).
They use a more sophisticated methodology based on weather-routing software and a higher spatio-temporal resolution. They also include a human factor. Their results show a bit slower navigation, but their ship model is based on the smaller Ma’agan Mikhael II ship replica described by Palzur, 2021.
GAL, D., SAARONI, H., CVIKEL, D., 2023, "Windward Sailing in Antiquity: The Elephant in the Room", IJNA International Journal of Nautical Archaeology, DOI: 10.1080/10572414.2023.2186688
PALZUR, Y. & CVIKEL, D., 2021, “Sailing Ma‘agan Mikhael II”, Archaeonautica[Online], 21 | 2021, (p 277-282).

route via Rhodos, but this does not prevent you from doing so if you have some lucrative business there.

It must have been quite a temptation to sail in wintertime (during “mare clausum”), but the risk of an unexpected storm was much higher (see Luke’s final trip to Rome, Luke’s Acts, 27, 11).

Another recurring question is what the fastest route from Alexandria to Rhodes in summer is, with north-western etesian winds. The direct route from Alexandria to Rhodes is around 350 nautical miles; the next shortest is via Paphos (Cyprus), with 500 n. miles; the next is via Tyre (Lebanon) and Paphos with 750 n. miles and the longest is via Tyre, Seleucia Pieria and along the southern Turkish coast, with 800 n. miles. The travel times are respectively 120 h, 150 h, 225 h and 230 h. The direct route is fastest but requires quite some struggle with the wind at close reach. The trip via Paphos will be fast to Paphos and rough after that. Both trips along the Levantine coast are much longer and are justified only if particular business can be done there during the trip.

We may thus confirm that two return trips between Alexandria and Portus could be undertaken each year as follows:

- Alexandria to Portus in spring, just after the Egyptian harvest, arriving in Portus in May-June (note the ‘Alexandrian ships’ were overwintering in Alexandria in order to be ready for departure in spring as soon as harvesting was conducted),
- Portus to Alexandria in summer, arriving in Alexandria in July-August,
- Alexandria to Portus in fall, arriving in Portus in September-October,
- Portus to Alexandria in fall, arriving in Alexandria by the end of October.

6.5 Red Sea versus Nile sailing

Much discussion has taken place concerning the route when sailing back from the Indian coast, the Somalian and the Yemenite coasts. The southern part of the Red Sea is subject to reversing monsoon winds and sailors could make use of that. However, north of 20° of latitude, the northern winds blow all year round on the Red Sea, making the trip back to the north quite uneasy. Some merchants therefore had their ships calling at ports like Berenike (near Ras Banas), Myos Hormos (Quseir al-Qadim) and Saww (Marsa Gawasis) in order to continue the journey by land via Coptos (Qift) and the Nile down to Memphis (Cairo) and Alexandria. Other merchants decided to call at Leuke Kome (possibly Sharm al-Wajh in Saudi Arabia, acc. to Nehmé, 2014[214]) and further by land to Petra and Gaza. These routes were an alternative to sailing (or rowing) to Clysma (Suez), Ayn Sukhna or Wadi el-Jarf with continuous northerlies, or to Charax Spasinou (Jebel Khayabir, about 50 km north of Basra), via the Gulf, in order to reach the Mediterranean coast near Palmyra, but with lots of NW winds also.

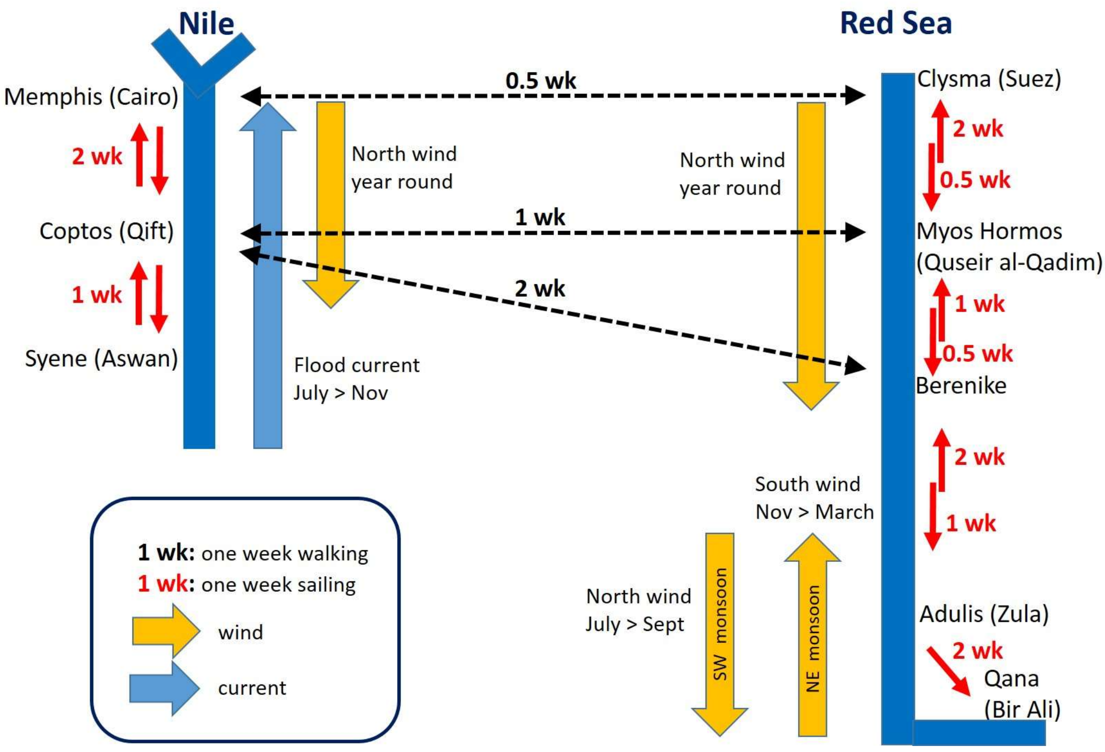
Physical conditions concern current and wind. Schematically, the current in the Nile varies between 1 knot (ca. 2 km/h) in the low water season (December to June) and 3 knots (ca. 6 km/h) at the peak of the flood season (September). The wind is blowing from north, against the current, most of the time in the Nile valley (note that the Nile delta is subject to seasonal variations with its famous summer northerlies). The Red Sea is subjected to a similar wind regime in its northern part (say north of Port Sudan at 20° latitude) and the Red Sea Pilot states that "you should not count on any south winds from Ras Banas northwards" (at 24°

[214] NEHME, L., 2014, “La rive orientale de la mer Rouge”, conference at Collège de France, 24/11/2014, ed. JP BRUN (MP4 movie of the complete 1.5 hr conference).

latitude). The southern Red Sea has seasonal variations due to the monsoon regime and winds can be strong in the Straits of Bab el-Mandeb.

Cooper (2011)[215] shows that both routes had pros and cons. The journey time from Berenike to Memphis was quite similar for both routes (at best around 3-4 weeks). Both routes induced a number of risks (grounding at sea and on the Nile, pirates at sea and on land, etc.). Sidebotham (1989)[216] suggested that bulky agricultural cargoes might have travelled through Clysma, while more luxury cargoes might have taken the land route and the Nile.

The final answer may not yet be given but the sketch below will provide a summary of the physical conditions and approximate journey times.



Physical conditions and journey times on the Red Sea and on the Nile.

Journey times for northbound and southbound shipping are shown on the sketch. These are of course approximate times without stops at ports. Southbound on the Red Sea is pretty fast with around 50 to 80 nautical miles per day (i.e., 4 to 6.5 knots assuming 12 hours/day sailing time). Northbound on the Red Sea is very slow as sailing is not possible in a straight line and no more than 20 to 25 nautical miles/day can be done (i.e., less than 2 knots assuming 12 hours/day sailing or rowing time). These values are confirmed by Pascal Arnaud who is a Roman historian *and a sailor* himself[217].

[215] COOPER, J.P., 2011, “No easy option: Nile versus Red Sea in ancient and medieval north-south navigation”. In W.V. Harris & K. Iara (eds), Maritime Technology in the Ancient Economy: Ship Design and Navigation. Journal of Roman Archaeology Supplementary Series 84: 189–210

[216] SIDEBOTHAM, S.E., 1989, “Ports of the Red Sea and the Arabia-India Trade”, in Fahd, T. (ed.), “L'Arabie préislamique et son environment historique et culturel”, (Strasbourg, 1989), (p 195–223).

[217] ARNAUD, P., 2005, “Les routes de la navigation antique”, éd. Errance.
and:
ARNAUD, P., 2014, “Marseille grecque et les routes du commerce maritime”, in “Les territoires de Marseille antique”, Arles, Paris, éd. Errance, (p 185-213).

Journey times on land between the Red Sea ports and the Nile are provided also, and as a result, the journey time from Berenike to Memphis was ca 3.5 weeks by the Red Sea via Clysma, and ca 4 weeks by the Nile.

A small difference that may not have been that important in ancient times
when "time is money" was less important than
"have a safe trip back home" ...

and:
TAMMUZ, O., 2005, "Mare clausum? Sailing Seasons in the Mediterranean in Early Antiquity", Mediterranean Historical Review, Vol 20, No. 2, December 2005, (p 145-162).

7 ANCIENT MARITIME TRADE

7.1 Containers

Merchant ships have been sailing the Mediterranean Sea and the Red Sea for 5000 years, gradually leading to a 'Mediterranisation' of the economy. Today's globalised economy extends across the whole planet.

Goods (also called 'commodities') have always been shipped either as loose units or as dry or liquid bulk. Ancient units were amphorae, dolia, barrels and sacks that could be placed on a ship, a cart, a camel or a donkey[218]. Until 100 years ago, this cargo, called 'break bulk', had to be loaded on board almost individually. Wooden 'pallets' moved by forklifts were introduced during World War II. They were quickly followed by larger 'containers' made of steel providing better protection and easier transportation as they could be placed on a ship (sea and river), a train and a truck. As a matter of fact, containers opened the way to 'globalisation'.

Containers were standardised to optimise storage on land, and on board ships and trucks. This aim has been achieved quite well in modern times (so far), taking around 50 years to reach right around the planet, but was not achieved in ancient times, since many different types of amphorae were used across the Mediterranean area, which is fortunate as it enabled experts in 'amphorology' to determine where and when amphorae found in wrecks were made.

Many different types of amphorae have been identified, depending on their date and place of production. The first amphorae were used for transporting wine and date from around 350 BC (the so-called 'Greco-Italic' type). Millions of them were produced, especially during the Roman Empire.

A full amphora quadrantal (containing olive oil, wine or fish sauce) weights around 50 kg, around half of which is the tare (see 'Ancient Measures'). It should be noted that Egyptian grain was transported in sacks weighing one Ptolemaic artaba (39 litres) with a unit weight of wheat of ca. 30 kg. It should also be noted that wooden oak barrels (500 to 1000 litres) gradually took over from amphorae (and dolia) for storing wine during the Roman Empire.

Amphorae and other goods were unloaded by ship-to-ship transfer from larger to smaller ships, or by beaching the ship, or by stevedores in large ports with adequate infrastructure. Following measurement, the goods were stored in warehouses (*horrea*).

The impressive Monte Testaccio dump in Rome contains over 50 million amphorae, mainly Spanish and North African Dressel 20 olive oil amphorae. Perhaps, these amphorae were too fatty and the smell of rancid oil prevented any further use, as a result of which they were disposed of. An internal coating of vegetal pitch was used to seal the walls of wine and garum amphorae, but not for oil amphorae because oil dissolves the pitch and would thus become unsuitable for consumption[219]. Hence, pitched amphorae could be reused, but unpitched oil amphorae could not.

As wine amphorae were not dumped in such large numbers, one might think they were reused, but as Pena (2021) puts it, "in the current state of our knowledge, it seems fair to say

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[218] DE GRAAUW, A., 2017, ''From Amphora to TEU : Journey of a container - An engineer's perspective'', Portus Limen Project workshop, Rome, January 2017.

[219] ANDRÉ, J., 1964, "La résine et la poix dans l'antiquité. Technique et terminologie", in L'antiquité classique, Tome 33, fasc. 1, 1964. (p 86-97).

that the evidence for the reuse of amphoras as packaging containers in the Roman world is scattered, uneven, and less than substantial." [220]

7.2 Why trade?!

In order to provide your country's consumers with the goods they wish, you need to import some of them and to pay foreign producers for the goods and for their transportation. The required money can be obtained by exporting your own goods and services.

Roman individuals could export Roman goods as a return cargo when sailing back to foreign countries. The Roman state could provide the 'service' of military protection of provinces within the empire, receiving a tribute for this service. However, the main Roman export was gold and silver bullion used for payment of imported goods!

7.3 How trade?

Trust between buyers and sellers is required, hence regular trading contacts are necessary, and therefore repetition of trade routes. To be 'professional', you need to specialise: choose your goods, choose your trade cities and routes, choose your trade contacts[221]. That will be 'your' trade network. The nodes of each network may be large inter-regional ports ('hubs') or smaller regional, or even local, ports.

7.4 Trade hubs

According to Wikipedia, a hub is the central part of a wheel that connects the axle to the wheel itself. Many expressions use the term for a literal or figurative central structure connecting to a periphery. A transport hub is a place where cargo is exchanged from one transport mode to another. With the growth of containerisation, intermodal freight transport has become more efficient.

Today, there are several major nodal points for maritime traffic which are related to the network of main streams of traffic:

- consumer goods transported in containers from China, Korea and Japan to Europe via the Suez Canal and to the US west coast via the Pacific Ocean;
- energy such as oil, Liquid Natural Gas (LNG) transported in bulk from the Middle East, to China, Korea and Japan and many other countries;
- other raw materials such as coal and iron ore are also transported in bulk from Africa, Australia and South America to many countries.

The major nodal points, now called 'hubs', are therefore located in Europe (Rotterdam, Hamburg), in USA (Los Angeles, San Francisco, New York, New Orleans), in Asia, (Shanghai, Hong Kong, Busan, Yokohama, Singapore)[222].

Alexandria was the "greatest emporium of the world", acc. to Strabo (Geogr. 17, 1, 13): Goods were imported from, and exported to, South Arabia, East Africa and India[223], and paid

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[220] PENA, J. Th., 2021, "The reuse of transport amphoras as packaging containers in the Roman world: an overview", in "Roman Amphora Contents Reflecting on the Maritime Trade of Foodstuffs in Antiquity", Cadiz, 2015, (22 p).

[221] ARNAUD, P., 2012, "La mer, vecteur des mobilités grecques", in "Mobilités grecques", Capdetrey & Zurbach (edt.), Scripta Antiqua 46, Ausonius, Bordeaux, (p 89-135).

[222] DUCRUET, C., 2015, "Inside the pond: an analysis of Northeast Asia's long-term maritime dynamics", International Journal of Maritime Affairs and Fisheries, Korea Maritime Institute, 2015, 7 (2), (p 25-40).

[223] ARNAUD, P., 2015c, " La batellerie de fret nilotique d'après la documentation papyrologique (300 avant J.-C.-400 après J.-C.) ", in La batellerie égyptienne, Archéologie, histoire, ethnographie, éd. P. Pomey, Centre

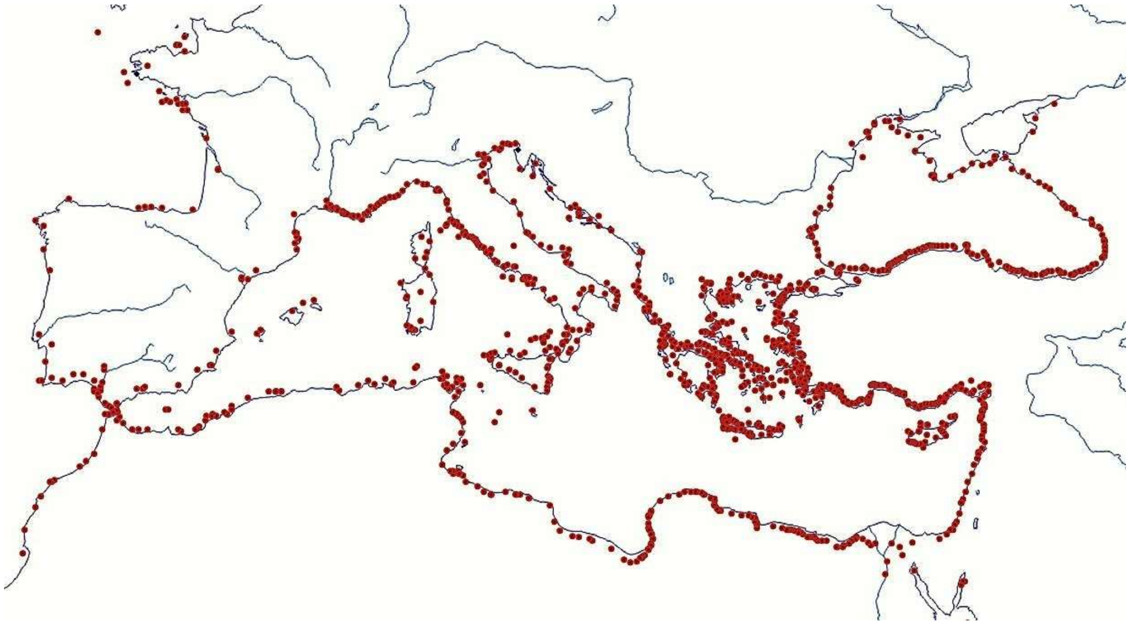
for with gold and silver bullion; they were taxed at 25% by the Roman state, thereby providing a substantial part of its total income:

- Some goods, such as perfumes and dyed silk, were transformed and manufactured in Alexandria, thereby adding great value to the imported goods;
- Goods were exported to Rome and other cities of the empire: not only exotic spices and goods from beyond the Red Sea, but also vast quantities of grain produced in Egypt.

Alexandria was a hub of the Roman economy. Additional nodes of a large-mesh Roman trade network might be located at **Gades** (Baetica, for garum, salted fish, olive oil) and at **Carthago** (Proconsular Africa, for wheat and olive oil). This coarse network shows 3 lines converging on **Rome**. The question is whether finer-mesh networks might be added to the coarse one by including nodal points of smaller importance[224].

Data base analysis

Let's elaborate on this with an analysis of our database on ancient ports: we know of nearly 6000 ancient coastal settlements, out of which around 2000 are explicitly mentioned as ports by ancient authors (see Volume I, The Catalogue):



Ancient ports mentioned explicitly by at least one ancient author.

This map has no pretention of precision; it just intends to show concentrations of ports; more accurate locations are available on Google Earth maps shown on: www.AncientPortsAntiques.com

A corpus of 87 ancient authors from 1500 BC to 500 AD has been analysed, searching for the word 'port' in the 19th c. French translations available on the web (mainly www.remacle.org), (see Volume II, Citations). Each author is counted only once for each port, even if he mentioned the port several times in several books or chapters.

d'Etudes Alexandrines, 34 – 2015: Kerkouros-type ships were sailing and rowing southward on the Nile in winter time, at least during the Hellenistic period.

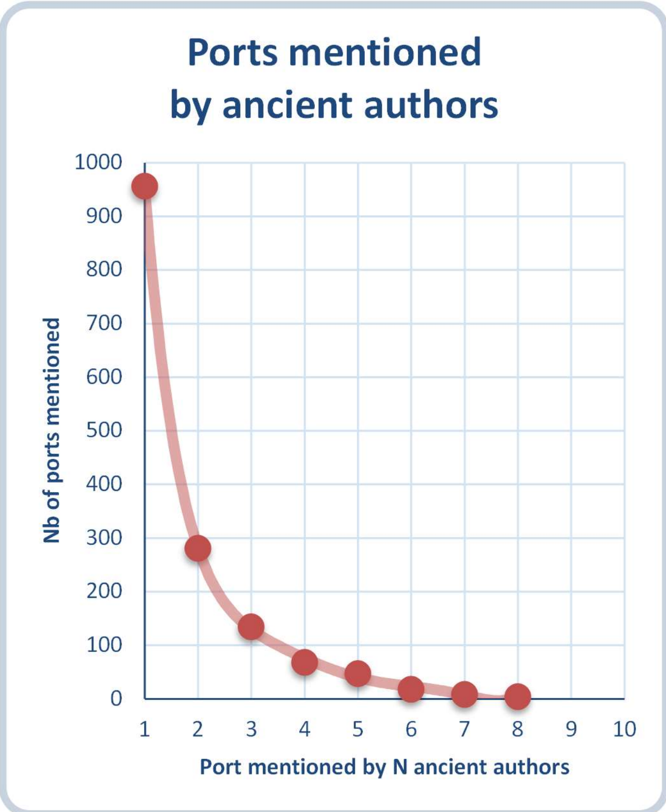
224 BRAUDEL, F., 1949, "La Méditerranée et le monde méditerranéen à l'époque de Philippe II", éd. Armand Colin, Paris, (533 p) : he distinguishes various basins: "La Méditerranée n'est pas une mer, mais une succession de plaines liquides communiquant entre elles par des portes plus ou moins larges." Each basin is the result of human cultures superimposed upon physical constraints, with continuous changes always going on. See also ARNAUD, P., 2005, "Les routes de la navigation antique", éd. Errance, Paris, (248 p).

Obviously, various reasons motivated ancient authors to mention these ports: historical (military, naval), commercial (trade, emporia), geographical (description of land and peoples) or sailors following the coasts. In the picture above, trips like those of Arrian on the Black Sea or the Stadiasmus can nearly be distinguished.
Furthermore, ancient authors may sometimes have been somewhat egocentric when describing only their own part of the world, like Pausanias in Greece, which may have led to 'zooming' effects in some areas.
Conversely, some areas were not much mentioned by ancient authors, like Hispania, Lusitania, Gaul, and it cannot be said if that is because there were no ports (which is surely untrue) or because these somewhat remote areas were of lesser interest to ancient Greek and Roman authors. Anyway, a concentration of ports mentioned by ancient authors can be seen around the Aegean Sea.

Further analysis of the data base shows:

- Nearly 1000 ports are mentioned by only one ancient author.
- Nearly 300 are mentioned by two ancient authors.

Port is mentioned by N ancient authors	Nb of ports
1	956
2	281
3	134
4	68
5	47
6	18
7	8
8	4
9	5
10	5
Over 10	10
Total:	**1536**



Detailed results of the database analysis

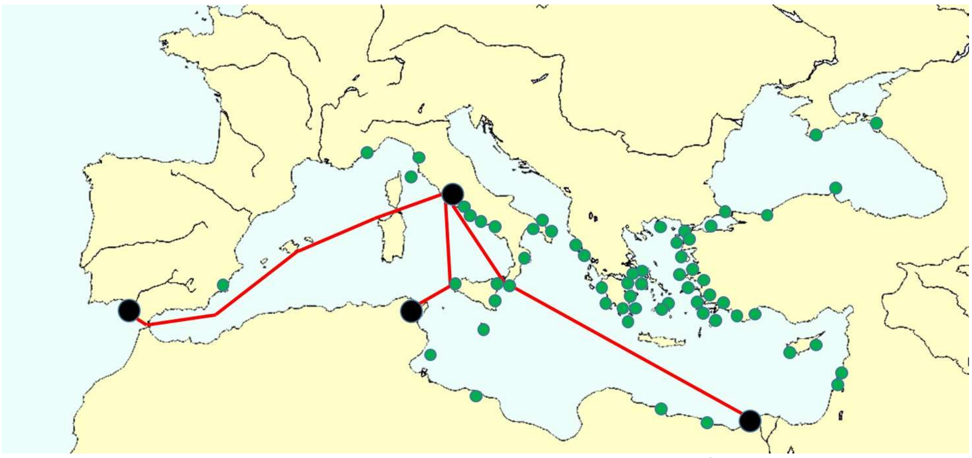
- Nearly 100 ports are mentioned by five or more ancient authors. These places are listed below in a clockwise ranking around the Mediterranean, with the number of authors mentioning it in brackets:
  - Hibernia (Isle of Ireland) (5)
  - **Gades (5)**
  - Carthago Nova (5)
  - Massalia (5)
  - Monoeci (Monaco) (5)
  - Portus Pisanus (6)
  - Aithalia (Isle of Elba) (5)

- **Portus Augusti Ostiensis (over 10) and Ostia (7)**
- Antium (5)
- Caiete (5)
- Misenum (6) and Puteoli (5)
- Rhegium (7)
- Zankle (Messina) (9)
- Syracuse (over 10)
- Crotone (5)
- Lilybaion (5)
- Tarentum (7)
- Hydruntum (Otrante) (6)
- Brindes (9)
- Corcyra (8) and Casiope (5) (Isle of Corfu)
- Glykys Limen (5)
- Nisea (5)
- Kytlene (5)
- Pylos (5)
- Gytheion (7)
- Skandeia (Isle of Kythera) (7)
- Nauplia-Argos (5)
- Lechaion-Corinth (10) and Sicyon (8)
- Kenchreai-Corinth (over 10)
- Salamis (Isle of Salamis) (6)
- Piraeus (over 10)
- Phaleron (7) and Munychia (5)
- Aegina (6)
- Aulis (6), Chalkis (5) and Eretria (5) (Isle of Evia)
- Thasos (Isle of Thasos) (5)
- Abydos (10) and Sestos (6)
- Byzantium (6)
- Portus Symbolorum (Crimea) (5)
- Sindicos (Anapa) (5)
- Sinop (6) and Armene (5)
- Calpe (5)
- Cyzikos (5)
- Sigeion (5)
- Delos (Isle of Delos) (10)
- Naxos (Isle of Naxos) (5)
- Tenedos (Isle of Tenedos) (8) and Troy (6)
- Mytilene (Isle of Lesbos) (over 10)
- Phokeia (6)
- Elaia (5)
- Chios (Isle of Chios) (over 10)
- Ephesus (10)
- Pythagoreion (isle of Samos) (over 10)
- Miletos (9)
- Kos (Isle of Kos) (5)
- Knidos (7)
- Rhodes (over 10)
- Kaunos (5)
- Patara (8)
- Korikos (Kizkalesi) (5)
- Phaselis (5)
- Paphos (Isle of Cyprus) (5)
- Salamis (Isle ofCyprus) (5)

- Sidon (6)
- Tyr (6)
- **Alexandria (over 10)**
- Paretonius (5),
- Menelaus (5),
- Neapolis-Leptis (5)
- Cercenna (6)
- **Carthago (8) and Utica (5)**
- Melite (Isle of Malta) (6)

The listed places are shown on the map below (green dots) together with the four 'main hubs' (black dots). The listed places are fairly concentrated in an area between Rome and Rhodes covering the southern part of Italy, Greece, the Aegean Sea and Asia Minor. It cannot be denied that this area was the most active area both for trade and for naval operations during a millennium from the 5thc. BC to the 5th c. AD.

Note that no time frame was defined, hence Greek hubs of the 5th c. BC are mixed with imperial Roman hubs of the 1st c. AD. Had we restricted the time frame to e.g., the 6th to 4th c. BC, we would have seen Piraeus (over 10), Emporion (Spain) (4), and Naucratis (Egypt) (1) as main hubs. Had we taken the 3rd and 2nd c. BC, we would have mentioned Delos (10).



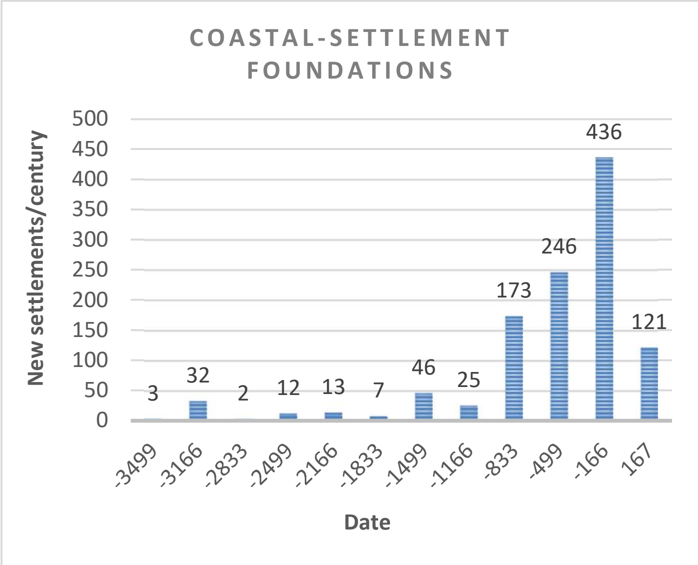
Trade networks in the Roman Mediterranean Sea:
Black dots are main hubs: Rome, Alexandria, Carthage, Gades;
Green dots are explicitly mentioned as ports by five or more ancient authors.

It must be admitted that the above approach based on the number of ancient authors mentioning places does not show the trade networks we would expect intuitively because major cities are missing (Tarraco, Narbo, places on the Adriatic, on the Black Sea, in northern Africa).

7.5 Foundation of coastal settlements

Out of nearly 6000 coastal settlements, around 4000 places were listed with an approximate foundation date (see Volume I, The Catalogue). Let's consider the time frame from 5000 BC to 333 AD and subdivide it in periods of 333 years roughly corresponding to the main historical periods. The number of new settlements founded in each period of 333 years is taken from the data base and divided by 3.33 in order to obtain the number of new settlements per century.
The resulting table below shows that the Hellenistic period (schematised from 332 BC to 0 and centred on 166 BC) yields the largest number of new settlements/century (436). A gradual increase of this number starts around 1000 BC at the end of the Late Bronze Age (LBA) when Phoenician, Greek and Hellenistic civilisations emerged. A decline is seen in the Roman period which shows that less new places were created, possibly because 'good places' were already in use and further developed by the Romans.

Dates		Nb/cent.	Hist. period
<- 5000 BC		-	
-5000	-4666	0	
-4665	-4333	1	
-4332	-4000	4	
-3999	-3666	0	
-3665	-3333	3	
-3332	-3000	32	Early Egypt
-2999	-2666	2	
-2665	-2333	12	
-2332	-2000	13	
-1999	-1666	7	Minoan
-1665	-1333	46	Mycenaean
-1332	-1000	25	LBA
-999	-666	173	Phoenician
-665	-333	246	Greek
-332	0	436	Hellenistic
1	333	121	Roman
> 333 AD		-	



Detailed results of the database analysis

Note a threshold effect at 3000 BC, as places were dated “3000” instead of “2999”. Anyway, a small concentration of new settlements is noted in the Early Egyptian period. After that, a trend of 10 to 20 new settlements per century continued until ca. 1000 BC.

7.6 Imported goods

How can we further study these networks? We may look into shipping, we may distinguish different historical periods, we may search ancient texts … we may study commodities[225], i.e., try to find out from where they come and where they go (mostly to Rome!). A literature survey yielded the following:

[225] RICE, C., 2016, "Shipwreck cargoes in the western Mediterranean and the organization of Roman maritime trade", Journal of Roman Archaeology, 29.
RICE, C., 2011, "Ceramic assemblages and ports", in Maritime Archaeology and Ancient Trade in the Mediterranean, edt. D. Robinson & A. Wilson, Oxford Centre for Maritime Archaeology Monographs.
BOETTO, G., 2012, "Les épaves comme sources pour l’étude de la navigation et des routes commerciales: une approche méthodologique", in: Rome, Portus and the Mediterranean, edt. S. Keay, British School at Rome, Oxbow Books.

"imports, not exports, are the purpose of trade" (P. Krugman, 1993)						
PEOPLES importing goods from distant places						
GOODS	**Romans**	**Greeks**	**Phoenicians**	**Egyptians**	**Mycenaeans**	**Minoans**
Minerals:						
white marble, alabaster	Italy (Luna, Volterra), Spain (Ebro valley), Attica (Mount Pentelikon), Naxos, Thasos, Marmara	Thasos, Naxos, Paros, Marmara			Thasos, Naxos, Paros, Marmara, Egypt	Thasos, Naxos, Paros, Marmara, Egypt
granite	France i.a.			Aswan		
millstones	Orvieto, Mount Etna, Hyblaean Mountains, Pantelleria island	Milos, Kimolos, Nisyros and other Aegean islands, Thrace (Petrota)	Golan, Tiberias	Kharga oasis and other places	Poros, Methone	
pozzolana	Pozzuoli	-	-	-	-	-
obsidian	Anatolia (central & eastern), Melos, Gyali, Pantelleria, Sardinia (Mt Arci), Lipari, Ponza (Palmarola)	Anatolia (central & eastern), Melos, Pantelleria, Sardinia (Mt Arci), Lipari, Ponza (Palmarola)		Anatolia (central & eastern), Nubia	Anatolia (central & eastern), Melos, Pantelleria, Sardinia (Mt Arci), Lipari, Ponza (Palmarola)	Anatolia (central & eastern), Melos
turquoise	Sinai (wadi Maghara, Serabit el-Khadim)			Sinai (wadi Maghara, Serabit el-Khadim)		
lapis lazuli	Syria (from Afghanistan/Bactria)	Syria (from Afghanistan/Bactria)		Ugarit (from Afghanistan/Bactria)	Ugarit (from Afghanistan/Bactri a)	Ugarit (from Afghanistan/Bactri a)

malachite	Cairo (Maadi), Negev (Timna)			Cairo (Maadi), Negev (Timna)		
amethyst	Aswan (wadi el-Hudi)			Aswan (wadi el-Hudi)		Aswan (wadi el-Hudi)
topaz	Red Sea (St. John's Island)			Red Sea (St. John's Island)		
Metals (ingots):						

gold (& electrum)	Ireland (Wicklow Mountain), Britain (Dolaucothi), France (Limousin, Vaulry), Spain NW (Laza, Caurel-Quiroga, Los Ancares, Las Médulas-Teleno-Maragateria-Llamas de Cabrera, Villablino-Las Omanas, Ibias-Tineo, Rio Carrion), Lusitania (Valongo Paredes, Tres Minas-Jales-Boticas), Dalmatia (Crvena Zemlja, Mracaj), Thrace (Pautalia), Dacia (many places around Rosia Montana in Transylvania), Georgia (R Phase), Turkey (Bakla Tepe NW of Ephesos), Cyprus, Nubia	Thrace (Pautalia), Macedonia (Pangaion, Cassandreia), Thasos, Samothraca, Siphnos, Georgia (R Phase), Turkey (Bakla Tepe NW of Ephesos), Libya?	Egypt	Eastern Desert (wadi Sid, wadi Hammamat), Nubia	Egypt	Egypt

silver	Britain (Charterhouse), Lusitania (Aljustrel), Spain (Rio Tinto, Palazuelos, Diogenes, Malaga, Cartagena, Linares), Sardinia (Iglesiente, Domusnovas), Carthage, Dalmatia (Srebrenica), Attica (Laurion), Thrace (Pautalia), Turkey (Ordu, Lesbos, Troad, Milet, Bodrum, Mersin)	Thrace (Pautalia), Macedonia (Pangaion, Cassandreia), Turkey (Ordu, Lesbos, Troad, Milet, Bodrum, Mersin), Thasos, Samothraca, Keos, Naxos, Koufonisia, Siphnos	Sardinia (Iglesiente), Spain (Rio Tinto upstream Huelva, Malaga, Cartagena), Tuscany (Massa Marittima)?	Eastern Desert (wadi Sid, wadi Hammamat), Nubia, Ugarit?	Anatolia (Troy)	Anatolia (Troy)

copper	Ireland (Great Orme, Ross Island, Cork, Wicklow), Britain (Beauport Park, Llanymynech, Nantyrarian), Asturias (Aramo), Lusitania (Aljustrel, Sto Estevao), Huelva (Rio Tinto, Sotiel Coronado), Dalmatia (Majdanpek, Belovode), Attica (Laurion), Thrace (Pautalia, Burgas), Turkey (Trabzon area), Petra (wadi Feynan), Negev (Timna valley, wadi Arabah), Cyprus (Kourion & Kalavasos, Soli & Skouriotissa), Algeria	Thrace (Pautalia, Burgas), Dalmatia (Majdanpek, Belovode), Cyprus (Kourion & Kalavasos, Soli & Skouriotissa), Evia (Eretria, Chalkis), Delos, Paros, Seriphos, Turkey (Trabzon area)	Cyprus (Kourion & Kalavasos, Soli & Skouriotissa), Petra (wadi Feynan), Negev (Timna valley, wadi Arabah), Sardinia (Iglesiente, Sarrabus), North Africa, Huelva (Rio Tinto, Sotiel Coronado), Lusitania (Aljustrel, Sto Estevao)? Tuscany (Fucinaia, Campiglia, Massa Marittima)?	Sinai (wadi Maghara), Eastern Desert, Petra (wadi Feynan), Negev (Timna valley, wadi Arabah), Cyprus (Soli & Apliki), Ugarit	Cyprus (Soli & Apliki), Samos (to Chrysokamino), Turkey (Trabzon area), Sardinia	Cyprus (Soli & Apliki), Samos (to Chrysokamino), Turkey (Trabzon area), Sardinia

tin (cassiterite)	Cornwall (Ictis), France (Ploermel), Spain (Laza), Germany (Erzgebirge), Tuscany (Mte Rombolo & Valerio), Dalmatia (Mt Cer), Turkey (Uludag near Bursa, Bakla Tepe NW of Ephesos,Mersin area: Kestel/Göltepe mines)? Syria (from NW Iran & Afghanistan/Bactria)?	Narbo (British tin shipped to Burdigala), Marseille (British & German tin brought overland/rivers), Thrace (Pautalia), Turkey (Bakla Tepe NW of Ephesos,Mersin area: Kestel/Göltepe mines)?	Marseille (British & German tin brought overland/rivers), Syria (from NW Iran & Afghanistan/Bactria), Tuscany (Mte Rombolo & Valerio)? Turkey (Bakla Tepe NW of Ephesos,Mersin area: Kestel/Göltepe mines)?	Ugarit (from NW Iran & Afghanistan/Bactria)	Tuscany (Mte Rombolo & Valerio)? Turkey (Bakla Tepe NW of Ephesos,Mersin area: Kestel/Göltepe mines), Ugarit (from NW Iran & Afghanistan/Bactria)	Tuscany (Mte Rombolo & Valerio)? Turkey (Bakla Tepe NW of Ephesos,Mersin area: Kestel/Göltepe mines), Ugarit (from NW Iran & Afghanistan/Bactria)
lead	Britain (Charterhouse, Cornwall), Aquitaine, Spain (Galicia, Palazuelos, Diogenes, Cartagena, Linares), Sardinia (Iglesiente, Domusnovas), Algeria (Arksib, Denaïra), Dalmatia (Srebrenica), Attica (Laurion), Turkey (Mersin area)	Thasos, Naxos, Koufonisia, Siphnos, Turkey (Mersin area)	Sardinia (Iglesiente, Sarrabus), Algeria (Arksib, Denaïra), Spain (Cartagena), Tuscany?	Aswan, Eastern Desert		

iron	Britain (Sussex, Cornwall, Great Doward), Aquitaine, Galicia, Algeria, Elba, Dalmatia, Attica (Laurion), Trabzon, Cyprus (Mitsero)	Cyprus (Mitsero), Evia, Andros (Agios Petros), Syros, Seriphos, Kythnos, Trabzon	Cyprus (Mitsero), Sardinia (Iglesiente, Sarrabus), Etruria & Elba, Algeria	Sinai, Eastern Desert, Cyprus (Mitsero)	-	-
raw glass	Egypt (wadi Natrun, Taposiris), Israel (near Dor), and potential places in Italy (beach Piombino-Follonica, beach Policoro-Metaponto, beaches Brindisi-Torre Rinalda), in Spain (outlet of R Guadiana, beach of Aguilas near Cartagena), and in France (Bay of Hyeres)	Egypt (wadi Natrun, Taposiris), Israel (near Dor)	Egypt (Qantir, Amarna, Malkata), Mesopotamia, Italy (Frattesina)?		Egypt (Qantir, Amarna, Malkata), Mesopotamia, Italy (Frattesina)	
Timber:						
cedar	Phoenicia (Byblos)	Phoenicia (Byblos)		Phoenicia (Byblos)		
papyrus	Egypt (via Byblos)	Egypt (via Byblos)	Egypt			Egypt
Ceramics, terracotta:						
tiles (tegulae-imbrices)	export only					

bricks	export only					
oil lamps	Tunisia (Carthage)					
Edibles:						
wheat	Alexandria, Tunisia, Sicily	Black Sea (R Tanais, Borysthenes)			Black Sea (R Tanais, Borysthenes), Egypt	Black Sea (R Tanais, Borysthenes), Egypt
wine	Greece, Gaul (Rhone valley, Bordeaux), Spain (Tarraconensis, Baetica), Tunisia (Carthage), Levant (Byblos, Gaza), Cyprus, Crete, Aegean (Skopelos, Chios, Samos, Naxos, Thera), Sardinia? Black Sea, Dalmatia, Istria	Aegean (Thasos, Lemnos, Lesbos, Chios, Samos, Kos, Naxos), Levant (Byblos, Gaza), Cyprus, Crete, Sardinia? Black Sea	Aegean (Thasos, Lemnos, Lesbos, Chios, Samos, Kos, Naxos), Gaza, Cyprus, Crete	Aegean (Thasos, Lemnos, Lesbos, Chios, Samos, Kos, Naxos), Levant (Byblos, Gaza), Cyprus, Crete	Aegean (Thasos, Lemnos, Lesbos, Chios, Samos, Kos, Naxos, Crete), Phoenicia (Byblos), Sicily	
defrutum, siraion, epsima (reduced fruit must)	Baetica, Cyprus?	Baetica, Cyprus?				

