Christophe Morhange, Nick Marriner
and Nicolas Carayon

The eco-history of ancient Mediterranean harbours

1. Introduction

Up until recent times, coastal sediments uncovered during Mediterranean excavations received little attention from archaeologists.[1] Before 1990, the relationships between populations and their coastal environments had largely been studied within anthropological and naturalist frameworks, and largely considered in isolation. During the past twenty years, Mediterranean archaeology has changed significantly, underpinned by the emergence of a new culture–nature duality that has drawn on the north European examples of waterfront archaeology. Because of the challenges of coastal contexts, the archaeological community is nowadays increasingly aware of the importance of the environment in understanding the socio-economic and natural frameworks in which ancient societies lived, and multidisciplinary research has become a central pillar of large-scale Mediterranean coastal excavations.[2]

Ancient harbour contexts have emerged as particularly novel and original archives, shedding light on how humans have interacted with and modified coastal zones since the Neolithic. Around 7,000 years ago, at the end of the post-glacial marine transgression, societies started to settle along 'present' coastlines.[3] During the past 5,000 years, harbour technology has evolved to exploit a plethora of environmental contexts, from natural bays and pocket beaches through to the artificial basins of the Roman period.[4] Although some of these ancient port complexes continue to be thriving transport centres (such as Marseille, Istanbul, Alexandria, Beirut, etc.), many millennia after their foundation, the majority have been abandoned and their precise whereabouts remain unknown. Although not the sole agent of cultural change, these environmental modifications partly reflect that long-term human activities have prioritized access to the open sea. Societies have developed adaptive strategies in response to the rapidly changing face of coasts, and harbour sites closely mirror the shoreline modifications and natural hazards that form part of history's *longue durée*.[5]

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1 Marriner and Morhange 2007.
2 E. g., Raban et al. 2009; Carayon 2012–3.
3 Van Andel 1989.
4 E. g., Raban (ed) 1985; 1995; Frost 1995; Morhange (ed.) 2000.
5 E. g., Kraft et al. 1980; Stock et al. 2013.

Since the multidisciplinary studies of Marseille in France[6] and Caesarea Maritima in Israel,[7] there has been a proliferation of studies looking into coastal and ancient harbour geoarchaeology,[8] building on pioneering archaeological work in the first half of the twentieth century.[9] Ancient harbour basins are particularly interesting because: (1) they served as important economic centres and nodal points for maritime navigation;[10] (2) there is generally excellent preservation of the material culture due to the anoxic conditions induced by the water table;[11] and (3) there is an abundance of source material for palaeo-environmental reconstruction.[12]

2. Eastern Mediterranean origins

The ease of water transport, via fluvial and maritime routes, was important in the development of civilisations. Four areas – the Indus, China, Mesopotamia and Egypt – played an important role in the development of harbours.

It is often argued that the Egyptians were one of the earliest Mediterranean civilisations to engage in water transport. Circumstantial evidence for the use of boats in ancient Egypt derives from deep-water fish bones found at prehistoric hunter/gatherer campsites.[13] The earliest boats were probably papyrus rafts which enabled these societies to navigate.[14] It is speculated that wooden boats were adopted during Neolithic times with the introduction of agriculture and animal husbandry. The rise of chiefdoms during the Egyptian Predynastic period was accompanied by the widespread adoption of boats as attested by the archaeological evidence. North of the First Cataract of the Nile in Egypt, ships could travel to almost anywhere along the river. For example, Bronze Age harbourworks are known from Memphis and Giza. Despite excavations at a number of sites, however, the exact locations of many of the river ports are equivocal.[15]

On the delta, the then seven branches of the Nile served as waterways into the eastern Mediterranean. The eastern Mediterranean was also a natural communications link between the major cultural centres of Syria-Palestine, Cyprus, Crete, Greece and Libya. In light of this, it is unsurprising that the works along the fluvial banks of the Nile and the coastlines of the Red Sea and Mediterranean were many and varied. During the third millennium BC, canals were excavated from the Nile to the valley temples of the Giza pyramids so that building materials could be transported. Quays were also commonly established along the Nile: for instance, at fourteenth-century BC Amarna, boats were depicted parallel to shoreside quays equipped with bollards.[16] An artificial quay dating to the second millennium BC is attested

6 Hesnard 1994.
7 Raban and Holum (eds) 1996.
8 See Marriner and Morhange 2007 and Goiran et al. 2011a for references.
9 E. g., Pâris 1915; 1916; Lehmann-Hartleben 1923; Poidebard 1939; Poidebard and Lauffray 1951.
10 E. g., Arnaud 2005; Keay (ed.) 2012.
11 E. g., recent research in Narbonne, southern France: Sanchez et al. 2013.
12 E. g., Reinhardt et al. 1998; Marriner 2009a; 2009b.
13 Shaw et al. 1993.
14 Basch 1987.
15 Fabre 2004–5.
16 Blackman 1982a; 1982b.