Garum, liquamen (fish sauces) & salsamenta, tarichos (salted fish)	Baetica (Cadix, Cartagena), Lusitania (Lisbon, Troia), Morocco (Lixus, Cotta), Tunisia (Carthage, Nabeul), Gaul (Mareille, Antibes), Libya (Leptis Magna), Black Sea (Crimea, Bithynia)	Black Sea (Crimea, Bithynia), Baetica (to Corinth)	Baetica (Cadix), Lusitania (Lisbon), Morocco (Lixus, Cotta), Tunisia (Carthage, Nabeul)			
olive oil	Istria, Dalmatia, Sicily, Sardinia, Attica, Samos, Turkey (Ionia, Cilicia), Cyprus, Crete, Levant (Syria, Phoenicia, Canaan), Cyrenaica, North Africa (Tunisia, Algeria, Morocco), Baetica (Cadix)	Samos, Ionia, Cyprus, Crete (Kommos), Levant (Syria, Phoenicia, Canaan)		Crete, Levant (Syria, Phoenicia, Canaan)	Crete	
pepper	India (Muziris on Malabar coast)	India (transported overland from Muziris on Malabar coast)	-	India (Muziris on Malabar coast)	-	-
cinnamon malabathrum	India (by sea via Socotra, and overland via Syria)				-	-
Luxuries:						
ivory	Punt (Red Sea), India	Egypt	Punt (Red Sea)	Punt (Red Sea), Nubia	Egypt,	Egypt
perls	Red Sea, Persian Gulf	Egypt	Red Sea, Persian	Red Sea		

			Gulf?			
fashioned glass	Dalmatia (Zadar), Germany (Trier), Phoenicia (Sidon), Alexandria	Phoenicia (Sidon), Alexandria		Phoenicia (Sidon)		
silk & cotton	Kos, China & India (via Alexandria, Carthage?)	Kos, China & India (via Syria, Egypt, Cyprus)	China & India (via Syria, Egypt, Cyprus)	China & India		
linen	Spain (Xativa)					Egypt
purple dye	Lesbos, Rhodes, Phoenicia (Tyre, Sarepta, Sidon), Tunisia (Jerba, Kerkouane, Carthage), Sicily (Motya), Morocco (Essaouira)	Lesbos, Rhodes, Phoenicia (Tyre, Sarepta, Sidon), Sicily (Motya)			Phoenicia	Phoenicia
frankincense (& myrrh)	Punt (Red Sea), Somalia (Heis, Bosaso), Oman (Salalah)	Punt (Red Sea), Somalia (Heis, Bosaso), Oman (Salalah)	Punt (Red Sea), Somalia (Heis, Bosaso), Oman (Salalah)	Punt (Red Sea), Somalia (Heis, Bosaso)		
perfume	Alexandria, Cyprus (Kato Pyrgos)	Cyprus (Kato Pyrgos), Egypt	Mesopotamia, Egypt, Cyprus (Kato Pyrgos)	Mesopotamia, Cyprus (Kato Pyrgos)	Mesopotamia, Cyprus (Kato Pyrgos)	
ebony, hbony	Punt (Red Sea), Nubia	Punt (Red Sea), Nubia	Punt (Red Sea), Nubia	Punt (Red Sea), Nubia		

amber	Baltic (overland/rivers to Olbia-Borysthenes, to Hatria & Aquileia, to Marseille)	Baltic (overland/rivers to Olbia-Borysthenes, to Hatria & Aquileia, to Marseille)	Baltic (via Wessex in GB & overland/rivers?)		Baltic (via Wessex in GB & overland/rivers?)	Baltic (via Wessex in GB & overland/rivers?)
Art:						
bronze artwork	Greece			Crete	Crete	
marble artwork	Greece			Crete	Crete	
terra sigillata, African Red Slip, fineware	Greece (Attic), Tunisia (Sidi Bouzid area)		Attica (to Carthage)	Crete, Greece (Mycenae)	Crete	
Humans:						
slaves	Delos i.a.	Delos i.a.	Sudan, Morocco	Nubia, Levant		

Exporting country	Goods imported by Romans
Baltic	amber
GB & Ireland	metals
Lusitania & Baetica	metals, olive oil, garum, wine, defrutum
Cartagena	metals, linen
Tarraco	metals from Galicia, marble, wine
Gaul (Narbo, Massalia)	metals from GB & Germany, glass from Germany, amber from Baltic, wine, garum
Tuscany & Elba	metals, marble
Sicily & Lipari	wheat, obsidian, olive oil, purple dye
Hatria & Aquileia	amber from Baltic
Istria & Dalmatia	metals, olive oil, wine, fashioned glass
Greece	silver & copper at Laurion, marble, olive oil, wine, bronze & marble artwork, ceramics
Thrace	metals
Dacia (Transylvania)	metals
Borysthenes & Crimea & Tanais	wheat, garum, amber from Baltic
Georgia (R Phase)	gold
Anatolia (Trabzon, Nicomedia, Ephesos, Attaleia, Mersin)	metals, obsidian, olive oil
Marmara Sea	marble
Thasos	metals
Lesbos	purple dye

Peparethos (Skopelos)	wine
Chios	wine
Keos	silver, lead
Delos	slaves
Naxos	marble, silver, lead, wine
Koufonisia	silver, lead
Paros	copper
Siphnos	gold, silver, lead (exhausted in Roman times)
Milos	obsidian
Samos	olive oil, wine
Thera (Santorini)	wine
Rhodes	purple dye
Crete	olive oil, wine
Cyprus (Kourion & Soli)	metals, olive oil, wine, perfume
Cilicia (Mersin)	metals
Ugarit & Syria (NW Iran & Afghan./Bactria)	tin, Lapis lazuli
Levant	timber, metals, raw glass & fashioned glass, purple dye, olive oil, wine at Gaza, gems & perls & spices from Red Sea & Gulf/India
Egypt & Sinai	wheat, papyrus, metals & ebony from Nubia, gems, glass, ivory & silk & cotton & incense & spices from Red Sea/India
Libya	garum at Leptis Magna, olive oil in Cyrenaica
Tunisia	wheat, olive oil, garum, wine, purple dye, ceramics
Sardinia	silver, obsidian, olive oil

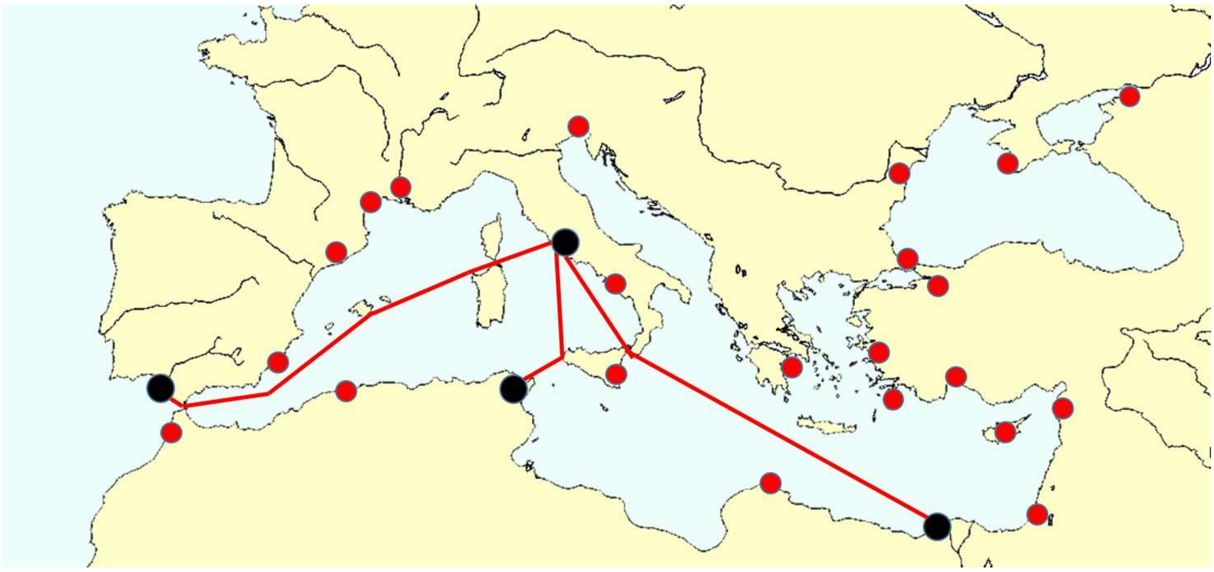
Algeria	metals, olive oil
Morocco	garum, olive oil, purple dye

These tables are probably incomplete. Please help!

Similar studies can be conducted for other cultures: Greeks, Phoenicians, Egyptians, Mycenaeans, Minoans, etc.

Realise that this result includes only primary imports, i.e., goods needed by the peoples for their own consumption, but does not take into account imports aimed at being re-exported, possibly after some manufacturing.
Hence, this is only a first step towards a better understanding of ancient trade networks

Further to the above-mentioned overview of ancient trades, the following hubs might be defined:



Trade networks in the Roman Mediterranean Sea: Black dots are main hubs: Rome, Alexandria, Carthage, Gades; Red dots are regional hubs.

In addition to the four main hubs, the above survey of Roman imports provides a series of ‘regional hubs’, including Carthago Nova, Tarraco[226], Narbo[227], Arelate[228], Puteoli, Syracusa, Aquileia, Athens, Byzantium, Tomis, Crimea, the Tanaïs river area, Nicomedia[229], Ephesus, Rhodes, Attaleia[230], Cyprus, Antioch ad Orontem/Seleucia Pieria, Gaza (if it was more than a place of transit such as Myos Hormo and Berenike), Apollonia of Cyrene, Caesarea Mauretania, Lixus.

In addition to Indian places such as Muziris (Pattanam, north of Cochin), lesser known places such as Omana (possibly located at al-Dur, ed-Dur, in Umm al-Quwain Emirate) and Tylos (Bahrain) should be mentioned here too, in order not to under-estimate ancient traffic in the Gulf to Palmyra and Antioch[231].

A pattern of imbricated networks could be refined almost indefinitely as each regional hub may have its own trade with its hinterland and other nearby small ports. Like a fractal that exhibits a repeating pattern displayed at every scale.

[226] Tarraco may have been the exporting place for metals from the north-western Tarraconensis (Galicia).
[227] Narbo may have been a place of transit of metals from Great Britain sailing to Burdigala.
[228] Arelate may have been a place of transit for goods originating in northern Europe.
[229] Byzantion and Nicomedia were both ancient Greek cities, but they were on each side of the Bosphorus, on different continents: Thracia on the western side, was rather undeveloped, and Asia Minor on the southern side, was highly developed since many centuries. Nicomedia was a major Roman city in the 2nd and 3rd c. AD, while Byzantium was reconstructing after Septimus Severus’ destructions in 195 AD and finally heading for becoming a capital city when renamed Constantinopolis as late as 330 AD.
[230] Pergé was part of the Roman Empire since 188 BC and was the capital city of Pamphylia. It had its own river port some 16 km from the sea, but the seaport of Attaleia could be used when the coast was free of pirates.
[231] SCHÖRLE, K., 2017, “Palmyrene merchant networks and economic integration in competitive markets”, in “Sinews of Empire”, ed. Teigen & Seland, Oxbow Books, (p 147-154).

7.7 *Some trade routes*

Sailing from cape to cape (cabotage) is the most obvious route for any seafarer, except for those sailing a direct route on offshore waters.

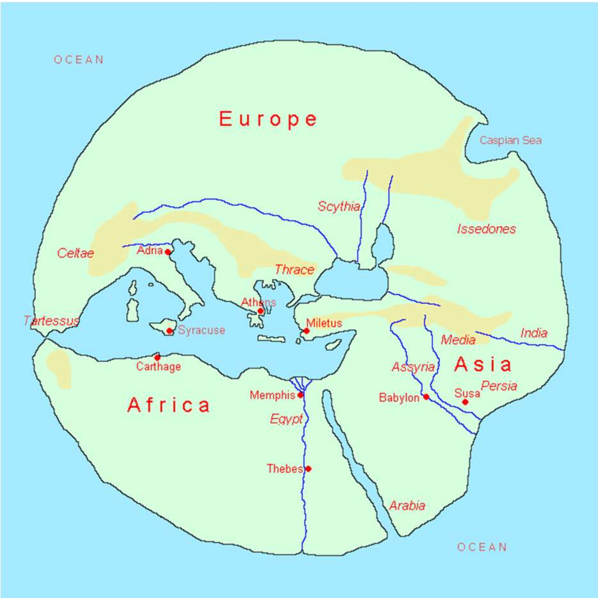
Goods	Routes
Amber from Baltic	R Daugava, R Dniepr, Borysthenes, Bosphorus
	R Vistula & R Oder, R Morava, Carnuntum (near Vienna), R Danube, Bosphorus
	R Vistula & R Oder, R Morava, Carnuntum (near Vienna), Aquileia, Adriatic, Delphi & Corinth & Mycenae, Crete, Levant & Egypt & Cyrene
	R Elbe, Prague, Brenner pass, Aquileia, Adriatic, Delphi & Corinth & Mycenae, Crete, Levant & Egypt & Cyrene
	R Rhine, Basilia (Basel), R Doubs/Saône/Rhône, Massalia (NB: Basel has same Latin name as Samland: coïncidence? Ships from Samland arrived at Basel …)
	R Rhine, R Danube, Bosphorus
Tin from GB	Ictis, La Coruna, Gades
	Ictis, Burdigala, Narbo
	Ictis (?), R Seine (?), R Saône/Rhône, Massalia
Tin from Armorica	Poërmel, R Oust, R Villaine, Pénestin (?), Burdigala, Narbo
Tin from Galicia	Laza, R Ebro, Tarraco
	Laza, R Sil, R Mino, Ourense, Gibraltar
Tin from Anatolia	Uludag near Bursa, Bakla Tepe NW of Ephesos, Mersin area: Kestel/Göltepe mines, Anchialeia, Rhodes & Levant
Tin from NW Iran	Antioch, Rhodes & Levant
Incense from Dhofar	Moscha area (Salalah), Shabwa, Najran, Mecca, Medina, Petra, Gaza (100% overland)
	Moscha area (Salalah), Qana, Leuke Kome (al-Wajh?), Hegra (Mada'in Saleh), Petra, Gaza (25% overland)
	Moscha area (Salalah), Qana, Berenike or Myos Hormos, Coptos, Alexandria (25% overland/river)
	Moscha area (Salalah), Hormuz, Babylon, Antioch (35% overland/river)
Incense from Somalia	Mundus-Mosylium area (Heis- Bosaso), Nubia, Coptos, Alexandria (100% overland/river)
	Mundus-Mosylium area (Heis- Bosaso), Berenike or Myos Hormos, Coptos, Alexandria (30% overland/river)

8 ANCIENT MAPS

8.1 From T-O maps to Google Earth

Humans have been watching the sky for immemorial times. They built astronomical observatories[232] used for setting yearly calendars. This full 3-dimensional view would be the base of a cosmography showing celestial objects and deities. The first description of this kind was provided by Homer on the "great and sturdy shield" made by Hephaestus for Achilles (Illiad, 18, 484-609). It even showed both time and space on the same picture, thus linking Homer and Einstein to each other. However, it proved to be more difficult to describe the earth floor.

After travelling the world, the ancients felt a need to put their knowledge into a simple overall view. They first looked for the borders of the inhabited world (*oikoumene*) and described it as a circular island in the middle of an external ocean according to the Homeric concept that survived two millennia until the Middle Ages. Anaximander of Miletus is considered to be the first to design a map of the world around 550 BC. He was followed by Hecataeus, also from Miletus (Geus, 2018[233]).



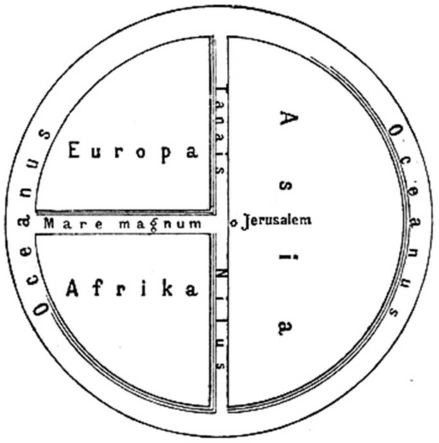
Modern restitution of a typical world-map of around 500 BC, based on Hecataeus of Miletus' telling about his travels around the world ('*periegesis*' or '*periplus*'). (http://www.livius.org/concept/the-edges-of-the-earth-1/the-edges-of-the-earth-2/)

In the wake of Ephorus' description of the *oikoumene* (ca. 350 BC), Eratosthenes[234] came with a rectangular shape (around 200 BC) that was not widely adhered to until much later (see Cosmas Indicopleustes around 550 AD). Meanwhile, the simplified 'T-O' scheme was widely used, possibly based on Lucan's description (Pharsalia, Book 9, verse 411, around 60 AD, acc. to P. Arnaud, 1990, p 283):

[232] See : http://solar-center.stanford.edu/AO/

[233] References are listed at the end of this chapter.

[234] Eratosthenes is more famous for his correct estimate of the earth's circumference (see "Ancient Measures" above).



The map is oriented with the north upside. The 'T' is the Mediterranean, the Nile and the Don (formerly called the Tanais) dividing the three continents, Asia, Europe and Africa, and the 'O' is the encircling ocean. Jerusalem (or Delphi, or Rhodes) was generally represented in the centre of the map (Wikipedia).

Thanks to Eratothenes, and to Pythagoras before him, the ancients realised that the *oikoumene* was located on the surface of a sphere (3-dimensional) and that putting this on paper (2-dimensional) would require some kind of geometrical projection. Strabo suggested that such a map would be shown best on a 10 feet diameter globe (Strabo, Geogr. 2, 5, 10, around 10 BC). This was not only a very large object, but it was also quite useless, as the *oikoumene* covered only a small part of its surface. A good reason why none survived (if such a globe was ever built).

Having set the borders of the *oikoumene*, the ancient cartographers had to add more information about landscapes (e.g., rivers and mountains) and human settlements (cities and peoples) e.g., the map of Aristagoras (Herodotus, Hist., 5, 49). This appeared to be a problem simply because the maps had to be large enough to host that much information. Hence, such maps had to be monumental wall-maps ('*pinax'* or '*tabula'* on a large wall or floor). Another option was to distort the maps to include this information, e.g., increase the size of densely populated areas and reduce the size of deserts (see Ptolemy, Geography, 8,1).

Clearly, geography had to combine several needs, out of which choices had to be made:

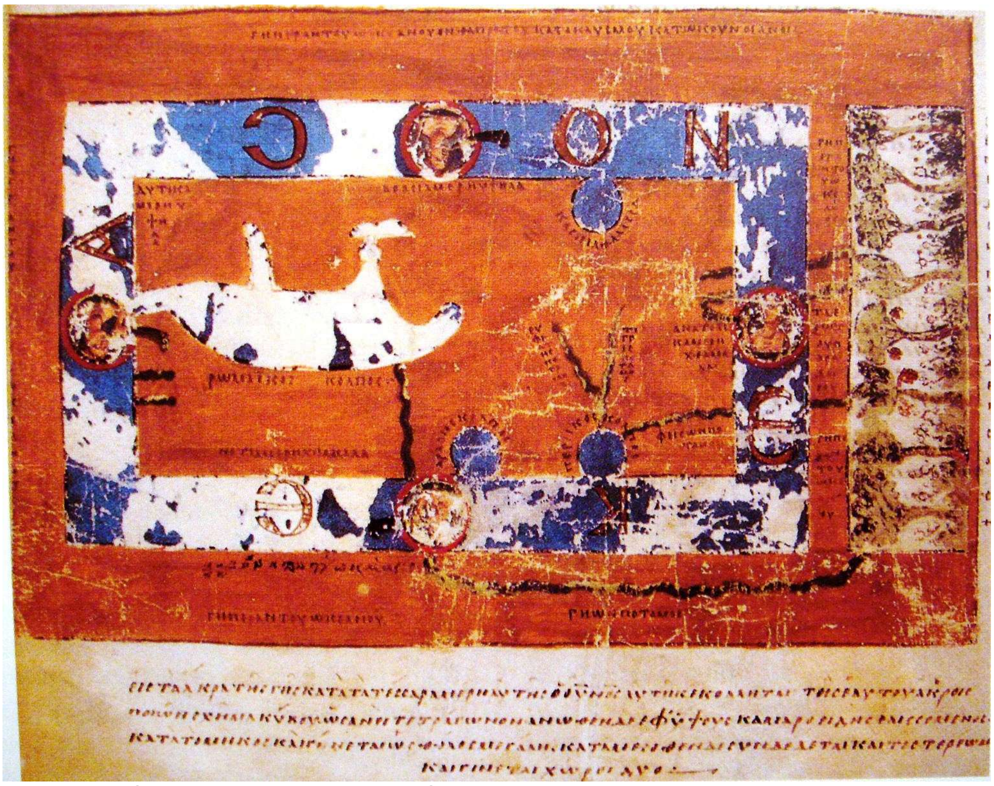
- accuracy of land contours and place location (cartography),
- volume of information concerning rivers, mountains and cities (chorography),
- description of territories concerning climates, inhabitants, etc. (climatology, human geography),
- pictures showing real landscapes (painting or mosaic like the Haidra one in Tunisia),
- encompassing the whole *oikoumene*,
- to be beautiful.

Many cartographers (possibly including Agrippa) also had a political approach trying to show an impressive number of conquered cities and tribes to please a proud emperor. Others denied the existence of a livable world in the southern hemisphere, despite accounts of sailors (Strabo, Geogr. 2, 5, 3 & Pliny, NH, 6, 39). As a matter of fact, many maps had a hidden agenda, while Ptolemy just had a scientific approach looking for an accurate map. The answer found by Ptolemy (around 160 AD) and his predecessors (Dicaearchus around 300 BC and Marinus of Tyre around 100 AD) by suggesting subdividing the world into parallelograms defined by meridians and parallels, introduced the idea of modern atlases. However, his idea could only be put into practice when the ancient papyrus scroll (*volumen*, several meters long, but with no more than 25 to 35 cm height) was replaced by the larger parchment codex (*menbrana*, with a maximum size of up to 70 x 40 cm) around the 6th c. in

Europe, although it was already used in Asia Minor during the Hellenistic period. Only then could drawn maps really start to replace the textual maps used in Antiquity.

In addition, ancient texts and maps had to be copied at regular intervals to be preserved over time. This was done by more or less knowledgeable people who often tried to 'improve' the document by adding or changing information. The maps resulting from this process were therefore closer to an 'evolution' than to a simple copy.

Only four world-maps ('*mappaemundi*') dating before year 1000 were found to date (Arnaud, 2014):



Cosmas Indicopleustes' "Christian Topography", around 540 AD,
from a 9th c. manuscript called Vaticanus Graecus 699 (0.23 x 0.32 m, top is north).
(Wikipedia).

Mappa mundi by **Beatus de Liebana**, 8th c., from an 11th c. copy
(0.367 x 0.286 m, top is east) (BnF, Latin Manuscripts 8878, f. 45v-46).

Albi's mappa mundi, from an 8th c. manuscript
found in the St Cecilia cathedral of Albi, France (0.27 x 0.225 m, top is east) (Dan, 2017).

Cottoniana, from Priscian's *periegesis*, around 1000 AD, found by Sir Robert Cotton in 1598, and restored by Miller in 1895 (0.21 x 0.18 m, top is east).
(http://swanrad.ch/mappae-mundi-from-the-edition-of-konrad-miller/)

All other 'ancient' maps we can see today were redrawn based on ancient texts without any drawings: e.g., the remains of the 'map' of Agrippa consist of text only and his monumental Porticus Vipsania did not survive (if it was ever built). Agrippa's work is dated around 15 BC and mentioned by Pliny around 77 AD. It was probably used for the Cottoniana around 1000 AD and used at Ebstorf around 1235 AD and Hereford around 1300 AD (Arnaud, 1990, p 1279-1298).

This is also the case for all maps based on Ptolemy's tables of coordinates, which were forgotten for a long time, which reappeared in Constantinople around 1300 AD thanks to Maximus Planudes, and which proved to be (by far) the best representation of the oikoumene until the Middle Ages.

Information provided by 'itineraries' written by travellers surely had a lot of influence on these maps, even if this information could not be retrieved as such on them (Arnaud, 2007). The famous Peutinger map (*Tabula Peutingeriana*) from the 13th c. was found in 1507 by Conrad Celtis and given to his friend Konrad Peutinger in 1508. In contrast with the maps mentioned above, it might be called '1-dimensional' because of its distorted and linear aspect fitting the ancient scrolls (the size of the Peutinger map is 0.34 x 6.75 m). The Peutinger map can perhaps be seen as the outcome of a long evolution of itineraries. It was probably based on late 4th c. Roman itineraries (Emperor Julian the Apostate, acc. to Arnaud, 1990, p 945 & 916), themselves inspired by others such as the much older Scylax of Caryanda (around 515 BC, acc. to Wikipedia), Pseudo-Scylax (around 330 BC, acc. to Wikipedia), Nearchus (325-324 BC), the Stadiasmus Maris Magni (around 150 to 50 BC?), Pseudo-Scymnos (between 133 and 110 BC, acc. to Marcotte, 2000) and the Antonine Itinerary (around 350 AD, for the non-maritime parts, and between the 4th and the 6th c. AD for the maritime parts, acc. to Arnaud, 2004).

Portolans provide information for seafarers sailing from port to port. A portolan consists of a marine chart with port names and 16 or 32 'rhumb lines' (directions at 22.5° or 11.25° angles), and of written nautical instructions. Some charts are still available: the oldest known chart is the "Carta Pisana" dated slightly before 1300 AD and possibly using information from "Lo compasso da navigare" (13th c.). The oldest known portolan (but the chart is missing) is the "Liber de Existencia Riverierarum et Forma Maris Nostri Mediterranei" dated around 1200 AD and studied by Patrick Gautier-Dalché in 1995. Note that early portolan charts were drawn **before** Ptolemy's coordinate system was rediscovered around 1300 AD. The surprising accuracy of portolans is probably linked to the use of the compass, which was already in use in the early 12th c., and using dead reckoning and triangulation.

One might say that both Eratosthenes and Ptolemy had it right from the onset, but that it took a millennium or so, to have their vision of a spherical *oikoumene* widely accepted. It was Gerardus Mercator who brilliantly combined portolan charts with Ptolemy's system in 1569.

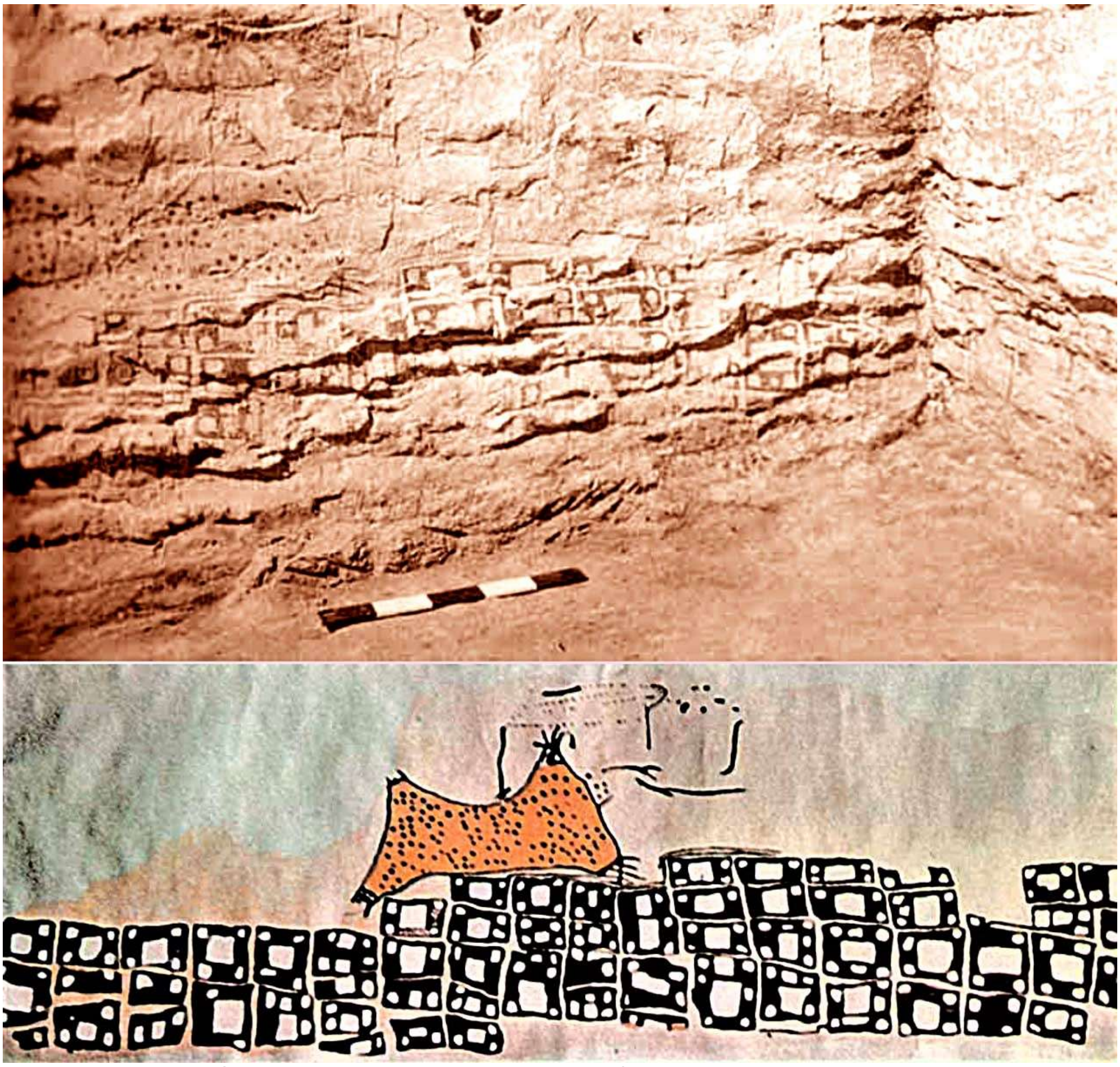
We may perhaps summarize by saying that:
travellers had a mostly linear (1-dimensional) perception of the world,
geographers ('chorographers') had a planar (2-dimensional) view, and
astronomers ('geographers') had a spherical 3-dimensional view.
cosmographers had a 4-dimensional view combining space and time.

But all of them seem to have been badly limited in their capacity of drawing maps and relied mainly on textual descriptions of their world.
(Arnaud, 1990, p 1299-1307)

Eventually, the problem of a single map including all information was solved in 2004 by Google Earth's revolutionary zooming tool.

8.2 Regional maps

The oldest maps found so far are regional maps:



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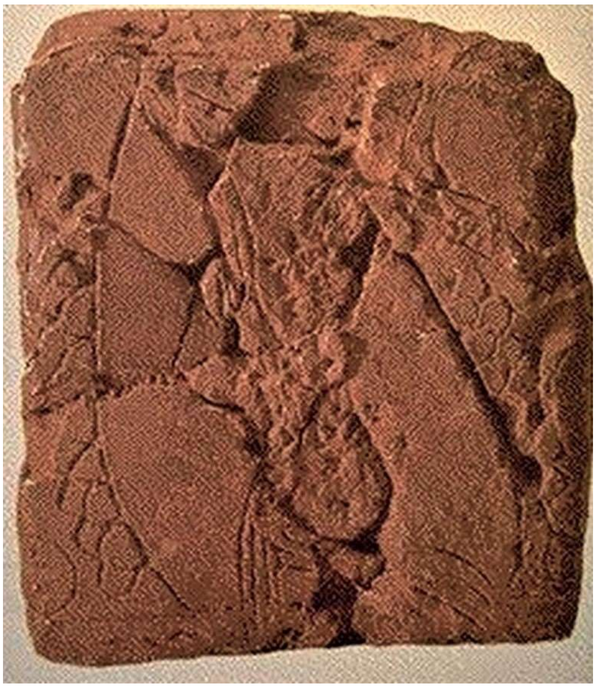
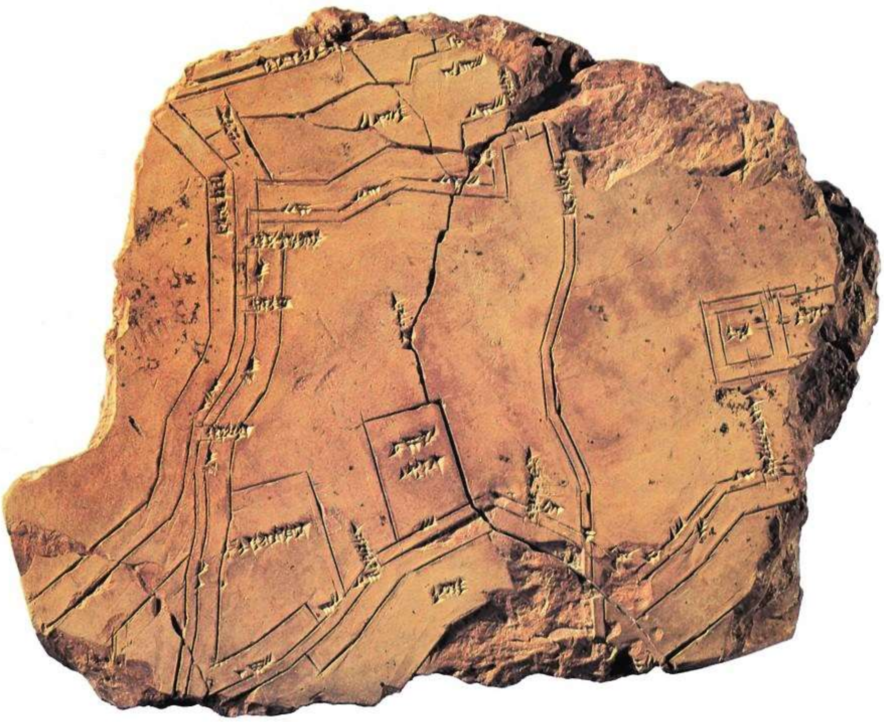
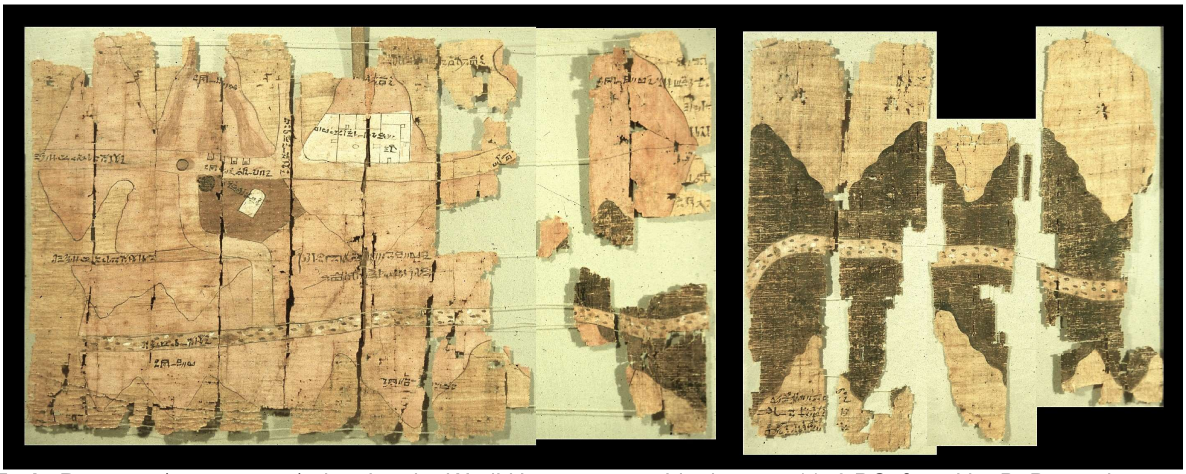
Çatalhöyük city map with the eruption of Mount Hasan volcano, ca 6200 BC, found in 1963 near Konya,Turkey (3 x 0.9 m) (Ankara Mus. of Anatolian Civilizations) (http://yerindecizer.blogspot.com/2018/02/catalhouk-haritas.html) (https://arkeonews.net/the-oldest-map-of-the-world-found-in-catalhoyuk/)



Ga-Sur map showing a river valley, ca. 2500 BC, found in 1930
at Yorghan Tepe (Nuzi), near Kirkouk, Iraq
(0.076 x 0.068 m, top is south) (University of Harvard Mus.)
(http://www.myoldmaps.com/maps-from-antiquity-6200-bc/100title-the-earliest-known/)

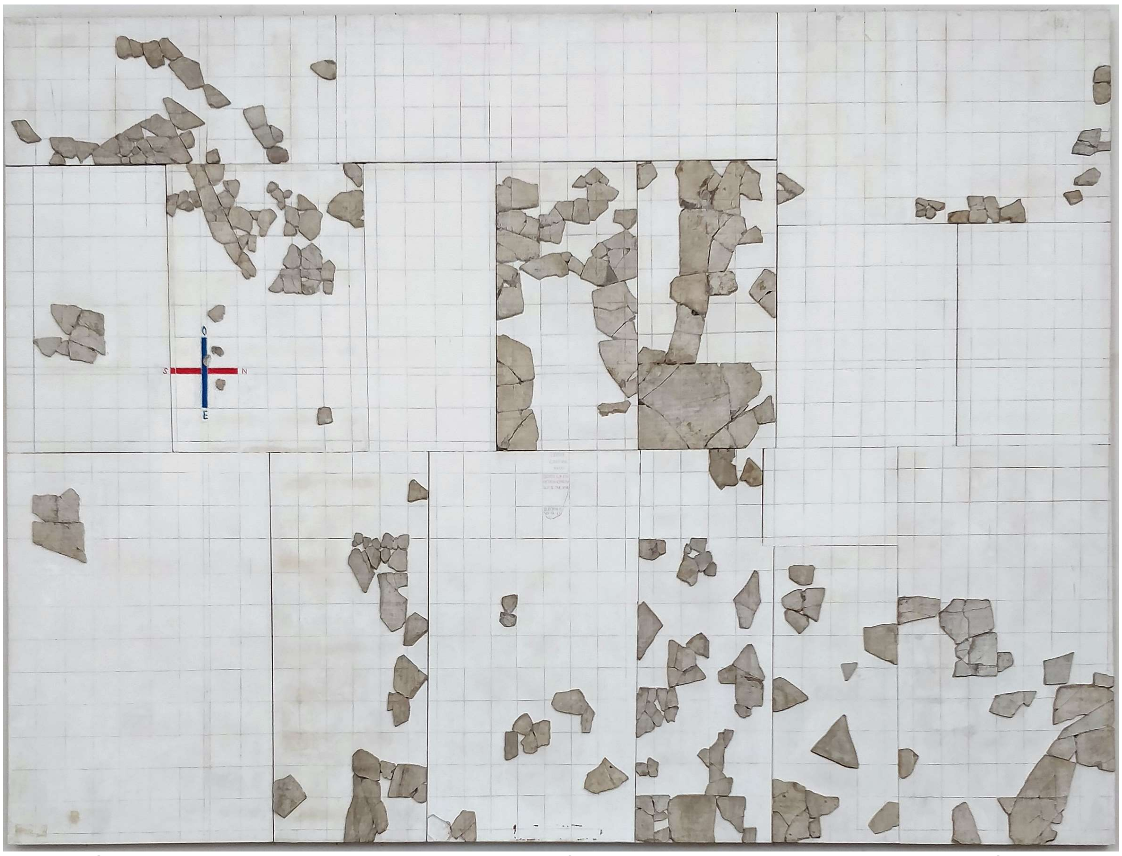


Nippur map showing the city with its walls, temples and canals, ca. 1300 BC, found around 1899
at Nippur (Irak) (0.21 x 0.18 m) (University of Pennsylvania Mus.)
(http://www.myoldmaps.com/maps-from-antiquity-6200-bc/101-mesopotamian-city-plan/)



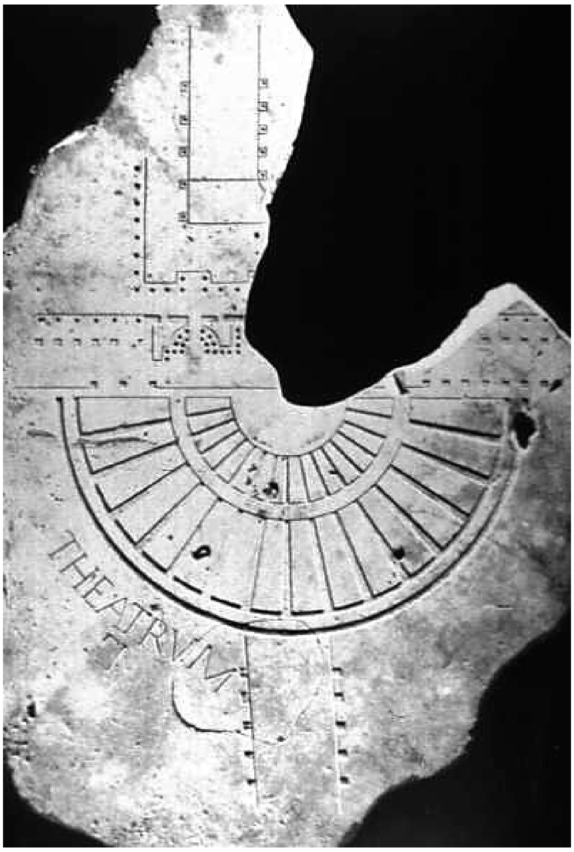
Turin Papyrus (eastern part) showing the Wadi Hammamat gold mine, ca. 1150 BC, found by B. Drovetti around 1820 at Deir el-Medina (Egypt). (2.10 x 0.41 m, top is south). (Torino Mus.) (http://www.myoldmaps.com/maps-from-antiquity-6200-bc/102-turin-papyrus/).

Imago Mundi clay tablet, showing the Babylon area, ca. 6th c. BC, found by H. Rassam in 1882 at Sippar (Irak), (0.122 x 0.082 m, top is north), (British Mus. N°92687) (http://www.myoldmaps.com/maps-from-antiquity-6200-bc/title-babylonian-world-map/)

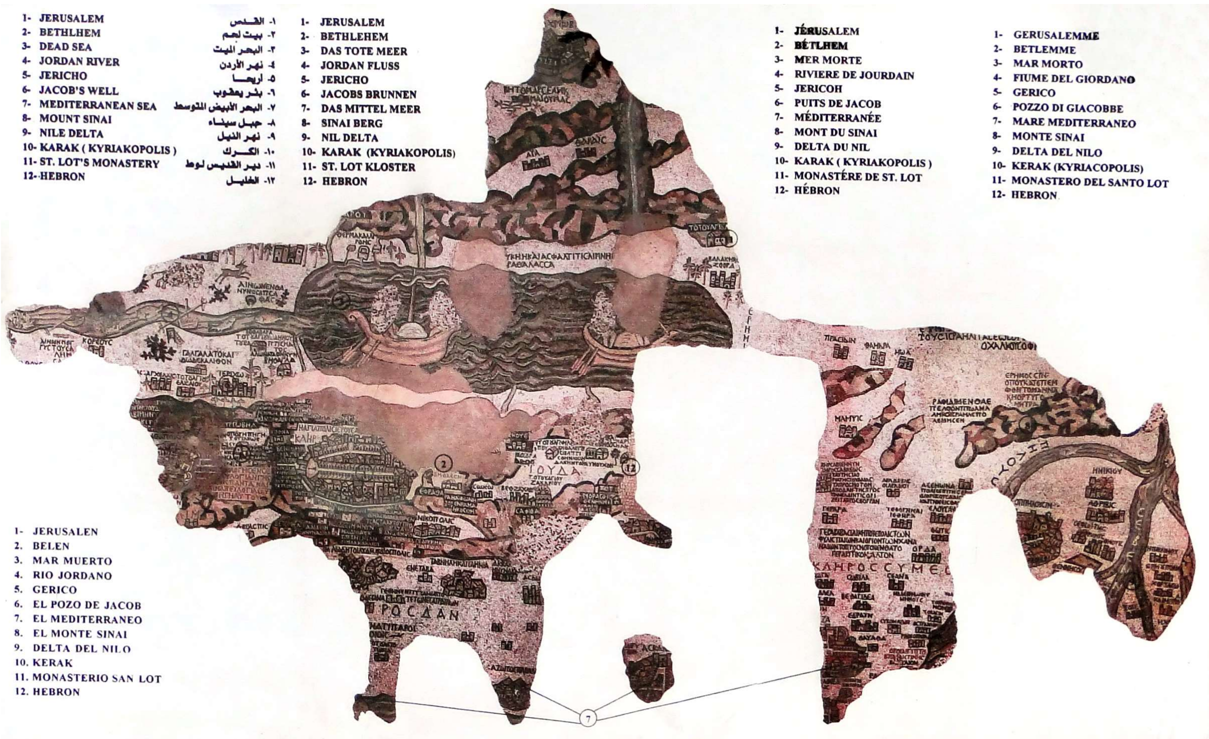


Marbres d'Orange tabula, showing the cadastral map of the Roman colony Julia Firma Arausio Secundanorum (77 AD) consisting of three maps (the largest is 7.56 x 5.90 m) (Orange Mus. picture A. de Graauw, 2020).

Dura-Europos parchment, showing a part of the Black Sea coast, around 200 AD, found in 1923 by F. Cumont in Syria (0.45 x 0.18 m). (Wikipedia).



Map of Rome, the Marble Plan, or Forma Urbis Romae, built around 203-211 AD on a wall of Templum Pacis (18.22 x 12.87 m)
(Wikipedia & Stanford Univ.)



Madaba mosaic, showing Palestina, around 550 AD, probably based on a 3rd c. Roman map (acc. to P. Arnaud, 1990), found in 1896 in Jordan (15.7 x 5.6 m). (Wikipedia)

9.1 Claudius Ptolemy's Geography (85 - 165 AD)

Ptolemy's work consists of a list of ca. 8000 place names in the Roman Empire of the 2nd c. AD (Stückelberger & Graßhoff, 2006). Each place is located with latitude and longitude aiming at enabling a reconstruction of the complete map of the world he was living in, but it is believed that he probably never published a drawing of such a map.

His latitudes are related to the equator, like we do today, and the value of one minute of latitude is 1852 m (or one nautical mile, by definition).

The value of one minute of longitude depends on the latitude: it is around one nautical mile at the equator[235] and nil at the poles. Elsewhere its value is[236]:

- 0.74 nautical mile in the south of France, or 1375 m at 42° of north latitude,
- 0.81 nautical mile near Rhodes, or 1500 m at 36° of north latitude,
- 0.85 nautical mile near Alexandria, or 1570 m at 32° of north latitude
  (NB: one degree of longitude in Alexandria is ca. 600 Egyptian stadia of 157.5 m),
- 0.97 nautical mile near Massawa and Dakar, or 1790 m at 15° of north latitude.

His reference point for longitudes is located at the Fortunate islands, somewhere west of Greenwich which is today's reference. However, a shift increasing towards the east is observed: shift of 20-22° in France, around 25-30° in Greece and 35-40° in the Red Sea.

It appears that he also underestimated the value of one degree of longitude.

This subject has been discussed for nearly two millennia (!) … Without entering into this discussion, it appears quite clearly that Ptolemy's 'errors' might be corrected by a combination of a shift and a reduction factor.

We have therefore carried out an analysis (called 'linear regression') on a sample of 42 well known coastal sites by comparing Ptolemy's latitude-longitudes with the present values.

The result is so clear that it is worth showing here:

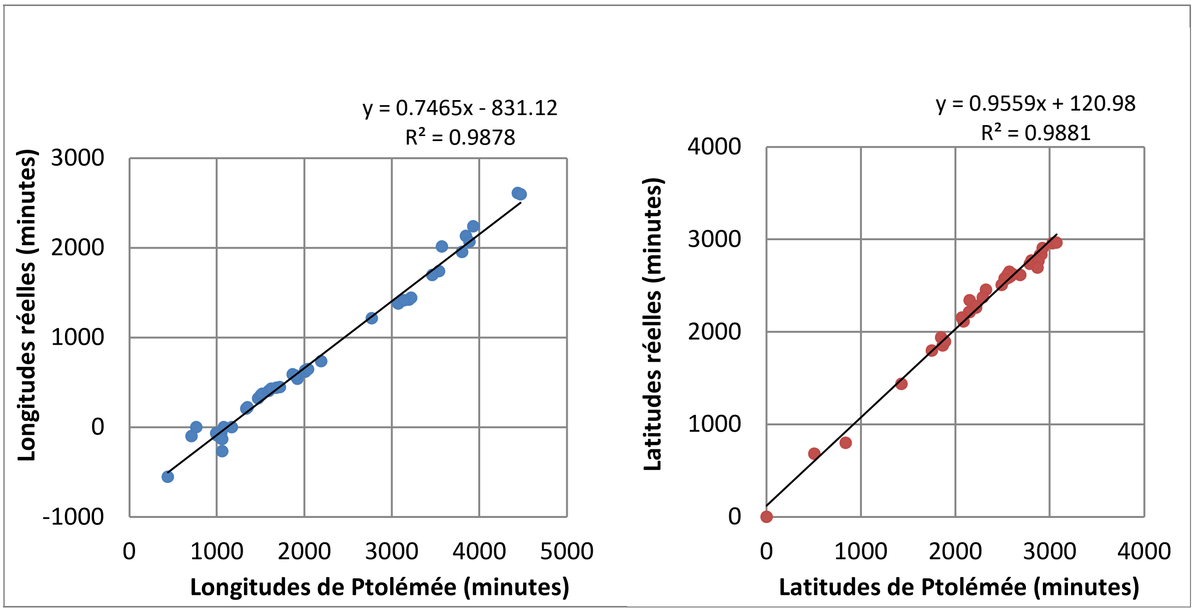
[235] More precisely 1.0018 nautical mile due to the slight bulge of the earth at the equator.
[236] According to the formula provided by the French IGN:
Consider two points A and B on a sphere, with latitudes φ_A and φ_B and longitudes λ_A and λ_B , then the *angular* distance s(AB) between A and B is given by the following fundamental spherical trigonometry formulae:

$s(AB) = \arccos(\sin\varphi_A \sin\varphi_B + \cos\varphi_A \cos\varphi_B \cos d\lambda)$

where: $d\lambda = \lambda_B - \lambda_A$

and with: $\varphi_A = \varphi_B$ and $\lambda_A = 0$ and $d\lambda = 1°$ for the case of interest here.

The result s(AB) is given in radians, to be converted into degrees of latitude and into nautical miles, knowing that one degree of latitude equals 60 nautical miles.



Comparison of Ptolemy's longitudes and latitudes with real values.

Ptolemy's longitudes (left figure) and his latitudes (right figure) are set out horizontally; the real latitudes and longitudes are set out vertically. It can be seen first that the points are quite well aligned on straight lines (correlation coefficient R is 0.994) which shows that the mathematical formulation ("y = ax + b") is correct.

The straight line for latitudes shows that Ptolemy's values are, globally, equal to the real values (factor 0.9559 close to 1, and shift of 120.98 minutes; that is still 2°).

The straight line for longitudes shows a larger correction than for the latitudes:

Longitude (minutes) = 0.7465 x Long. Ptolemy (minutes) - 831.12 minutes, which can be rounded to:

Longitude (degrees) = 0.75 x Long. Ptolemy (degrees) – 14°

In other words, Ptolemy's reference point is at 14° west of ours (Greenwich), which leads to the Canary Islands which are between 13°30' and 18°, but not to the Cape Verde Islands which are between 22°30' and 25°30'.

Apart from this correction of 14° for the reference point, Ptolemy's longitudes are still too large and a fraction of only ¾ (factor 0.75) must be taken.

These figures would probably be confirmed with a larger sample of places than the 42 taken here.

A possible explanation is that Ptolemy chose to assimilate one degree of latitude (or longitude at the equator) with 500 Egyptian stadia as wrongly suggested by Marinus of Tyr, leading to a circumference of the earth of 180 000 Egyptian stadia; instead of nearly 700 Egyptian stadia as correctly suggested by Eratosthenes, deduced from a circumference of 250 000 Egyptian stadia as calculated by him from his measurements at Alexandria and Syene (Strabo, Geogr. 2, 2 and Ptolemy, Geogr. 1, 7). The latter yields a circumference of 39 375 km, if Egyptian stadia of 157.5 m are used, and this is very close to today's accepted equatorial value of 40 075 km.

It is thus noted that, at Alexandria, one degree of longitude measures ca. 600 Egyptian stadia, and one degree of latitude is ca. 700 Egyptian stadia.

When using Ptolemy's data, we must realise that the accuracy of his latitude-longitudes is not very high. Basically, and as shown above, latitudes are more accurate than longitudes, as they can be checked with the Sun's positions, e.g., the duration of the longest day of the year, while longitudes must be deduced from distances reported by travellers (without chronometers).

It was shown above that Ptolemy's latitudes can easily shift by one or two degrees (around one hundred minutes in the figure above). It is noted also that all of Ptolemy's figures for degrees of latitude and longitude are given with a smallest approximation of 1/12° or 5 minutes, in the oldest available manuscript of 1460-1477. In the 1562 manuscript, the translator provides figures in degrees and minutes and the latter are all multiples of 5[237]. This indicates an estimated precision to + or – 2.5 minutes (around + or – 2 nautical miles). Ptolemy was therefore very optimistic on his precision!

Ptolemy's work allows us to position ancient ports based mainly on their latitude.
It may be of interest to compare the longitudes of some places,
but only within a short distance.

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Map of Jacob d'Angelo (1467) after Claudius Ptolemaeus' indications (around 150 AD)
(National Library, Warsaw)

10 ANCIENT MEASURES

Many web sites deal with this, but we would like to point out a few ancient units concerning length, weight and time used in the maritime world.
Furthermore, two methods are given for computation of latitudes based on the sun and on the North Star – Polaris.

10.1 Units of measurement

The Greeks had a coherent system for short distances which was inherited from the Egyptians (probably by Solon) and transmitted to the Romans:

- one Greek finger[238], daktylos: 19.25 mm, a Roman finger[239] is 18.50 mm and an Egyptian finger[240] is 18.75 mm
- one Greek palm, palaiste: 77 mm, a Roman palm is 74 mm and an Egyptian palm is 75 mm (4 fingers)
- one Greek foot, pous: 0.308 m, a Roman foot is 0.296 m and an Egyptian foot is 0.300 m (16 fingers)
- one Greek cubit, pechos: 0.462 m, a Roman cubit is 0.444 m (24 fingers, 1.5 feet), but an Egyptian royal cubit is 0.525 m (28 fingers, 7/4 of a foot)
- one Greek step, bema: 0.77 m and a Roman step is 0.74 m (2.5 feet)
- one Greek pace: 1.54 m and a Roman pace, passus is 1.48 m (5 feet)
- one Greek fathom, orguia, orgye: 1.85 m (6 feet, 4 cubits)
- one Greek pleather, plethron: 30.8 m (100 feet, 40 steps), but also an area of 100 x 100 pleather: ca. 950 m^2

The most commonly used unit for sailing distances was the stadium, but before the Romans put some order into it, there was much confusion on the length of an ancient stadium:

- one Athens stadium is 240 Greek steps, 600 Greek feet; this unit was used for the **Roman stadium: 185 m,** note this value is also equal to **1/10 nautical mile** (or 1/10 of a minute of latitude[241]); it is still in use today as a ‘cable’. This unit was used by Pliny and by Strabo.
- one Delphi stadium: 177.7 m (used by Strabo and by Polybius)
- one Olympia stadium: 192.3 m (also used by Strabo)
- one Egyptian stadium: 157.5 m (used by Eratosthenes and by Arrian)

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[238] https://en.wikipedia.org/wiki/Ancient_Greek_units_of_measurement
[239] https://en.wikipedia.org/wiki/Ancient_Roman_units_of_measurement
[240] https://en.wikipedia.org/wiki/Ancient_Egyptian_units_of_measurement
[241] Eratosthenes (276-194 BC) already estimated the terrestrial meridian at 250 000 Egyptian stadia, that is 39 375 km. The circumference of the Earth being 360x60=21 600 minutes of latitude or as many nautical miles, one nautical mile therefore is 1823 m for Eratosthenes, which is remarkably close to today’s value of 1852 m. To find this remarkable result, Eratosthenes measured the distance between Syene and Alexandria (he found 5 000 stadia) and estimated this at 1/50 of the earth’s circumference from his famous experiment with a gnomon, based on the location of Syene exactly on the Tropic of Cancer. Note that the north-south distance between Syene and Alexandria is 790 km, leading to 158 m for one stadion and *confirming Eratosthenes used Egyptian stadia of 157.5 m*.
Eratosthenes also estimated the distance between Rhodes and Alexandria at 3 750 Egyptian stadia (acc. to Strabo, Geogr. 2, 5) that is 591 km, almost exactly what we would say today based on Google Earth (600 km from Mandraki to Pharos). It can be noted that Ptolemy (350 years later) will be heavily mistaken on these figures.

A Roman mile is 1480 m (8 Roman stadia, or 1000 Roman paces, or 2000 Roman steps, or 5000 Roman feet).

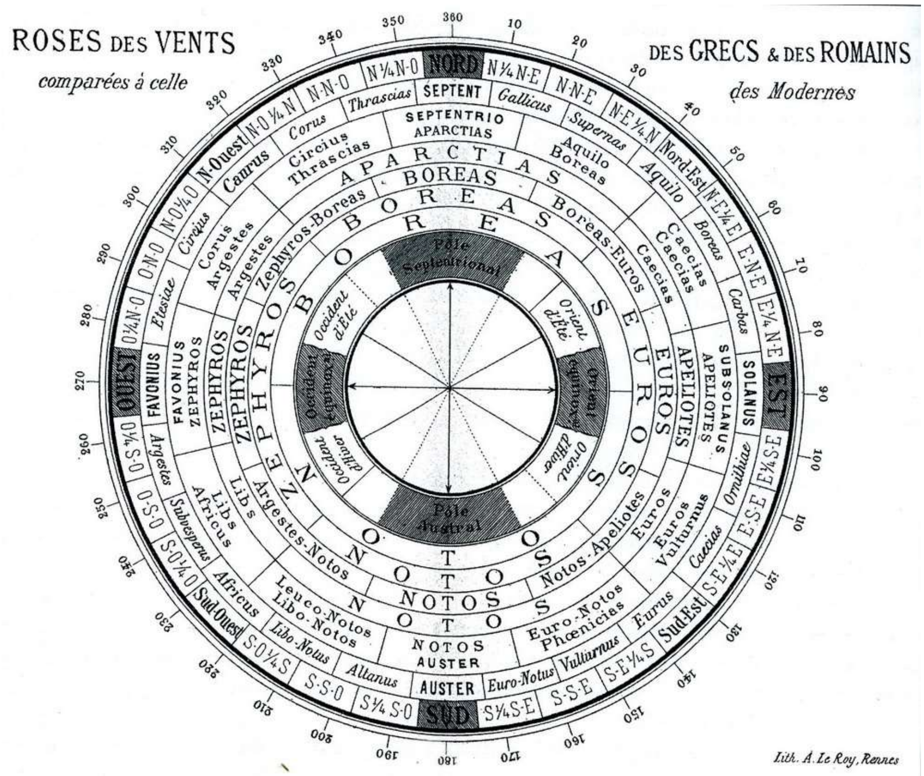
In times without any charts, the measure of distances at sea was focussed on the time needed to sail a given distance and sailors used the '**day of navigation**' of a sailing cargo ship (see section on "Modelling Mediterranean sailing routes"). They nevertheless had a few averaged benchmarks:

- 1 day of navigation (12 to 17 hours)[242]: 500 to 700 stadia (50 to 70 nautical miles).
- 1 day and 1 night (24 hours): around 1000 stadia (100 nautical miles).

This yields an average speed of around 4 knots (4 nautical miles/hour, 7.4 km/h).

For a trireme of the 5th c. BC, an average speed of 5 knots is accepted for a duration of 10 to 15 hours/day. Under sail, these ships were a bit slower than under oar[243].

More information on the origin of time measurement by Vincent Boqueho (2021).



Detailed wind rose[244] showing the archaic 2-direction wind rose ('Boreas' and 'Notos'), the 4-direction rose, both 8-direction roses according to Homer and Aristotle, the 12-direction rose according to Timosthenes, the 24-direction rose by Vitruvius, and finally the 19th c. 32-direction rose on the outer ring.

Wind directions are defined according to their origin: to sail eastward, you are pushed by a western wind ("westerlies"), typically like the Zephyr which leads to Alexandria (where they call it the "etesian winds" or "summer winds") if you leave from ... Zephyrion Acra (modern Capo Bruzzano, in Calabria). A stable wind direction could therefore be used as a guide, but a rose with more than 8 directions has little practical value for an ancient sailor.

[242] A "long day" probably refers to a summer solstice day (Arnaud, 2014), that is 13.5 hours in Berenike Troglodytika, 14.0 hr in Alexandria, 15.0 hr in Istanbul, 15.6 hr in Aquileia, 16.0 hr in Paris.

[243] MORRISON, J.S.; COATES J.F.; RANKOV, N.B., 2000, "The Athenian Trireme", Cambridge University Press.

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"If a man does not know to which port he is steering, no wind is favorable to him"
(Seneca, Epistolae, 71, 3... but one might not agree...).

Other important units are:

- one **Roman talent**: mass of ca. 33 kg (60 Roman minae, or 100 Roman libra) but a **Greek talent** is only 26 kg. It is also a currency: a Greek talent of silver is 6000 Greek drachmas, or 36 000 Greek obols, or 24 000 Roman sesterces; but an **Egyptian talent** is only 6000 Roman sesterces.
- **one sesterce: 10 €**, based on the fairly low annual salary of a 1st c. soldier or worker of 1000 sesterces/year[245], compared to the French lowest revenue (RSA) of 6 720 €/year and to the netto minimum legal wage (SMIC) of 14 500 €/year in 2019 for a single man.
  Similarly, one 'denarius communis' from Diocletian's Price Edict is worth around 1.5 €.
- **amphora quadrantal**: as a volume, one amphora is one Roman cubic foot (nearly one modern cubic foot) = 2 modii castrensis = 3 Italic modii = 8 congii = 48 sextarii, or around 26 litres. A full Dressel 1B amphora of the 1st c. BC weights around 50 kg (olive oil, wine, fish brine), out of which around half is tare. However, an empty 1st c. AD Gauloise 4 amphora from Narbonensis weights only ca. 10 kg and holds 30 to 38 litres because its wall is thinner.
- For dry bulk like grain, in Egypt, the Greeks used a larger unit of 52 liters (2 amphorae) called **Ptolemaic medimnos** weighting 40 kg when filled with wheat (dry wheat weights 780 kg/m3). One Greek **metretes** was around 39 litres (1.5 amphorae). It may be noted that Egyptian wheat was transported in sacks of one **Ptolemaic artaba** (ca. 39 litres) with a unit weight of ca. 30 kg. The Romans also commonly used the **modius** (1/3 of an amphora, or ca. 8.6 litres, or ca. 6.7 kg of wheat), hence one artaba is 4.5 modii, and 150 modii of wheat is one ton[246].
- Note also that wooden oak **barrels** (500 to 1000 litres) took over from amphorae (and dolia) for storage of wine during the Roman Empire.

[245] Salary of one denarius = 4 sesterces = 16 asses per day, acc. to Tacitus, Annals, I, 17, and on 250 days/year, i.e., 1000 sesterces/year (around 110 AD). Note that before 140 BC one denarius = 4 sesterces = only 10 asses. 270 years before Tacitus, Cato tells us in his De Agricultura, 22, 3 (around 160 BC) that "the charge for transportation by oxen, with six days' wages of six men, drivers included, is 72 sesterces", that is 2 sesterces or 0.5 denarius per man-day. Inflation might thus be estimated as follows from the cost of one labourer's man-day: ca. 0.5 denarius in 160 BC; 1 denarius in 110 AD; 4 denarii in 240 AD; 25 denarii in 301 AD in Diocletian's Price Edict. The highest inflation rate (between 240 AD and 301 AD) is around 3% per annum.
See also: https://web.archive.org/web/20130210071801/http://dougsmith.ancients.info/worth.html

[246] The Romans reduced the value of one artaba to that of an amphora (ca. 26 litres) but the Ptolemaic artaba of 39 litres survived even after the end of the Roman empire.
DUNCAN-JONES, R., 1976, "The Choenix, the Artaba, and the Modius", Zeitschrift für Papyrologie und Epigraphik, 21, (p 43–52) (https://www.jstor.org/stable/20181077).
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Stevedores loading the river boat Isis Giminiana, 3rd c. AD, ca. 70x35 cm fresco (Vatican Mus. N° 79638)

Mosaic in the Aula dei Mensores at Ostia, dated ca. 235 AD (3.8 x 2.7 m) showing a mensor with a grain measure of 9 sacks of 26 liters (source & explanation: https://www.ostia-antica.org/regio1/19/19-1.htm).

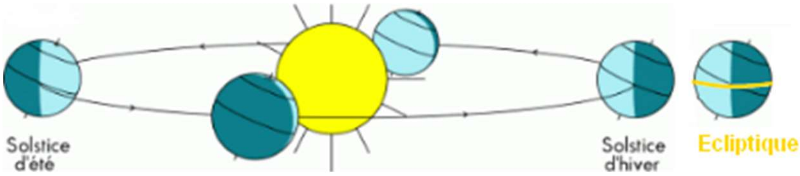
10.2 Measure of latitude with the Sun

The ancients have of course much observed the sun, its cycles and remarkable points in the sky, mostly at noon when the sun is, by definition, at its daily highest point, called ‘zenith’. What is of interest to us here is to find the latitude of a given location (see also the section on Ptolemy).

Let’s consider the earth’s yearly track around the sun on an ellipse[247]. The earth also rotates on itself. The axis of the earth is inclined on the plane of its orbit around the sun with an angle of around 23° 26’ and this orientation is constant during one revolution around the sun. Consequently, during one half of the year the northern hemisphere is more inclined to the sun than the southern hemisphere, with a maximum on June 21st. During the other half of the year the southern hemisphere is more inclined to the sun than the northern hemisphere, with a maximum on December 22nd. These maxima are called solstices. On these dates, the sun at

[247] Information accessible to non specialists in astronomy is available in textbooks on sundials (e.g., by Denis Savoie (2003), ed. Belin, France) and, of course, on Wikipedia. See also Journès & Georgelin (2000), “Pythéas, explorateur et astronome”, ed. Nerthes, Ollioules, France, for fascinating explanations on Pytheas' astronomy.

noon is at its highest above the horizon on June 21st and at its lowest on December 22nd (in the northern hemisphere)[248].



Source : http://freveille.perso.sfr.fr/ecliptique.png

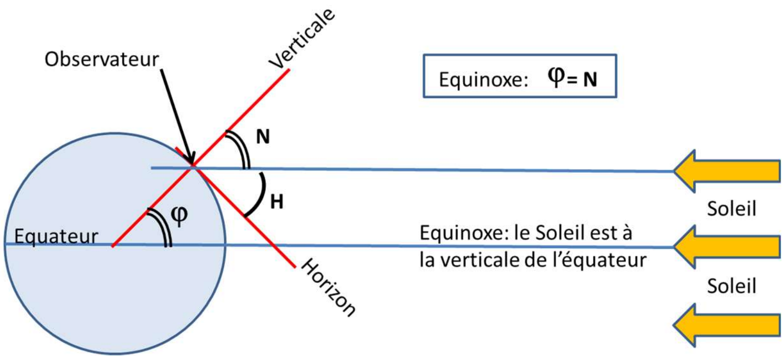
At these two solstices, the sun at noon is, by definition, vertical above the Tropic of Cancer (around June 21st) and vertical above the Tropic of Capricorn (around December 22nd). The ancients said that "there is no shade at noon"; today we say that the sun is at its zenith.

Between these two dates, the sun at noon is vertical above the equator on two days called equinoxes (around March 21st and September 23rd); we say that the declination of the sun is nil on these two dates.

The sun at noon is in fact every day vertical of a point located between both tropics, and this happens twice a year for every location. E.g., the sun is vertical of a point located at 17° of latitude 45 days before and 45 days after the solstice and this fits Plini's description of Ptolemais Theron (now called Agig located at 18.18° of latitude north, Plini the Elder, Natural History, 6, 34)

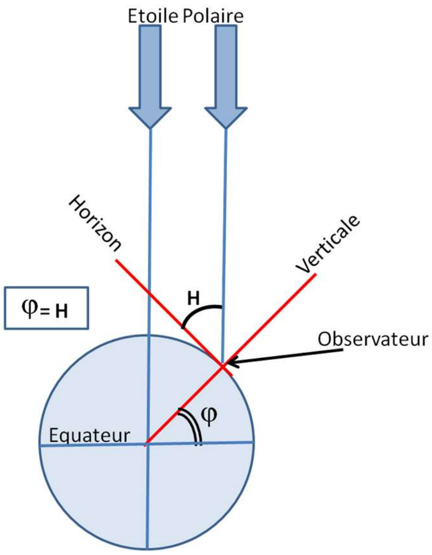
If one measures the angle H of the sun on the horizon at an equinox (when the sun at noon is above the equator), one in fact measures the complement of the latitude, thus:

Latitude phi = 90° - H measured



248 The annual track of the Sun at noon is called 'ecliptic'. The plane of the ecliptic is inclined on the plane of the equator with an angle of around 23°26'. This value is presently decreasing with around 1' per century (it was 23°27' at the beginning of the 20th c.). It varies between 24.5° and 22.1°, within a cycle of 41 000 years.

10.3 Measure of latitude with Polaris

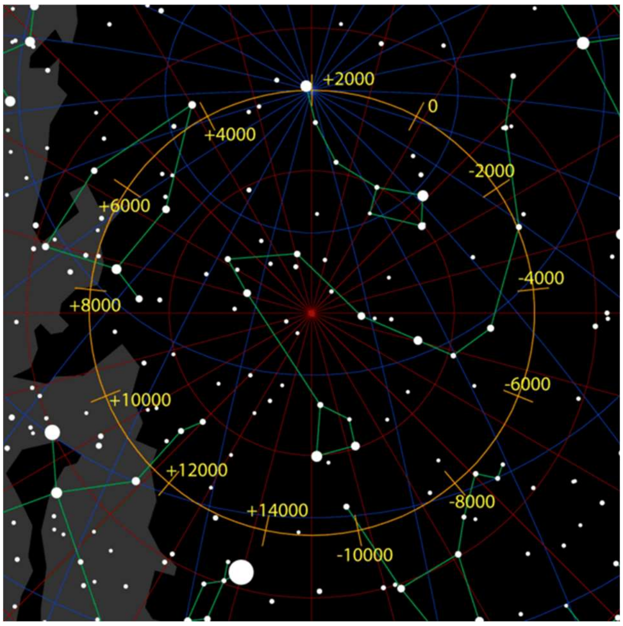


Another method is to measure the height of Polaris above the horizon. A similar exercise as measuring the latitude with the sun shows that:

Latitude phi = H measured

The precession of the equinoxes shifts the celestial system by around 50 seconds of arc per year (or 28° in 2000 years). This variation is due to a slow conical movement of the rotation axis of the earth (one full turn in 25 800 years). This means that the earth's axis does not always point to the same location in the sky. In other words, todays 'north star' has not always been on the earth's axis.

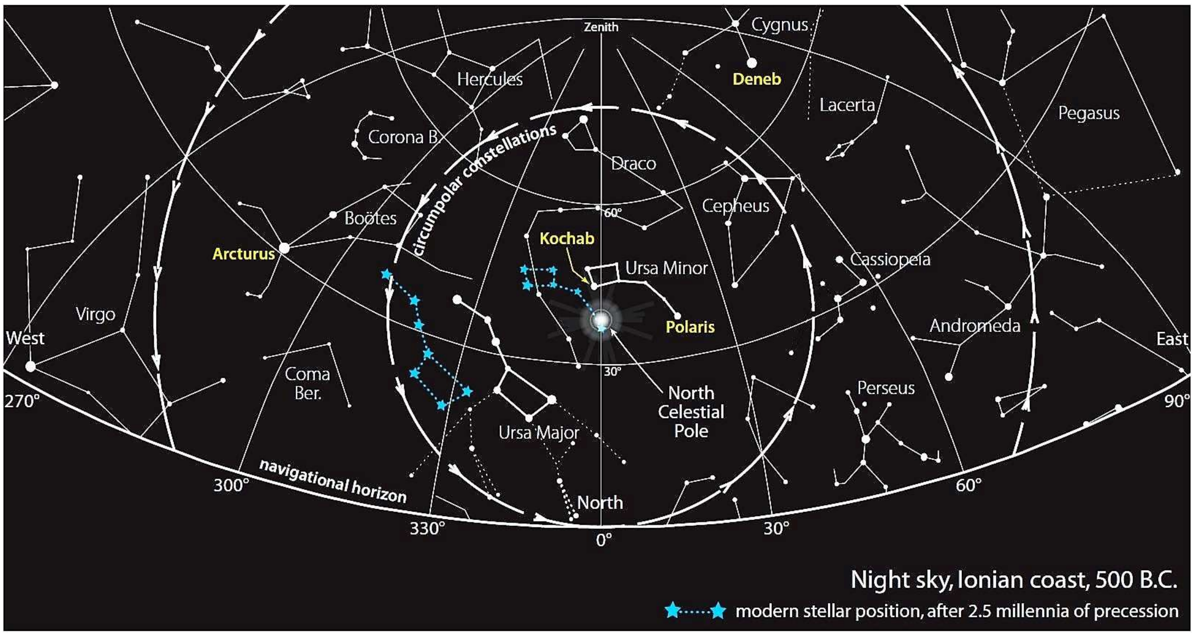
In fact, today's north star, Polaris, is at less than 1° of the earth's axis, but ancient astronomers had no bright north star available.



Source : http://fr.wikipedia.org/wiki/Fichier:Precession_N.gif

Track of the Earth's rotation axis on the northern celestial sphere
its present position (in +2000 AD) is close to Polaris located in the Lesser Bear
and called "α Ursae Minoris" or "α UMi".

Ancient seafarers looked for "Cynosura" (Lesser Bear or Ursa Minor) to find the north at night (see Lucan, La Pharsale, Book 8) and looked for the sun at zenith for the south in daytime.



The northern night sky from the Ionian coast, 500 BC. Note the movements of Ursa Major and Ursa Minor (in blue dots) due to the effects of precession over the past 2.5 millennia.
(Danny Lee Davis, 2009).

Cynosura, being close to the earth's axis, moves little during the night and is therefore quite convenient as a landmark in the night sky. Obviously, this is not very accurate navigation: if you are sailing at 45° latitude (e.g., somewhere between the Danube estuary and Crimea) and heading north, Cynosura will be at 45° above the horizon. Seen from the position of the helmsman on board, near the stern, he will see Cynosura behind the mast of his ship, around halfway the mast height. When moving further north, increasing his latitude, Cynosura will appear higher above the horizon and higher behind the mast. If he is sailing eastbound, he will keep Cynosura to his left, on the ‘port side’ of his ship, like Odysseus after leaving Calypso’s island:

“he sat and guided his raft skilfully with the steering-oar, nor did sleep fall upon his eyelids, as he watched the Pleiads, and late-setting Bootes, and the Bear, which men also call the Wain, which ever circles where it is and watches Orion, and alone has no part in the baths of Ocean. For this star, Calypso the beautiful goddess, had bidden him to keep on the left hand as he sailed over the sea.” (Homer, Odyssey, 5, 270).

Further reading:

Information accessible to non-specialists in astronomy is available in textbooks on sundials (e.g., by Denis SAVOIE, 2003, ed. Belin, France) and, of course, on Wikipedia.

See also JOURNÈS & GEORGELIN, 2000, “Pythéas, explorateur et astronome”, ed. Nerthes, Ollioules, France, for fascinating explanations on Pytheas' astronomy.

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10.4 Radiocarbon dating

Let's start with a few sentences taken from Wikipedia:

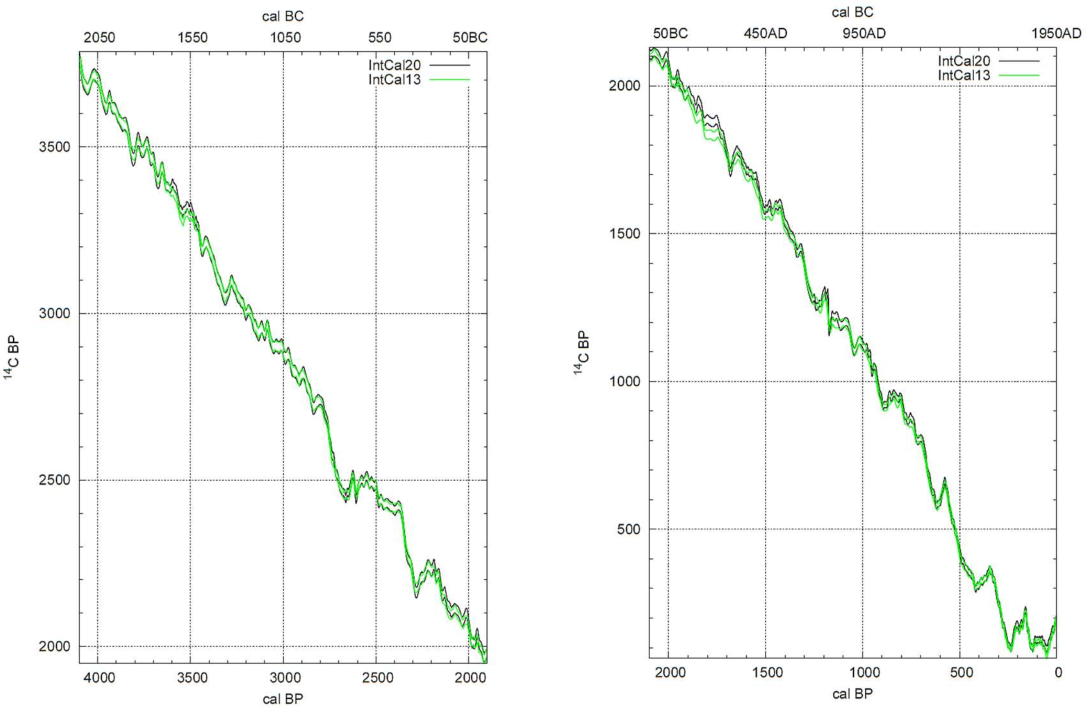
"Radiocarbon dating is a method for determining the age of an object containing organic material by using the properties of radiocarbon, a radioactive isotope of carbon (carbon-14, or ^{14}C). […]
In nature, carbon exists as three isotopes: two stable, non-radioactive (carbon-12 or ^{12}C), and carbon-13, or ^{13}C), and one radioactive (carbon-14, or ^{14}C, also known as "radiocarbon"). The half-life of ^{14}C (the time it takes for half of a given amount of ^{14}C to decay) is about 5730 years, so its concentration in the atmosphere might be expected to decrease over thousands of years, but ^{14}C is constantly being produced in the upper atmosphere, primarily by galactic cosmic rays. […]
During its life, a plant or animal is in equilibrium with its surroundings by exchanging carbon either with the atmosphere or through its diet. It will, therefore, have the same proportion of ^{14}C as the atmosphere, or in the case of marine animals or plants, with the ocean. Once it dies, it ceases to acquire ^{14}C, but the ^{14}C within its biological material at that time will continue to decay, and so the ratio of ^{14}C to ^{12}C in its remains will gradually decrease. Because ^{14}C decays at a known rate (-50% after 5730 years), the proportion of radiocarbon can be used to determine how long it has been since a given sample stopped exchanging carbon: the older the sample, the less ^{14}C will be left."

Let's not go here into the details of how ^{14}C isotopes are counted with accelerator mass spectrometry, to find the ratio $^{14}C/^{12}C$ that will lead us to the age of the sample. Let's just remember that the initial ratio, when the sample was still alive, was around 10^{-12} and that we are looking for a fraction of that. This obviously requires some quite sophisticated equipment.

This would be nice and clear if the level of ^{14}C in the atmosphere had remained constant over time. In fact, the level of ^{14}C in the atmosphere varied significantly and as a result, the values provided by the dating above must be corrected by calibration curves that convert a measured ^{14}C age into an estimated calendar age. This calibration is based on dendrochronology which is a surprisingly accurate method for dating tree-samples up to 14 000 years old (in 2020). The latest calibration curve was published by Paula Reimer (2020) with a large group of researchers from all over the world.

Let's have a look at the resulting calibration curves ('IntCal20') for the periods 0-2000 BP and 2000-4000 BP (Before Present, i.e., before 1950 AD). The horizontal axes show "cal BP" (below) and cal BC (top) with 0 cal BP = 1950 AD on the right side. The vertical axis shows "^{14}C BP" which is the dating resulting from the spectrometer measurement.
Suppose you found 1000 ^{14}C BP: that will convert to ca. 900 cal BP, or ca. 1050 cal AD.
Suppose you found 2500 ^{14}C BP: that will convert to ca. 2700 to 2500 cal BP, or ca. 750 to 550 cal BC. In this case, the calibration curve yields an unprecise 200-year span.
Suppose you found 2950 ^{14}C BP: that will convert to ca. 3150 to 3050 cal BP, or ca. 1200 to 1100 cal BC. This is around the end of the Late Bronze Age (LBA), and again, we have an unprecise conversion of the ^{14}C date to the calendar date. This is unfortunate as debate on the dating of Sea Peoples' invasions during several decades near the end of LBA is still ongoing and one cannot yet make a better guess than a range of 1250 to 1100 BC (Manning in Fischer & Bürge, 2017).

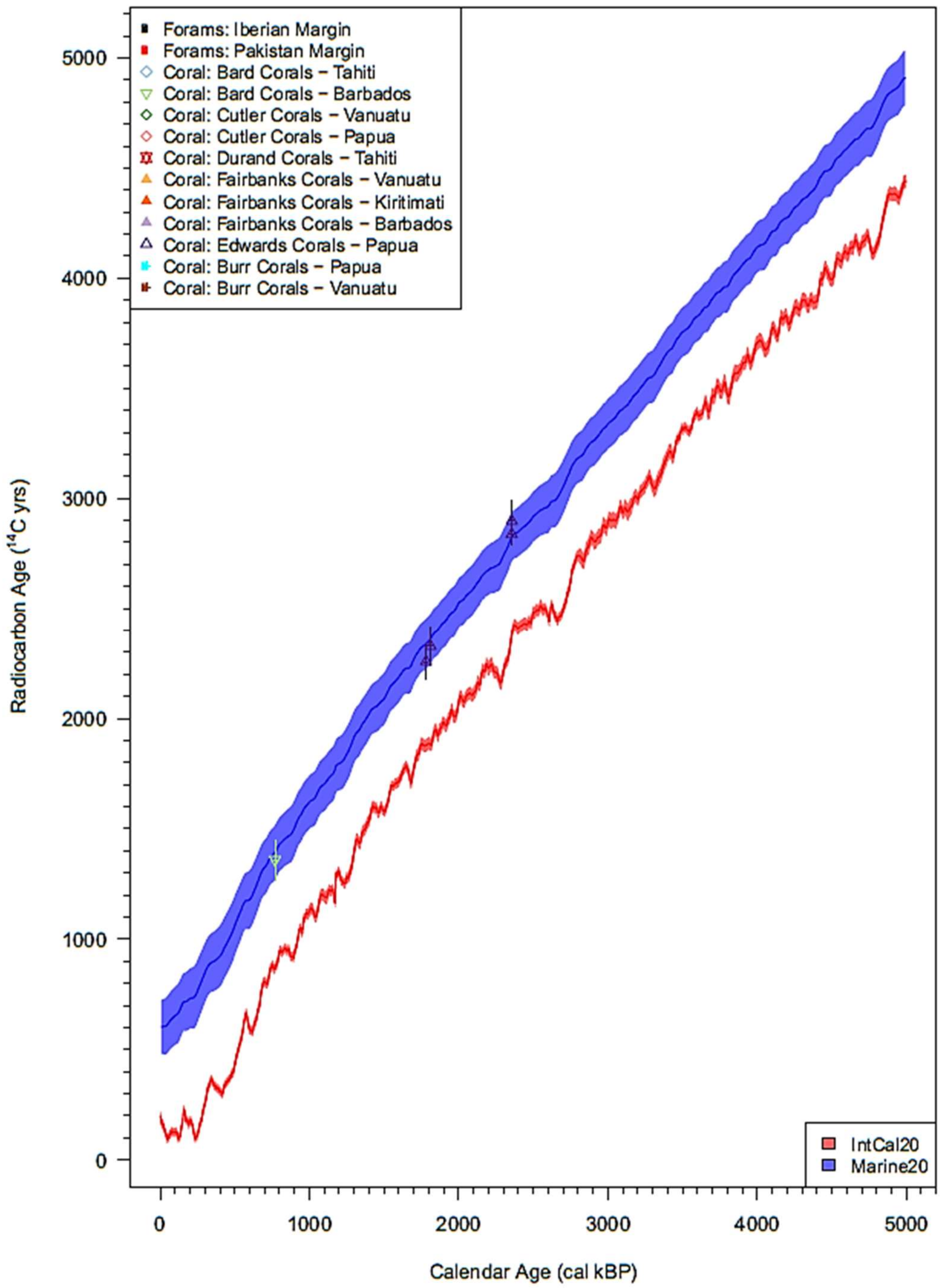
These examples show that radiocarbon dating is not a straightforward exercise and the least we can say is that it is far from being "high resolution" in time, as this would require an annual precision or better (even decennial precision cannot be provided by radiocarbon dating).



IntCal20 radiocarbon calibration curve plotted with only one standard deviation (68%) envelopes (Reimer, P., et al., 2020).

Let's now turn to marine conditions that require a specific calibration curve (called 'Marine20') because of the so-called 'reservoir effect'. Indeed, ^{14}C contained in atmospheric CO_2 transfers to the ocean by dissolving in the surface water as carbonate and bicarbonate ions; at the same time carbonate ions in the water are returning to the air as CO_2. This exchange process bringing ^{14}C from the atmosphere into the surface waters of the ocean takes time, and even more time is needed for deeper water layers. This introduces a bias in the radiocarbon dating method because what you measure is 'old carbon' that is older than the terrestrial carbon found on nearby land.

The surface-waters calibration curve ('Marine20') was thus prepared from a comparison of the dating of marine samples (corals) with that of nearby terrestrial samples.



Marine20 and IntCal20 radiocarbon calibration curve plotted with 95% probability envelopes (Heaton, et al., 2020).

It shows a (minus) ca. 500 ± 100-year shift for the Holocene era (Heaton, et al., 2020). This curve is a global average of the marine reservoir age (also called 'MRA', or 'R' or 'R-age'), and it can be understood that because of local atmospheric and oceanic current patterns, specific locations will deviate from this average. For this reason, a correction to the global averaged Marine20 calibration curve is used in the form of a 'Delta-R correction'. This work is still ongoing and is collected on an online database (http://calib.org/marine/index.html). A quick look at this database for the Mediterranean area, shows that most corrections range from +100 to -250 years, emphasising that for the Holocene era in shallow water marine conditions, radiocarbon dating yields a quite limited precision of at best ± one century.