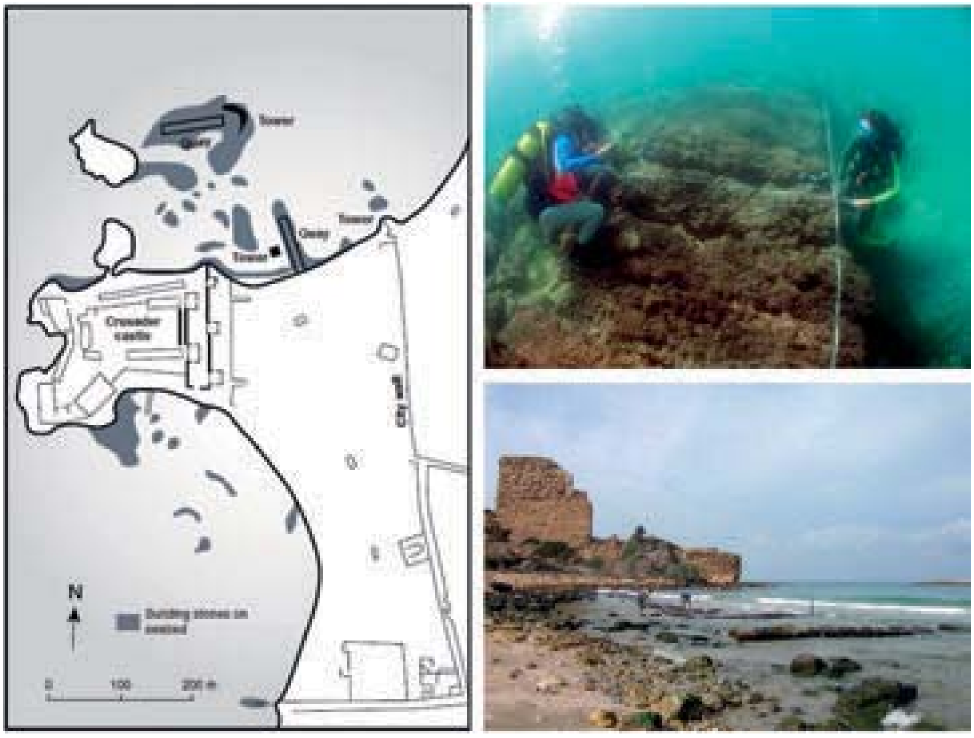

Fig. 3.1: Plan of Atlit and its harbour. Atlit is a Phoenician harbour in present-day Israel. It was used during Iron Age II and until the end of the Persian era. The study of Atlit has provided invaluable information on the planning and construction of Phoenician harbours in the Levant. The harbour occupies an ideal natural bay on the north and north-east of the promontory upon which the Crusader castle stands. This promontory protects the area from the prevailing winds and swells from the south-west. To the west, protection is afforded by two rocky islets. In c. 2700 years cal. BP (c. 700 BC) the natural bay was improved by the construction of two moles, each consisting of two parallel walls of ashlars with a stone filling in between: a common Phoenician technique. (Based on a drawing by A. Raban, after Haggi and Artzy 2007).

at Karnak, on the Nile.[17] High sediment supply and rapid changes in fluvial systems mean that few conspicuous remains of these early fluvial harbours are still visible, particularly on the delta.

Navigation in the Red Sea during Pharaonic times is a theme that has attracted renewed interest during the past 30 years, underpinned by the discovery of numerous coastal sites shedding new light on the extent and chronology of human impacts in maritime areas. Extending for over 2,000 km from the Mediterranean Sea to the Arabian Sea, the Red Sea was a major communications link. Recent findings have been made at Ayn Soukhna, El-Markha

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[17] Fabre 2004–5.

and Wadi el-Jarf.[18] At Mersa Gawasis, archaeological excavations have documented evidence for some of the world's earliest long-distance seafaring.[19] The site was used extensively during the Middle Kingdom (c. 4,000–3,775 years ago), when seafaring ships departed from the Egyptian harbour for trade routes along the African Red Sea coast.

3. Chrono-typology

In the Mediterranean, the first artificial harbour structures appear to date to the Middle Bronze Age. For example, submerged boulder piles are attested at Yavne-Yam on the coast of Israel; these suggest human enterprise to improve the quality of the natural anchorage. Recent geoarchaeological work in Sidon has elucidated the presence of a semi-protected basin beginning around 4410 ± 40 BP.[20] This sedimentological unit has been interpreted as a proto-harbour, with possible artificial reinforcement of the shielding sandstone ridge to improve the natural anchorage quality. It is suggested that small boats were hauled onto the beach face, with larger vessels being anchored in the outer harbour of Zire.[21] After this period, the maritime harbours of the ancient Mediterranean evolved in four broad technological leaps as outlined below.

3.1 Bronze Age to Early Iron Age ashlar technology

A double ashlar wall with a filling of fieldstones (pier-and-rubble technique) is a harbour construction method commonly attributed to the Phoenicians.[22] This harbour construction technique appeared in the Levant at the end of the ninth century BC and the first examples are attested at Atlit in Israel[23] and Tabbat-al-Hammam in Syria.[24]

This technique spread from the Levant to the western colonies and Greece where it can be found as late as the sixth century AD. For instance, the use of ashlar techniques can be seen in the Persian harbour of Akko (Israel), the Hellenistic harbour at Amathus on Cyprus, the Punic harbour of Carthage and the Roman quay at Dor. Iron Age Athlit is one of the best-studied Phoenician harbours.[25] The northern harbour's mole extends about 100 m into the sea and is about 10 m wide. It is constructed of two parallel ashlar headers of 2–3 m in width. Between the ashlar walls, a fill of stones was placed. This form of construction added stability so that the mole could withstand the high energy of the waves. The northern part of the mole ends with north-facing ashlar headers. The mole was placed on a foundation of ballast pebbles. Radiometric dating of wood fragments constrains this structure to the ninth century BC, although there is very little pottery dating from this period.[26]

18 Tallet 2009.
19 Bard and Fattovich 2010.
20 Marriner et al. 2006a.
21 Carayon 2008; 2012–3.
22 Raban 1985; 1995.
23 Haggi and Artzy 2007.
24 Braidwood 1940.
25 Haggi and Artzy 2007.
26 M. Artzy, pers. comm.

3.2 Artificial, dug harbours (Iron Age to the Roman period)

During the Iron Age a new harbour construction technique appeared in the Mediterranean. This technique comprised either the digging of artificial harbour basins along the coastline or the deepening and extension of natural lagoons.[27] The method is attested as early as the Bronze Age in fluvial contexts in Egypt[28] and Mesopotamia.[29] The artificial, dug harbour of Coral Island in the Red Sea,[30] believed to be the naval station of Salomon and Hiram of Tyre mentioned in the Bible, could date to the tenth century BC, and thereby constitute one of the oldest examples of an excavated harbour in a maritime context. This technique was subsequently propagated throughout the Mediterranean, probably via the Phoenicians. It is attested during the period of Carthaginian domination over the western Mediterranean, from the fifth century BC onwards, at Mahdia and Carthage in Tunisia.[31] The cothon at Carthage, which sheltered the city's fleet during the third Punic War (146 BC), was an artificial harbour that was equipped with slipways for 220 war vessels.[32] The technique is also attested in the Greek world, with examples at Lechaion-Corinth,[33] and in the Roman world at Portus,[34] where the harbour was constructed by the Emperor Trajan (AD 98–117) and attests to a monumentalisation of the technique.

3.3 Hydraulic concrete

Pre-Roman ashlar block methods continued to be used throughout the Roman era. Nonetheless, another technique was introduced during this period that completely revolutionised harbour design – the use of hydraulic/pozzolana concrete. This technological breakthrough meant that natural roadsteads were no longer a prerequisite to harbour loci and completely artificial ports, enveloped by imposing concrete moles, could be located offshore on open coasts. The material could be cast and set underwater, and started to be used during the second century BC. Roman engineers were free to create structures in the sea or along high-energy shorelines.[35] Pozzolana concrete facilitated the construction of offshore basins such as Claudius' harbour at Portus.[36]

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[27] Carayon 2005.
[28] Kemp and O'Connor 1974.
[29] Woolley 1930.
[30] Flinder 1977.
[31] Carayon 2005.
[32] Hurst and Stager 1978.
[33] Morhange et al. 2012.
[34] Keay et al. (eds) 2005.
[35] Hohlfelder 1997; Brandon et al. 2010.
[36] Goiran et al. 2011a.


Sinai
Continental harbour
Northern jetty
Southern jetty
Outer harbour
Jezirat Fara'un
Cothon ?
Carayon
Ancient jetties ?
Outer harbour
Cothon ?
Image @2016 DigitalGlobe Google (date 17/02/2011)
Outer harbour
Cothon ?
Metwali

← Fig. 3.2: The artificial harbour of Jezirat Fara'un Coral Island, Egypt. The island of Jezirat Fara'un lies in the Gulf of Aqaba, about 300 m offshore and 10 km south of Eilat (ancient Eloth). It measures c. 325 m north to south and 150 m east to west. The northernmost and highest of its three hills is topped by an Islamic fortress. The other two hills to the south and east are smaller and have Byzantine architectural remains. In the southwest of the island, facing the continent, a small rocky cove, today silted, was connected to the sea by a narrow channel. Jezirat Fara'un is also surrounded by a coral reef. The stretch of sea separating the island from the mainland is well protected and the best natural anchorage in the Gulf of Aqaba.
The anchorage has a landing site, comprising a pebble beach, near an ancient trade route. The docking facilities were improved by the construction of two jetties. On the island, the rocky cove also served as a loading and unloading area.
The 'cothon' of Jezirat Fara'un is semi-artificial. The basin was roughly rectangular (60 by 30 m and 2.5-3 m in depth) with a 10 m wide entrance. The seaward opening of the pocket beach was closed by a breakwater. This served as the foundation for the island's wall that encircles the harbour basin. Ceramic fragments collected from the site have been dated to the beginning of the early Iron Age. (References in Carayon 2008).