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11 ANCIENT CLIMATE

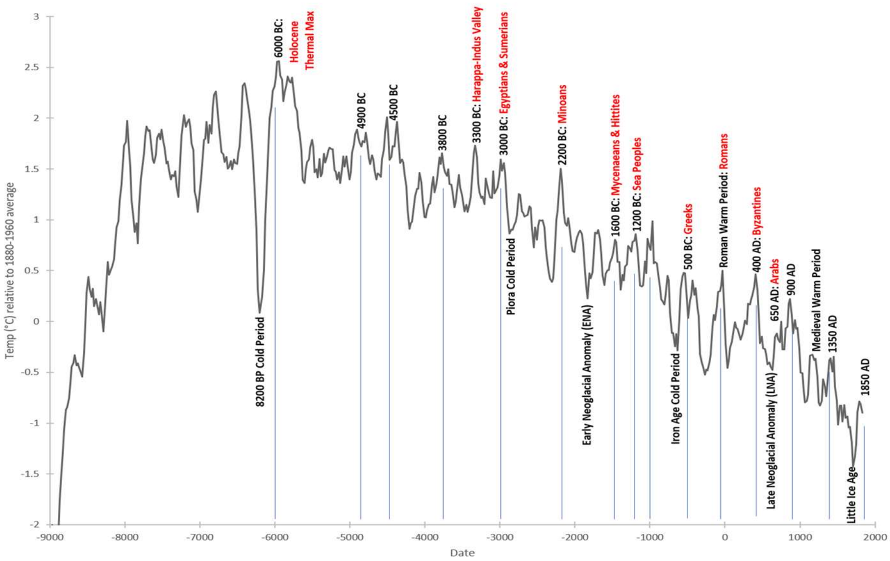
Climate is certainly not the only factor influencing human civilisation (and the development of ancient ports), but it is probably a major one.

A first (simplistic?) approach would be to state that a stable and mild climate favours human civilisation as it allows farming. A warmer or a colder climate reduces the development of human civilisation as it induces droughts leading to famine and migration of peoples, yielding instability and war. In this process, civilisations may be submerged by others who will emerge as leaders. Civilisations may die and others be born due to climate change.

It is not our intention to provide complete information about the vast subject of paleoclimatology, but some synthetising seems to be required here in relation to historical events.[249]

11.1 Temperature

So-called 'climate proxies' (indicators) are preserved physical characteristics of the past that stand in for direct meteorological measurements and enable scientists to reconstruct the climatic conditions. They provide the only means for scientists to determine climatic patterns before record-keeping began (around 1880) (Wikipedia). The most common climate proxies are gas bubbles, pollens, dinocysts, isotopes, the quantities of which tell us something about past climate conditions. Proxies are found in lake sediment, marine sediment, peat bogs, ice, speleothems, tree rings and coral skeleton rings. Coring is often used to extract the proxies.



Civilisation changes and climate changes
based on Greenland reconstructed paleotemperatures from six ice cores, Vinther (2009)[250])

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[249] ROUTSON, C., et al., 2019, "Mid-latitude net precipitation decreased with Arctic warming during the Holocene", Nature, Volume 568, Issue 7750, (p 83-87).
Acc. to Routson (2019) "The Arctic has warmed more than low latitudes naturally in the past […] resulting in smaller temperature differences between the Equator and the pole, the jet stream gets weaker and less precipitation falls in the mid-latitudes" because of "reduced baroclinic potential energy that fuels storm systems, reducing mid-latitude cyclone frequency and intensity".
See also: Northern Arizona University News.

[250] VINTHER, B., et al., 2009, "Holocene thinning of the Greenland ice sheet", Nature, volume 461, (p 385-388).
See: https://www.carbonbrief.org/factcheck-what-greenland-ice-cores-say-about-past-and-present-climate-change. According to Richard B ALLEY (2010), "ice cores are remarkably faithful recorders of past climate". The temperature reconstruction produced using ^{18}O isotope data from six ice cores is shown in the figure, and

Let's look at the temperature variations of surface ice in Greenland (deduced from ice cores, Wikipedia, see also: http://www.dandebat.dk/eng-klima7.htm) which is assimilated with temperatures in the European area and possibly in the whole Mediterranean area, and let's compare it with the initiation of the major civilisations.

The so-called 'Holocene Climatic Optimum' (7000-4000 BC) is clearly visible with a thermal maximum around 6000 BC. It can be noted that the drop of temperature between this maximum and the 20th c. temperature is around 3°C. The temperature variations between warm and cold peaks are in the order of 1°C, except for the '8200 BP event' where it is around 2°C. A quick look at the intervals between the warm peaks shows that they are fairly equidistant with an average of ca. 400 years. This is perhaps showing some astronomical influence?[251]

The main Holocene warm and cold periods are listed very schematically as follows[252]:

- Around 6200 BC: cold peak: '8200 BP Cold Period'
- Around 6000 BC: warm peak ('Holocene Thermal Maximum')
- Around 4900 BC: warm peak
- Around 4500 BC: warm peak
- Around 3800 BC: warm peak
- Around 3300 BC: warm peak (initiation of Harappa-Indus Valley civilisation)
- Around 3000 BC: warm peak (initiation of Egyptian and Sumerian civilisations)
- Around 2900 BC: cold peak ('Piora Cold Period')
- Around 2300 BC: cold peak
- Around 2200 BC: warm peak with severe drought ('4.2 ka BP event') (initiation of Minoan civilisation, start of First Intermediate Period in Egypt)
- Around 1900 BC: cold peak ('Early Neoglacial Anomaly', ENA) (migration of the Harappa-Indus Valley civilisation[253])
- Around 1800 BC: warm peak (start of 'Second Intermediate Period' in Egypt)
- Around 1600 BC: warm peak (initiation of Mycenaean and Hittite civilisations, and of New Kingdom in Egypt)
- Around 1200 BC: warm peak (Sea Peoples raiding the eastern Med, end of Bronze Age)[254]

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spans the period from 9690 BC to 1970 AD. It has a resolution of around 20 years, meaning that each data point represents the average temperature of the surrounding 20 years. So, the end of the record (1970) shows the average temperature between 1960 and 1980. The present author added a 200-year triangular filtering in order to smooth the signal without altering the main peaks.

[251] TURNER, T., et al., 2016, "Solar cycles or random processes? Evaluating solar variability in Holocene climate records", Scientific Reports, **6**, 23961, https://www.nature.com/articles/srep23961 .

[252] See also: https://en.wikipedia.org/wiki/Holocene & http://www.dandebat.dk/eng-klima7.htm

[253] GIOSAN, L., 2018, "Neoglacial Climate Anomalies and the Harappan Metamorphosis", Climate of the Past,

[254] CLINE, E., 2014, "1177 BC, The Year Civilisation Collapsed", Princeton University Press, (264 p).
KNAPP, A. & MANNING, S., 2016, "Crisis in Context: The End of the Late Bronze Age in the Eastern Mediterranean", American Journal of Archaeology, Volume 120, Number 1, (p 99-149).
MILLEK, J., 2023, "Destruction and Its Impact on Ancient Societies at the End of the Bronze Age", Lockwood Press Online, (394 p).
MANNING, S., et al., 2023, Severe multi-year drought coincident with Hittite collapse around 1198–1196 BC, Nature, 614, (p 719-724).

- Around 1100 BC: cold peak, possibly triggered by the Hekla 3 volcano eruption (Iceland) that obscured the northern hemisphere
- Around 1000 BC: warm peak (start of 'Third Intermediate Period' in Egypt)
- Around 700 BC: 'Iron Age Cold Period'
- Around 500 BC: warm peak (initiation of Greek civilisation during a period of rising temperatures starting in 700 BC)
- Around 200 BC: cold peak
- Around 0 AD: Roman Warm Period (initiation of Roman civilisation during a period of rising temperatures starting in 200 BC)
- 100-200 AD: cold period: decline of Roman Empire
- Around 400 AD: warm peak: Byzantine civilisation
- 400-900 AD: 'Late Antique Little Ice Age' or 'Late Neoglacial Anomaly', LNA, possibly triggered by a 536 AD volcano eruption that obscured the northern hemisphere (Migration Period, Arab Conquest, European Dark Age)
- 900 -1350 AD: 'Medieval Warm Period' (initiation of European Renaissance)
- 1350-1850 AD: 'Little Ice Age'.

Even though such a comparison between temperatures and the initiation of civilisations leaves some room for wishful thinking, it is quite striking that the initiation of civilisations[255] occurred around the warm peaks. It might perhaps be suggested that *civilisations were initiated during periods with rising temperature and collapsed with prolonged droughts of several decades due to falling temperatures*. Clearly, cooling down of the atmosphere induces less evaporation, less humidity and less rain, leading to droughts and famine (but excessive warmth may also lead to drought!). This makes sense from a farming point of view, but obviously, exceptions exist, and endless discussion may arise around this analogy which is considered 'simplistic' by many scientists (see Knapp, 2016 for an overview).

Let's stress again that the climate is not the only factor involved: to explain the end of the Bronze Age, Cline (2014) adds earthquakes/volcanic activity, droughts/famines, internal mismanagement/rebellion/civil war, outside migrants/pandemics/invaders with new technologies, disruption of international trade with domino-effect on inter-dependent states. All of these factors may have co-operated in some way during several decades to put an end to the Bronze Age and to the Roman Empire...

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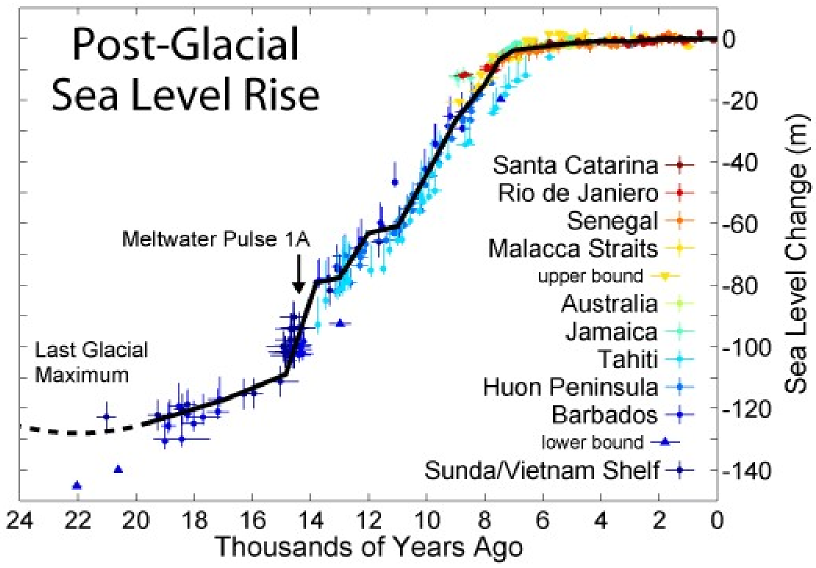
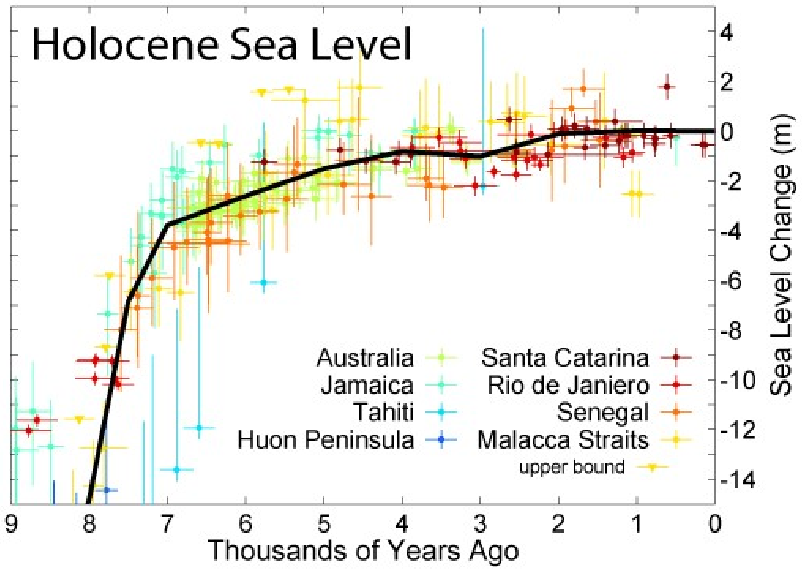
11.2 Sea Level Rise

The best I can do to summarise the complex subject of secular 'Sea Level Rise' (SLR) is to start with Wikipedia (note that here, we define time as BP,'Before Present', i.e., with a 1950 year shift compared to BC):

"eustatic sea level has fluctuated significantly over the earth's history. The main factors affecting sea level are the amount and volume of available water and the shape and volume of the ocean basins. The primary influences on water volume are the temperature of the seawater, which affects density, and the amounts of water retained in other reservoirs like rivers, aquifers, lakes, glaciers, polar ice caps and sea ice. Over geological timescales, changes in the shape of the oceanic basins and in land/sea distribution affect sea level. In addition to eustatic changes, local changes in sea level are caused by tectonic uplift and subsidence."
It is obviously difficult to differentiate eustatic SLR from crustal movements of the earth as our measuring instruments are placed on the earth. The best approach is to assess that water is supposed to remain 'horizontal' on a large basin like the Mediterranean Sea, while crustal movements occur at a more local scale (e.g., Crete). Hence, the average of all measured sea level movements on the entire basin will reflect the eustatic SLR, while local deviations from this average will reflect the local crust movements.



Sea Level Rise over the past 20 000 years (Wikipedia)



Sea Level Rise over the past 8000 years (Wikimedia Commons)

Many studies were conducted in recent decades to evaluate past **eustatic SLR** and to predict future eustatic SLR for the next century(s). The best known is the work of Kevin Fleming's (1998). To make it short, the results are as follows, in round figures:

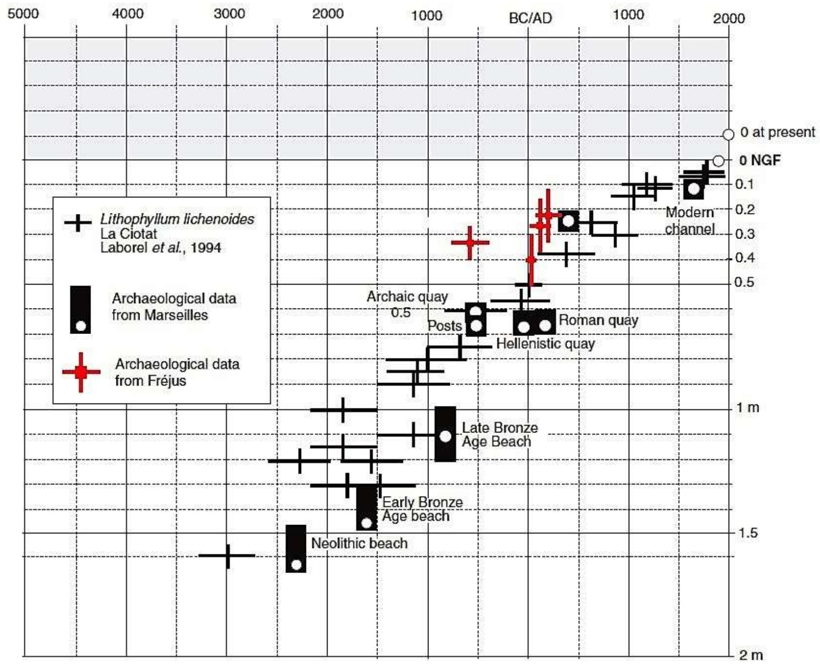
Predicted for the 21st c.: around **5 to 10 mm/year**, and more depending on prediction model used;
Observed in the 20th c.: around **2 mm/year**;
Observed in the past 1 500 years: around **0.3 mm/year**, resulting in ca. 0.50 m eustatic SLR over this period;
Observed between 6 500 and 1 500 BP: around **0.7 mm/year**, resulting in ca. 3.50 m eustatic SLR over this period;
Observed between 15 000 and 6 500 BC: around **14 mm/year**, resulting in ca. 110 m eustatic SLR over this period.

These figures are in accordance with work of Nic Flemming (1973 & 1986) who was the forerunner on this subject and with Christophe Morhange (2013).

Since the rise of human civilisations around 6 500 BP, eustatic SLR has been around 4 m. This value must obviously be combined with local crustal movements which may have reached several meters uplift (e.g., Phalasarna in western Crete) or subsidence (e.g., Alexandria, Apollonia Cyrenaica, Portus Iulius, Rome, and many others) and sometimes both (Pozzuoli, near Naples). The total change of sea level resulting from both eustatic and crustal movements is called “relative sea level rise”. Note that eustatic SLR is a fairly continuous phenomenon that may be expressed in mm/year over specific period of time as in the table above. However, crustal movements may be much more hectic (e.g., during earthquakes) and can therefore not be expressed in mm/year. Hence, the Relative SLR should not be expressed in mm/year. This RSLR was estimated from the vertical position of coastal structures such as quay walls, quarries and fish tanks, of horizontal rims of biological material, and of tidal notches. Fish tanks and biological rims are more accurate indicators of RSLR than port structures because of the uncertainty of the latter's "functional height". However, the precise dating of these indicators is often a problem.

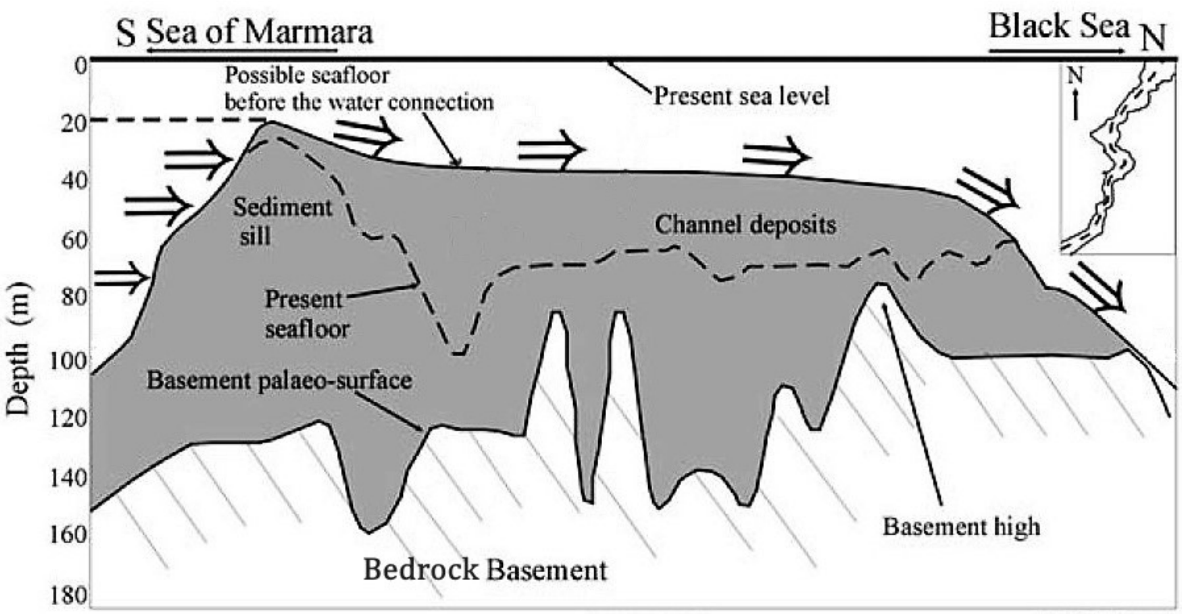
As an example, let’s take the area of Rome over a period of 2 000 years, studied in detail by Goiran (2009) based on an analysis of marine shells, and by Lambeck (2018) based on an analysis of coastal fish tanks. The first concludes with a relative SLR of 0.8 m, and the latter with 1.22 m, hence both are quite close to 1.0 m. This *relative SLR* is thus composed of 0.5 m *eustatic SLR* + 0.5 m *crustal subsidence*.

Another interesting case is given by Morhange (2013) who shows that the relative SLR of 0.5 m in 2 000 years in Marseille-La Ciotat-Fréjus equals the eustatic SLR because no significant crustal movements occurred in this area during several millennia.



Relative SLR at Marseille, La Ciotat and Fréjus (Morhange, 2013).

A more controversial case is the Black Sea. It is accepted that it was once a fresh-water lake disconnected from the Mediterranean Sea by a sediment sill in the Bosphorus located around -36 m below present sea level (deepest spot of the shallowest cross-section in the Bosphorus located in front of Dolmabahçe Palace).



Bosphorus sill gradually overflowed by global Sea Level Rise in the Mediterranean Sea
(Gökasan, 2005)

This configuration existed until around 9000 BP when, due to global eustatic SLR, Mediterranean water started to flow over the sill into the Black Sea-lake. The questions are: how deep was the lake water level at that time, and how fast did the water level rise? Even if the lake water level was much deeper than the Bosphorus sill, e.g., -80 to -100 m acc. to Yanchilina (2017), flooding must have been rather progressive because, as mentioned above, global SLR was around 14 mm/year … unless the sill in the Bosphorus collapsed, perhaps during an earthquake[256].
In any case, scholars agree on the fact that after reconnection with the Mediterranean Sea, the Black Sea water level followed the global eustatic SLR. This means that Neolithic and Bronze Age settlements were not affected by the controversy about the Black Sea water levels, i.e, Neolithic settlements dated around 6000-3000 BC might be found down to 15 m depth below the present sea level.

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11.3 Wind and waves

It is acknowledged that we have almost no information about the occurrence of storms in ancient times (say before the 20th c.). Past climate changes have been identified, inducing cooler and warmer periods. During one of the cold periods, a "moderate increase in storminess

[256] A simple hydraulic computation with a sill at -36 m shows that this global SLR would induce a rise of the Black Sea level (from -90 m) within around 200 years, inducing a gradually increasing SLR in the Black Sea not exceeding 1 m/year. This is fast, but it is not a catastrophic flood. The "deluge hypothesis" can only be explained by collapse of (a part of) the Bosphorus sill (further details and hydraulic computations are provided in the section on "The Bosphorus").

in the high-latitude North Atlantic region" is mentioned (Giosan, 2018, O'Brien, 1995). More recently, we may have an indication that warming of the Arctic area is reducing the frequency and the intensity of storms (Routson, 2019). According to him "The Arctic has warmed more than low latitudes naturally in the past […] resulting in smaller temperature differences between the Equator and the pole, the jet stream gets weaker and less precipitation falls in the mid-latitudes" because of "reduced baroclinic potential energy that fuels storm systems, reducing mid-latitude cyclone frequency and intensity". See also: Northern Arizona University News.
Similarly, recent mathematical modelling shows that 21st c. global warming may lead to "a decrease in average wave height but increases in the maximum waves" (Bricheno, 2018).
A new promising field of research, called "paleotempestology", consists in analysing sediment deposits left by storms, e.g., overwash of sand due to wave action on coastal barrier islands, or eaolian sand transport into coastal wetlands (Wikipedia, Sabatier, 2012; Oliva, 2018; Azuara, 2020).

For the time being and awaiting further results from above mentioned research, the climate of the Roman period from 200 BC to 100 AD is considered fairly close to ours, with a cooler period before that and after that (see section on "Ancient Climate/Temperature", Beresford, 2013, p 60). William Murray (1987) compared ancient winds as described by Aristotle and Theoprastos with modern wind data, and found very good agreement. Hence, as waves are generated by winds, we usually suppose that the ancient wave climate (see section on "Design waves") is similar to the present one.

References on waves

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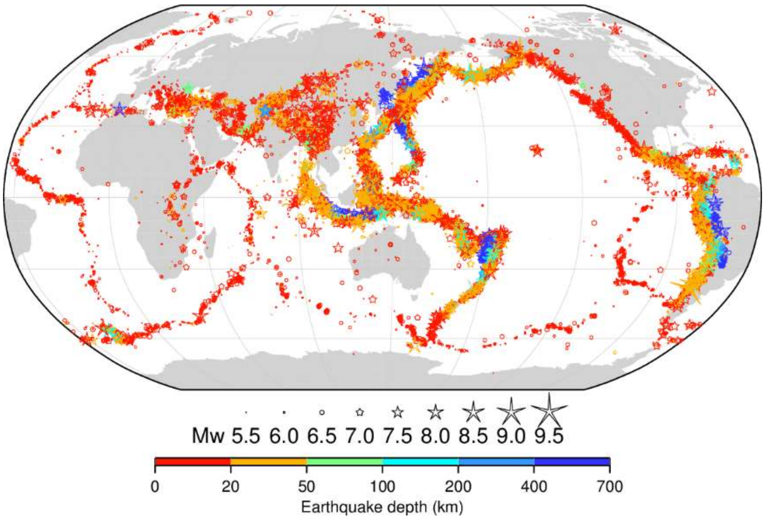
WIKIPEDIA, "Paleotempestology", https://en.wikipedia.org/wiki/Paleotempestology .

11.4 Tsunamis

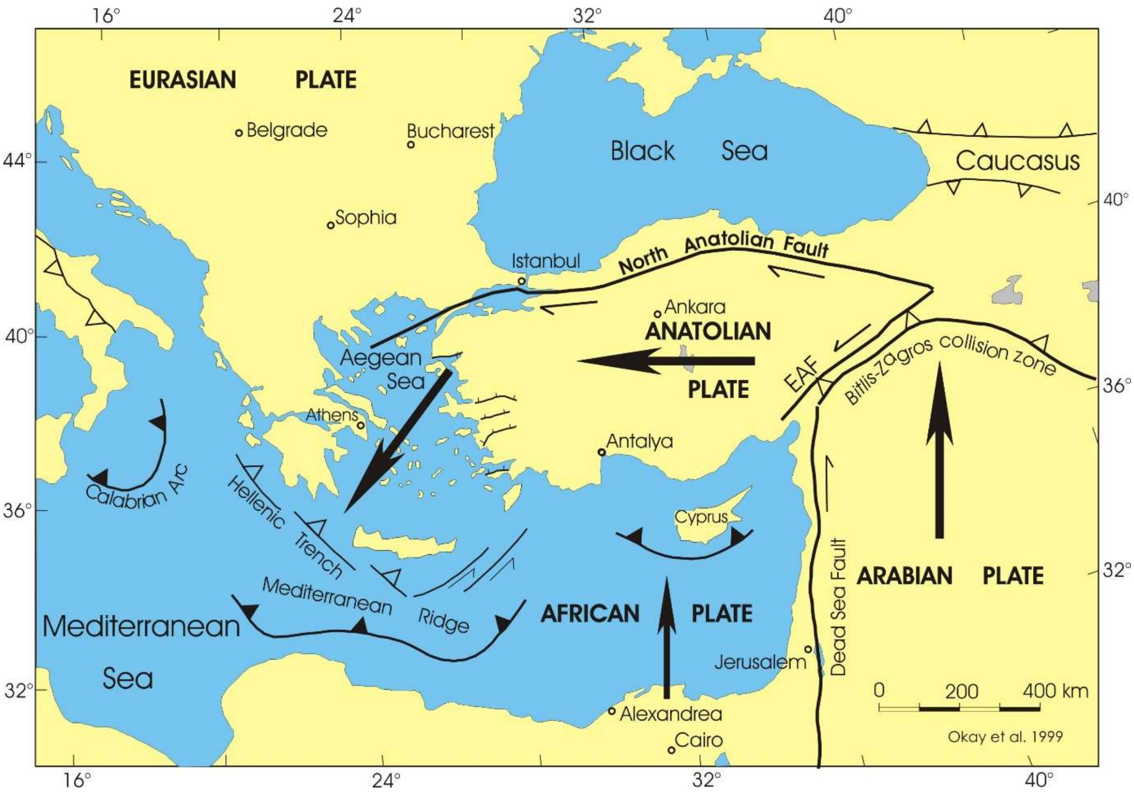
11.4.1 Earthquakes

As 75-80% of tsunamis are related to a submarine earthquake, let's have a look at the latter first.

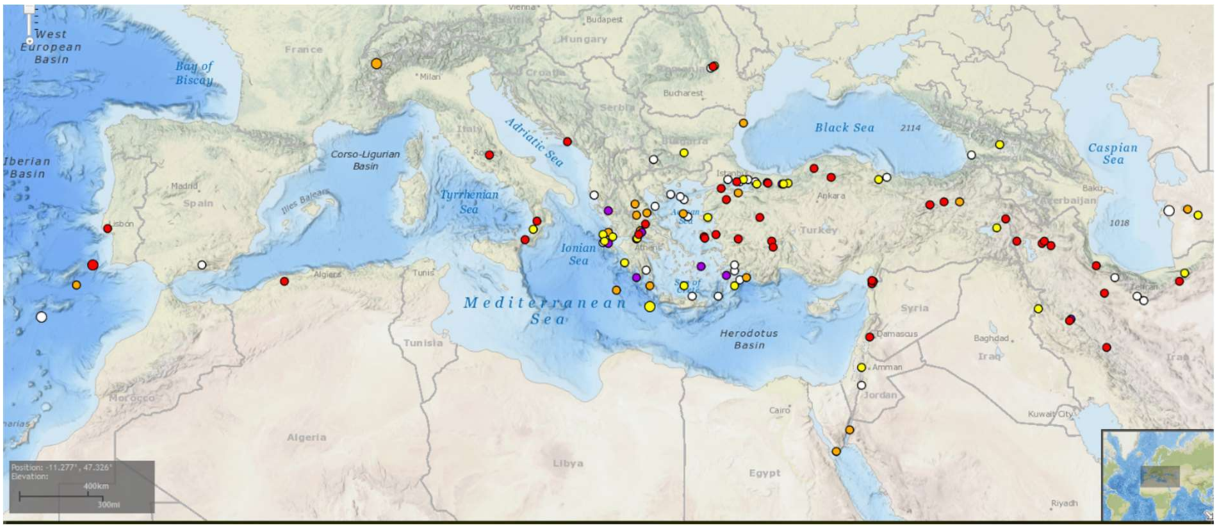
Earthquakes and volcano eruptions usually occur along faults separating tectonic plates moving with respect to each other.



Earthquakes between 1904 and 2015 (ICS 2019).



Main faults and tectonic plates in the Near East. (New Scientist, 2011).
The African plate is moving northwards *under* the Anatolian plate;
The Arabian plate is moving northwards inducing a rotation of the Anatolian and Aegean plates;
The boundary between the African and the Arabian plates is on the Dead Sea Fault, Jordan valley and Beqaa valley.
The North Anatolian Fault is passing near Istanbul
and a volcanic arc follows the isles of Aegina, Milos, Santorini, Nysiros/Gyali/Kos;
In this process, the Aegean plate is sucked downwards, inducing subsidence of islands.

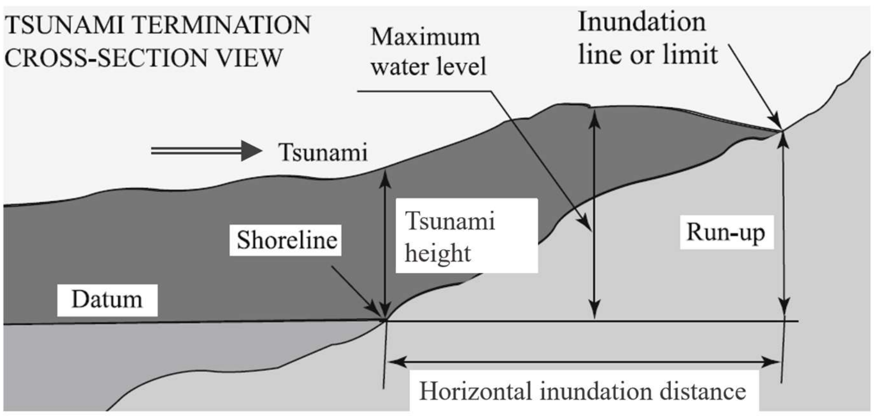


Earthquakes with magnitude > VII (source: NOAA, 2019).
Most of them are located along the faults mentioned in the previous figure.

Measuring the 'size' of an earthquake is not a simple matter. One can describe the damage that occurred at a certain location and thus define a local 'earthquake intensity' (Mercalli, EMS-98 and others, usually ranging from 1 to 12). However, this may seem subjective and is location-dependent. Therefore, more scientific 'earthquake magnitudes' were defined (Richter and others) that are based on seismographic measurements and reflect the size of the earthquake at its epicentre.

11.4.2 Tsunamis

The size of a tsunami is also hard to define. It can be described as the horizontal inundation distance of inland flooding, or as the vertical run-up on a sloping shoreline, and/or as the maximum rise of the water level above the normal tidal level at the time of occurence of the tsunami (called 'tsunami height' H), and/or as the water depth (and flow velocity) of the flow flooding the shoreline.



The Datum is the tidal sea level at the time of the tsunami occurrence

The Maximum water level may be located at the shoreline, or at the inundation limit, or anywhere in between

Adapted from Levin (2016)

Definition of tsunami parameters

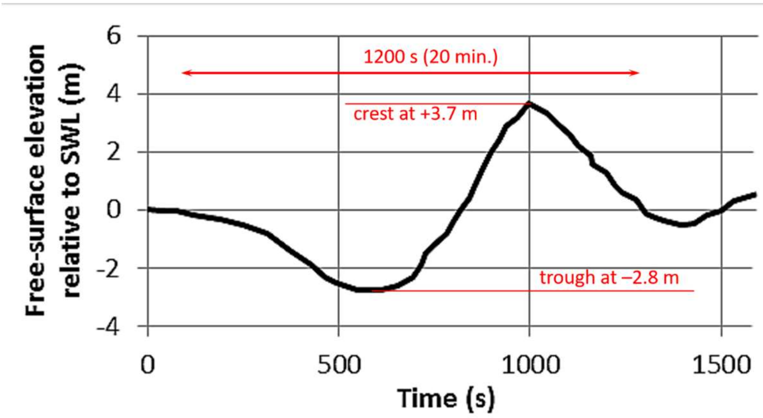
Soloviev (1974)[257] proposed a 'Soloviev-Imamura tsunami intensity scale' 'I' based on the tsunami height, averaged along the nearest coastline (H_{av}): for H_{av} = 2.8 m, I = 2, and for H_{av} = 5.5 m, I = 3. More recently, a new Integrated Tsunami Intensity Scale (ITIS-2012) with a scale ranging from 1 to 12, was proposed by Lekkas et alii (2013)[258].

Attention has been focused on this natural phenomenon in recent times, and has been well known by the Japanese over the past millennia, reason why we use the Japanese word 'tsunami' to designate a group of a few waves, that travels on the sea surface and reaches the coast inducing more or less damage and casualties. A tsunami is not a storm consisting of many high waves. A tsunami might be compared to a tidal bore, but its generation is not due to the tide (triggered by moon and sun).

A tsunami is a large-scale, short-duration disturbance of the free water surface usually generated by crustal movements of the earth. Such movements can be generated by earthquakes and by volcanic eruptions inducing submarine landslides. This was intuitively understood by Thucydides (History of the Peloponnesian war, 3, 89). Other generating factors can be coastal landslides from the shore into the sea (ca. 10% of tsunamis), submarine volcano eruptions or explosions (ca. 5% of tsunamis), high-density pyroclastic flows, glacier calvings, and even meteorite impacts[259]. Note that an earthquake does not generate a large tsunami by itself because the vibrations of the earth are of a frequency (say 0.1 Hz) unable to move a large body of water like a sea, but it can generate an onshore or a submarine vertical landslide, which may generate a tsunami if it is large enough and sudden enough. For this reason, the formal relationship between the intensity of a tsunami and the intensity of its generating earthquake is rather loose, i.e., a strong earthquake may generate only a small tsunami and vice-versa.

You can make your own small-scale modelling just by throwing a stone in still water!

From its area of generation, a tsunami propagates like a sea wave on the sea surface. However, its speed is much larger (say 500 to 1000 km/h, e.g., if generated near Crete, it may reach any eastern-Med coast in less than one or two hours). On deep water, the tsunami may have a fairly small height (say less than one meter), but when it reaches shallow waters (say less than 1000 m), the wave will gradually steepen and its height will increase. By a very fortunate coincidence, a Belgian yacht, the Mercator, was anchored on 14 m water depth at 1.6 km offshore Phuket during the 2004 Indian Ocean tsunami, and they registered the following water-level variation:



Signal recorded by the Mercator yacht during 2004 Indian Ocean tsunami (adapted from Chandler, et al, 2016).

[257] SOLOVIEV, S., & GO, N., 1974, (English transl 1984), "Catalogue of tsunamis on the western shore of the Pacific Ocean", Canadian Translation of Fisheries and Aquatic Sciences, No. 5077, (447 p), see p 16.
[258] LEKKAS, E., ANDREADAKIS, E., KOSTAKI, I., KAPOURANI, E., 2012, "A Proposal for a New Integrated Tsunami Intensity Scale (ITIS-2012)", Bulletin of the Seismological Society of America, Vol. 103, No. 2B, (p 1493–1502).
[259] DE LANGE, G., et al., 2011, "Executive Summary", in "Marine geo-hazards in the Mediterranean", CIESM Workshop, Nicosia, 2 - 5 February 2011, (p 7–20).

If you follow the graph from left to right, you see a 2.8 m deep trough coming first, followed by a 3.7 m crest, yielding a 6.5 m wave height. The total duration of the wave passing by was around 1200 s, or 20 minutes, and the rise from -2.8 to +3.7 m took only around 6 minutes and must have been quite impressive on board the yacht. This graph also shows that the shoaling tsunami wave becomes ‘non-linear’, featuring a narrower crest and a wider trough, deviating from the ‘linear’ sinusoidal shape.

Like any wave, a tsunami will break when it reaches relatively shallow waters (local wave height/local water depth = 0.5 to 1). Hydraulic research on scale models has shown that the tsunami wave front splits into a few short waves that are amplified by shoaling just before breaking (factors of 3 to 5 times the offshore wave height have been recorded)[260]. You might imagine that due to friction on the seabed, the bottom of the wave will travel slower than the top of the wave, thus leading to a ‘spilling’ (or 'plunging') of the top of the wave over the bottom side of the wave. The problem with a tsunami is that its wave length on deep water (order of 100 km) is much larger than that of a normal wave (order of 100 m), thus containing much more energy. Therefore, the volume of water involved in this spilling process is huge, resulting in a high-speed horizontal flow of water on the beach and adjacent coastal area (say 5-10 m/s, and more, video). This incoming wave might be called a ‘tsunami bore’, similarly to a tidal bore[261].The height of this water flow is usually limited to a few meters (6 m at Tohoku, 2011), but it can reach a considerable run-up height on an inland hill-slope (up to 40 m at Tohoku, 2011) or propagate over several kilometers inland on horizontal terrain (10 km at Tohoku, 2011). Obviously, this huge volume of water must flow back to the sea, inducing further damage, depending on the inland slope.
Moreover, the flooding may consist of several waves within say one hour (further reading on Wikipedia).
In the most dramatic historical events, the effects of an earthquake were combined with those of a tsunami, e.g., a coastal area was subjected to subsidence (or uplift) and to flooding by a tsunami generated elsewhere by the same earthquake. This probably happened on July 21, 365 when Crete literally tilted (9 m uplift on the south western side and 4 m subsidence on the north eastern side) with effects felt all over the eastern Mediterranean Sea.

The most (in)famous ancient tsunamis can be listed shortly as follows:

- ca. 1600 BC during the Thera (Santorini) volcanic eruption, inducing a tsunami that partly destroyed the Knossos Minoan civilisation,
- 1365 BC at Ugarit, mentioned in an Amarna letter,
- 525 BC at Tyre and Sidon, mentioned by Strabo,
- 479 BC at Potidaia, described by Herodotus,
- 426 BC at Orobiae (north Euboea), mentioned by Thucydides,

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[260] CHANDLER, I., et al., 2016, “Understanding wave generation in pneumatic tsunami simulators”, Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16), Ottawa, Canada, May 10-13, 2016
MATSUYAMA, M., et al., 2007, “A study of tsunami wave fission in an undistorted experiment”, Pure Appl. Geophys. 164(2–3), (p 617–631).
YOSHII, T., TANAKA, S., MATSUYAMA, M., 2017, "Tsunami deposits in a super-large wave flume", Marine Geology 391, (p 98-107).
YOSHII, T., TANAKA, S., MATSUYAMA, M., 2018, "Tsunami inundation, sediment transport, and deposition process of tsunami deposits on coastal lowland inferred from the Tsunami Sand Transport Laboratory Experiment (TSTLE)", Marine Geology 400, (p 107-118).
[261] See the most impressive Qiantang tidal bore in Hangzhou Bay (China) featuring a 5-6 meters sudden rise of water level.

- 373 BC at Helike (northern Peloponnesus), when the city disappeared,
- 227 BC at Rhodes, when the Colossus collapsed,
- 92 BC large tsunami on the Levantine coast,
- 79 AD initiated by the Vesuvius eruption near Pompei,
- 365 AD initiated on western Crete but felt from the Levant to Sicily,
- 458 AD at Antioch,
- 551 AD on the Levantine coast, one of the largest ancient earthquakes,
- 747 AD, large earthquake in Galilea and the Beqaa valley,
- 854 AD large earthquake in lake Tiberias
- 881 AD initiated on the Levantine coast but felt from the Levant to Andalucia,
- 991, 1002 or 1003, 1089, 1157, 1202,
- 1303 initiated near Rhodes but felt from Akko to Tunis and Istanbul,
- 1408 around Lattakia,
- and others after 1500.

At least 400 earthquakes and/or tsunamis occurred in the Mediterranean area between 500 BC and 1500 AD, i.e., **20 tsunamis/century**.

11.4.3 Sedimentological impact of tsunamis

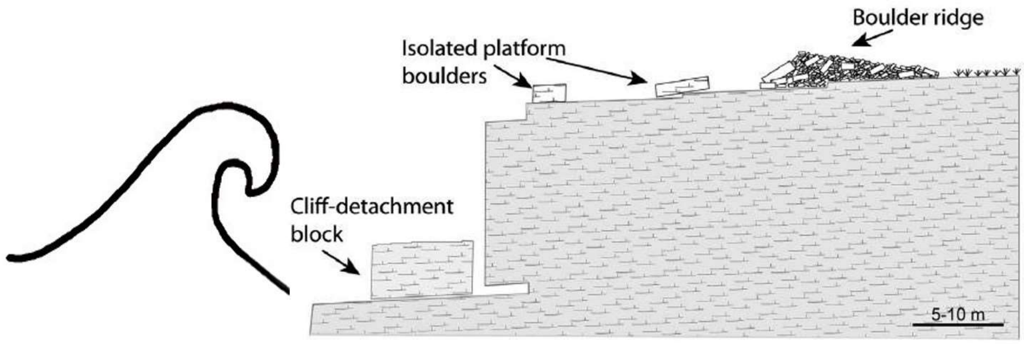
"… to simply identify a palaeotsunami in the geological record is by no means simple. Over the past decade or more, geologists have carefully constructed a proxy toolkit for identifying palaeotsunamis."[262] This sentence implies that hydrodynamics of tsunamis is a complex field and only few mathematical formulations have been published[263]. The study of movement of materials under the effect of a tsunami is of an even higher level of complexity and must therefore be roughly schematised.

Without going into details, it should be kept in mind that a tsunami consists of a small number of long waves out of which the second is often the highest. Quite differently, a storm, defined by a "significant wave height" H_s, consists of thousands of short waves out of which only one maximum wave is moving more materials than any other wave (it is usually accepted that $H_{max} = 2\ H_s$).

We may distinguish the impact of tsunamis on rock boulders resting near the shore and on various types of offshore marine deposits[264].