3.4 Romano-Byzantine harbour dredging

Ancient authors mention harbor dredging,[37] although direct archaeological evidence has, until now, remained elusive. The ancient harbours of Marseille and Naples have both undergone widespread excavations,[38] and multidisciplinary datasets now exist for numerous sites including Lechaion-Corinth,[39] Tyre and Sidon[40] or Naples.[41]

On decadal timescales, continued silting induced a shortening of the water column. De-silting infrastructure, such as vaulted moles and channels, partially attenuated the problem, but in the long term these appear to have been relatively ineffective. In light of this, repeated dredging was the only means of maintaining a practicable draught depth and ensuring long-term harbour viability. At Marseille, although dredging phases are recorded from the third century BC onwards, the most extensive enterprises were undertaken during the first century AD, at which time huge tracts of Greek sediment were extracted. Three dredging boats have been unearthed. The vessels were abandoned at the bottom of the harbour during the first and second centuries AD. They are characterised by an open central well that is inferred to have accommodated the dredging arm.[42] At the excavations of Naples, the absence of pre-fourth-century BC layers has been linked to extensive dredging between the fourth and second centuries BC.[43] Unprecedented traces 165–80 cm wide and 30–50 cm

[37] Tacitus, *Annals* 16.23.1; cf Strabo 14.1.24.
[38] Morhange and Marriner 2010.
[39] Morhange et al. 2012.
[40] Marriner and Morhange 2006.
[41] Amato et al. 2009; Carsana et al. 2009.
[42] Pomey 1995.
[43] Carsana et al. 2009.

Fig. 3.3: Submerged Roman harbor of Portus Julius near Puteoli, Italy. One marker of the majesty of ancient Rome is its surviving architectural legacy, the remains of which are scattered throughout the Mediterranean landscape. Surprisingly, one remarkable aspect of this heritage remains relatively unknown. Beneath the waters of the Mediterranean lie the remnants of a vast maritime infrastructure that sustained and connected the Roman empire and its economy. The key to this incredible accomplishment and to the survival of structures in a hostile marine environment was hydraulic concrete. This building material was discovered by the Romans and employed to construct harbour installations wherever needed, rather than only in locations with advantageous geography. The discovery of hydraulic concrete during the early Roman period marked a technological revolution in coastal engineering. (Photo courtesy of the Centre Jean Bérard, Naples).

deep attest to powerful dredging technology that scoured into the volcanic substratum, reshaping the harbour bottom.[44] Notwithstanding scouring of the harbour bottoms, this newly created space was rapidly infilled and necessitated regular intervention due to sedimentation rates up to ten times superior to those in a natural environment.

44 Boetto 2010.

Fig. 3.4: Late medieval dredging of a harbour. (Woodcut from Olaus Magnus 1555, 420).

4. Geoarchaeological study of harbour basins

In tandem with the development of rescue archaeology, particularly in urban contexts, the study of sedimentary archives has grown into a flourishing branch of archaeological inquiry.[45] This growing corpus of sites and data demonstrates that ancient harbours constitute rich archives of both the cultural and environmental pasts. Ancient harbour sediments are particularly rich in archaeological remains, bioindicators and macro-remains yielding insights into the history of human occupation at a given site, coastal changes and the natural processes and hazards that have impacted these waterfronts.[46] Ancient harbours are both natural and constructed landscapes and, from a geoarchaeological perspective, comprise three elements of note.

4.1 The harbour basin

In architectural terms, the harbour basin is characterised by its artificial structures, such as quays and moles.[47] Since the Bronze Age, there has been a great diversity in harbour infrastructure in coastal areas, reflecting changing technologies and human needs. These include, for instance, natural pocket beaches serving as proto-harbours, the first Phoenician mole attributed to around 900 BC and the offshore Roman constructions made possible by the discovery of hydraulic concrete.[48]

[45] Walsh 2004.
[46] Morhange and Marriner 2010b.
[47] Oleson 1988.
[48] Oleson et al. 2004.

Fig. 3.5: Evidence of ancient harbour dredging in Piazza Municipio, Naples. The coastal landscape of the port of Neapolis has been precisely elucidated after 10 years of archaeological excavations and geoarchaeological investigations. The Graeco-Roman harbour has been located in a large cove lying between Municipio square and Bovio square. The excavations revealed several levels of the sandy sea floor of the harbour, which was in used from the late fourth century BC to the fifth century AD.
The photograph shows traces of dredging of Hellenistic sediment and volcanic tufa in the Piazza Municipio excavation, line 1. The red line corresponds to the upper surface of dredging scars. Hellenistic sediments filled the dredging depressions. (Photo courtesy of the Soprintendenza Speciale per i Beni Archeologici di Napoli).