[262] GOFF, J., et al., 2012, "Progress in palaeotsunami research", Sedimentary Geology, 243–244, (p 70–88).
[263] LEVIN, B., & NOSOV, M., 2014, "Physics of Tsunamis", Springer, (399 p).
WEI, GE, et al., 1995, "A fully nonlinear Boussinesq model for surface waves. Part 1. Highly nonlinear unsteady waves", Journal of Fluid Mechanics, July 1995, vol. 294, (p 71-92).
FENGYAN SHI, et al., 2012, "A high-order adaptive time-stepping TVD solver for Boussinesq modeling of breaking waves and coastal inundation", Elseviers, Ocean Modelling, Vol. 43-44, (p 36-51). FUNWAVE-TVD.
GRILLI, S., et al., 2012, "Numerical modeling of coastal tsunami impact dissipation and impact", Proceedings of the Coastal Engineering Conference, 33.
[264] https://en.wikipedia.org/wiki/Tsunami_deposit

- **Boulders**

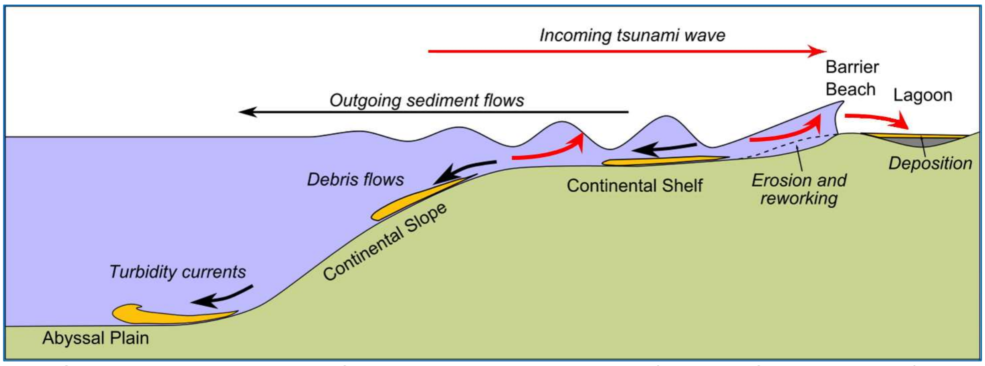


Tsunami impact on boulders on a rocky coast (adapted from Cox, 2018).

Several formulations have been proposed to compute the storm-wave height and tsunami height required to move a given size of boulder, but results show discrepencies[265] which are mainly due to erroneous schematisations of the tsunami hydrodynamics[266].
On rocky coasts, we may distinguish small boulders and large boulders.
Small boulders may be moved by large storm-waves, if such waves can reach the location where boulders are resting on the coastline. The largest significant wave heights in the Mediterrnean are aound H_s = 10 m for a one-hundred-year storm on the coasts of northern Algeria-Tunisia, Cyrenaica and the Levant (see section on "Design waves"). The, for coastal engineers, famous Hudson equation shows that the largest boulders that such a storm might move do not exceed 50 tons. This involves a flow velocity in the order of 10-12 m/s. Hence, in these regions, all boulders smaller than 50 ton might be moved by large storms as well as by tsunamis, but l*arger boulders* can be moved only by tsunamis.
The travelling distance of boulders obviously depends on the tsunami size and on the boulder size, and large boulders have been seen moving over tens of meters on a horizontal surface, or several meters in a vertical movement, e.g., from the waterline to the top of a small cliff[267].
As the hydrodynamics involved are complex, further study of the movement of boulders due to storm waves and to tsunamis must be performed on small-scale models[268], in addition to computations with mathematical models[269].

[265] PISCITELLI, A., et al., 2016, "Numerical approach to the study of coastal boulders: The case of Martigues, Marseille, France", Quaternary International, Volume 439, Part A, (p 52-64).
[266] COX, R., 2020, "Systematic Review Shows That Work Done by Storm Waves Can Be Misinterpreted as Tsunami-Related Because Commonly Used Hydrodynamic Equations Are Flawed", Front. Mar. Sci., 7:4, (18 p).
[267] MAOUCHE, S., et al., 2009, "Large boulder accumulation on the Algerian coast evidence tsunami events in the western Mediterranean", Marine Geology, 262 (p 96–104).
[268] LIU, H, & SATO, S., 2014, "An experimental study on the tsunami boulder movement", Coastal Engineering Proceedings, (11 p).
[269] BUCKLEY, M., et al., 2011, "Inverse modeling of velocities and inferred cause of overwash that emplaced inland fields of boulders at Anegada, British Virgin Islands", Nat Hazards, Springer, (17 p).

- **Marine deposits**



Sedimentological impact of a tsunami on a sandy coast (adapted from Wikipedia).

A tsunami wave starts to disturb the seabed as from a long distance of the shore, where the water depth is many tens of meters. At such a water depth, the seabed often consists of very fine sediment like silt and marine mud. While disturbing seabed materials, the tsunami bore becomes turbid, bringing large quantities of fine offshore sediment to the shore. A similar picture occurs when the tsunami is nearing a sandy coast where large volumes of fine dune-sand may be picked up by the bore and transported further inland. If the hinterland is a flat plain, this sediment is thus deposited inland in a layer with decreasing thickness of a few decimetres near the coast to a few millimetres at several kilometres inland. Moreover, the grain size in a vertical section of the deposit is fining upwards[270]. Subsequently to the massive inflow of water, a strong backwash is unavoidable, taking deposited sediment and possibly some terrestrial material back to the sea. It is obviously difficult to predict the result ... Similar deposits may also occur in quiescent coastal lagoons where marine sediment, marine microfauna (foraminifera tests, ostracods, diatoms) and marine macrofauna (bivalve shells) brought by a tsunami may be deposited on top of lagoonal sediment which usually contains brackish-water fauna. However, such deposits may also be due to a super-storm that might have broken through the coastal barrier islands *locally*, generating a wash-over fan[271].

It might be reminded here that a super-storm on a sandy coast, with say a Hs = 10 m wave height, will show wave breaking at ca. 20 m water depth. That is well offshore the coast, but such a storm will nevertheless induce severe erosion of the seabed and coastline. However, damage induced by a tsunami would be much larger.
It is even more difficult to distinguish between autochthonous and allochthonous deposits in the case of estuaries where river sediment due to river floods is mixed up with marine sediment due to storms, and possibly to tsunamis[272].

[270] PILARCZYK, J., et al., 2012, "Sedimentary and foraminiferal evidence of the 2011 Tōhoku-oki tsunami on the Sendai coastal plain, Japan", Sedimentary Geology, 282 (p 78–89).
[271] SABATIER, P., et al., 2012, "7000 years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events", Quaternary Research, 77, (p 1–11).
[272] DELILE, H., & SALOMON, F, 2020, "Palaeotsunami deposits at the Tiber River mouth (Ostia Antica, Italy): Do they really exist?", Earth-Science Reviews, Volume 208, https://doi.org/10.1016/j.earscirev.2020.103268.

In case of uncertainty about the origin of some ancient coastal sediment layers, we like to speak of a “high-energy event”.

A high-energy deposit in the Byzantine harbour of Yenikapı, Istanbul (5th to 6th c. AD).
(photo: D. Perincek, 2010)

11.4.4 List of historical earthquakes and tsunamis

A list of ‘all’ known historical earthquakes and tsunamis in the Mediterranean that occurred before 1500 AD, area can be found in Appendix 4 hereafter.

This list shows the following:

- A total number of around 460 earthquakes was reported from 2000 BC to 1500 AD. Around 130 of these earthquakes generated a tsunami that was reported (28%).
- Earthquakes are fairly well distributed in time and in magnitude, although some concentrations in time are found in 0-150 AD, 300-600 AD, 850-1000 AD.
- The largest earthquake was reported on 21/7/365 AD, with an intensity evaluated to X-XI.

APPENDIX 1: Ancient texts on maritime structures

It might be considered that we would not be able to shed any new light on ancient texts that have already been studied so many times in the past centuries. It is nevertheless worth the effort of reading the complete corpus of ancient texts providing a description of ancient port structures. We shall therefore limit ourselves to a juxtaposition of ancient texts in chronological order.

These texts were initially collected in the French language and are therefore reproduced here in that language.

Philon de Byzance, ca. 250 BC, Le 'Traité de Mécanique' est constitué de 9 livres, dont un sur la construction des ports qui ne nous est hélas pas parvenu (λιμενοποιικά). Son 'Traité de fortification' donne cependant des éléments sur les ports au chap 3 & 4.

Chap. 3 – La défense des places

28. — Si l'approche (ἡ προσαγωγή) se fait par mer, on placera dans les endroits où l'ennemi doit débarquer des portes garnies de clous et dissimulées à la vue. On sèmera des chausse-trappes (τριβόλους) soit de fer, soit de bois. On interceptera avec des palissades les passages d'accès facile.

29. — On fermera les entrées des ports avec des clôtures à travers lesquelles on puisse faire circuler même des vaisseaux de transport. Pour cela, il faudra, en certains points, des chaînes de fer ou des grilles, et ailleurs on coulera, au fond de l'eau, de très grosses pierres s'entrecroisant autant que possible. Sur ces pierres, on fixera des pieux (σταυρούς) de fer disposés obliquement et reliés les uns aux autres en forme de treillis; leur extrémité supérieure ne doit pas arriver au niveau de l'eau, mais s'arrêter à environ une palme (0,08 m) au-dessous; on pourra encore placer, vis-à-vis, des navires (πλοῖα) armés en guerre, et, si l'on n'en a pas, il faudra mouiller, les uns près des autres, des *lembes* (λέμβους) et les autres petites embarcations que vous pourrez vous procurer; on les réunira à l'aide de poutres longues de quatre coudées (1,85 m) adaptées en avant de la proue et fixées les unes aux autres de façon à ne former qu'un tout; leurs pointes devront être munies d'éperons.

30. — Auprès de ces fermetures (κλεῖθρα) et de ces passes (ζεύγματα), il faut arrêter les barques dites *acatias* (πλοῖα ἀκάτια), pleines de poix, de soufre et de chausse-trappes garnies d'étoupes. On préparera de même des *olcas* (ὁλκάδες).

31. — On établira enfin, pour chacune des entrées (στόμα) et de chaque côté de l'entrée, des pétroboles [catapultes] de vingt mines (8,726 kg).

32. — De cette manière, si quelques-uns des navires de guerre de l'ennemi venaient à forcer l'entrée des ports, ils seraient ou incendiés, ou percés par les éperons, ou submergés par les amphores de plomb et par les projectiles des pétroboles.

33. — S'il y a un grand intervalle à l'entrée du port, on construira, au milieu, une tour dans laquelle on placera une pétrobole de quarante mines (17,5 kg).

34. — Contre les tours de charpente que l'on amènera et contre les navires qui s'avanceront, il faut se servir surtout de pétroboles, de machines incendiaires (πυροφόροις) et de doryboles.

35. — Si les murs sont baignés en quelque endroit par une mer profonde, il faudra protéger le pied de ces murs au moyen d'une jetée (προσχώματι), pour que l'approche n'ait pas lieu de ce côté-là, et afin que l'ennemi ne puisse détruire les remparts au moyen de l'éperon de ses grands navires, ou s'emparer de quelque tour en y jetant des ponts.

36. — Pendant la nuit et quand la mer sera houleuse, il faudra envoyer des plongeurs pour couper les cordages d’ancre des navires qui sont au mouillage et percer leur coque ; c’est le meilleur moyen d’empêcher l’ennemi de rester en station devant la ville.

Chap. 4 – L’attaque des places

17. — Tu suivras une marche analogue quand tu auras à faire une attaque par mer. Tu placeras tes tours de charpente sur des olcas et des lembes et tu t’approcheras de la place. Puis, lorsque, avec les plus grandes de tes chaloupes (σκάφη), tu auras forcé l’entrée du port, tu engageras, si tu as des navires pontés (καταφράκτη ναῦς), la lutte avec l’aide de ceux de tes soldats qui seront les plus aguerris aux combats sur mer.

18. — Il faut rompre les barrières et les clôtures des ports, ou bien en les choquant avec les éperons des vaisseaux (ταῖς ἐμβολαῖς τῶν νεῶν), ou bien en les tirant au moyen d’ancres remorquées par des olcas.

19. — Lorsque les tours de charpente auront été amenées près des remparts, tu rassembleras les soldats et tu leur feras connaître la proclamation citée plus haut (§ 7) ; puis tu commenceras l’attaque sur tout le pourtour de la ville, par terre et aussi par mer, si la mer baigne quelque endroit des murs. Tu inspireras ainsi plus de terreur à l’ennemi et tu diviseras mieux ses forces. […]

76. — Si tu dois résister à une attaque par mer, ferme, si tu le peux, par une jetée l’entrée du port. Si cela n’est pas possible, il faudra l’obstruer avec des olcas et tous les navires qui seront susceptibles de servir à cet usage puis, avec les bois que tu auras sous la main tu construiras un radeau [organisé pour la défense] (σχεδίαν) que tu fixeras à ces embarcations.

77. — Observe attentivement les signaux qui seront faits au moyen de flambeaux allumés (τοὺς φρυκτούς) et fais bonne garde, surtout la nuit, afin que l’armée de secours ne te surprenne pas en entrant dans la ville du côté opposé à la mer.

78. — Si tu te trouves avoir des forces navales à peu près équivalentes à celles de ton adversaire, tu devras tenter le combat. Tu choisiras dans tes troupes les soldats les plus vaillants et le plus expérimentés, et tu les placeras sur les ponts des navires ; tu donneras les ordres pour qu’on ne cherche ni à désarmer (ἀκρωτηριάζειν), ni aborder (ἀναβαίνειν) les vaisseaux ennemis, mais pour qu’on les coule avec l’éperon (τῷ χαλκώματι χρᾶσθαι). Tu attaqueras ensuite, en disposant ta flotte en forme de croissant les navires les meilleurs, ceux qui obéissent le mieux soit à la voile, soit aux rames, seront aux ailes ; les navires non pontés (τὰ ἄφρακτα) et les bateaux de charge seront au milieu à côté du radeau.

79. — Quand tu seras à portée de l’ennemi, tu embraseras ses navires avec des matières incendiaires (τοῖς πυροφόροις), des chausse-trappes enflammés (τοῖς ἡμμένοις τριβόλοις), de la poix, si tu en as, et des torches. Il faut que tes marins lancent la plus grande quantité, possible de flèches et d’autres projectiles. Tu tâcheras de couler et d’incendier les bâtiments des ennemis, soit à l’aide des machines qui sont à terre, soit avec des tours de charpente portées sur des bateaux, soit enfin en les brisant à l’aide d’autres navires. Quand tu auras ainsi porté la plus grande confusion chez ton adversaire, soit qu’il résiste, soit qu’il se retire, tu engageras la mêlée en réunissant tes ailes ; tu submergeras ses vaisseaux en les prenant de flanc, ou bien tu briseras et tu incendieras, comme nous l’avons dit plus haut, ceux qui t’attaqueront de front.

80. — Si tu les surprends naviguant à la débandade, tu t’avanceras sur eux avec toute ta flotte rangée en ordre ; tu t’efforceras de couler et d’incendier ceux qui te résisteront. Quant à ceux qui tenteront de fuir, il faudra, après les avoir pris, briser leur gouvernail, enlever leurs rames et les conduire à terre.

81. — Si tu n’as point de flotte, sers-toi du feu et des traits pour empêcher l’ennemi de faire quelque chose ; on peut, de cette façon, continuer à assiéger la ville sans être trop incommodé par la flotte de secours.

Les ports et les constructions qui doivent se faire dans l'eau (Vitruve, de Architectura, 5, 12, ca. 20 BC, traduction Ch. Maufras, 1848)

Les ports présentent de grands avantages ; je ne dois point les passer sous silence ; les moyens d'y mettre les vaisseaux à l'abri de la tempête vont faire le sujet de ce chapitre. Si les ports doivent à la nature une position avantageuse, s'ils sont naturellement bordés de collines, et qu'ils aient des promontoires qui, en avançant, s'arrondissent intérieurement en forme d'amphithéâtre, il sera bien facile de les rendre très commodes, puisqu'il n'y aura plus qu'à les entourer de portiques ou d'arsenaux, qu'à ouvrir des rues qui conduisent des portiques aux marchés, qu'à élever, aux deux coins, des tours qui, à l'aide de machines, puissent soutenir des chaînes passant de l'une à l'autre.
Si nous n'avons point de port naturel qui soit en état de défendre les vaisseaux contre la tempête, voici à quels moyens il faudra avoir recours : s'il ne coule dans cet endroit aucune rivière qui fasse obstacle, s'il se trouve d'un côté un mouillage sûr, il faudra construire de l'autre un môle[273], une levée qui s'avance dans la mer, et forme l'entrée du port. Voici comment il faut faire ces jetées qui doivent se bâtir dans l'eau.

On se procurera de cette poussière dont sont formées les plaines qui s'étendent entre Cumes et le promontoire de Minerve[274], et on en fera dans un bassin un mortier composé de deux parties de poudre contre une de chaux.
Dans le lieu destiné à la construction de la jetée, des batardeaux, formés de madriers de chêne, attachés entre eux, seront construits dans la mer, où on les fixera solidement. On remplira ensuite les intervalles avec de fortes planches, après avoir nettoyé et nivelé le fond de l'eau ; puis on y entassera des pierres mêlées avec le mortier, dont nous venons de parler, jusqu'à ce qu'on ait comblé l'espace ménagé dans les batardeaux pour la maçonnerie. [Méthode 1]

Mais si la violence des flots, roulant de la pleine mer, vient à rompre les batardeaux, il faudra construire, avec la plus grande solidité possible, un massif contre la terre même ou contre le parapet ; la moitié de ce massif sera élevée au niveau du terre-plein ; l'autre, qui est la plus rapprochée du rivage, sera en talus.
Ensuite, du côté de l'eau et le long du massif, on construira, en forme d'enceinte, un mur d'environ un pied et demie, qui s'élèvera à la hauteur du niveau dont il vient d'être parlé. Le creux du talus sera alors rempli de sable jusqu'au niveau de ce mur et de la surface du massif. Au-dessus de cette esplanade, on bâtira un corps de maçonnerie d'une grandeur déterminée, puis on le laissera sécher, au moins pendant deux mois. On abattra alors les rebords qui soutiennent le sable, et le sable emporté par les flots ne pourra plus soutenir cette masse, qui tombera dans la mer. Par cette opération, renouvelée autant de fois qu'il sera nécessaire, on pourra s'avancer dans les eaux.

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[273] Les ingénieurs portuaires modernes distinguent :

- Les « brise-lames » (souvent appelés « digues » à tort) (en anglais : « breakwaters ») qui sont souvent des amoncellements de blocs de pierre (« digues à talus ») mais qui peuvent être des ouvrages verticaux fabriqués à l'aide de blocs de pierre taillés, voire de caissons préfabriqués,
- Les « jetées » qui sont plutôt des ouvrages d'intérieur de port en maçonnerie et pourvus de deux quais, on parle d'appontement lorsqu'il s'agit d'une structure sur pieux,
- Les « quais » qui servent à accoster les bateaux. Ils peuvent être constitués d'un parement vertical ou d'un alignement de pieux sur lequel on aménage une plate-forme de transfert des marchandises.

Le terme « môle » n'est plus guère utilisé par les ingénieurs, mais les traducteurs de textes anciens semblent vouloir désigner un brise-lames.

[274] La pouzzolane, encore utilisée de nos jours pour fabriquer le « béton hydraulique » qui *durcit sous l'eau*. Cette trouvaille des romains est à la base de l'opus caementicium et est une invention majeure du génie maritime. Les premières applications à Cosa, Pompéi et Pouzzoles remontent à env. 200 av. J-C. Elle a été oubliée et redécouverte au début du 19ème siècle par Louis Vicat et il faudra attendre François Hennebique à la fin du même siècle pour l'application du béton armé (d'acier).

La pouzzolane se trouve en abondance dans les lieux dont nous avons parlé plus haut. [Méthode 2]

Dans ceux où cet avantage ne se rencontre pas, voici comment on y pourra suppléer : un double rang de madriers réunis par des planches et fortement attachés sera enfoncé dans le lieu choisi, et l'intervalle sera rempli de craie renfermée dans des paniers de jonc de marais. Quand on les aura bien battus pour les affermir, l'endroit circonscrit dans cette enceinte sera vidé et mis à sec à l'aide de limaces, de roues, de tympans, et on y creusera des fondements ; si l'on rencontre de la terre, on creusera jusqu'au solide, en desséchant à mesure, et on donnera aux fondements plus de largeur que n'en aura le mur qu'ils doivent porter; la maçonnerie se composera de moellons liés avec de la chaux et du sable. [Méthode 3]

Si le lieu n'est pas ferme, on y enfoncera des pilotis de bois d'aune ou d'olivier, ou de chêne, durcis au feu, et on remplira les intervalles de charbon, comme je l'ai dit pour les fondements des théâtres et des murailles. On élèvera ensuite le mur avec des pierres de taille, dont les plus longues seront mises aux angles, afin que celles du milieu soient plus solidement liées; l'intérieur du mur sera alors rempli de hourdage ou de maçonnerie, afin que dessus on puisse construire une tour.
Après ces travaux, on s'occupera des arsenaux, qu'on aura soin de construire de préférence du côté du septentrion : car l'exposition du midi, à cause de la chaleur, engendre la pourriture, nourrit et conserve les teignes, les térédons et toutes les espèces d'insectes nuisibles. Il ne doit point entrer de bois dans la construction de ces édifices, crainte du feu. Quant à leur grandeur, elle ne saurait être déterminée ; il suffit qu'elle soit telle que les plus grands vaisseaux puissent y trouver largement place.
Après avoir écrit dans ce livre tout ce qui m'a paru utile et nécessaire pour le bon état des villes, en ce qui regarde les édifices publics, dont j'ai donné les proportions et le plan, je vais, dans celui qui suit, traiter des bâtiments particuliers, de l'utilité et de la convenance de leurs parties.

Notes du traducteur Ch. L. Maufras, 1848 :

127. - *De opportunitate autem portuum non est praetermittendum*. On sait ce que c'est qu'un port. On n'ignore pas qu'il y eu a de naturels, qu'il y en a d'artificiels. Athènes avait trois ports naturels (THUCYDIDE, liv. I, ch. 93; PAUSANIAS, liv. 1, ch. 2). La description que fait Tite-Live de celui de Carthagène (liv. XXVI, ch. 42) a inspiré à Virgile le tableau qui commence ainsi : *Est in secessu longe locus ......* (Aen. lib. 1, v. 159)
Pour bien comprendre ce que dit Vitruve de la construction des ports, il faut se rapporter au temps où il écrivait. Point de boussole alors ; on ne pouvait donc guère naviguer que sur les côtes; aussi ne se servait-on que de petits bâtiments plats et à rames qui ne tiraient que fort peu d'eau. Presque toutes les rades étaient pour eux des ports, dit de Bioul ; et lorsqu'il n'y en avait point de naturels dans les lieux où besoin était qu'il y en eût, on en avait bientôt forme un au moyen d'une simple jetée ou môle. Ainsi, dans ce chapitre, Vitruve ne parle que de la construction de ces môles, et de celle des arsenaux où l'on construisait les navires, où même on les enfermait, puisqu'ils étaient si légers qu'on pouvait assez facilement les tirer à terre.
Voyez M. de CAUMONT, 3e part., ch. 4.

128. - *Uti si nullum flumen in his locis impedierit*. Cette observation ne peut convenir qu'aux ports de la Méditerranée, où le flux et le reflux ne se font point sentir. Les rivières d'Italie, qui viennent presque toutes des montagnes de l'Apennin qui sont la plupart volcanique, composées de cendres, de pierre ponces, de terre et d'autre matières légères qu'elles charrient, auraient bientôt encombré un port qui serait à leur embouchure. Il n'en est pas de même de ceux de l'Océan : l'agitation du flux et du reflux empêche que la vase et les immondices des rivières ne comblent les ports, et le flux qui y fait monter l'eau très haut, permet à l'art de se servir avantageusement de ce secours de la nature, en retenant l'eau qui est montée pendant le flux dans les écluses et dans les barres que l'on ouvre quand la mer est descendue, et qui, par sa chute impétueuse, achève de balayer le port, ce que le reflux a commencé à faire.

129.- *Sed erit ex un parte statio*. Ulpien, au liv. XLIII des *Pandectes*, de Fluminibus, interprète le mot *statio* par un lieu où les vaisseaux peuvent rester en sûreté. Ce mot, en effet, signifie généralement un lieu commode pour les vaisseaux. Et pour cela il faut deux choses : l'une, qu'il y ait assez de fond pour porter les vaisseaux ; l'autre, que ce lieu soit à couvert des vents. Or, il est évident qu'il ne s'agit ici que de la première, parce que le môle qui doit être bâti mettra les vaisseaux à l'abri des vents.

130. - *Arcae stipitibus robusteis et catenis inclusae*. Perrault traduit *arcæ* par pièce de bois rainée, c'est-à-dire creusée sur son épaisseur par un petit canal destiné à recevoir une coulisse. Philander et Barbaro partagent cette

opinion.
J. Martin donne à ce mot la signification de coffres, qu'on aurait remplis de mortier fait avec de la pouzzolane, pour les jeter dans la mer. Bien que cette manière se pratique eu quelques endroits, le texte de Vitruve ne s'accorde pas avec ce genre de structure, continue Perrault, parce qu'il est dit que les choses appelées *arcæ* une fois plantées dans la mer, on garnit d'ais les entre-deux, et qu'ensuite tout l'espace destiné à la maçonnerie est rempli de mortier et de pierres qui, par leur pesanteur, rejettent toute l'eau hors de l'enceinte formée par les cloisons, et par la vertu particulière que la pouzzolane a de sécher et de s'endurcir dans l'eau, font comme une masse fusible coulée dans un moule.
Galiani n'adopte pas ce sentiment. Il dit que les paroles de Vitruve semblent faire entendre qu'on doit seulement lier avec des chaînes toute l'enceinte de pieux; que, comme nous nous servons aussi d'ais terminés en queue d'aronde pour unir ces pieux les uns aux autres, au moyen des rainures destinées à recevoir les tenons, Perrault, qui a cru cet usage antique, s'est persuadé qu'ici *arca* signifiait un poteau aux deux côtés duquel on avait creusé des rainures propres à recevoir les tenons d'une autre pièce de bois; qu'il lui semble très clair qu'une fois qu'on a donné à *arca* l'épithète d'*inclusa*, ce mot ne peut signifier autre chose que la totalité de l'arc formé par les pieux, c'est-à-dire toute l'enceinte même; et que l'expression de *dimittere arcam* ne doit pas apporter une difficulté, puisqu'il s'en sert probablement eu lieu de *dimittere stipites quibus fiunt arcae*.
L'opinion de Perrault est assurément la plus vraisemblable, la véritable. *Arca* signifie un batardeau, c'est-à-dire un ouvrage quelconque construit dans l'eau avec des madriers et des pilots qui forment une espèce de coffre ; *stipitibus robusteis* sont ces madriers de chêne qui, solidement fixés au fond de la mer, le sont également par le bout d'en haut à l'aide de pièces de bois mises en travers : car les mots *catenæ* et *catenationes*, dans Vitruve, signifient, selon Perrault, les liaisons qui se font des pièces de bois avec le bois même, comme *claves* dans la charpenterie et la menuiserie ne signifie pas des clés de fer; et s'il faut niveler la terre, c'est pour que les ais qui glissent dans les rainures, la touchent partout également, afin qu'il ne reste point d'ouverture par laquelle le mortier puisse s'échapper.

131. - *Pulvinus*. Ce mot signifie proprement un oreiller. Par métaphore on l'emploie pour désigner une plate-forme, ou assemblage de charpenterie sur lequel on traîne de lourds fardeaux, et qu'on appelle en français poulain, peut-être de *pulvinus* Ici, il signifie un massif de maçonnerie, dont plus de la moitié posait sur un amas de sable soutenu par un petit mur qu'on abattait, lorsque la maçonnerie était sèche. La mer alors emportait le sable, et la masse qui se trouvait dessus tombait dans l'eau. Virgile (*Énéide*, liv. IX, v. 710) décrit cette manière de faire un môle.
Il semblerait par-là que les anciens ne faisaient pas leurs môles, comme nous les faisons aujourd'hui, en jetant dans la mer, les uns sur les autres, de gros quartiers de pierres. Peut-être n'avaient-ils pas remarqué combien les moules et tous les autres coquillages, en s'attachant aux pierres roulées sur le rivage, les attachent et les lient les unes aux autres; ce qui leur donne une solidité inébranlable, supérieure peut-être à celle des rochers produits par la nature.
Cependant dans *l'Hydrographie* du P. Fournier, et dans *l'Architecture hydraulique* de M. Bélidor, on lit qu'à l'ancienne Tyr, deux môles fondés à pierres perdues, à la profondeur de vingt-cinq à trente pieds d'eau, dirigés en portion de cercle et s'étendant dans la mer, formaient l'entrée du grand port qu'un troisième môle couvrait , eu le garantissant de l'impétuosité des vagues. Voyez dans Pline le Jeune (liv. VI, lettre 31) la manière dont fut construit le port de Trajan.

132. - *Inter destinas creta meronibus ex ulva palustri factis calcetur*. La véritable signification du mot *mero* est très incertaine, bien que le sens indique clairement qu'il est ici question de sacs ou autres choses semblables. Cesariano, Caporali et Philander croient qu'il faut lire *perones*, qui signifie bottes ou chausses, comme si Vitruve voulait que ces paquets fussent longs et étroits, de même qu'étaient les sacs dont Pline dit que Chersiphron se servit pour poser les pierres énormes des architraves du temple de Diane d'Éphèse (*Hist. Nat*., liv. XXVI , ch. 21). Différentes éditions de Pline portent *perones, herones, ærones*, Cujas, Turnèbe et Saumaise veulent qu'on lise *herones*, mannequins.
Ex ulva palustri. Ce jonc ou plante de marais, que les anciens appellent *ulva*, est demeurée inconnue aux botanistes. Virgile en parle (*Énéide* liv. II , v. 135 , et liv. VI , v. 416) comme d'une plante aquatique. Ce doit être cette espèce de joncs, très communs dans les marais, dont on se sert en Italie pour rempailler les chaises et entourer les bouteilles. Ces joncs entrelacés empêchaient l'argile qui était dedans de se dissoudre trop vite dans l'eau, ce qui donnait le temps de battre et de pétrir ces paquets.

133.- *Tunc cochleis, rotis, tympanis*. Ces machines sont expliquées aux ch. 4 à 7 du liv. X

134. - *Navaliorum*. Ce mot est mis pour *navalium*, par le changement de déclinaison. On trouve aussi *viridiorum, anciliorum, saturnaliorum*. *Vectigaliorum* a souvent été employé par Asinius Pollion, s'il faut en croire ce que dit Macrobe au liv. 1er de ses *Saturnales*.

135. - *Tineam, teredines.... procreant*. Vitruve établit une différence entre la teigne et le térédon, comme Pline qui fait du térédon un insecte marin, et de la teigne un insecte terrestre. Théophraste avait dit avant lui (*Hist. des plantes*, Liv.V) : « Le térédon a le corps petit, la tête grosse ; il est armé de dents. La teigne ressemble à un petit ver qui perce insensiblement le bois. »
Les Latins ont écrit que le térédon rongeait les vaisseaux
Estur ut occulta vitiata teredine navis.
(OVIDE, *de Ponto*, lib. I, ep. 1.)
Voyez PLINE, *Hist. Nat*., liv. XVI , ch. 80.

Puteoli (Strabon, Géographie, 5, 4)

6. Le golfe Lucrin, qui, dans le sens de sa largeur, s'étend jusqu'à Baies, est séparé lui-même par une digue de la mer extérieure. Cette digue est longue de huit stades et a la largeur d'un chariot de grande voie ; suivant la tradition, elle aurait été élevée par Hercule, [comme il revenait d'Ibérie] ramenant avec lui les troupeaux de Géryon. Agrippa en a fait récemment exhausser la plate-forme, car, pour peu que la mer fût grosse, elle était toujours balayée par la vague, ce qui rendait le passage de la digue difficile aux piétons. Les embarcations légères ont accès dans le Lucrin : à vrai dire, ce golfe ne saurait servir de mouillage ni d'abri, mais la pêche des huîtres n'est nulle part aussi abondante. Quelques auteurs ont confondu le Lucrin avec le lac Achérusien ; Artémidore, lui, le confond avec l'Averne. Ajoutons, au sujet de Baïes, qu'on dérive son nom de celui de Baïus, l'un des compagnons d'Ulysse, comme on dérive du nom [de Misenus] celui du cap Misène. - Suit la côte escarpée de Dicæarchie, et Dicæarchie elle-même : bâtie sur un mamelon au bord de la mer, cette ville ne fut d'abord que l'arsenal maritime de Cumes, mais, ayant reçu, à l'époque de l'expédition d'Annibal en Italie, une colonie romaine, elle vit changer son nom en celui de Puteoli […]. Avec le temps, l'ancienne Dicæarchie est devenue un emporium considérable, ce qu'elle doit aux vastes bassins qu'une précieuse propriété du sable de cette côte a permis d'y construire : uni, en effet, à de la chaux en proportion convenable, ce sable acquiert une consistance, une dureté incroyable, et l'on n'a qu'à mêler du caillou à ce ciment de chaux et de sable, pour pouvoir bâtir des jetées aussi avant qu'on veut dans la mer et créer ainsi sur des côtes toutes droites des sinuosités ou enfoncements qui deviennent autant d'abris sûrs ouverts aux plus grands navires du commerce.

Civitavecchia (Pline le Jeune, Lettres, 6, 31)

Représentez-vous une magnifique villa, environnée de vertes campagnes, et dominant le rivage où un port se construit en ce moment. De solides ouvrages en fortifient la partie gauche ; on travaille à l'autre côté. Devant le port s'élève une île, destinée à rompre les flots que les vents y poussent avec violence, et qui protège des deux côtés le passage des vaisseaux. Elle est formée avec un art digne d'attirer l'attention. D'énormes pierres y sont apportées sur un large navire. Jetées sans cesse l'une sur l'autre, elles demeurent fixées par leur propre poids, et s'amoncellent peu à peu en forme de digue. Déjà apparaît et se dresse la cime du rocher qui brise et lance au loin dans les airs les flots dont il est assailli. La mer s'agite avec fracas, blanchissante d'écume. On lie cette masse de pierres par des constructions faites pour donner un jour à cet ouvrage l'apparence d'une île naturelle. Ce port s'appellera du nom de celui qui l'a construit [Trajan], et il sera fort commode ; car c'est une retraite sur une côte qui s'étend fort loin, et qui n'en offrait aucune.

John Oleson’s translation (2014) reads as follows:

The technique by which the mole is built has got to be seen. A wide barge brings enormous stones right up to it and throws them in one on top of another. Their weight keeps them in position, and little by little a sort of rampart is constructed. A kind of stony hump can already be seen rising above the water which breaks the waves that beat upon it and tosses the spray high in the air with great roar; the sea all around is white with foam. Masses of concrete will be laid on top of the stones, and as time passes it will come to resemble an island.

Portus Claudius (Suétone, Claude, 20)

En fait de travaux publics, il s'attacha moins à en exécuter un grand nombre qu'à entreprendre ceux qui étaient nécessaires. Parmi les principaux on compte l'aqueduc commencé par Caius, le canal d'écoulement du lac Fucin et le port à Ostie. Il savait qu'Auguste avait refusé obstinément aux Marses le dernier de ces ouvrages, et que Jules César avait souvent projeté, mais toujours remis l'autre, à cause des difficultés de l'exécution. […] En construisant le port d'Ostie, il l'entoura de deux môles à droite et à gauche, et éleva à l'entrée une digue sur un sol profond. Afin de mieux l’asseoir, il commença par submerger le navire sur lequel le grand obélisque était venu d’Égypte ;

puis il y établit des piliers, et la surmonta d'une très haute tour, semblable au phare antique d'Alexandrie, pour éclairer les vaisseaux pendant la nuit.

Portus Claudius (Dion Cassius, Histoire, 60, 11)

Une grande famine étant survenue, Claude avisa aux moyens d'avoir, non seulement dans le présent, mais aussi toujours dans l'avenir, des vivres en abondance. Presque tout le blé, en effet, que consomment les Romains étant apporté du dehors, et le pays situé à l'embouchure du Tibre, n'offrant ni rades sûres ni ports convenables, rendait inutile aux Romains l'empire de la mer ; car, excepté celui qui arrivait dans la belle saison et qu'on portait dans les greniers, il n'en venait point l'hiver, et, si quelqu'un essayait d'en amener, la tentative réussissait mal. Claude, comprenant ces difficultés, entreprit de construire un port, sans se laisser détourner de son projet par les architectes, qui, lorsqu'il leur demanda à combien monterait la dépense, lui répondirent : « Tu ne le feras pas, » tant ils espéraient, par la grandeur de la dépense, s'il en était informé à l'avance, le forcer de renoncer à son dessein ; mais, bien loin de là, il crut la chose digne de la majesté et de la grandeur de Rome, et il la mena à son terme. Il creusa bien avant dans le rivage un espace qu'il garnit de quais, et y fit entrer la mer ; puis il jeta de chaque côté dans les flots des môles immenses, dont il entoura une grande portion de mer et y fit une île où il bâtit une tour portant des fanaux. Le Port, qui aujourd'hui conserve ce nom dans la langue du pays, fut alors construit par lui. Il voulut aussi, par la dérivation du lac Fucin dans le Liris, chez les Marses, donner les terres d'alentour à l'agriculture et rendre le fleuve plus navigable, mais ces dépenses ont été en pure perte.

Portus Claudius (Pline l'Ancien, Histoire Naturelle, 16, 76)

On a vu un sapin merveilleux, mât du vaisseau qui apporta d'Égypte, par l'ordre de l'empereur Caligula, l'obélisque, (XXXVI, 14) placé dans le cirque du Vatican, et les quatre blocs de pierre destinés à le soutenir. On n'a certainement rien vu en mer de plus admirable que ce navire ; cent vingt mille boisseaux de lentilles lui servaient de lest : la longueur en occupait en grande partie le côté gauche du port d'Ostie ; il fut coulé bas en cet endroit par l'empereur Claude avec trois môles de la hauteur d'une tour, en pouzzolane (XXXVI, 14), qui y avaient été construits, et que le navire avait apportés de Pouzzoles. Il fallait quatre hommes pour embrasser ce mât. On dit que des mâts pareils se vendent 80 000 sesterces et plus, et qu'on fait des radeaux dont le prix est ordinairement de 40 000 sesterces. En Égypte et en Syrie, les rois, manquant de sapin, se sont, dit-on, servis de cèdre pour la marine ; le plus gros cèdre dont on fasse mention venait de l'île de Chypre. Il fut abattu pour la galère à onze rangs de rames de Démétrius [Poliorcète]; il avait cent trente pieds de long, et il fallait trois hommes pour l'embrasser. Les pirates de la Germanie naviguent sur des pirogues faites avec un seul tronc d'arbre creusé ; quelques-unes de ces pirogues portent jusqu'à trente hommes.

Portus Claudius (Pline l'Ancien, Histoire Naturelle, 36, 14)

Quant au vaisseau que l'empereur Caligula avait employé pour transporter l'autre obélisque, il fut conservé pendant quelques années, c'était le bâtiment le plus merveilleux qu'on ait jamais vu en mer : l'empereur Claude le fit venir à Ostie après avoir élevé dessus des tours en terre de Pouzzoles (XXXV, 47), et le coula dans l'intérêt du port qu'il construisait. Puis il fallut faire d'autres bâtiments pour conduire l'obélisque par le Tibre, ce qui donna lieu de connaître que ce fleuve n'a pas moins d'eau que le Nil.

Portus Iulius (Dion Cassius, Histoire, 48, 50)

A Cumes, en Campanie, entre Misène et Pouzzoles, est une plaine en forme de croissant ; elle est entourée de montagnes peu élevées et nues, à l'exception d'un petit nombre, et renferme trois lacs sinueux. Le premier est en dehors de la plaine et près des villes ; le second n'est séparé du précédent que par une étroite langue de terre ; le troisième, sorte de marécage, se voit au fond même du croissant. On l'appelle Averne, et celui du milieu Lucrin ; quant à celui qui est en dehors de la Tyrrhénie, il s'étend jusqu'à cette contrée, et en tire son nom. Dans le lac du milieu, Agrippa ayant, par des ouvertures étroites pratiquées le long du continent, coupé l'espace qui des deux côtés séparait le Lac Lucrin de la mer, en fit un port commode pour les vaisseaux. [cf Oleson, 2014, Fig. 4.32 – p 82).

Portus Iulius (Suétone, Auguste, 16)

Mais, quand il eut fait reconstruire ses vaisseaux, quand il eut transformé en matelots vingt mille esclaves affranchis, il créa le port de Jules dans le voisinage de Baïes, et introduisit la mer dans le lac Lucrin et dans l'Averne.

Brindes (Cesar, Guerre civile, 1, 25)

César, craignant que Pompée ne voulût pas quitter l'Italie, résolut de fermer la sortie du port de Brindes, et d'empêcher le service. (5) Voici les travaux qu'il fit pour cela. Là où l'entrée du port était le plus resserrée, il jeta aux deux côtés du rivage un môle et des digues, chose que les bas-fonds rendaient facile en cet endroit. (6) Plus loin, comme la digue ne pouvait se maintenir à cause de la profondeur des eaux, il plaça, à trente pieds des digues, (7) deux radeaux qu'il fixa aux quatre angles par des ancres, pour que les vagues ne pussent les ébranler. (8) Quand ces radeaux furent posés et établis, il en ajouta d'autres de pareille grandeur, (9) et les couvrit de terre et de fascines, afin qu'on pût marcher dessus librement quand il s'agirait de les défendre. Sur le front et sur les côtés, il les garnit de parapets et de claies ; (10) et de quatre en quatre de ces radeaux il éleva des tours à deux étages, pour les mieux garantir de l'attaque des vaisseaux et de l'incendie.

Hereum Promontorium (Fenerbahce, Chalcédoine) (Procope, Edifices, 1, 11)

L'Empereur [Justinien] a élevé deux autres Palais l'un à Héréum, et l'autre à Jucondienne[?], desquels la magnificence ne peut être égalée par mon discours. Il suffit de dire qu'ils ont été bâtis en sa présence, que ses pensées enchérissaient sur les dessins des Architectes, qu'il n'oubliait rien de ce qui pouvait contribuer à leur beauté, et que pour cela il ne méprisait rien que l'argent, dont il faisait une profusion incroyable. Il fît faire un nouveau Port dans le même endroit. Comme l'ancien était exposé à la violence des vents et des tempêtes, il y remédia de la manière que je vais dire. Il fit jeter quantité de caisses des deux côtés dans le fond, et il éleva par ce moyen deux moles jusqu'à la surface de l'eau, au-dessus desquels il posa des roches pour résister à l'impétuosité des vagues. Ainsi il rendit ce Port fort sûr, même pendant l'hiver, et durant les plus furieuses tempêtes. Nous avons vu comme il construisît au même lieu des Eglises, des galeries, des bains et d'autres Edifices qui ne cèdent à ceux de Constantinople ni en grandeur, ni en beauté. Il fit encore près d'Héréum un autre port sur le rivage d'Eutrope.