4.2 Ancient harbour sediments

Shifts in the granularity of ancient harbour sediments translate the degree of harbour protection, often characterised by a rapid accumulation of sediments following a sharp fall in water competence brought about by artificial harbourworks. The harbour facies is characterised by three poorly-sorted fractions: (1) human waste products, especially at the base of quays and in areas of unloading (harbour depositional contexts are particularly conducive to the preservation of perishable artefacts such as leather and wood); (2) poorly-sorted sand; and (3) an important fraction (> 90 %) of silt that translates the sheltered environmental conditions of the harbour. These areas are characterised by rapid accumulation rates of 10–20 mm per annum. High-resolution study of the sediments can help shed light on the nature of ancient harbourworks, such as those at Tyre[49] or Portus.[50] Recent research has sought to characterise these chronostratigraphic phases using the unique sedimentary signature that each technology brings about. Changes in sediment supply at the watershed scale are particularly important in understanding base-level changes in deltaic contexts, as in Cyprus[51] or the palaeo-island of Piraeus.[52]

4.3 Relative sea-level changes versus draught depth

Nowadays, most ancient harbours are completely infilled with sediments. Within this context, it is possible to identify and date former sea-level positions using biological indicators fixed to quays, that, when compared with the marine bottom, allow the height of the palaeo-water column to be estimated.[53] Such relative sea-level data are critical in understanding the history of sedimentary accretion in addition to estimating the draught depth for ancient ships.[54] These two reference levels, the palaeo-sea level and sediment bottom, are mobile as a function of crustal movements (e. g., local-scale neotectonics, regional isostasy, sediment budgets) and human impacts such as dumping and dredging. All these factors can potentially impact upon the available accommodation space for sediment accretion.

One of the key problems posed by artificially-protected harbours relates to accelerated sediment trapping. In the most acute instances it could rapidly reduce the draught depths necessary in accommodating large ships. From an economic perspective, harbours were important, and many changes in basin location can be explained functionally by the need to maintain an interface with the sea in the face of rapid sedimentation. The best example of this coastal relocation derives from Aegean Anatolia (present-day Turkey) where Brückner et al.[55] have reconstructed a progradation of several tens of kilometres in a number of ancient rias such as the Meander.

5. Ancient harbour location

During the past twenty years, multidisciplinary geoscience inquiry has allowed a better understanding of where, when and how ancient Mediterranean harbours evolved. This is set within the wider context of the utilisation of new palaeo-environmental proxies. A battery of research tools is available that broadly draw on (1) geomorphology and (2) the sediment archives located within this complex.

The geography of ancient harbours constitutes a dual investigation that probes both the location and the extension of the basins. Biostratigraphical studies of sediments, married with GIS investigation, can be used to reconstruct coastal evolution and identify possible anchorage areas. Urban contexts are particularly problematic for accurate archaeological studies because the urban fabric can hide many of the most important landscape features.

49 Marriner et al. 2008.
50 Goiran et al. 2010.
51 Devillers 2008.
52 Goiran et al. 2011b.
53 Laborel and Laborel-Deguen 1994; Morhange et al. 2006.
54 Morhange et al. 2001; Goiran et al. 2009; Boetto 2010.
55 Brückner et al. 2005.

In such instances, chronostratigraphy can be particularly useful in reconstructing coastal changes. This approach helps not only in reconstructing ancient shorelines through time but can also aid in locating ports for which no conspicuous archaeological evidence presently exists, as in the case of Cuma[56] or Byblos.[57]

Geophysical techniques, such as electrical tomography and georadar, can provide a great multiplicity of mapping possibilities, notably in areas where it is difficult to draw clear parallels between the archaeology and certain landscape features. Because geophysical techniques are non-destructive, they have been widely employed in archaeology, and are gaining importance in coastal geoarchaeology[58] and ancient harbour contexts.[59] Reliable information can be provided on the location, depth and nature of buried archaeological features before excavation.

6. Ancient harbour stratigraphy

The aim of geoarchaeological harbour studies is to write a 'sedimentary' history of human coastal impacts, using geoscience tools. Research attests to considerable repetition in ancient harbour stratigraphy, both in terms of the facies observed and their temporal envelopes. There are three distinct facies of note: (1) middle-energy beach sands at the base of each unit (i. e. the pre-harbour phase); (2) low-energy silts and gravels (i. e. the active harbour phase); and (3) coarsening beach sands or terrestrial sediments which cap the sequences (i. e. the post-harbour facies). In the broadest terms, this stratigraphic pattern translates a shift from natural coastal environments to anthropogenically-modified contexts, before a partial or complete abandonment of the harbour.[60]

The ancient harbour facies corresponds to the active harbour unit. This artificialisation is translated in the sedimentary record by lower energy sediments consistent with a barring of the anchorage by artificial means. Harbour infrastructure accentuates the sediment sink properties by attenuating marine energy (swell and waves) leading to a sharp fall in water competence. Research has demonstrated that this unit is by no means homogeneous, with harbour infrastructure and the nature of sediment sources playing key roles in shaping facies architecture. Of note is the grain-size paradox of this unit: fine-grained silts juxtaposed with coarse gravels made-up of ceramics and other urban waste.