Une traduction en anglais parait plus claire (Henry Bronson Dewing, 1940, vol VII Loeb Classical Library) :

He prepared great numbers of what are called "chests" or cribs [caissons], of huge size, and threw them out for a great distance from the shore along oblique lines on either side of the harbour, and by constantly setting a layer of other chests in regular courses upon those underneath he erected two very long walls, which lay at an angle to each other on the opposite sides of the harbour, rising from their foundations deep in the water up to the surface on which the ships float. Then upon these walls he threw rough-cut stones, which are pounded by the surf and beat back the force of the waves; and even when a severe storm comes down in the winter, the whole space between the walls remains calm, a single entrance being left between the breakwaters for the ships to enter the harbour. […] And he also constructed another harbour on the opposite mainland, in the place which bears the name of Eutropius, not far distant from this Heraeum, executed in the same manner as the harbour which I have just mentioned.

Passage de Xerxès sur l’Hellespont (Hérodote, Histoire, 7, 34-37)

Ceux que le roi avait chargés de ces ponts les commencèrent du côté d'Abydos, et les continuèrent jusqu'à cette côte, les Phéniciens en attachant des vaisseaux avec des cordages de lin, et les Égyptiens en se servant pour le même effet de cordages d'écorce de Byblos. Or, depuis Abydos jusqu'à la côte opposée, il y a un trajet de sept stades. Ces ponts achevés, il s'éleva une affreuse tempête qui rompit les cordages et brisa les vaisseaux.
À cette nouvelle, Xerxès, indigné, fit donner, dans sa colère, trois cents coups de fouet à l'Hellespont, et y fit jeter une paire de ceps. J'ai ouï dire qu'il avait aussi envoyé avec les exécuteurs de cet ordre des gens pour en marquer les eaux d'un fer ardent. Mais il est certain qu'il commanda qu'en les frappant à coups de fouet, on leur tint ce discours barbare et insensé : « Eau amère et salée, ton maître te punit ainsi parce que lu l'as offensé sans qu'il t'en ait donné sujet. Le roi Xerxès te passera de force ou de gré. C'est avec raison que personne ne t'offre des sacrifices, puisque tu es un fleuve trompeur et salé. » Il fit ainsi châtier la mer, et l'on coupa par son ordre la tête à ceux qui avaient présidé à la construction des ponts.
Ceux qu'il avait chargés de cet ordre barbare l'ayant exécuté, il employa d'autres entrepreneurs à ce même ouvrage. Voici comment ils s'y prirent. Ils attachèrent ensemble trois cent soixante vaisseaux de cinquante rames et des trirèmes, et de l'autre côté trois cent quatorze. Les premiers présentaient le flanc au Pont-Euxin, et les autres, du côté de l'Hellespont, répondaient au courant de l'eau, afin de tenir les cordages encore plus tendus. Les vaisseaux ainsi disposés, ils jetèrent de grosses ancres, en partie du côté du Pont-Euxin pour résister aux vents qui soufflent de cette mer, en partie du côté de l'occident et de la mer Égée, à cause des vents qui viennent du sud et du sud-est. Ils laissèrent aussi en trois endroits différents un passage libre entre les vaisseaux à cinquante rames pour les petits bâtiments qui voudraient entrer dans le Pont-Euxin ou en sortir. Ce travail fini, on tendit les câbles avec des machines de bois qui étaient à terre. On ne se servit pas de cordages simples, comme on avait fait la première fois, mais on les entortilla, ceux de lin blanc deux à deux, et ceux d'écorce de Byblos quatre à quatre. Ces câbles étaient également beaux et d'une égale épaisseur, mais ceux de lin étaient à proportion plus forts, et chaque coudée pesait un talent. Le pont achevé, on scia de grosses pièces de bois suivant la largeur du pont, et on les plaça l'une à côté de l'autre dessus les câbles qui étaient bien tendus. On les joignit ensuite ensemble, et lorsque cela fut fait, on posa dessus des planches bien jointes les unes avec les autres, et puis on les couvrit de terre qu'on aplanit. Tout étant fini, on pratiqua de chaque côté une barrière, de crainte que les chevaux et autres bêtes de charge ne fussent effrayés en voyant la mer.

Ephèse (Strabon, Géographie, 14, 1)

La ville [d'Ephèse] possède un arsenal et un port. Malheureusement les architectes ont été trop prompts à partager l'erreur de leur maître, et, mal à propos, ils ont rétréci l'entrée du port. Attale Philadelphe (car c'est de lui qu'il s'agit) s'était imaginé que, pour rendre accessibles aux plus forts vaisseaux marchands l'entrée du port et le port lui-même, sujet, jusque-là à s'envaser par suite des dépôts ou atterrissements du Caystre, il suffisait d'augmenter la profondeur d'eau en barrant par une digue une partie de l'entrée, ladite entrée se trouvant être exceptionnellement large, et il avait en conséquence ordonné la construction de cette digue. Mais ce fut le contraire justement qui arriva : désormais retenu en dedans de la digue, le limon déposé par le fleuve accrut rapidement le nombre et l'étendue des bas-fonds, qui finirent par gagner même l'entrée du port, tandis qu'auparavant les débordements de la mer et le mouvement alternatif du flux et du reflux réussissaient jusqu'à un certain point à enlever ces dépôts de limon et à les entraîner au large.

Samos (Hérodote, Histoire, 3, 60)

[…] un môle, ou une grande digue faite dans la mer, près du port, d'environ vingt orgyies de haut et de deux stades et plus de long. […]

Prise de Tyr (Quinte Curce, Histoires, 4, 2)

Tyr, en effet, est séparée du continent par un détroit de quatre stades, exposé surtout au souffle de l'Africus, qui fait rouler sur le rivage les flots amoncelés de la haute mer. Nul

obstacle, plus que ce vent, n'était fait pour contrarier les ouvrages par lesquels les Macédoniens se préparaient à joindre l'île au continent: car à peine une jetée peut-elle se construire dans une mer tranquille et unie; mais, quand les vagues sont soulevées par l'Africus, leur choc va renverser les premiers matériaux entassés; et il n'est point de digue si solide que ne minent les eaux; en se faisant jour à travers les jointures, et en se répandant par-dessus tout l'ouvrage, si le vent souffle avec plus de violence. À cette difficulté s'en joignait une autre non moins grande: les murs et les tours de la ville étaient entourés d'une mer très profonde; ni les machines ne pouvaient jouer, si ce n'est de loin et sur des vaisseaux; ni les échelles ne pouvaient s'appliquer aux murailles: le mur qui descendait à pic dans les eaux interdisait toute approche par terre; et pour des vaisseaux, le roi n'en avait pas; et quand il en eût fait approcher, ballottés et incertains dans leurs manœuvres, les projectiles de l'ennemi pouvaient les repousser. […] alors il [Alexandre] résolut de faire le siège de la ville.
Mais il fallait, avant tout, jeter une chaussée qui la joignit au continent. Un violent désespoir s'empara des soldats à la vue de cette profonde mer, qu'à peine la puissance divine était capable de combler. Où trouver des pierres assez grosses, des arbres assez grands ? Il faudrait épuiser des contrées entières pour convertir en chaussée un pareil abîme ; la mer était toujours agitée dans ce détroit, et, plus elle roulait ses flots à l'étroit entre l'île et le continent, plus elle était furieuse. […] On avait sous la main un amas considérable de pierres, fourni par l'ancienne Tyr ; le bois nécessaire pour construire les radeaux et les tours était apporté du mont Liban. Déjà l'ouvrage s'élevait du fond de la mer à une certaine hauteur, sans cependant se trouver encore à fleur d'eau, et, à mesure que la chaussée s'éloignait du rivage, la mer, devenant plus profonde, absorbait en plus grande quantité les matériaux que l'on y jetait. […]
Du reste, l'incendie ne causa pas seul la ruine des ouvrages ; le hasard voulut que ce même jour un vent violent poussât contre la chaussée la mer soulevée dans ses profondeurs ; le battement redoublé des flots en relâcha les jointures, et l'eau, se faisant jour à travers les pierres, rompit l'ouvrage par le milieu. Lorsque se furent ainsi écroulés les monceaux de pierres sur lesquels la terre avait été jetée, et qui la soutenaient, tout fut en un instant englouti, et de ce travail gigantesque à peine restait-il quelques vestiges […]
Le roi entreprit aussitôt l'œuvre d'une nouvelle jetée; et cette fois il l'opposa, non de flanc, mais de front au vent: elle devait ainsi protéger les autres travaux, cachés, pour ainsi dire, sous son ombre; il donna aussi à la chaussée plus de largeur, afin que les tours élevées au milieu fussent hors de la portée du trait. Des arbres entiers, avec leurs grandes branches, étaient jetés dans la mer, et ensuite chargés de pierres : sur ce premier entassement, on jetait de nouveaux arbres ; on y amassait alors de la terre, et après un dernier amoncellement de pierres et d'arbres, on était parvenu à faire en quelque sorte une construction d'une seule pièce. […]

Caesarea Maritima (Flavius, Guerre des juifs, 1, 21)

Bien que le terrain contrariât tous ses projets, il combattit si bien les obstacles, qu'il garantit contre les attaques de la mer la solidité de ses constructions, tout en leur donnant une beauté qui éloignait toute idée de difficulté. En effet, après avoir mesuré pour le port la superficie que nous avons indiquée, il fit immerger dans la mer, jusqu'à une profondeur de vingt brasses, des blocs de pierre dont la plupart mesuraient cinquante pieds de longueur, neuf de hauteur et dix de largeur ; quelques-uns même étaient plus grands encore. Quand le fond eut été ainsi comblé, il dressa sur ces assises, au-dessus de l'eau, un môle large de deux cents pieds : la moitié, cent pieds, servait à recevoir l'assaut des vagues, - d'où son nom de 'brise-lames' - le reste soutenait un mur de pierre, qui faisait tout le tour du port ; de ce mur surgissaient, de distance en distance, de hautes tours dont la plus grande et la plus magnifique fut appelée Drusion, du nom du beau-fils de l'empereur.
Il ménagea dans le mur un grand nombre de chambres voûtées, où s'abritaient les marins qui venaient jeter l'ancre : toute la terrasse circulaire, courant devant ces arcades, formait un large promenoir pour ceux qui débarquaient. L'entrée du port s'ouvrait au nord, car, dans ces parages, c'est le vent du nord qui est, de tous, le plus favorable. Dans la passe on voyait de chaque côté trois colosses, étayés sur des colonnes ; ceux que les navires entrants avaient à

bâbord s'élevaient sur une tour massive, ceux à tribord sur deux blocs de pierre dressés et reliés entre eux, dont la hauteur dépassait celle de la tour vis-à-vis. Adjoignant au port on voyait des édifices construits eux aussi en pierre blanche, et c'était vers le port que convergeaient les rues de la ville, tracées à des intervalles égaux les unes des autres. En face de l'entrée du port s'élevait sur une éminence le temple d'Auguste, remarquable par sa beauté et sa grandeur ; il renfermait une statue colossale de l'empereur, qui ne le cédait point à celle du Zeus d'Olympie dont elle était inspirée, et une statue de Rome, semblable à celle d'Héra, à Argos. Hérode dédia la ville à la province, le port à ceux qui naviguaient dans ces parages, à César la gloire de cette fondation ; aussi donna-t-il à la cité le nom de Césarée.

Caesarea Maritima (Flavius, Antiquités judaïques, 15, 9)

6. Il avait remarqué sur le bord de la mer un emplacement tout à fait propre à la fondation d'une ville : c'était le lieu autrefois appelé Tour de Straton. Il dressa un plan grandiose de la ville même et de ses édifices et la construisit entièrement, non pas de matériaux quelconques, mais en pierre blanche. [332] Il l'orna de palais somptueux et de monuments à l'usage du public ; et, ce qui fut le plus important et exigea le plus de travail, la pourvut d'un port, parfaitement abrité, aussi grand que le Pirée, avec des quais de débarquement à l'intérieur et un second bassin. Le plus remarquable dans la construction de cet ouvrage, c'est qu'Hérode ne trouva sur les lieux mêmes aucune facilité pour le mener à bien, et qu'on ne put l'achever qu'avec des matériaux amenés à grands frais du dehors. La ville est, en effet, située en Phénicie, sur la route maritime d'Égypte, entre Jopé et Dora, petites marines, d'accès difficile à cause du régime des vents de sud-ouest qui arrivent du large, chargés de sable dont ils couvrent le rivage, entravant le débarquement, si bien que le plus souvent les marchands sont obligés de jeter l'ancre en pleine mer. Hérode remédia aux inconvénients de ce régime ; il traça le port en forme circulaire, de façon que de grandes flottes pussent mouiller tout près du rivage, immergeant à cet effet des rochers énormes jusqu'à une profondeur de vingt brasses ; ces rochers avaient pour la plupart cinquante pieds de longueur, au moins dix-huit de largeur et neuf d'épaisseur, quelques-uns plus, d'autres moins. Le môle, bâti sur ces fondements, qu'il projeta dans la mer, avait une longueur de deux cents pieds. La moitié, véritable rempart contre la grosse mer, était destinée à soutenir l'assaut des flots qui venaient s'y briser de tous côtés ; on l'appela donc le brise-lames. Le reste soutenait un mur de pierre coupé de distance en distance par des tours dont la plus grande s'appelle Drusus, très bel ouvrage, tirant son nom de Drusus, beau-fils de César, mort jeune. On construisit une série d'abris voûtés pour servir d'asile aux matelots ; sur le devant, on traça un large quai de débarquement, enveloppant dans son pourtour le port tout entier et offrant une promenade charmante. L'entrée et l'ouverture du port se trouvaient exposées au vent du nord, qui est le plus favorable. A l'extrémité de la jetée, à gauche de l'entrée, s'élevait une tour (bourrée de pierres ?), pouvant opposer une forte résistance ; à droite se dressaient, reliés entre eux, deux énormes piédestaux, plus grands que la tour d'en face. Tout autour du port est une suite ininterrompue de bâtiments construits en pierre soigneusement polie ; au centre est une colline sur laquelle on bâtit le temple de César, visible de loin pour les navigateurs et renfermant les statues de Rome et de César. La ville elle-même reçut le nom de Césarée ; elle est remarquable par la qualité des matériaux employés et le soin apporté à la construction. Les souterrains et les égouts construits sous la ville ne furent pas moins soignés que les édifices élevés au-dessus d'eux. Les uns, espacés à intervalles réguliers, aboutissent au port et à la mer ; un autre, transversal, les réunit tous de façon à emporter facilement les pluies et les immondices et à permettre à la mer, lorsqu'elle est poussée par le vent du large, de s'étendre et de laver en dessous la ville entière. Hérode bâtit aussi un théâtre de pierre et, au sud du port et en arrière, un amphithéâtre pouvant contenir un très grand nombre de spectateurs et parfaitement situé, avec vue sur la mer. La ville fut terminée en douze ans, car le roi ne souffrit aucune interruption dans les travaux et n'épargna aucune dépense.

Alexandrie (Strabon, Géographie, 17, 1)

La passe ou ouverture de l'ouest, sans être non plus d'un accès très facile, n'exige pourtant pas les mêmes précautions. Elle aussi forme proprement un port, un second port dit de l'Eunostos ; mais elle sert plutôt de rade au port fermé, bassin intérieur creusé de main d'homme. Le grand port est celui dont la tour du Phare domine l'entrée, et les deux autres ports lui sont comme adossés, la digue ou chaussée de l'Heptastade formant la séparation. Cette digue n'est autre chose qu'un pont destiné à relier le continent à la partie occidentale de l'île ; seulement, on y a ménagé deux ouvertures donnant accès aux vaisseaux dans l'Eunostos et pouvant être franchies par les piétons au moyen d'une double passerelle. Ajoutons que la digue à l'origine ne devait pas faire uniquement l'office de pont conduisant dans l'île ; elle devait aussi, quand l'île était habitée, servir d'aqueduc. Mais depuis que le divin César, dans sa guerre contre les Alexandrins, a dévasté l'île pour la punir d'avoir embrassé le parti des rois, l'île n'est plus qu'un désert et c'est à peine si quelques familles de marins y habitent, groupées au pied du Phare.
Grâce à la présence de la digue et à la disposition naturelle des lieux, le grand port a l'avantage d'être bien fermé ; il en a encore un autre, celui d'avoir une si grande profondeur d'eau jusque sur ses bords, que les plus forts vaisseaux peuvent y accoster les échelles mêmes du quai. Et comme il se divise en plusieurs bras, ces bras forment autant de ports distincts.

Alexandrie (Pline l'Ancien, Histoire Naturelle, 36, 18)

Un autre monument qu'on vante, c'est la tour faite par un roi dans l'île de Pharos, à l'entrée du port d'Alexandrie. Elle coûta, dit-on 800 talents (600 000 €). A ce propos je ne dois pas omettre la magnanimité du roi Ptolémée, qui permit à l'architecte Sostrate de Cnide d'inscrire son nom sur l'édifice même. Ce phare sert à signaler par son feu aux navires, dans leur marche nocturne, les bas-fonds et l'entrée du port. De pareils feux sont allumés aujourd'hui en divers lieux, tels qu'Ostie et Ravenne. Le risque est de prendre pour une étoile ces feux non interrompus, parce que de loin ils en ont l'aspect. C'est ce même architecte qui passe pour avoir le premier exécuté un promenoir suspendu, lequel est à Cnide.

Alexandrie (Athénée de Naucratis, Le Banquet des Savants, 5, 9)

[…] Ce vaisseau [la « 40 » de Ptolémée Philopator] avait été tiré à l'eau, de dessus un chantier où il était entré la quantité de bois qu'il fallait pour construire cinquante vaisseaux à cinq files de rameurs. C'était aux clameurs d'une foule immense, et au son des trompettes qu'on l'avait amené à l'eau ; mais un Phénicien imagina ensuite le moyen de l'en retirer (et de le remettre à flot). Il fit creuser près du port une fosse profonde [forme de radoub, dry-dock], de la longueur du vaisseau, et poser au fond de chaque côté, à la hauteur de cinq coudées, une bâtisse de pierres très solides, faisant entrer de chaque côté de grosses poutres qui traversaient la fosse, et toutes l'une à côté de l'autre. Il laissa sous ces pièces de bois un espace vide de quatre coudées entre le lit de la fosse ; puis y introduisant l'eau de la mer, il en remplit toute la capacité ; de sorte que, par ce moyen, les premiers qui se trouvaient là pouvaient, en se réunissant à nombre suffisant, y faire entrer le vaisseau. Dès qu'il y était, il fermait l'ouverture de la fosse, en retirait l'eau avec des pompes, et, cela fait, le vaisseau demeurait en sûreté sur cette espèce de plate-forme que faisaient les poutres transversales.

Carthage (Appien, Libyca, Livre 8 : le Livre Africain, chap. 96)

[…] Les ports de Carthage étaient disposés de telle sorte que les navires passaient de l'un dans l'autre; de la mer, on pénétrait par une entrée, large de 70 pieds, qui se fermait avec des chaînes de fer. Le premier port, réservé aux marchands, était pourvu d'amarres nombreuses et variées. Au milieu du port intérieur était une île. L'île et le port étaient bordés de grands quais. Tout le long de ces quais, il y avait des loges, faites pour contenir 220 vaisseaux, et, au-dessus des loges, des magasins pour les agrès. En avant de chaque loge s'élevaient deux colonnes ioniques qui donnaient à la circonférence du port et de l'île l'aspect d'un portique. Sur l'île on avait construit pour l'amiral un pavillon d'où partaient les signaux des trompettes et les appels des hérauts et d'où l'amiral exerçait sa surveillance. L'île était située en face de l'entrée et elle s’élevait fortement : ainsi l’amiral voyait ce qui se passait en mer tandis que ceux qui venaient du large ne pouvaient pas distinguer nettement l’intérieur du port. Même pour les marchands qui entraient sur leurs vaisseaux, les arsenaux restaient invisibles : ils étaient en effet entourés d’un double mur et de portes qui permettaient aux marchands de passer du premier port dans la ville sans qu’ils eussent à traverser les arsenaux. […]

Le sable (Vitruve, de Architectura, 2, 4, traduction Ch. Maufras, 1848)

1. Dans les constructions en moellon, le point le plus important est de s'assurer si le sable est d'une qualité propre à entrer dans la confection du mortier, s'il ne renferme point de matières terreuses. Il y a quatre espèces de sable fossile : le noir, le blanc, le rouge et le carboncle. De ces espèces la meilleure sera celle qui, frottée dans la main, aura produit un bruit sonore. Celui qui est terreux, qui n'est point rude au toucher, est mauvais ; mais celui qui, ayant été lancé contre un vêtement blanc, en est ensuite secoué ou enlevé à l'aide d'une baguette, sans y faire de tache, sans y laisser trace de terre, est excellent.

2. S'il n'y avait point de sablière d'où l'on pût retirer du sable fossile, on irait prendre au fond des rivières du gravier, dont on ferait disparaître tout corps étranger au sable ; les bords de la mer pourraient encore être mis à contribution. Pourtant le sable marin a le défaut de sécher difficilement, et d'empêcher qu'on ne bâtisse sans intermittence une muraille qui ne pourrait porter une grande charge, si on ne la maçonnait à plusieurs reprises pour lui donner le temps de se consolider ; il n'entre point dans la construction des voûtes. Il y a de plus que les murs dont le crépi a été fait avec de la chaux mêlée de ce sable, se remplissent de salpêtre, sont toujours humides, et finissent par s'en dégarnir.

3. Le mortier de sable fossile sèche, au contraire, promptement ; il dure longtemps dans les crépis et est très solide dans les plafonds, surtout quand le sable est nouvellement extrait des sablières : car s'il reste longtemps dehors sans être mis en œuvre, le soleil et la lune l'altèrent, le givre le dissout, et il devient terreux. Lorsque dans cet état il est employé dans la maçonnerie, les moellons ne peuvent tenir ; ils se détachent, ils tombent ; les murs ne sont point capables de soutenir un grand poids. Toutefois le sable fossile nouvellement extrait, bien qu'il convienne parfaitement à la maçonnerie, n'est pas aussi avantageux pour les crépis, parce qu'il est si gras et sèche si vite, que, mêlé à la chaux avec de la paille, il fait un mortier qui ne peut durcir sans se gercer. Mais le sable de rivière à cause de sa maigreur, quand il a été, comme le ciment, bien corroyé, bien battu, donne au crépi une grande solidité.

La chaux (Vitruve, de Architectura, 2, 5, traduction Ch. Maufras, 1848)

1. Après avoir expliqué de quelle utilité pouvaient être les différentes espèces de sable, il faut maintenant nous occuper de la chaux, et voir si elle doit être faite avec des pierres blanches ou des cailloux. Celle qu'on fait avec une pierre dure et compacte est bonne pour la maçonnerie ; celle que fournit une pierre spongieuse vaut mieux pour les enduits. Quand la chaux sera éteinte, il faudra la mêler avec le sable : si c'est du sable fossile, dans la proportion de trois parties de sable et d'une de chaux ; si c'est du sable de rivière ou de mer, dans la proportion de deux parties de sable sur une de chaux : c'est là la juste proportion de leur mélange. Si au sable de rivière ou de mer on voulait ajouter une troisième partie de tuileaux pilés et sassés, on obtiendrait un mélange d'un usage encore meilleur.

2. Pourquoi la chaux, en se mêlant à l'eau et au sable, donne-t-elle à la maçonnerie tant de solidité ? En voici, je crois, la raison. Les pierres, comme tous les autres corps, sont composées des éléments ; celles qui contiennent ou plus d'air, ou plus d'eau, ou plus de terre, ou plus de feu, sont ou plus légères, ou plus molles, ou plus dures, ou plus fragiles. Remarquons que si des pierres, avant d'être cuites, ont été pilées et mêlées à du sable, puis employées dans une construction, elles ne prennent aucune consistance et ne peuvent en lier la maçonnerie ; mais que si, jetées dans un four, elles viennent à perdre leur première solidité par l'action violente du feu auquel elles sont soumises, alors, par suite de cette chaleur qui en consume la force, elles se remplissent d'une infinité de petits trous. Ainsi l'humidité répandue dans ces pierres ayant été absorbée, et l'air qu'elles contenaient s'étant retiré, ne renfermant plus alors que la chaleur qui y reste cachée, qu'on vienne à les plonger dans l'eau avant que cette chaleur ne soit

dissipée, elles reprennent leur force : l'eau qui y pénètre de tous côtés produit une ébullition ; puis le refroidissement fait sortir de la chaux la chaleur qui s'y trouvait.

3. Voilà pourquoi le poids des pierres à chaux, au moment où on les jette dans le four, ne peut plus être le même quand on les en retire : si on les pèse après la cuisson, on les trouvera, bien qu'elles aient conservé le même volume, diminuées environ de la troisième partie de leur poids. Ainsi, grâce à tous ces trous, à tous ces pores, elles se mêlent promptement au sable, y adhèrent fortement, s'attachent en séchant aux moellons, et donnent à la maçonnerie une grande solidité.

Le mortier, la chaux (Pline l'Ancien, Histoire Naturelle, 36, 52-54)

Pour la construction des citernes il faut cinq parties de sable pur et graveleux, sur deux parties de la chaux la plus vive, et des fragments de silex pesant au plus une livre. Ainsi établis, on foule le fond et les parois avec des maillets ferrés. Le mieux est d'avoir des citernes doubles, de façon que les impuretés s'arrêtent dans la première, et que, se filtrant, l'eau passe aussi pure que possible dans la seconde.

Caton le Censeur (De re rustic. XXXVIII) n'approuve point la chaux faite de pierres de différentes couleurs. La pierre blanche donne la meilleure. La chaux faite de pierres dures vaut mieux pour les bâtisses ; celle de pierres poreuses, pour les enduits. Pour ces deux emplois on rejette la chaux faite avec la silice. La pierre extraite des carrières fournit de meilleure chaux que celle qu'on prend sur les rives des fleuves. La chaux de la pierre meulière est la meilleure, parce que cette pierre est naturellement plus grasse que les autres. Chose singulière, de voir une substance qui, ayant passé par le feu, s'allume dans l'eau !

Il y a trois espèces de sable : le fossile, auquel on doit ajouter un quart de chaux, le fluvial et le marin, auxquels en doit en ajouter un tiers. L'addition d'un tiers de poterie pilée rend le mortier meilleur. De l'Apennin au Pô, on ne trouve pas de sable fossile, non plus qu'au-delà des mers.

La pouzzolane (Vitruve, de Architectura, 2, 6, traduction Ch. Maufras, 1848)

1. Il existe une espèce de poudre à laquelle la nature a donné une propriété admirable. Elle se trouve au pays de Baïes et dans les terres des municipes qui entourent le mont Vésuve. Mêlée avec la chaux et le moellon, non seulement elle donne de la solidité aux édifices ordinaires, mais encore les môles qu'elle sert à construire dans la mer acquièrent sous l'eau une grande consistance. Voici comment j'en explique la cause. Sous ces montagnes et dans tout ce territoire, il y a un grand nombre de fontaines bouillantes ; elles n'existeraient pas, s'il ne se trouvait au fond de la terre de grands feux produits par des masses de soufre, ou d'alun, ou de bitume en incandescence. La vapeur qui s'exhale de ces profonds réservoirs de feu et de flamme, se répandant brûlante par les veines de la terre, la rend légère, et le tuf qui en est produit est aride et spongieux. Ainsi, lorsque ces trois choses que produit de la même manière la violence du feu, viennent par le moyen de l'eau à se mêler et à ne plus faire qu'un seul corps, elles se durcissent promptement ; et prennent une solidité telle, que ni les flots de la mer ni la poussée des eaux ne peuvent les désunir.
2. Une chose peut faire juger que de grands feux se trouvent dans ces localités, ce sont les grottes creusées dans les montagnes de Cumes et de Baïes pour servir d'étuves. Une vapeur chaude produite par la violence du feu, s'élevant des entrailles de la terre, qu'elle pénètre, vient se répandre dans ces lieux, et est d'une très grande utilité pour ceux dont elle provoque la sueur. On rapporte aussi qu'anciennement le Vésuve sentit croître dans ses flancs des feux excessifs, et vomit la flamme sur les campagnes d'alentour. De cet embrasement sont provenues ces pierres spongieuses qu'on appelle pierres ponces pompéiennes, auxquelles, le feu, en les cuisant, a ôté leur qualité première, pour leur donner, selon toute probabilité, celle qu'elles ont aujourd'hui.
3. L'espèce de pierre ponce qu'on retire de ce lieu ne se rencontre qu'aux environs de l'Etna, dans les montagnes de Mysie, et sans doute dans quelques autres lieux dont la position est analogue : les Grecs l'appellent κεκαυμένη. Si donc on trouve dans ces endroits des fontaines d'eau bouillante ; s'il y a dans les grottes de ces montagnes des vapeurs chaudes ; si, comme nous l'apprend l'antiquité, des flammes se sont autrefois répandues sur ces contrées, tout porte

à croire que la violence du feu a enlevé au tuf et à la terre, comme il le fait à la chaux dans les fours, leurs principes humides.
4. D'où il faut conclure que des matières entièrement différentes, quand elles ont été soumises à l'action du feu, et qu'elles ont acquis une même propriété, c'est-à-dire cette sécheresse chaude qui leur fait si promptement absorber l'eau dont on les mouille, s'échauffent par la force de la chaleur que contiennent tous les corps, se lient avec ténacité, et ne tardent pas à acquérir une dureté extraordinaire. Ce raisonnement trouvera sans doute des contradicteurs : car, puisqu'il existe en Étrurie un grand nombre de fontaines d'eaux chaudes, pourquoi n'y trouve-t-on pas cette poudre qui donne sous l'eau tant de solidité à la maçonnerie ? Qu'on veuille bien, avant de me condamner, entendre mon opinion à ce sujet.
5. Dans toutes les contrées, dans tous les pays, les terres, non plus que les pierres, ne sont pas de même nature : ici vous trouvez une terre franche, là un terrain où abonde le sable ou le gravier ; ailleurs du sablon. Autant de contrées, autant de terrains qui vous offrent des différences totales. C'est ce dont vous pouvez parfaitement vous convaincre en examinant cette partie de l'Italie et de l'Étrurie qu'embrasse le mont Apennin : on y trouve presque partout de la pouzzolane ; au-delà, vers la mer Adriatique, il n'y en a point du tout. En Achaïe, en Asie et dans les pays d'outre-mer, on en ignore jusqu'au nom. Il peut donc arriver que tous les lieux où l'on voit jaillir de nombreuses fontaines d'eaux chaudes ne présentent pas les mêmes particularités : la nature, sans consulter la volonté de l'homme, étale partout où il lui plaît une fécondité aussi riche que variée.
6. Ainsi, aux lieux où les montagnes sont formées non de terre, mais de rochers, la violence du feu, en pénétrant au travers, les brûle et consume tout ce qu'il y a de mou, de tendre, sans avoir d'action sur les parties dures : de sorte que dans la Campanie, la terre brûlée devient cendre ; en Étrurie, les roches calcinées produisent le carboncle. Ces deux matières sont excellentes pour la maçonnerie ; mais l'une vaut mieux pour les constructions qui se font sur terre, l'autre pour celles qui se font dans la mer. Or, cette matière dont la nature est plus molle que celle du tuf, plus solide que celle de la terre, quand elle est brûlée par la force de la vapeur, forme clans quelques endroits cette espèce de sable qu'on appelle carboncle.

La pouzzolane (Pline l'Ancien, Histoire Naturelle, 35, 47)

Mais la terre fournit encore d'autres ressources. Qui, en effet, ne serait émerveillé de voir la partie la plus vile de la terre, celle que pour cela on appelle poussière sur les collines de Pouzzoles, être opposée aux flots de la mer, et, aussitôt après l'immersion, devenir une seule et même pierre inattaquable aux eaux, et durcissant de jour en jour, surtout si on y mêle du ciment de Cumes ? […]

Le fer (Pline l'Ancien, Histoire Naturelle, 34, 39-43)

Maintenant nous avons à parler des mines de fer, pour l'homme l'instrument le meilleur et le pire. C'est avec le fer que nous labourons la terre, que nous plantons les arbres, que nous taillons les hautains, que nous dressons les vergers, que nous forçons tous les ans la vigne à se rajeunir en retranchant les branches décrépites ; c'est avec le fer que nous bâtissons les maisons, que nous taillons les pierres, et tant d'autres services que nous en retirons. Mais c'est aussi le fer qu'on emploie pour la guerre, pour le meurtre et le brigandage, non seulement de près, mais encore lancé de loin et volant dans les airs, mu, soit par les machines, soit par le bras, et souvent même empenné. C'est là, suivant moi, de tous les méfaits de l'esprit humain le plus criminel.
Quoi ! Pour que la mort parvienne plus rapidement à l'homme, nous lui avons donné des ailes, et nous avons fait voler le fer ! Qu'ainsi le mal qu'il produit ne soit pas imputé à la nature ; et quelques faits ont prouvé que le fer pouvait ne servir qu'à des usages innocents. Dans le traité que Porsenna accorda au peuple romain après l'expulsion des rois, nous trouvons la clause expresse que les Romains n'emploieront le fer que pour la culture des champs. De très anciens auteurs disent que les stylets de fer pour l'écriture étaient regardés comme dangereux. Nous avons du grand Pompée, dans son troisième consulat, un édit qui, à propos du tumulte causé par la mort de Clodius, défend qu'il y ait aucune arme dans Rome.

Cependant, grâce à l'industrie humaine, des usages plus doux n'ont pas manqué au fer. L'artiste Aristonidas, voulant exprimer sur Athamas le repentir succédant à la fureur après qu'il a précipité son fils Léarque, mêla le cuivre et le fer, afin que la rougeur de la confusion fût rendue par la rouille qui se distinguait à travers l'éclat du cuivre : cette statue existe aujourd'hui encore à Thèbes. On a dans la même ville un Hercule de fer, œuvre d'Alcon, conduit à employer ce métal par la patience du dieu dans les travaux. Nous voyons aussi à Rome des coupes de fer consacrées dans le temple de Mars Vengeur. Autant la nature s'est montrée bonne en limitant la puissance du fer, qu'elle punit par la rouille, autant elle s'est montrée prévoyante en ne mettant entre les mains de l'homme que ce qu'il y a de plus funeste à l'humanité.

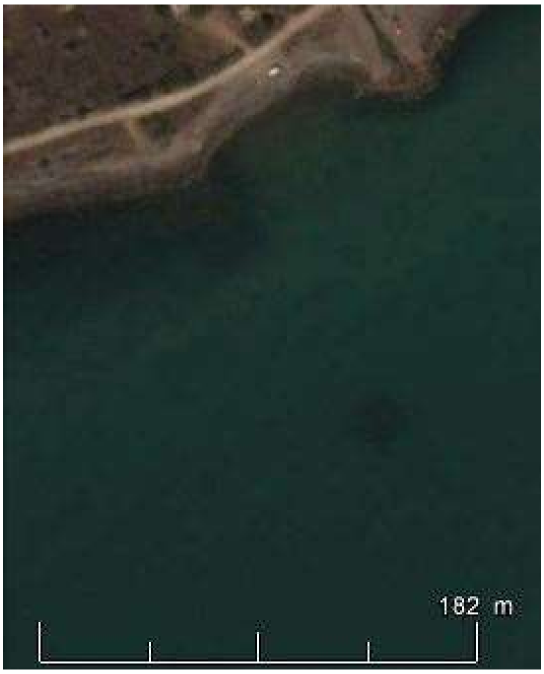
Les mines de fer se trouvent presque partout ; l'île même d'Ilva (Elbe), sur la côte d'Italie, en produit. Les terres ferrugineuses se reconnaissent sans difficulté à leur couleur. Le minerai se traite de la même manière que celui de cuivre, seulement, en Cappadoce, on se demande s'il est un présent de l'eau ou de la terre ; car ce n'est qu'arrosé avec l'eau d'un certain fleuve, que le minerai donne du fer dans les fourneaux.
Les variétés de fer sont nombreuses. La première cause en est dans les différences du sol ou du climat. Certaines terres ne donnent qu'un fer mou, et approchant du plomb ; d'autres, un fer cassant et cuivreux, détestable pour les roues et les clous, auxquels le fer mou convient ; un autre n'est bon qu'en petits morceaux : on l'emploie pour les clous des bottines ; un autre est très sujet à la rouille. Tous ces fers s'appellent strictures (*gueuses*), terme dont on ne se sert pas pour les autres métaux, et qui vient de *stringere aciem* (*tirer l'acier, fer forgé*).
Les fourneaux aussi établissent une grande différence : on y obtient un certain noyau de fer servant à fabriquer l'acier dur, ou, d'une autre façon, les enclumes compactes et les têtes de marteau. Mais la différence la plus grande provient de l'eau dans laquelle on plonge le fer incandescent : cette eau, dont la bonté varie suivant les lieux, a rendu certaines localités fameuses pour la fabrication du fer, telles que Bilbilis et Turiasson en Espagne, et Côme en Italie, bien que ces endroits n'aient pas de mines de fer. Mais de tous les fers la palme est à celui de la Sérique, qui nous l'envoie avec ses étoffes et ses pelleteries.
Le second rang appartient à celui des Parthes. Ce sont les seuls fers où il n'entre que de l'acier ; tous les autres sont mélangés d'un fer plus mou. Dans l'empire romain, en certains endroits, le filon donne du fer de cette qualité, comme en Norique ; c'est le procédé de fabrication en d'autres, comme à Sulmone ; c'est la qualité de l'eau dans les lieux que nous avons cités plus haut. Il est aussi à observer que pour aiguiser il vaut mieux arroser la pierre avec de l'huile qu'avec de l'eau : l'huile rend le tranchant plus fin. Chose singulière ! Dans la calcination du minerai, le fer devient liquide comme de l'eau, et, par le refroidissement, il devient spongieux. On est dans l'habitude d'éteindre dans l'huile les menus fragments de fer, de peur que l'eau ne les rende durs et cassants. Le sang humain se venge du fer, qui, lorsqu'il en a été mouillé, est plus promptement attaqué par la rouille.

Nous parlerons en son lieu (XXXVI, 25) de la pierre d'aimant, et de la sympathie qu'elle a pour le fer. Seul, ce métal emprunte à la pierre d'aimant des forces qu'il garde pendant longtemps, devenant capable de saisir un autre morceau de fer; et l'on peut voir retenus de la sorte toute une série d'anneaux. Le vulgaire ignorant appelle fer vif ce fer aimanté. Les blessures en sont plus dangereuses. La pierre d'aimant se trouve aussi dans la Cantabrie : non ce véritable aimant qui est en roches continues, mais un aimant en fragments disséminés qu'on nomme bullations. Je ne sais si cette espèce est aussi propre à la fusion du verre (XXXVI, 80) ; personne n'en a encore fait l'expérience ; toujours est-il qu'elle communique au fer la même force. L'architecte Dinocharès avait entrepris de faire la voûte du temple d'Arsinoé, à Alexandrie, en pierre d'aimant, afin que la statue en fer de cette princesse parût y être suspendue en l'air. La mort de l'architecte et du roi Ptolémée, qui avait ordonné le monument en l'honneur de sa sœur (VI, 12), empêcha ce projet d'être exécuté.

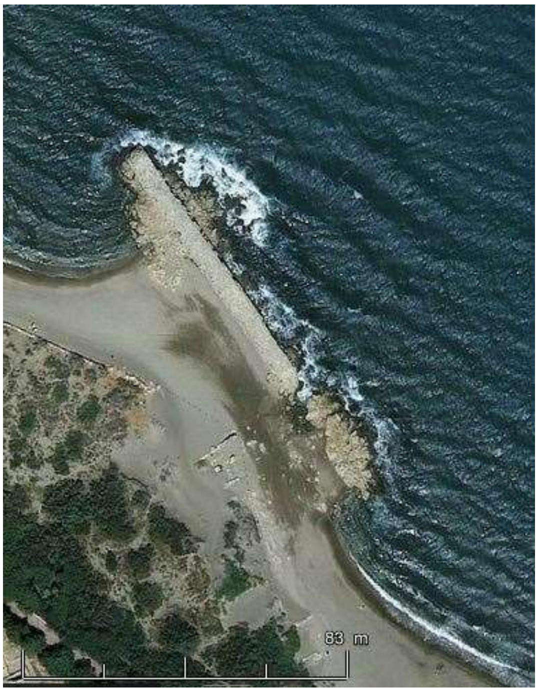
De tous les métaux c'est le fer qui est en plus grande abondance. Sur la côte de la Cantabrie que baigne l'Océan, il est une montagne très-élevée qui, chose incroyable, est tout entière de fer; nous en avons parlé en décrivant l'Océan (IV, 34). Le fer soumis à l'action du feu se gâte, si on ne le forge au marteau. Rouge, il n'est pas apte à être forgé ; il faut qu'il commence à passer au blanc. Enduit de vinaigre ou d'alun, il devient semblable au cuivre.

On le protège contre la rouille avec la céruse, le gypse et la poix liquide, préparation que les Grecs nomment antipathie. Quelques-uns prétendent qu'il y a en cela quelque cérémonie religieuse, et que dans la ville nommée Zeugma (V, 21), sur l'Euphrate, est une chaîne de fer qu'Alexandre avait employée là à la construction d'un pont, et dont les anneaux renouvelés sont attaqués par la rouille, tandis que les anneaux primitifs en sont exempts.