During the Early Iron Age, improvements in harbour engineering are recorded by increasingly fine-grained facies. Plastic clays tend to be the rule for Roman harbours and sedimentation rates 10–20 times greater than naturally prograding coastlines are recorded. The very well protected Roman harbours of Alexandria, Marseille[61] and Fréjus[62] all comprise plastic marine muds consisting of more than 90 % organic silts. Significant increases in sedimentation rates can also be attributed to human-induced increases in the supply term including, for example, anthropogenic changes in the catchments of supplying rivers due to

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56 Stefaniuk and Morhange 2009.
57 Stefaniuk et al. 2005.
58 Hesse 2000.
59 E. g., Keay et al. (eds) 2005 for Portus.
60 Marriner and Morhange 2006.
61 Morhange et al. 2003.
62 Gébara and Morhange 2010; Bony et al. 2011.

deforestation and agriculture practices, erosion of adobe constructions and, finally, use of the basins as ad hoc waste dumps. This underlines the importance of an explicit source-to-sink study integrating both the coastal area and the upland hinterland.

7. Coastal hazards

Human societies in coastal zones are arguably the populations most prone to the danger of natural hazards and the need to devise strategies to live with. Not only are coastal populations confronted with the major geological problems of earthquakes and volcanic eruptions, but such hazards are compounded by the interface situation. Tsunamis and storms are an obvious link between geological hazards and the sea, but slower connections are also encountered, for example post-glacial sea-level rise. Slow, crustal changes along coasts are also significant, and from the Neolithic period onwards, human activities have become a notable forcing factor. Here, we draw on current topical examples to focus on two types of coastal hazard: sea-level rise and coastal deformation linked to base-level sediment inputs.[63]

7.1 Slow post-glacial sea-level rise

Since 18,000 years BP a relative sea-level rise of about 120 m has drowned significant areas of Palaeolithic archaeology beneath the sea.[64] Until relatively recent times, human societies in coastal regions were totally at the mercy of sea-level rise. Only relatively late in history, essentially beginning with the Roman era, did societies acquire the engineering skills to deal with these problems. Many coastal Palaeolithic sites may therefore be drowned offshore, awaiting investigation by underwater archaeologists. The sea-level change has been too slow to constitute a hazard in the true meaning of the word, but, in any case, no technology was yet available to protect against the inexorable rise of the sea.

Since c. 7,000 years BP, relative sea-level changes have been characterised by a pronounced deceleration linked to the end of glacio-eustatic forcing agents. After 7,000 years BP, local adjustments are mostly attributed to crustal factors (i. e. isostasy and tectonics) and in the case of the Mediterranean coast, relative sea-level changes of less than 10 m are observed.[65] Within this context, coastal environments provide excellent sea-level archives due to a precise biological zonation of marine species living just above or below mean sea level and given the density of archaeological coastal remains such as harbours and drowned urban areas.[66] A methodology refined by Laborel and Laborel-Deguen[67] has been successfully applied to numerous excavations, including those of the ancient harbours of Marseille,[68] Pozzuoli[69] and Fréjus.[70] Where precise vertical relationships can be established between archaeological structures and biological indices it has been possible to

63 Morhange and Marriner 2010b.
64 Masters and Flemming (eds) 1983.
65 Pirazzoli 1976; Flemming and Webb 1986.
66 Blackman 1982a; 1982b.
67 Laborel and Laborel-Deguen 1994.
68 Pirazzoli and Thommeret 1973; Morhange et al. 2001.
69 Morhange et al. 2006.
70 Devillers et al. 2007; Morhange et al. 2013.

Fig. 3.6: Deltaic progradation of the Acheloos delta. Ancient Oiniadai lies at the base of the Trikardo palaeo-island in the centre of the Acheloos River delta (NW Greece) at a distance of 9 km from the present coastline. Its ancient shipsheds testify to a former connection with the Ionian Sea. Sedimentological, geochemical and faunal analyses of sediment samples from numerous cores were carried out in order to decipher the progradation of the delta in a context of sea-level stabilization since c. 6000 years BP. Based on sedimentary and archaeological evidence, it was found that during classical and Hellenistic to Roman times – when the shipsheds were in use – the northern harbour experienced continuous water inflow from the Acheloos River and communicated with the sea via a lagoon. Sedimentary evidence suggests that the island never had a seafront harbour. Trikardo, throughout the millennia, represented an excellent terrestrial outpost on a low-lying coast, well protected by the lagoon and marshy areas and, at the same time, providing rapid access to the sea. (After Vött 2007; Vött et al. 2007). →

reconstruct accurately relative sea-level trends since antiquity at a number of Mediterranean sites.[71] The strength of such results lies in the precision of biological palaeo-zonation with the chronological accuracy of well-dated archaeological remains.

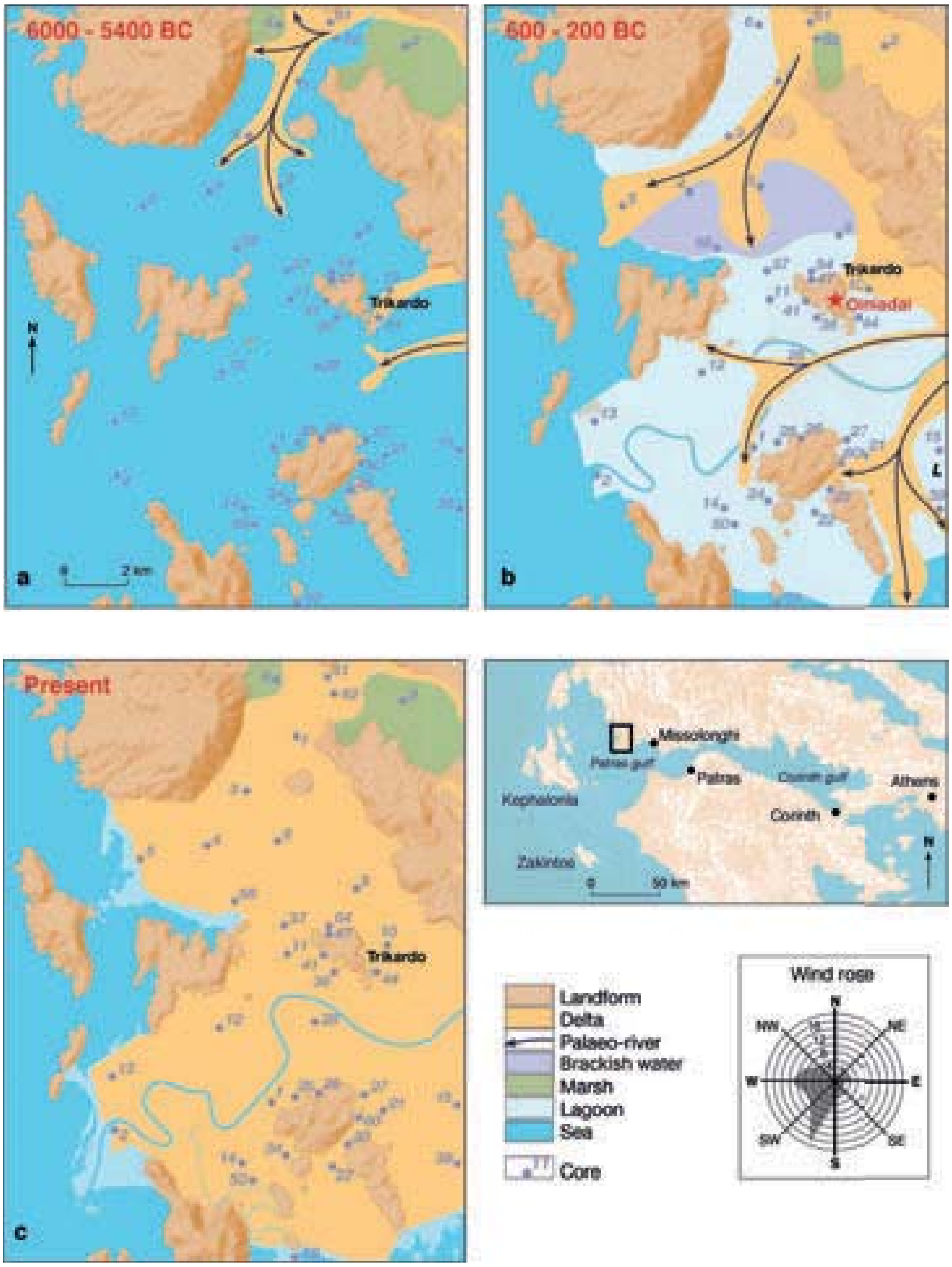
In so-called 'stable' areas, sea-level rise has averaged less than 1 mm a year during the last 2,000 years – hardly a hazard to the human population. Evidently, higher sea levels increase the risk of flooding during storms. A consequence of moderate sea-level rise was the gradual infilling of base-level depocentres such as lagoons, river mouths and coastal marshlands. During the Bronze Age, for example, the Levantine coastline was characterised by an indented morphology, where lagoons and estuaries were exploited as natural harbours. Limited accommodation space and high clastic inputs quickly infilled this indented morphology to yield a linear coastline. Bronze Age sites gradually became isolated from the sea, and human populations, unable to offset the rapid rates of sedimentation, were displaced to new locations on the rapidly prograding coasts.

7.2 Rapid sea-level rise

The effects of rapid sea-level rise may be illustrated by Alexandria, Egypt, where the late Roman harbour is submerged around 6 m below the present sea level.[72] To the west of the city, in Abukir Bay, this offset is even more pronounced at c. 8 m relative to present level.[73] The mechanisms responsible for the collapse of the western margin of the Nile delta are at present unclear, but appear to comprise fault tectonics, sediment compaction, offshore diapirism and slope instability of the prodelta.

Research has also highlighted the role of instantaneous sea-level changes causing harbour destruction during severe storm and tsunami events. For example, major excavation works in the Byzantine port of Theodosius (Yenikapı, Istanbul) have elucidated a scenario of catastrophic seaport destruction during the sixth century AD, attributed to the earthquake

71 See references in Morhange and Marriner 2010b.
72 Goiran et al. 2005; Stanley and Bernasconi 2006.
73 Stanley et al. 2001; 2004.