APPENDIX 2: Remains of submerged breakwaters on Google Earth



Saguntum, GE 2011 (Grao Vell at Sagunto, Spain)



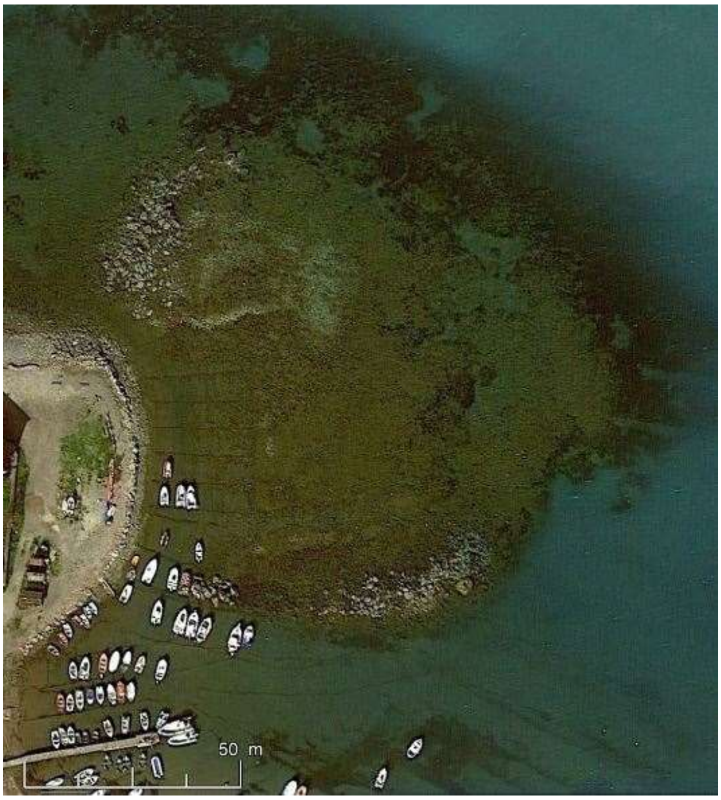
Emporia city wall, GE 2009 (Sant Marti d'Empuries, Spain)

Emporia city wall, de Graauw 2008 (Sant Marti d'Empuries, Spain)

Maritima Civitas Colonia, GE 2003 (Les Laurons, France)

Nora, GE 2013 (Capo di Pula, Sardinia)

Pisa, GE 2012 (Pisa-San Rossore, Italy)



Populonio, GE 2017 (Populonia, Italy)

Portus Domitianus, GE 2013 (Santa Liberata, Italy)

Pyrgi, GE 2006 (Santa Severa, Italy)

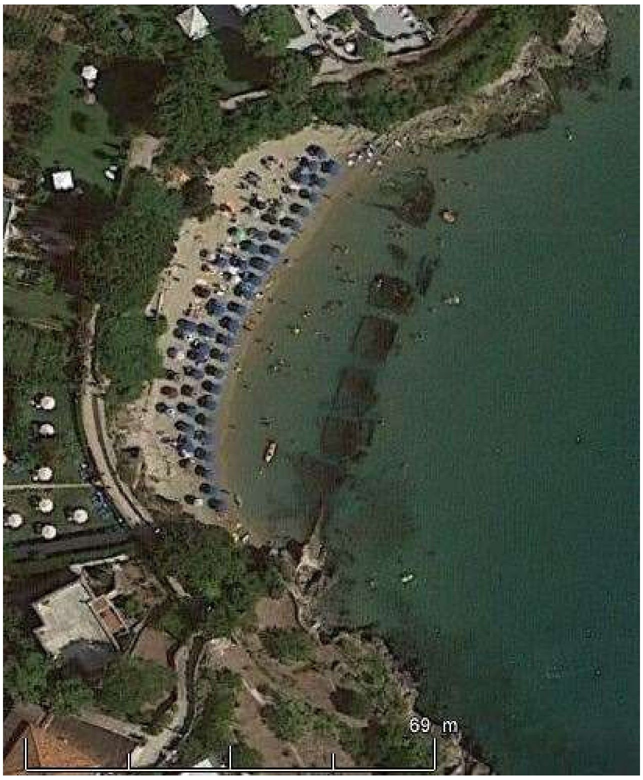
Portus, GE 2007 (Fiumicino, Italy)

Portus, de Graauw 2011 (Fiumicino, Italy)

Antium, GE 2010 (Anzio, Italy)

Astura, GE 2016 (Torre Astura, Italy)

Circei, GE 2014 (Cape Circeo, Italy)



Caieta, GE 2013 (Spiaggia di Fontania, at Gaeta, Italy)

Nesis, GE 2007 (Nisida, Italy)

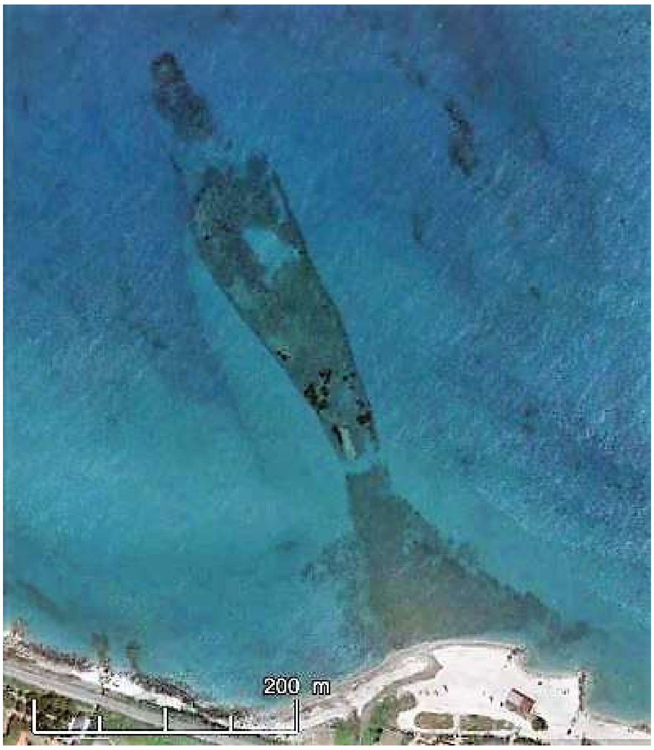
San Marco di Castellabate, GE 2007 (Italy)

Misenum, GE 2007 (Miseno, Italy)

Baiae, GE 2007 (Baia, Italy)

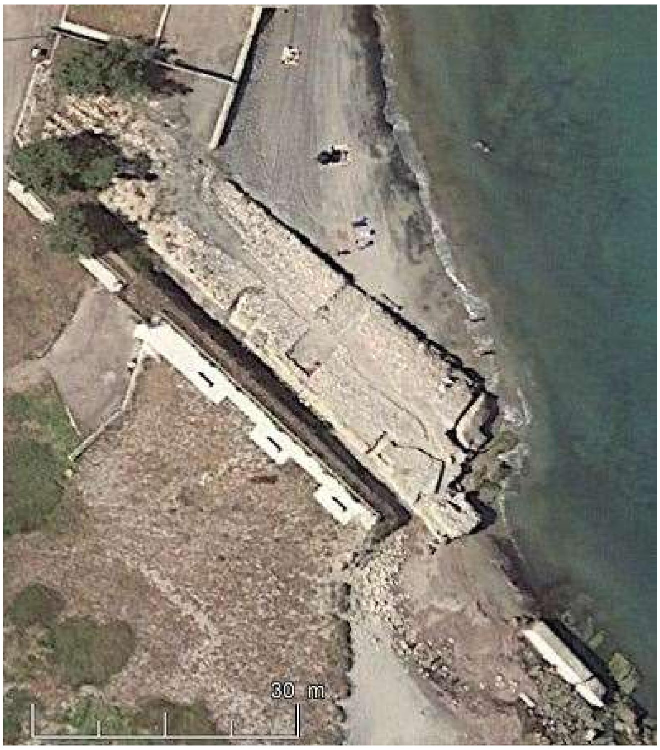
Portus Julius, GE 2007 (Lucrino, Italy)

Puteoli, GE 2017 (Pozzouli, Italy)



Hipponium, GE 2016 (Spiaggia di Trainiti, Italy)

Saturnum, GE 2015 (Torre Saturo, Italy)



Hadrianou Hormos, GE 2018 (San Cataldo, Italy)

Megara Hyblaea, GE 2007 (Banchinamento Orsi, in Augusta harbour, Sicily)

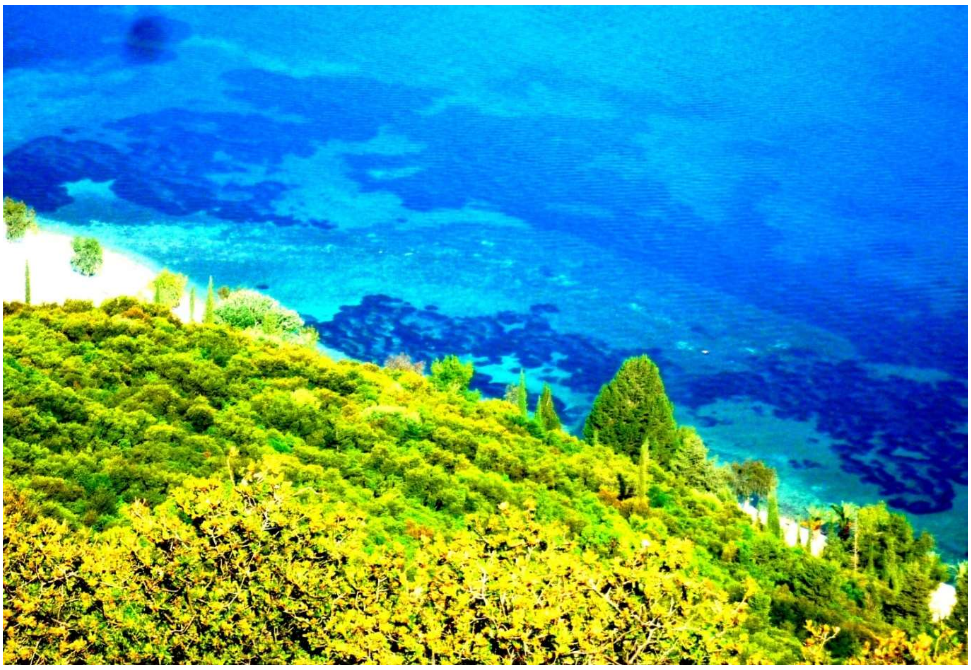
Kossura, GE 2012 (Pantelleria, Italy)

Ramla Beach, GE 2017 (Gozo, Malta)

Silvium, GE 2013 (Savudrija, Istria, Croatia)

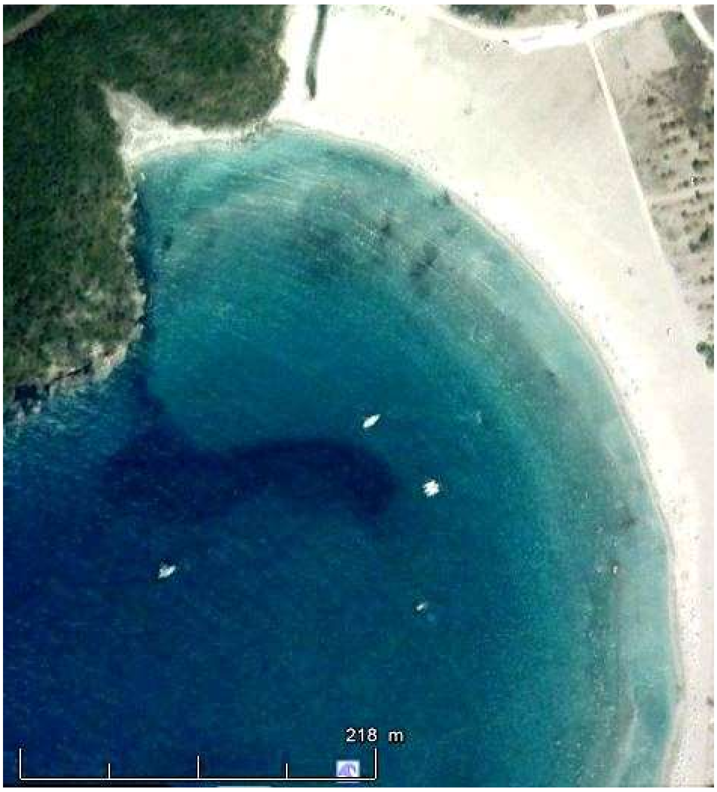
Pullaria, GE 2007 (Brioni island, Croatia)

Leukas, GE 2012 (Lefkas island, Greece)

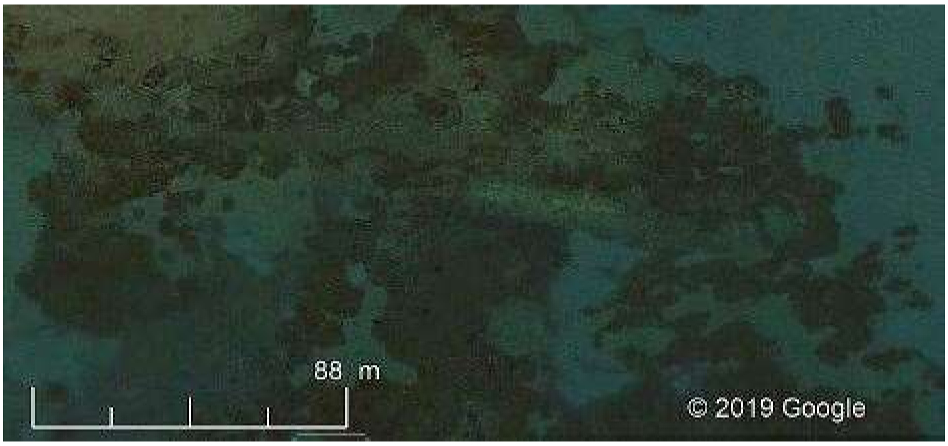


Sami, de Graauw 2013 (Kefalonia island, Greece)

Sami, GE 2017 (Kefalonia island, Greece)



Cheimerion, GE 2006 (Amoudia, Greece)



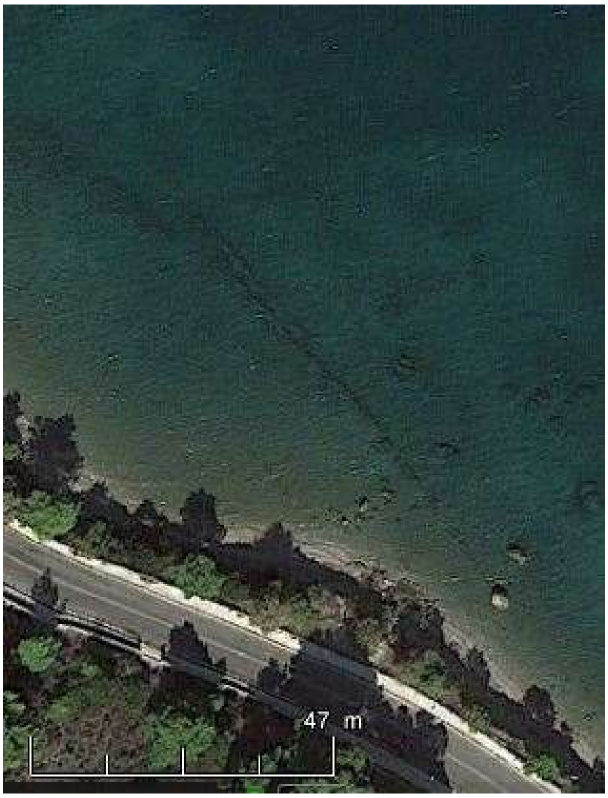
Pogonia, GE 2017 (Palairos, Greece)

Salamis, GE 2008 (Salamine island, Greece)

Delion, GE 2010 (Delesi, Greece)

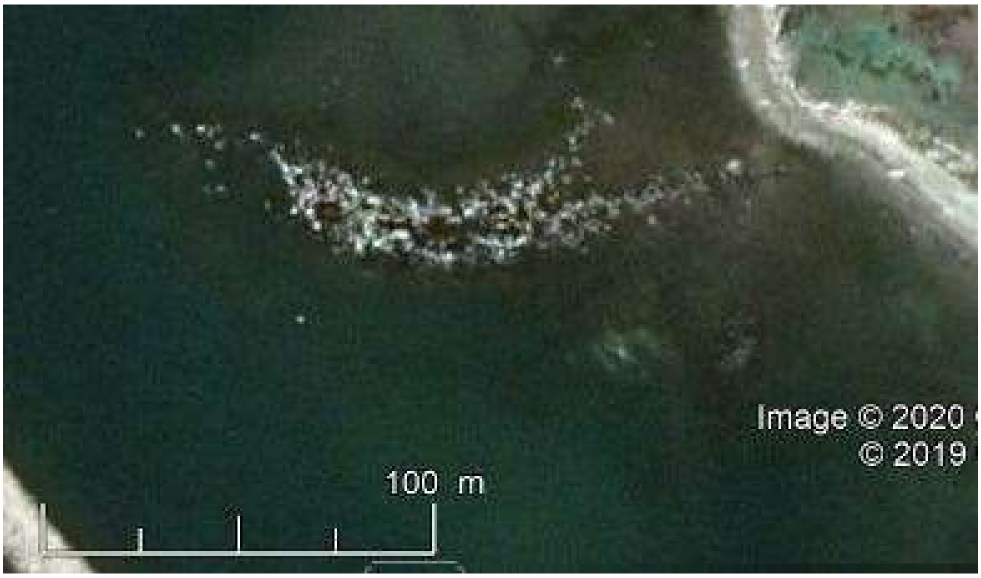
Anthedon, GE 2003 (Anthidonia, Greece)

Anthedon, GE 2015 (Anthidonia, Greece)



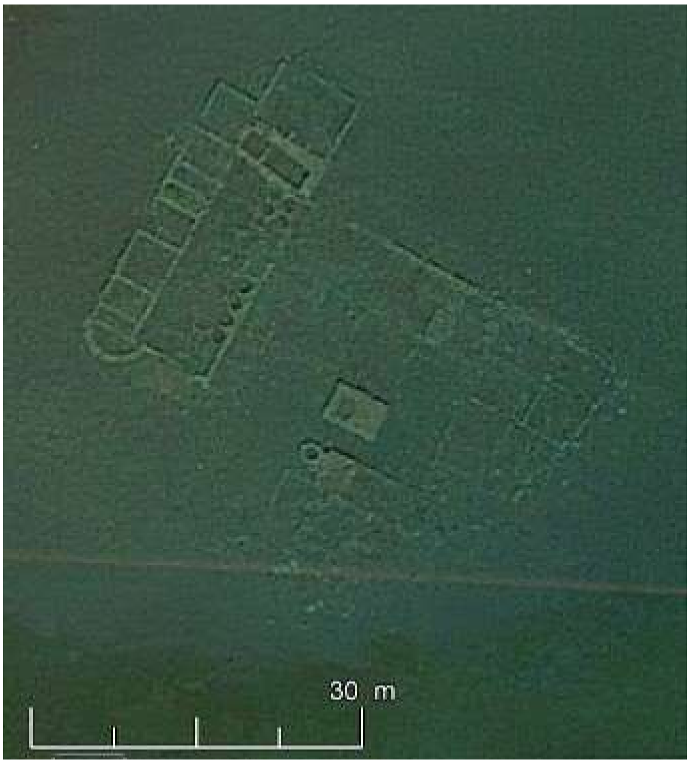
Hieros Limen, GE 2014 (Kamaraki-Vlastos, Greece)

Eretria, GE 2018 (Eretria, Evia, Greece)



Abdera, GE 2019 (Avdira, Greece)

Kenchreai, GE 2013 (Kenchreai, Peloponnesus)



Epidauros, GE 2013 (Epidauros, Peloponnesus)

Enopia, GE 2011 (Egina island, Greece)

Halieis, GE 2021 (Portocheli, Peloponnesus)

Gythion, GE 2013 (Gythio, Peloponnesus)

Methone, GE 2013 (Modon, Peloponnesus)

Kyllene, GE 2015 (Killini, Peloponnesus)

Lechaion west, GE 2017 (Lechion, Peloponnesus)

Lechaion centre, GE 2017 (Lechion, Peloponnesus)

Lechaion east, GE 2017 (Lechion, Peloponnesus)

Andros, GE 2003 (Andros island, Greece)

Karthaia, GE 2018 (Kea island, Greece)

Delos, GE 2004 (Delos island, Greece)

Rhenaia, GE 2014 (Rhenia island, Greece)

Paros, GE 2013 (Paros island, Greece)

Paros, Naoussa bay, GE 2019 (Paros island, Greece)

Thassos, GE 2009 (Thassos island, Greece)

Thanos, GE 2009 (Lemnos island, Greece)

Hephaistia, GE 2009 (Lemnos island, Greece)

Neftina, GE 2009 (Lemnos island, Greece)

Sotiras, GE 2009 (Lemnos island, Greece)

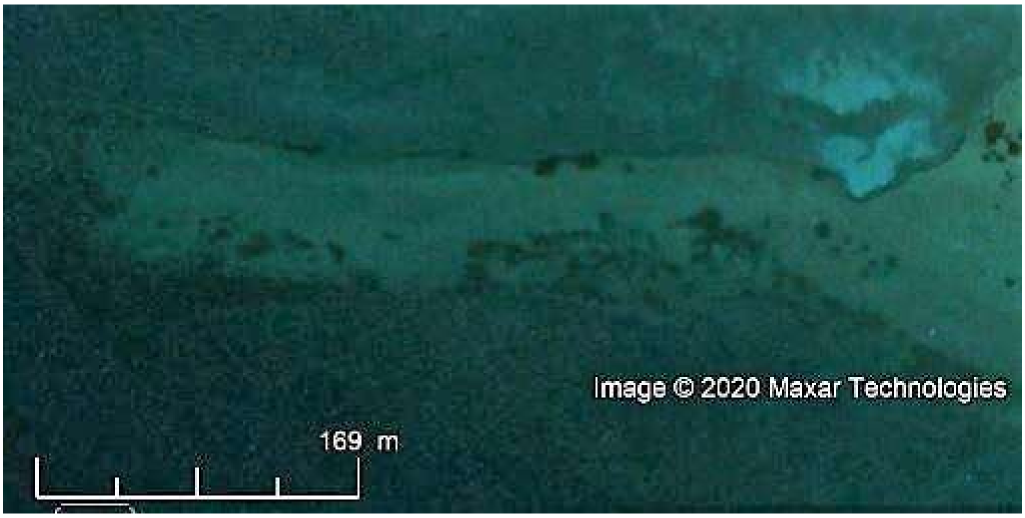
Mitylene, GE 2006 (Lesbos island, Greece)

Antissa, GE 2002 (Lesbos island, Greece)

Skiathos, GE 2016 (Skiathos island, Greece)

Psyra, GE 2010 (Psara island, Greece)

Pythagoreion, GE 2014 (Samos island, Greece)



Eleusis, GE 2018 (Vlychada, Santorini island, Greece)

Cisamo, GE 2013 (Kissamos-Kastelli, Crete)

Cisamo, Hampsa 2006 (Kissamos-Kastelli, Crete)

Dia insula, GE 2013 (Isle of Dia, Crete)

Nirou Khani, GE 2018 (Crete)

Chersonisos, GE 2002 (Hersonissos, Crete)

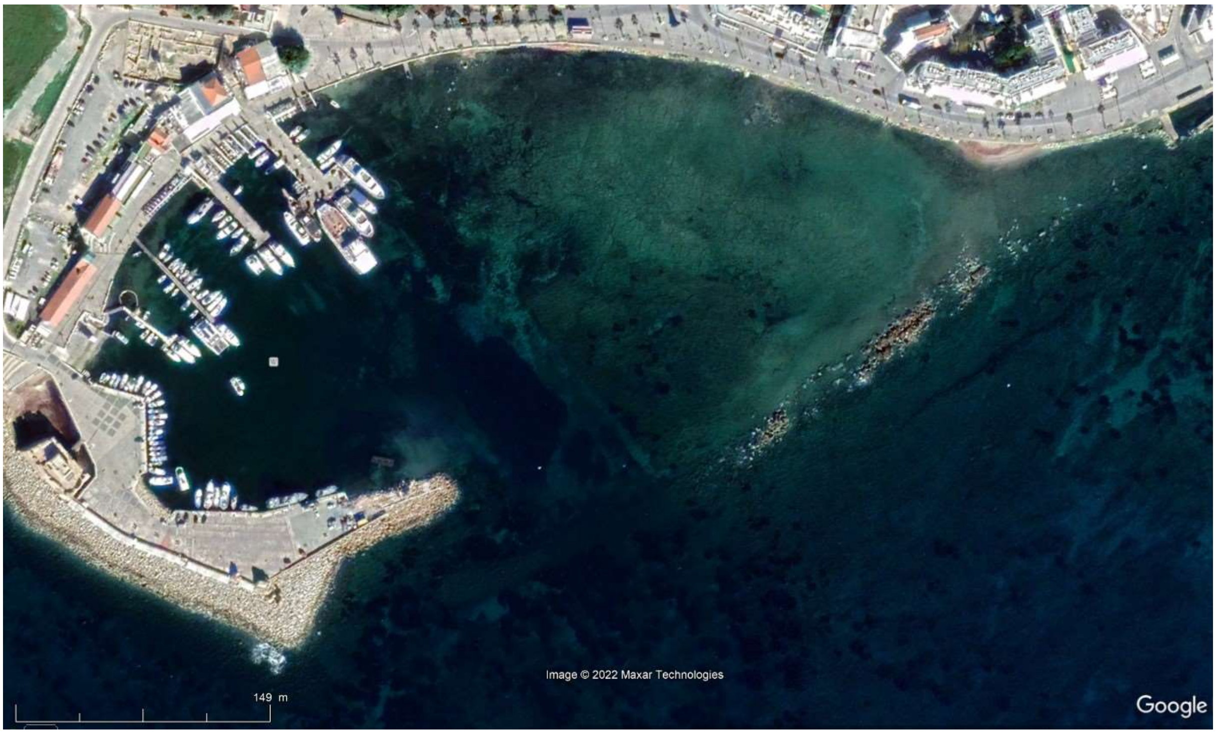
Hierapytna, GE 2010 (Ierapetra, Crete)

Lasea, GE 2004 (Chrysostomos, Crete)

Plakias Beach, GE 2015 (Plakias, Crete)

Amathonte, GE 2003 (Amathus, Cyprus)

Kourion, GE 2011 (Episkopi Phaneromeni, Cyprus)

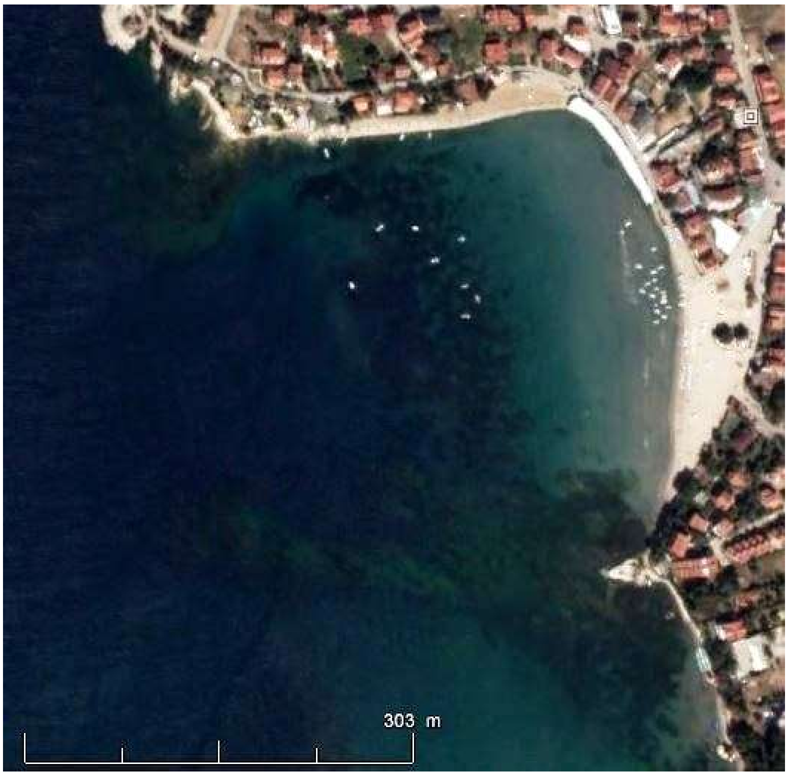


Paphos, GE 2017 (Paphos, Cyprus)

Soloi, GE 2015 (Potamos tou Kampou, Cyprus)

Galata, GE 2016 (Galata, Bulgaria)

Tieion, GE 2012 (Filyos, Turkey)



Calpe, GE 2013 (Kerpe, Turkey)

Sirakayalar, GE 2013 (Turkey)

Caesarea Germanica, GE 2013 (Kapanca, Turkey)

Daskyleion, GE 2011 (Ergili, Turkey)

Plakia, GE 2017 (Kursunlu Manastir, Turkey)

Elaious, GE 2009 (Abide, Turkey)

Assos, GE 2006 (Assos, Turkey)

Adramyttium, GE 2019 (Ören, Turkey)

Kane, GE 2006 (Karadag, Turkey)

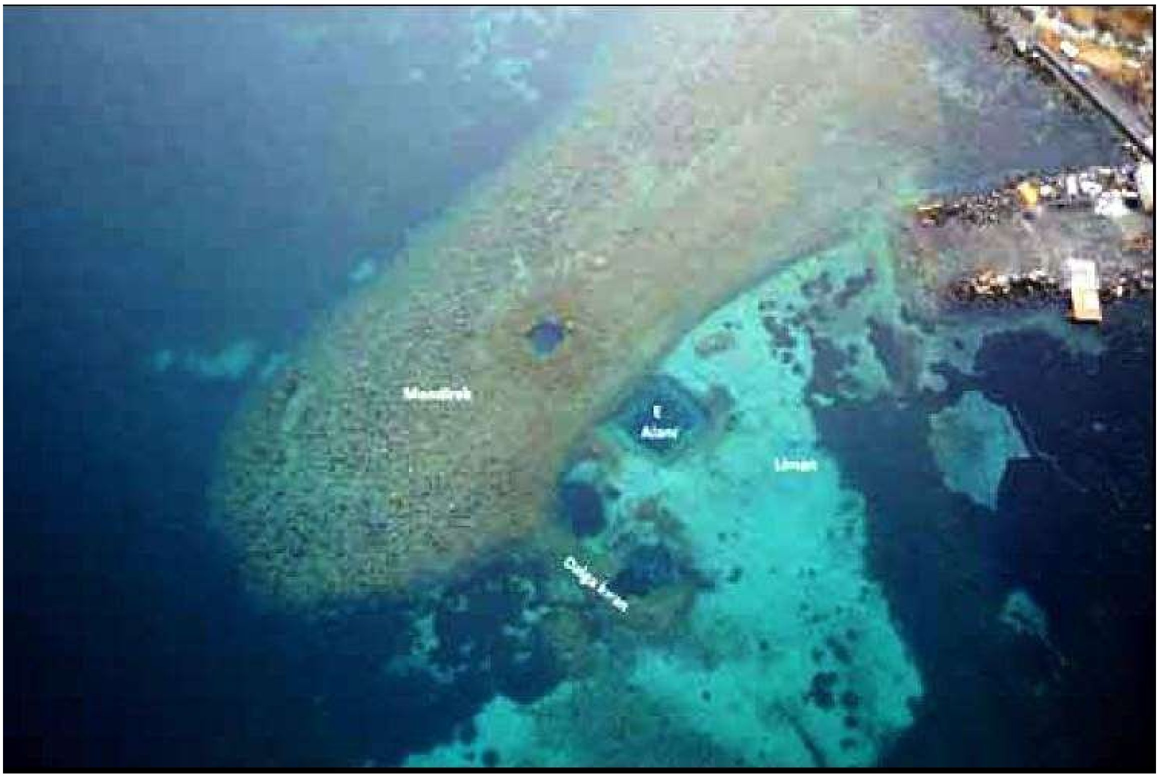
Elaia, GE 2016 (Kazikbaglar, Turkey)

Myrina, GE 2006 (Aliaga, Turkey)

Kyme, GE 2006 (Nemrut Limani, Turkey)

Klazomenae, GE 2006 (Karantina island, Turkey)

Klazomenae, GE 2002 (Liman Tepe, Turkey)

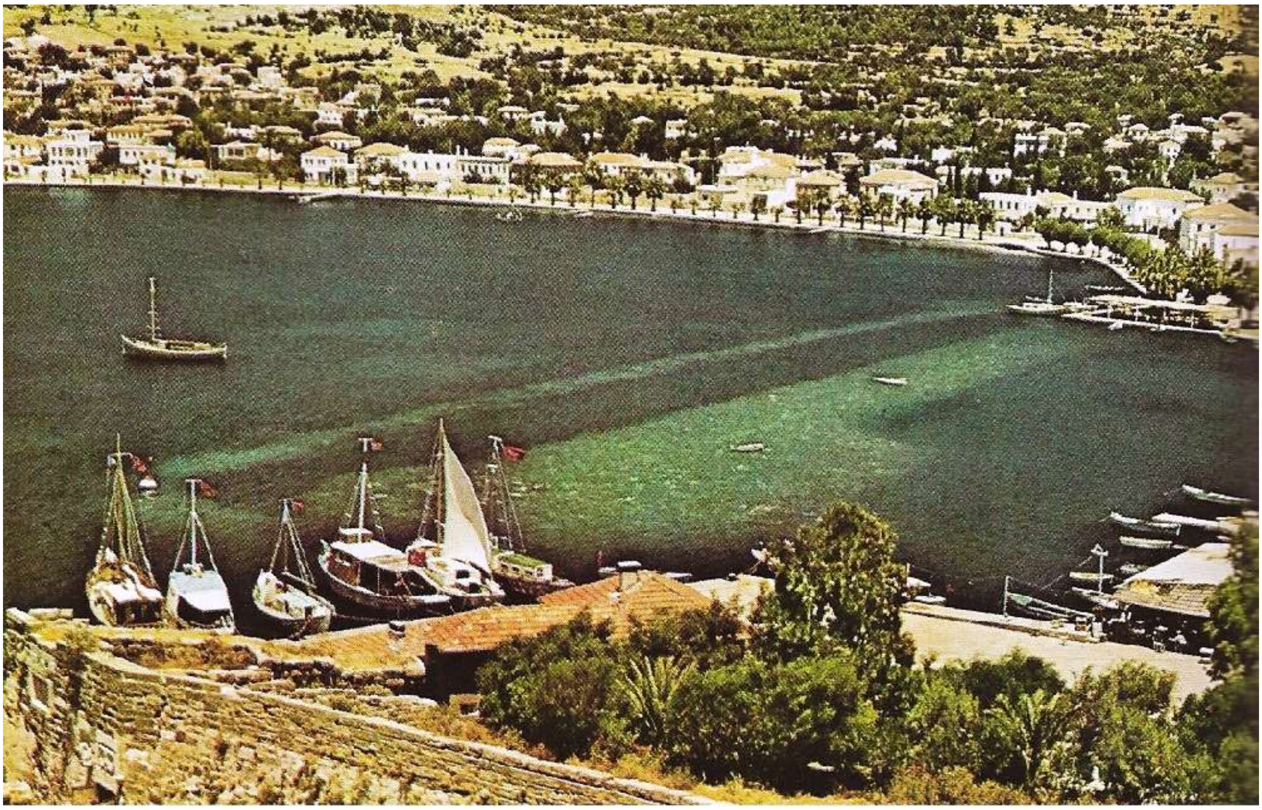


Klazomenae, Sahoglu 2011 (Liman Tepe, Turkey)

Myndus west, GE 2018 (Gümüslük, Turkey)

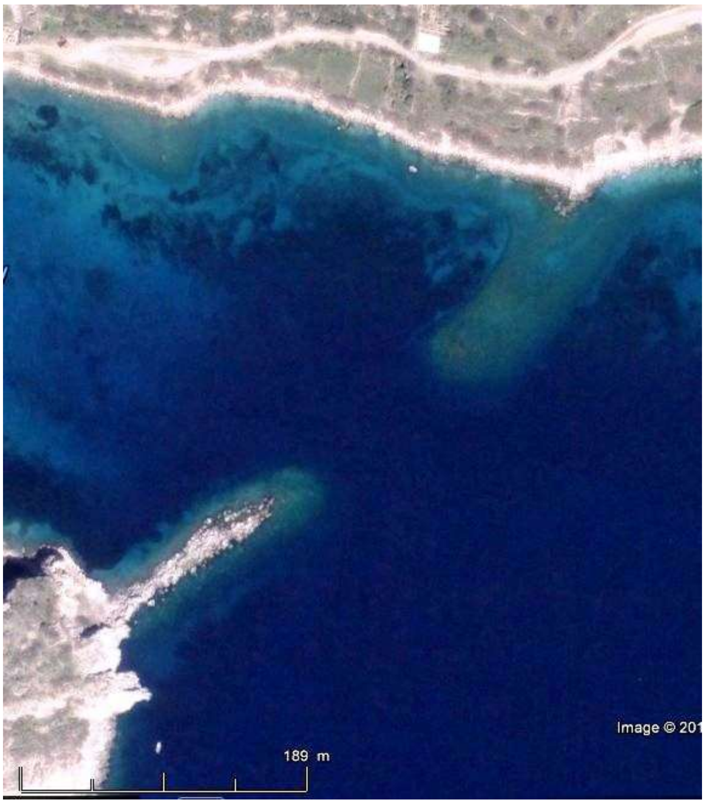
Myndus, GE 2011 (Gümüslük, Turkey)

Halicarnassus, GE 2006 (Bodrum, Turkey)



Halicarnassus, Flemming 1969 (Bodrum, Turkey)

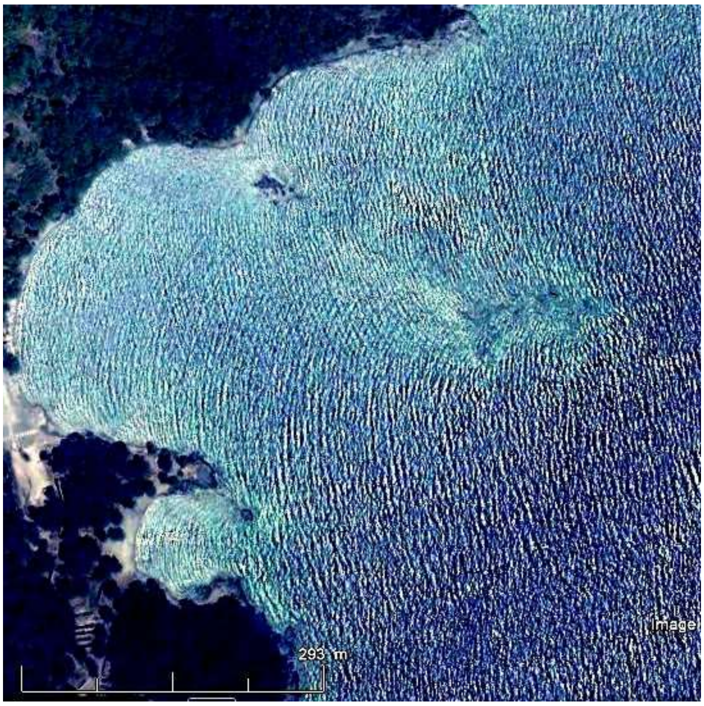
Iassos, GE 2002 (Kıyıkışlacık, Turkey)



Knidos, GE 2005 (Cnide, Turkey)

Larymna, GE 2014 (Incirli Ada, Turkey)

Sybola? GE 2021 (Ölüdeniz, Turkey)



Phaselis, GE 2002 (Tekirova, Turkey)

Phaselis, GE 2013 (Tekirova, Turkey)

Magydos, GE 2007 (Antalya, Turkey)

Side, GE 2011 (Selimiye, Turkey)

Ptolemais, GE 2015 (Aynaligöl bay on Cape Figla, Turkey)

Corycus, GE 2004 (Kizkalesi, Turkey)

Pompeiopolis, GE 2004 (Viransehir, Turkey)

Seleukia Pieria, GE 2008 (Seleukia, Syria)

Tyr south, GE 2019 (Sour, Lebanon)

Akko, GE 2010 (Acre, Israël)

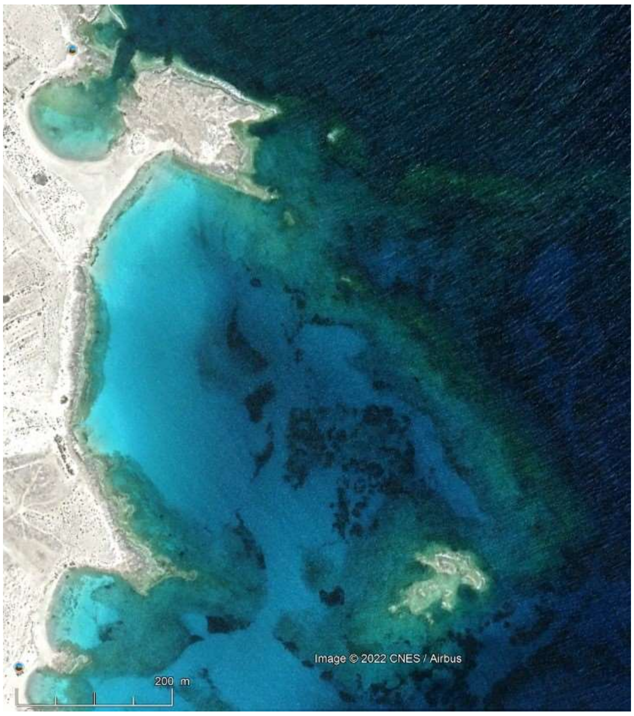
Caesarea, GE 2010 (Caesarea Maritima, Israël)

Wadi al-Jarf, GE 2004 (Gulf of Suez, Egypt)

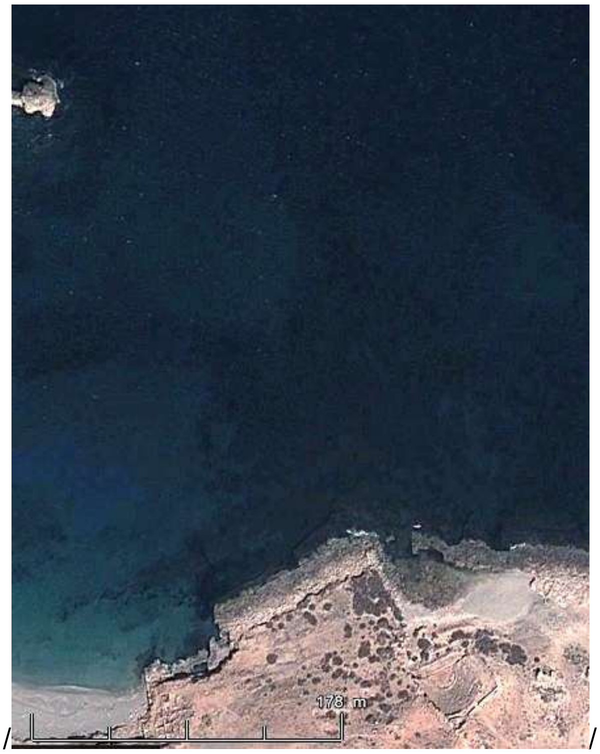
Charmothas, GE 2017 (Sharm Yanbu, Saudi Arabia)

Pharos, GE 20/1/2017 (Alexandria, Egypt)

Chersonesos, GE 2020 (Cape Agami, Egypt)



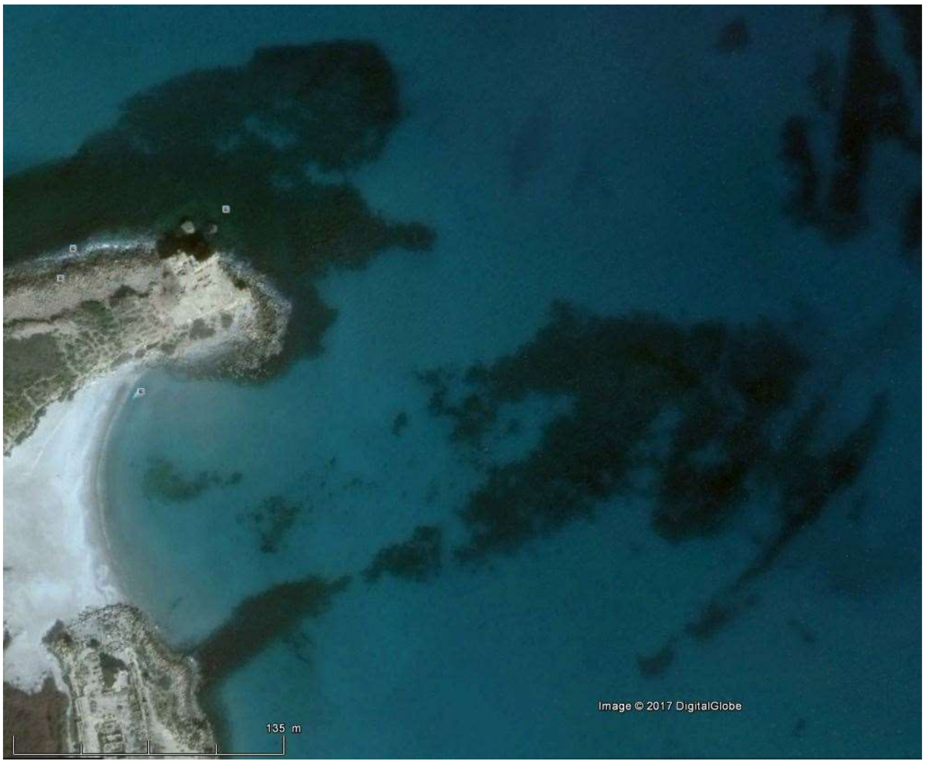
Leuke Akte, GE 2018 (Ras Kanayis, Egypt)



Apollonia, GE 2010 (Susah, Libya)

Kainopolis, GE 2004 (Maaten al Uqla, Libya)

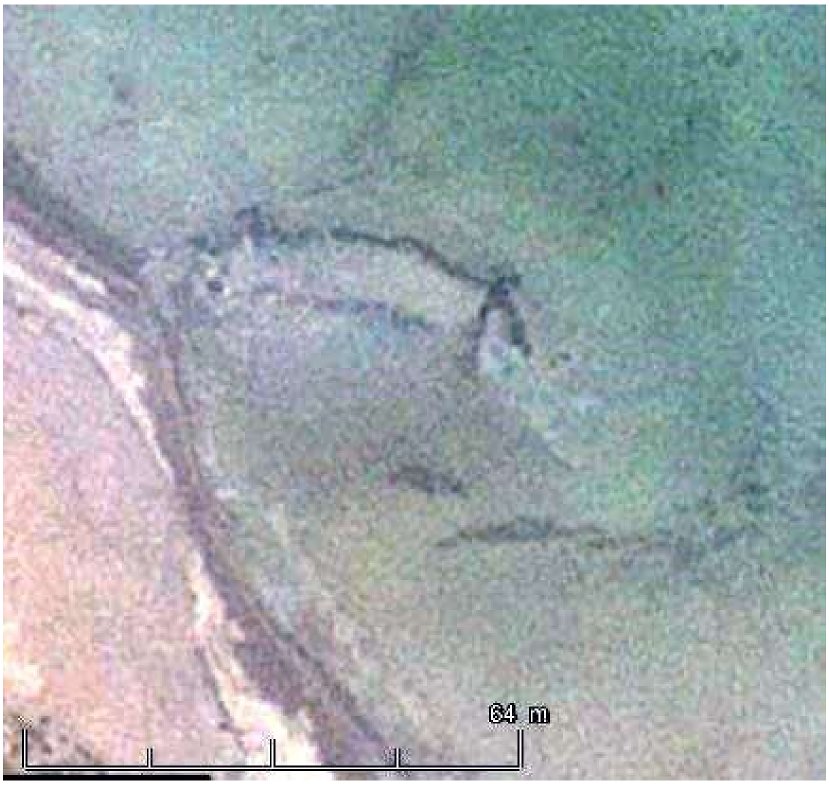
Ptolemais, GE 2009 (Tolmeita, Libya)



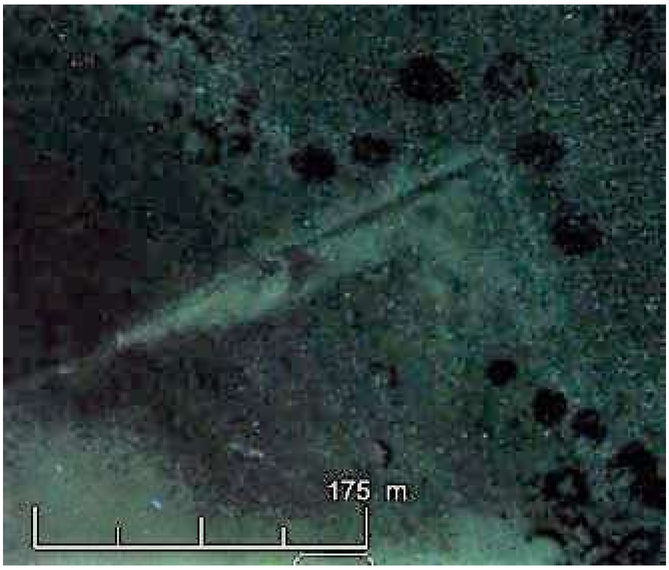
Leptis Magna, GE 2016 (Lebda, Libya)

Leptis Magna, de Graauw 2005 (Lebda, Libya)

Sabratha, GE 2013 (Sabratha, Libya)



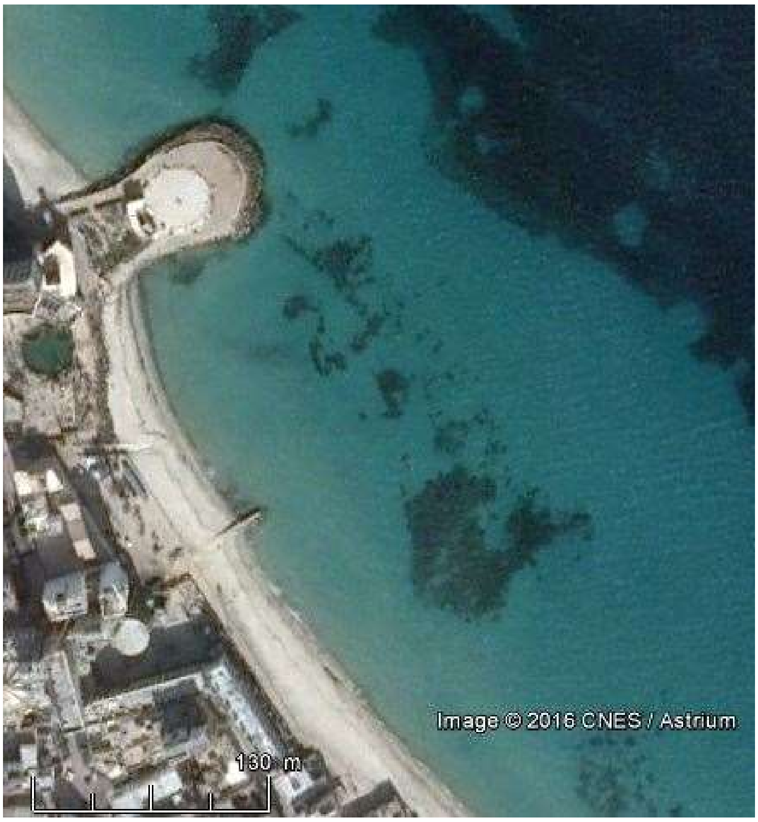
Gigthis, GE 2010 (Bou Ghrara, Tunisia)



Acholla, GE 2018 (Ras Boutria, Tunisia)

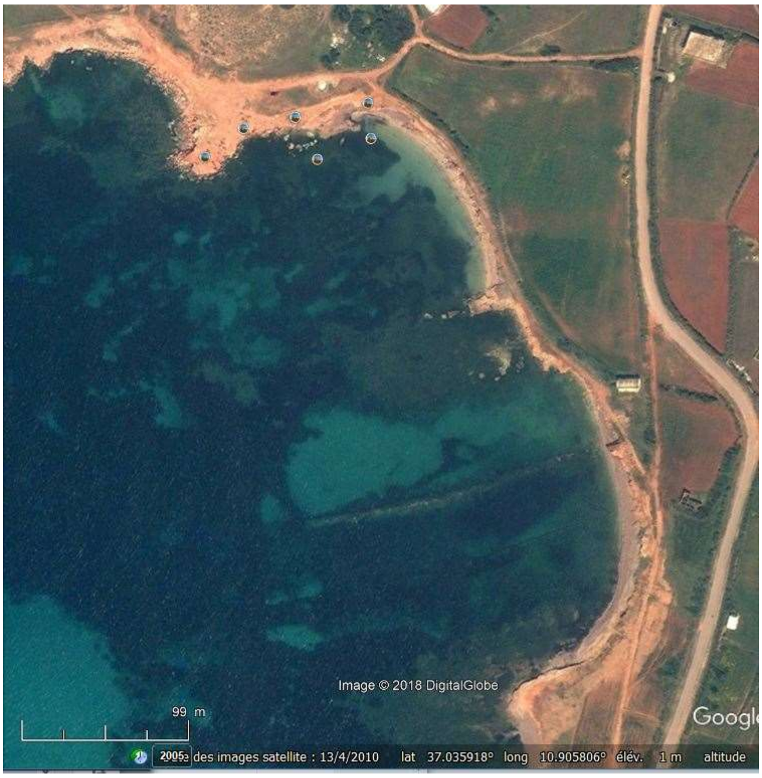
Syllectum, GE 2012 (Salakta, Tunisia)

Thapsus, GE 2009 (Bekalta, Tunisia)



Hadrumete, GE 2014 (Sousse, Tunisia)

Leptiminus, GE 2011 (Lamta, Tunisia)



Sidi Daoud, GE 2010 (Sidi Daoud, Tunisia)

Sidi Daoud, GE 2014 (Sidi Daoud, Tunisia)

Carpis, GE 2009 (Sidi Raïs, Tunisia)

Carthage, Falbe, GE 2015 (Carthage, Tunisia)

Carthage, Magon, GE 2020 (Carthage, Tunisia)

R’mel, GE 2021 (R’mel, Tunisia)

Iol-Caesarea, GE 2003 (Cherchel, Algeria)

Iol-Caesarea, GE 2013 (Cherchel, Algeria)

APPENDIX 3: Tombolos & salients

Tombolos and salients were searched on Google Earth over the 45 000 km of the Mediterranean Sea coasts. The list hereafter includes natural tombolos and natural salients generated by offshore islands, islets or reefs. In addition, a few sites with man-made single or multiple detached breakwaters were listed.

Location	Latitude (°N)	Longitude (°E)	Ancient name	Notes
Trafalgar	36.1824	-6.0333	Junonis prom.	
Tarifa	36.0065	-5.6085	Mellaria	lateral waves = headland?
Gibraltar	36.1515	-5.3457	-	lateral waves = headland?
Porto Banus	36.4826	-4.9627	-	
Malaga	36.7191	-4.4025	Malaca	
Mazaron	37.5582	-1.2860	Ficariensis Locus	
Mar Menor	37.7273	-0.7375	-	
Alicante	38.3476	-0.4730	Lucentum	
La Olla	38.6203	-0.0237	-	islet + nearshore reefs
Ifach	38.6413	0.0704	Hemeroscopion?	
Formentera	38.7535	1.4322	-	limit case tombolo/salient
Na Moltona islet	39.3065	3.0163	-	
Xilxes S	39.7641	-0.1567	-	
Xilxes N	39.7694	-0.1525	-	
Burriana	39.8527	-0.0896	Port of Sebelaci	
Castellon	39.9376	0.0020	-	
Peniscola	40.3588	0.4036	Tyreche	
Cambrils S	41.0569	1.0337	-	
Cambrils N	41.0587	1.0393	-	
Salou	41.0721	1.1130	Salauris	
Altafulla	41.1317	1.3701	-	
Vendrell	41.1794	1.5257	Palfuriana	
Villanova	41.2115	1.7184	-	
Blanes	41.6709	2.7909	Blanda	
Empuries	42.1355	3.1221	Emporia	limit case tombolo/salient
Barcarès	42.8077	3.0420	-	
Valras W	43.2350	3.2770	-	limit case tombolo/salient
Valras E	43.2350	3.2770	-	

Valras N	43.2432	3.2919	-	
Agde	43.2741	3.4737	-	
Frontignan	43.4277	3.7653	-	
Palavas	43.5195	3.9211	-	
Carnon	43.5427	3.9836	-	
La Ciotat	43.1851	5.6204	-	
Giens	43.0618	6.1408	Olbia	headland w/ 2 wave directions
St Aygulf	43.3966	6.7321	-	
Rondinara	41.4666	9.2676	-	
Porto Pollo	41.1933	9.3185	-	
Nora	38.9888	9.0130	Nora	
Sant'Antioco	39.0588	8.4756	Sulcitanus Portus	
Mandriola	40.0360	8.4070	Korakodes portus	
Piombino	42.9760	10.5460	Populonio	headland?
Orbetello	42.4383	11.2137	Portu Herculis	headland
Torre Flavia	41.9559	12.0496		
Torre Astura	41.4097	12.7651	Stora	headland
Circeo	41.2581	13.0722	Circaeum prom.	
Gaeta	41.2133	13.5678	Caieta	headland
Sant'Angelo	40.6961	13.8929	-	
Palinuro	40.0313	15.3132	-	
Saracinello	39.8737	15.7831	-	
Cirella	39.7001	15.8109	-	
Torre Ovo	40.3041	17.5010	-	
Klenovica	45.0972	14.8420	-	man-made connection?
Makarska	43.2952	17.0140	-	
Corfu	39.4330	19.9123	-	
Parga	39.2840	20.3983	Toryne	
Asprogiali	38.6000	21.0215	-	
Ag. Nikolaos	38.3481	22.1587	-	
Kafkalida	37.9370	21.1272	-	
Kokkinia	36.8068	21.7231	-	
Coron	36.7947	21.9578	Asine	headland?
Kotronas	36.6172	22.4873	Teuthrone	
Marathias	36.6038	22.9021	-	

Pavlopetri	36.5178	22.9852	Onougnathos	currents in strait?
Lefki	36.4675	22.9791	-	
Monemvasia	36.6860	23.0370	Minoa	man-made connection?
Piraeus	37.9501	23.6580	Kantharos	cf. Goiran (2011)
Ag. Dimitrios	37.8079	23.8466	-	limit case tombolo/salient
Anavysos	37.7183	23.9234	Hyphormus Portus	
Mikrolimano	37.7558	24.0740	-	
Daskalio	37.8259	24.0489	Porthmos	
Tragana	38.6334	23.1239	Anastasis	salient axis at 160°
Eretria	38.3886	23.8006	Eretria	
Paximadi	37.9618	24.3870	-	
Ag. Vasileios	38.8831	23.4436	-	
Aliki (Thasos)	40.6051	24.7416	Alike	
Molivoti	40.9324	25.2623	Stryme	
Darica	40.7883	29.3452	Potamoi	
Kapidag	40.3804	27.8884	Cyzicos	Cyzicos island is a monster!
Murtzeflos (Limnos)	39.9843	25.0462	-	
Kane	39.0312	26.8187	Cana	
Foça	38.6783	26.7392	Phokia	
Karantina	38.3656	26.7813	Klazomenai	man-made connection?
Demircili	38.2065	26.6873	Aerae	
Ciçek Adasi	38.1664	26.8084	Teos	
Cifit Adasi	38.0463	26.8578	Myonnesos	
Kizik	38.0766	26.9670	Lebedos	
Sapli Adasi	37.4146	27.4105	Teichiussa	
Cnide	36.6858	27.3732	Cnide-Triopion	
Kiyilari	36.7615	27.7642	-	
Perili	36.7586	27.7755	-	
Ciftlik Adasi	36.7558	27.8911	-	
Prasonisi (Rhodos)	35.8883	27.7722	Vroulia	
Tigani Cape (Crete)	35.5825	23.5883	Iusagura	
Ag. Theodori (Crete)	35.5195	23.9302	Akoition	
Ag. Apostoli (Crete)	35.5125	23.9828	-	
Nirou Khani (Crete)	35.3327	25.2435	-	
Ag. Varvara (Crete)	35.2937	25.4609	Mallia Metamorfosi	

Frangokastello (Crete)	35.1802	24.2330	-	
Paleochora (Crete)	35.2306	23.6813	Selino	
Patara beach	36.3152	29.2414	Patara	limit case tombolo/salient
Tisan	36.1580	33.6858	Aphrodisias	
Ras Ibn Hani	35.5853	35.7425	Ugarit	
Altinkum Beach	35.6362	34.5297	Phileunte	
Akrotiri	34.6163	32.9657	Curias Prom.	
Zire	33.5710	35.3773	Sidon	d-salient=200 m can be discussed (but see FIG)
Tyre	33.2685	35.2080	Tyre	
Haifa	32.8057	34.9554	-	
Tell Nami	32.6601	34.9269	-	
Pigeon islets	32.5547	34.9060	-	4 islets = dotted line over 500 m
Netanya	32.3301	34.8479	-	
Tel Aviv	32.0933	34.7709	-	
Alexandria	31.1991	29.8839	Alexandria	
Bombah	32.4021	23.1343	Platea	headland
Maaten al-Uqla	32.7747	21.3429	Kainopolis	3 islets = dotted line over 700 m
Ajdabiya	30.8978	20.0765	Hypali insulae	reefs = dotted line over 1200 m
Reefs	30.7593	19.9806	Mysinos	reefs = dotted line over 2000 m
Mahdia	35.5037	11.0695	Gummi	D=600 m can be discussed …
Haouaria	37.0451	11.0289	-	headland?
Carthage	36.8643	10.2658	Carthage	
Cap Serrat	37.2171	9.2421	-	
Tabarka	36.9590	8.7590	Thabraca	
Skikda	36.8876	6.9802	-	
Sidi Ferruch	36.7589	2.8467	Obori?	

APPENDIX 4: Ancient earthquakes and tsunamis

As each coastal earthquake does not necessarily induce a tsunami, we reported a "possible" tsunami when an earthquake occurred, but no tsunami was reported by ancient writers. Some places are located far enough inland to suppose they did not induce a tsunami (noted “-“).

The intensity of earthquakes is given acc. to the European Macroseismic Scale (EMS) with the following intensity scale (for VII and more):

VII	**Damaging.** Most people are frightened and run outdoors. Furniture is shifted and many objects fall from shelves. Many buildings suffer slight to moderate damage. Cracks in walls; partial collapse of chimneys.
VIII	**Heavily damaging.** Furniture may be overturned. Many to most buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse. Can be noticed by people driving cars.
IX	**Destructive.** Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely. Windows shatter.
X	**Very destructive.** Many buildings collapse. Cracks and landslides can be seen.
XI	**Devastating.** Most buildings collapse.
XII	**Completely devastating.** Almost all structures are destroyed. The ground changes.

The following sources were used to compile this list:

- ALTINOK, Y., 2011, “Revision of the tsunami catalogue affecting Turkish coasts and surrounding regions”, Nat. Hazards and Earth Systems Sciences, 11, (p 273–291).
- GEOLITHIC: http://geolithik.com/map/ (not operational anymore).
- GUIDOBONI, E., COMASTRI, A., TRAINA, G., 1994, “Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century”, Istituto Nazionale di Geofisica, Bologna, (504 p), with 300 earthquakes before 995 AD described in detail.
- NOAA: https://www.ngdc.noaa.gov/hazard/tsu_db.shtml
- PAPAZACHOS, B.C. & PAPAZACHOU C., 1997, "The earthquakes of Greece", Ziti Editions, Thessaloniki, Greece, (304 p), with 170 earthquakes before 1510 AD.
- SALAMON, A., et al., 2007, “Tsunami Hazard Evaluation of the Eastern Mediterranean: Historical Analysis and Selected Modeling", Bulletin of the Seismological Society of America, Vol. 97, No. 3, (p 705–724).
- SBEINATI, M., DARAWCHEH, R., MOUTY M., 2005, “The historical earthquakes of Syria: an analysis of large and moderate earthquakes from 1365 B.C. to 1900 A.D.”, Annals of Geophysics, Vol. 48, N. 3, June 2005, (89 p), with 181 Syrian earthquakes and tsunamis.
- SOLOVIEV, S., SOLOVIEVA, O., 2009, “Tsunamis in the Mediterranean Sea 2000 B.C.-2000 A.D.”, Advances in Natural and Technological Hazards Research, Springer, (239 p), with 341 tsunamis in historical times.
- WIKIPEDIA detailed articles about a few famous earthquakes, and lists of earthquakes and tsunamis.

Date	Location of tsunami	Location of earthquake	EMS
2000 BC	Syrian coast	Syrian coast	
1600 BC	Crete north coast	Santorini eruption	
1365 BC	Levant	Ugarit	VIII-IX
1300 BC	Aegean Sea	Troad	
1225-1175 BC	possible	Eastern Med, « Earthquake storm »?	
1075 BC	possible	Larnaca, Salamis (Cyprus)	
760-750 BC	Levant	Levant	
590 BC	Levant	Tyre	VII?
550 BC	possible	Sparta, Syros island	VI
525 BC	Tyre, Saida	Tyre, Saida	VIII-IX
510 BC	-	Thessalia	VII
500 BC	Antioch	Antioch	
496 BC	possible	Chios island (Greece)	VI
490 BC	possible	Delos island	VI
-/3/490 BC	possible	Aegina island	VI
29/9/480 BC	Aegean Sea	Salamis (Saronic Gulf)	VI
479 BC	Potidaia (Chalkidiki)	North Aegean	VII
469-464 BC	-	Sparta	IX
461 BC	possible	Rome	VI
436 BC	-	Central Italy	VIII
431 BC	possible	Delos island	
-/12/427 BC	possible	Attica, Maliakos Gulf	VII
-/7/426 BC	Orobiae (North Euboea)	Maliakos Gulf	X
425 BC	possible	Etna eruption	
-/3/424 BC	possible	Athens	VI
-/8/420 BC	possible	Corinth	VI
-/3/414 BC	possible	Cleonae	VI
-/12/413 BC	-	Sparta	VI
-/12/412 BC	possible	Kos island	X
403-400 BC	possible	Elis (Peloponnesus)	VI

388 BC	possible	Argos	VI
372 BC	possible	Delos island	VI
373 BC	Helike (Gulf of Corinth)	Gulf of Corinth	X
359 BC	Tyrrhenian Sea	Vulcano island eruption	
360 BC	possible	Sea of Marmara, Heraclea Pontica	IX
347-346 BC	-	Delphi	V
334 BC	-	Anatolia	VII
325-320 BC	possible	Apamea	
331 BC	possible	Syria	VI
330 BC	Aegean Sea	Lemnos island	VII
321 BC	possible	Naples	
321 BC	possible	Liguria	
-/12/304 BC	possible	Western Turkey	
303 BC	possible	Gulf of Corinth	VI
287 BC	possible	Lysimachia (Hellespont)	X
-/12/279 BC	-	Delphi	VI
268 BC	possible	Picenum (Ancona)	
231 BC	possible	Lesbos island	VII
227 BC	South Aegean Sea	Rhodes	X
-/10/223 BC	Maliakos Gulf	Cytinium, Doris (Greece)	IX
-/6/217 BC	Tyrrhenian Sea	Liguria & Etruria (Italy)	X
200 BC	possible	Samos island	VI
199-198 BC	Levant	Saida, Rhodes	X
199-198 BC	possible	Chalcis (Eubea)	VII
199-198 BC	Aegean Sea	Santorini eruption	X
197 BC	possible	Lemnos island	VII
-/3/193 BC	possible	Rome	
192 BC	possible	Rome	V
-/9/179 BC	possible	Rome	V
-/12/174 BC	possible	Sabina (Italy)	IX
148-130 BC	Tyre-Akko	Antioch	X

133 BC	Tyrrhenian Sea	Luna (Italy)	
126 BC	Tyrrhenian Sea	Etna eruption	
118 BC	possible	Rome	
117-113 BC	possible	Apulia (Italy)	
100 BC	possible	Picenum (Ancona)	VIII-IX
99 BC	possible	Rome	IX
92 BC	Syria-Israel	Caesarea Maritima (Israel)	IV
92 BC	possible	Regio Calabria	
90 BC	-	Anatolia	VII
87 BC	possible	Apamea (NW Turkey)	X
83 BC	possible	Rome	VII-VIII
76 BC	-	Rieti (Italy)	IX
72-70	possible	Rome	VIII
65 BC	possible	Antioch-Cyprus-Black Sea	X
63 BC	-	Spoletium (Italy)	VII-VIII
58 BC	Adriatic Sea	Albania	VII
-/5/56 BC	-	Potentia (Italy)	
50 BC	possible	Delos island	VI
50 BC	possible	Rome	
50 BC	Georgia	Sukhumi (Georgia)	VII
47 BC	possible	Rome	V
44 BC	-	Alps	
43 BC	possible	Rome	V
37 BC	possible	Dafneh (Lebanon)	VI-VII
31 BC	-	Jordan valley	VII
27 BC	possible	W Turkey, Chios island	IX
26 BC	Pelusion, Paphos	Paphos (Cyprus)	
23 BC	Alexandria	Alexandria	
17 BC	-	Central Italy	
17 BC	possible	Paphos (Cyprus)	
15 BC	possible	Salamis (Cyprus)	
2 BC	possible	Naples	VIII

5 AD	possible	Rome	V
15 AD	possible	Rome	VII-VIII
17 AD	possible	Regio Calabria	VII-VIII
17 AD	possible	Sardis (Lydia)	X
19 AD	possible	Saida	VI-VII
20 AD	Georgia	Sukhumi (Georgia)	VII
22 AD	-	Cibyra (SW Turkey)	IX
23 AD	possible	Patras	IX
24/11/29	possible	Nicea, Bithynia	X
33	-	Jordan valley	
-/3/37	possible	Capri (Naples)	VII
23/3/37	possible	Antioch, Dafneh	IX
46	possible	Santorini eruption	VII
47	possible	Antioch	IX
47	possible	Izmir, Samos	IX
50	possible	Philippi	
50	Bulgaria	Hellespont, Black Sea	VI
51	possible	Rome	VIII
53	possible	Turkey, Antioch, Lattakia	VII-VIII
53	possible	Apamea (NW Turkey)	IX
53? 62? 66?	Aegean Sea	Santorini eruption	IX
57	possible	Albania	VII
60	possible	NW Turkey	X
61	possible	Achaia (Peloponnesus)	VI
61	possible	Macedonia	
05/02/62	?	Pompei	IX
62	Eastern Med	Crete	VII
64	possible	Naples	
68	SW Anatolia	Patara	
-/6/68	possible	Rome	V
69	possible	Nicomedia (Bithynia)	IX
20/6/69-79	possible	Corinth	IX

20/06/76	Levant	Paphos, Salamis (Cyprus)	IX
24/08/79	Bay of Naples	Vesuvius eruption	
82-94	possible	Antioch	VI-VII
97	-	Nicopolis (Cilicia)	IX
99?	-	Pescolardo (Central Italy)	IX
101-200?	-	Aunobaris (Teboursouk, Tunisia)	IX
101-200	-	Interpromium (Pescara, Italy)	IX
105	possible	Cyme, Pitane (W Turkey)	X
105	possible	Opus, Oreus (Eubea)	X
110	possible	Galatia	X
13/12/115	Caesarea Maritima	Antioch	X
117-128	possible	Italy	
120? 128?	Sea of Marmara	Sea of Marmara	X
10/10/123	Sea of Marmara	Sea of Marmara	
127-130	possible	Caesarea Maritima (Israel)	IX-X
141? 142? 148?	SW Anatolia	Rhodes, Lycia	VII
160	-	Doura Europos (Syria)	
160? 161?	possible	Sea of Marmara	X
177	North Sicily	Sicily	
178	possible	Izmir (Turkey)	X
3/5/181?	possible	Sea of Marmara	IX
201-300	-	Anatolia	IX
217	possible	Albania	VI
233	-	Damascus	VII
235-236	-	Anatolia	IX
241	possible	Aphrodisias (Turkey)?	IX
242-245	possible	Antioch	VI-VII
251	possible	Crete north	VII-VIII
258	Tyrrhenian Sea	Tyrrhenian Sea	
262	Eastern Med	SW Anatolia, Libya, Rome	

267	-	Ad Maiores (Besseriani, Algeria)	VII-VIII
268-270	possible	Sea of Marmara	
275-276	possible	Rome?	
293-306	Eastern Med	Salamis (Cyprus)	X
301-400	possible	Corfou	IX
3/4/303	Levant	Saida-Tyre-Caesarea	X
315	-	Dead Sea	
320	possible	Alexandria	X
332	possible	Salamis (Cyprus)	X
334	possible	Albania	VI
334-335	possible	Kos island	IX
341	possible	Antioch-Beirut	VI-VII
341	-	Maximianopolis	IX
342	Levant	Paphos, Salamis (Cyprus)	X
343	possible	Neocaesarea (Turkey)	X
11/4/344	possible	Salerno (Italy)	
344	possible	Rhodes	X
344	possible	Dardanelles	
346	Adriatic Sea	Albania	X
346	possible	Rome-Naples	VIII
348? 349?	Levant	Beirut-Arwad	VIII-IX
351-400	-	Anatolia	IX
358	possible	Albania	VII
24/8/358	Sea of Marmara	Sea of Marmara	IX-X
361	possible	Delphi	VII
24/5/362	Dead Sea	Dead Sea	
2/12/362	Sea of Marmara & Black Sea	Sea of Marmara	VIII-IX
-/2/363	possible	Istanbul	
18/5/363	possible	Galilee	X
-/6/363	possible	Libya, Corinth, Sicily	X
21/7/365	Greece, Sicily, Libya, Egypt	Western Crete	X-XI

11/10/368	Sea of Marmara	Sea of Marmara	VI
368? 369?	possible	Germe (W Turkey)	X
370	possible	Paphos (Cyprus), W Anatolia	X
373	possible	Regio Calabria	IX
374	-	Benevento (Central Italy)	
-/11/394	possible	Istanbul	
396	possible	Istanbul	
400	possible	Libya	IX
402	possible	Istanbul	
1/4/407	Sea of Marmara	Istanbul	VII-VIII
408	possible	Rome	
408-450	possible	Crete	IX
-/7/409	possible	Istanbul	
412	possible	Utique (Tunisia)	
417	possible	Cibyra (SW Turkey)	X
20/4/417	possible	Istanbul	
419	possible	Antipatris (Israel)	X
422	possible	Istanbul	
7/4/423	possible	Istanbul	
425	possible	Jerusalem	X
426	Euboia Gulf	Euboia Gulf	
25/8/429	possible	Ravenna (Italy)	
25/9/437	possible	Sea of Marmara	VII
17/4/442	possible	Istanbul	
443	possible	Rome	IX
15/4/443	possible	Ravenna (Italy)	
26/1/447	Sea of Marmara	Istanbul	X
11/6/448	possible	Crete south	VII
26/1/450	Sea of Marmara	Sea of Marmara	VII
450-457	possible	Tripoli (Lebanon)	IX
14/9/458	possible	Antioch	VIII-IX
459	possible	Kos island (Greece)	VII

460	possible	Sea of Marmara, Aegean Sea	VIII-IX
472	possible	W Turkey	X
474-478	possible	Rhodes	IX
-/9/475	possible	Jableh	IX
478	possible	Dardanelles	VII
25/9/478	Sea of Marmara	Istanbul	IX
485?	possible	Rome	VII
26/5/492	possible	Ravenna (Italy)	
494	possible	Anatolia	X
-/9/499	-	Anatolia	IX-X
500	possible	Antioch, Seleucia	VII?
501-525	possible	Faenza (Ravenna)	VI-VII
9/10/501	possible	Ravenna (Italy)	
14/4/502	possible	Ravenna (Italy)	X
22/8/502	Levant	Akko-Tyre-Saida-Beirut	X
506	possible	Albania	VI
515	possible	Rhodes	IX
518	-	Dardania (Balkans)	X
521? 522?	possible	Durres (Albania)	IX
521? 522?	possible	Corinth	IX
523? 525?	possible	Cilicia (Turkey)	X
29/5/525	Levant	Byblos-Saida	VII-VIII
20/5/526	Seleucia	Antioch, Seleucia, Dafneh	X
527	possible	Pompeiopolis (SE Turkey)	IX
29/11/528	possible	Antioch	IX
2/1/529	Lattakia	Lattakia (Syria)	VI-VII
-/7/529	possible	N Turkey	> VIII
530	possible	Myra (S Turkey)	> VIII
531-534	possible	Antioch-Aleppo-Homs	VI-VII
16/8/542	Sea of Marmara	Istanbul	VII
543	possible	Corinth	IX
6/9/543	Sea of Marmara	Sea of Marmara	VII

-/8/545	Bulgaria	Varna (Bulgaria)	VII-VIII
-/4/546	possible	Istanbul	IX
-/2/548	possible	Istanbul	
-/1/549	Sea of Marmara	Istanbul	
551	possible	Maliakos Gulf	VII
-/4/551	Gulf of Corinth	Etolia (Greece)	X
9/7/551	Caesarea-Tyre-Beirut-Tripoli (Leb.)	Lebanon	X
-/5/552	Gulf of Corinth	Itea (Gulf of Corinth)	
15/8/554	Sea of Marmara	Istanbul	VIII-IX
14/10/554	possible	Alexandria	X
554-558	Aegean Sea	Kos island (Greece)	IX-X
11/7/555	Sea of Marmara	Istanbul	
-/8/556	possible	Kos island (Greece)	VII
19/10/557	possible	Istanbul	
14/12/557	Sea of Marmara & Black Sea	Istanbul	IX-X
558	Aegean Sea	Rhodes	
25/12/558	possible	Ancona	
570	possible	Antioch, Seleucia, Cilicia	X
580	possible	Corinth	VI
580-581	possible	Antioch-Dafneh	VI-VII
10/5/583	possible	Istanbul	
584-585	-	Arabissus (SE Turkey)	IX-X
-/10/588	possible	Antioch-Dafneh	VIII-IX
590	Levant	Lebanon	
597	possible	Thracia (Greece)	VII
601-625	-	Anatolia	IX
601-602	possible	Syria-Cilicia	X
602-603	-	Surb Karapet (E Turkey)	VIII
620	possible	Thracia (Greece)	VII
633	-	Yarmouk valley (Israel)	
634	possible	Aleppo	VII-VIII

-/9/634	-	Jerusalem	IX
641-668	possible	Istanbul, W Turkey	IX
651-700	possible	Vulcano island eruption	
-/6/659	-	Jerusalem	IX
659-660	-	Jericho (Israel)	IX
672	possible	Gaza	
677	possible	Thracia (Greece)	VI
678	possible	Antioch-Cilicia	VI-VII
3/4/679	-	Sürüç (E Turkey)	X
700	possible	Thessaloniki	VII
28/2/713	possible	Antioch-Aleppo	IX
24/12/717	possible	Antioch-Aleppo	VI-VII
725-744	possible	Ravenna (Italy)	VII-VIII
735	-	Vayoc'Jor (Armenia)	X
26/10/740	Sea of Marmara	Sea of Marmara	X
743-744	-	Derbend (Anatolia)	
18/1/746	Levant, Egypt	Levant, Egypt	VII
18/1/749	Israel	Galilee, Baalbek, Damascus	IX-X
9/3/757	possible	Syria	IX
778	possible	Treviso (Italy)	VIII-IX
17/3/780-797	possible	Istanbul	VI
30/4/792	Adriatic Sea	Venice	
796-797	possible	Alexandria	VI-VII
-/4/796	possible	Crete	
4/5/796	possible	Istanbul	VII-VIII
800	Ionian Sea	Ionian Sea	
29/4/801	possible	Rome	
19/12/803	Bay of Iskenderum	Adana (Turkey)	
808	-	Jerusalem	
813-820	possible	Turkey	
5/5/824	possible	Panion (Sea of Marmara)	VIII

829-842		Turkey	
835	possible	Antioch	X
30/12/836	possible	Pavia (Italy)	
-/6/847	possible	Rome	
24/11/847	possible	Damascus-Antioch	X
-/6/848	-	Central Italy	X
853-854	-	Lake Tiberias	IX
31/8/853	possible	Sicily	
3/12/856	possible	Tunis	
-/12/856	possible	Corinth	
-/4/857	possible	Cairo	IX
30/12/859	Levant	Samandag (Turkey)	
859-860	possible	Maghreb	IX
-/01/860	possible	Antioch, Latakkia, Jableh	IX-X
28/5/862	possible	Istanbul	VIII
13/2/863	-	Dvin (Armenia)	X
9/1/869	possible	Istanbul	IX
16/5/881	Akko	Levant	
-/12/885	possible	Cairo	VIII-IX
27/12/893	-	Dvin (Armenia)	X
894	possible	Apulia (Italy)	
896	possible	Thessaloniki	VI
906	-	Kargop (Armenia)	IX
911-912	-	Kairouan (Tunisia)	
911-912	possible	Egypt	IX
926? 927?	possible	Thrace (Bulgaria)	IX
4/10/935	possible	Egypt	IX
2/7/944	possible	Cordoba (Spain)	VII
945	possible	Istanbul	
25/7/950	possible	Cairo	IX
951-1004	possible	Rossano (Italy)	IX
15/9/951	possible	Alexandria	IX

951-952	possible	Aleppo	IX
5/1/956	possible	Alexandria	
12/5/963	possible	Egypt	
22/7/963	Sicily	Sicily	
-/9/967	possible	SE Turkey	X
22/12/968	possible	Corfou	VII
1/7/969	possible	Egypt	IX
972	possible	Antioch, Damascus	VII-VIII
26/10/975	Sea of Marmara & Black Sea	Istanbul	
977-978	possible	Mahdia	
26/10/989	Sea of Marmara	Istanbul	VIII
989-990	-	Central Italy	IX-X
5/4/991	Levant	Baalbek, Damascus	IX
995	-	Armenia	X
996	possible	Delphi	VII
1002-1003	possible	Western Syria	>VIII
9/3/1011	possible	Istanbul	VII
1016	possible	Jaffa (Israel)	
1029-1030	possible	Damascus	VII
5/12/1033	Levant	Akko, Jericho (Israel)	VII
1036-1037	Cilicia (Turkey)	Cilicia (Turkey)	
2/11/1037	possible	Istanbul	VI
2/2/1039-1040	Sea of Marmara & Black Sea	Istanbul	VII
1042-1043	possible	Palmyra-Baalbek	>VII
1050	Aegean Sea	Santorini eruption	
27/8/1063	possible	Tripoli (Lebanon)	VII-VIII
23/9/1063-1064	Sea of Marmara	Istanbul	VII
1065	possible	Istanbul	VII
18/3/1068	Levant	Israel	VII
1070	possible	Beqaa (Lebanon)	
6/12/1087	possible	Istanbul	VII

1089	possible	Palmyra	>VIII
26/9/1091	possible	Antioch	VI-VII
3/1106	Adriatic Sea	Venice	
20/6/1112	Bay of Naples	Naples (Italy)	
12/3/1114	Calabrian arc	Calabrian arc (Italy)	
10/8/1114	Levant	Antioch, Samandag	?
1128	possible	Tyre	?
11/10/1138	possible	Aleppo	VI-VII
1140-1141	possible	Sheizar (Syria)	VI-VII
1147	possible	Gulf of Corinth	VII
1153	possible	Gulf of Corinth	VI
8/12/1156	possible	Sheizar (Syria)	VII-VIII
12/8/1157	possible	Hama (Syria), Lattakia, Tripoli (Leb.)	VIII-IX
4/2/1169	Messina-Paterno	Etna eruption	VII
29/6/1170	Levant	Damascus, Lattakia	VII-VIII
1172	Sicily	Sicily	
20/5/1202	Cyprus & Levant	Baalbek, Tyre, Damascus, Akko	IX
1211	possible	Thessaloniki	VI
11/5/1222	Libya, Alexandria	Paphos, Limasol (Cyprus)	VII
11/3/1231	Sea of Marmara	Sea of Marmara	VII
1246	possible	Western Crete	VII
1261	Levant	Levant	
11/8/1265	Sea of Marmara	Marmara island	
1268	possible	Adana (Cilicia)	
-/3/1270	Ionian Sea	Ionian Sea	
-/9/1273	Adriatic Sea	Albania	VII
22/3/1287	possible	Lattakia	VII-VIII
1/6/1296	possible	Istanbul	VII
17/7/1296	possible	Western Anatolia	VII
1300	possible	Corinth	VI
18/8/1303	Eastern Med	Crete-Rhodes	IX

1321	Adriatic Sea	Venice, Delphi	VI
12/5/1327	possible	Sea of Marmara	VI
28/6/1329	Sicily	Etna eruption	
12/2/1332	Sea of Marmara & Black Sea	Istanbul	VII
-/1/1339	possible	Tripoli (Lebanon)	VII
1/1/1341	possible	Crimea	
18/10/1343	Sea of Marmara & Black Sea	Istanbul	VIII
25/11/1343	Bay of Naples	Naples (Italy)	
2/1/1344	possible	Aleppo	VI-VII
19/5/1346	possible	Sea of Marmara	VI-VII
25/1/1348	Adriatic Sea	Friuli (Trieste)	
1/3/1354	possible	Sea of Marmara	VII-VIII
2/1/1365	Algeria	Algiers (Algeria)	
30/4/1366	possible	Rhodes	VII
1/6/1366	possible	North Aegean	VI-VII
1380	possible	Albania	VI
1383	possible	Lesbos island	VII
20/3/1389	Aegean Sea	Chios island (Greece)	VII
-/10/1395	possible	Thessaloniki	VII
-/6/1402	Gulf of Corinth	Gulf of Corinth	VII
28/7/1402	possible	Euboia	VI
16/11/1403	Levant	Aleppo	
20/2/1404	Syrian coast	Aleppo, Tripoli (Leb.)	VII-VIII
-/4/1407	possible	Antioch	VII
29/12/1408	Lattakia	Bkas, Lattakia, Jableh	VII-IX
1417	possible	Sea of Marmara	VI-VII
15/3/1419	possible	Istanbul	VII
25/5/1419	possible	Istanbul	VI-VII
18/12/1419	Sea of Marmara	Istanbul	
-/7/1420	possible	Thessaloniki	VI
-/12/1420	possible	Argos	VI
2/2/1428	possible	Camprodon (Catalonia)	

26/3/1430	possible	Thessaloniki	VI
4/9/1437	possible	Sea of Marmara	VII
28/11/1437	Aegean Sea	Aegean Sea	
-/7/1444	possible	Corfou	VII
1451	possible	Croatia	VII
16/6/1456	-	Serbia	VII
12/11/1456	possible	North Aegean	VI
5/12/1456	Bay of Naples	Naples (Italy)	
1457	possible	Argolid	VI
1469	possible	Kephalonia island	VII
1471	possible	North Aegean	VII
1471	possible	Albania	VII
23/4/1481	possible	Istanbul	VI-VII
3/5/1481	SW Turkey & Levant	Rhodes	VII
10/9/1481	possible	Rodigarganico (Italy)	
3/10/1481	SW Turkey & Levant	Rhodes	
15/2/1482	possible	Croatia	VII
1489	SW Turkey	Antalya (Turkey)	
1/11/1490	possible	Kos island (Greece)	
24/4/1491	possible	Cyprus	VII
18/8/1493	possible	Kos island (Greece)	VII
1/7/1494	Eastern Med	Crete	VII
7/12/1504	possible	Croatia	VII
29/5/1508	Eastern Med	Crete	VII
10/9/1509	Sea of Marmara & Black Sea	Istanbul	VIII