6000 - 5400 BC
Trikardo
a
2 km
600 - 200 BC
Trikardo
Oiniadai
b
Present
Trikardo
c
Missolonghi
Patras
Corinth
Athens
Kephalonia
Zakintos
50 km
Landform
Delta
Palaeo-river
Brackish water
Marsh
Lagoon
Sea
Core
Wind rose
N
NE
E
SE
S
SW
W
NW

of AD 553 and the possible tsunami associated with that event.[74] Similar high-energy impacts have been described for the ancient harbour of Caesarea in Israel.[75]

A review of the literature written during the past 30 years shows a shift away from the myth of drowned cities (e.g., Spyridon Marinatos for the lost harbour of Helike on the Corinthian Gulf) to a more modern paradigm of rapid sediment accretion driving coastal progradation and the landlocking of ancient harbours.

7.3 Hypersedimentation and coastal changes

From 6,000 years BP, Mediterranean coasts attest to exceptional coastal progradation linked to a deceleration of global glacio-eustasy at all spatial scales.[76] This phenomenon explains significant coastal changes to which ancient societies constantly had to adapt. The Bronze Age harbour of Gaza, for example, is currently landlocked due to sediment inputs from the Nile that have been reworked by the eastern Mediterranean gyre. This sweeps westward across the prodelta area before being deviated north towards the Levantine coast.[77] In a wave-dominated situation, sedimentary infilling has led to a change in the coastal geomorphology from an indented coastline to a rectilinear clastic coast. The effect on the pattern of human settlement has been a gradual dislocation of ancient settlements to keep pace with coastal progradation.

Research in the lower Argens (Fréjus, Var, France) has elucidated about 10 km of coastal progradation during the last 6,000 years.[78] In a similar vein, the Pedheios-Gialias ria (Cyprus) has undergone some 20 km of coastal progradation since the Neolithic. Ancient harbour palaeo-geography in this vast palaeo-bay attests to the gradual seaward displacement of settlements in order to keep pace with the rapid sedimentation and shoreline progradation.[79] Hypersedimentation of coastal areas, therefore, clearly engendered problems of access to the sea and hence the long-term viability of harbours. Many good examples are known from the Ionian coast of Turkey, an area where human-environment interactions have a long history of research.[80] This geomorphological evolution is particularly true of settlements located in rias, the best examples deriving from the Ionian coast of Turkey.[81] For example, the watersheds of Ephesus, Miletus, Troy, Priene and Ephesus correspond to narrow grabens, with limited accommodation space. Harbour displacement was linked to rapid shoreline progradation. Such high rates of harbour infilling were detrimental to the medium- to long-term viability of harbour basins.

The discovery of hydraulic concrete during the early Roman period marked a technological revolution in coastal engineering. Natural roadsteads were no longer a prerequisite for seaport construction and completely artificial harbour basins could be built offshore in high-energy environments, an enterprise which was difficult during the Iron Age.

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74 Bony et al. 2012.
75 Reinhardt et al. 1999; 2006.
76 Stanley and Warne 1994.
77 Morhange et al. 2005.
78 Dubar 2003.
79 Devillers 2008.
80 Kraft et al. 1977; 1980; 2003; 2007.
81 Brückner 1997; Brückner et al. 2002.

8. Human impacts

Human societies and the natural environment have long been considered independently of each other rather than as a co-evolution in which they are complimentary. Recent work demonstrates that coastal sediments can be used to reconstruct the history of humans and their interactions with the environment since prehistory. The presence and impact of societies can be reconstructed using a number of proxies, as outlined below.

a. Granulometric impacts: the construction of harbor works is recorded in the stratigraphic record by a unique fine-grained sedimentary facies. This lithoclastic signature facilitates a delimitation of the ancient basin topography.
b. Biological pollution: modification in faunal assemblages record local anthropogenic impacts such as increases in turbidity and use of the basin as a waste depocentre over many thousands of years.
c. Geochemical impacts: lead (Pb) has proved to be a powerful tool in elucidating ancient industrial activities. Within this context, it has been demonstrated that ancient harbours are particularly rich archives of palaeo-pollution. At Alexandria in Egypt, for example, lead isotope analyses have been used to elucidate the pre-Hellenistic occupation of the site.[82] The Graeco-Roman apogee of the city is attested by lead pollution levels twice as high as those measured in contemporary ports and estuaries. Similar patterns have also been reconstructed in harbour sediments from Marseille[83] and Sidon.[84]

9. Conclusion

Today, it is recognised that harbours should be studied within broader regional frameworks using a multidisciplinary methodology. The diversity of contexts investigated has brought to light some striking patterns. Numerous processes are important in explaining how these have come to be preserved in the geological record including the distance from the present coastline, position relative to present sea level and geomorphology. Some of the main advances made during the past twenty years include: (1) the precise characterisation of harbour facies in coastal contexts, using a variety of sedimentological, geochemical and palaeo-ecological proxies; (2) the characterisation and intensity of human impacts in coastal areas; and (3) the scope to derive high-resolution relative sea-level data.

Christophe Morhange
Aix Marseille University, IUF, CEREGE-CNRS UMR 7330
Europole de l'Arbois, F-13550 Aix-en-Provence
morhange@cerege.fr

Nick Marriner
Laboratoire Chrono-Environnement, UMR 6249 CNRS
Université de Franche-Comté, UFR ST, F-25030 Besançon
nick.marriner @univ-fcomte.fr

[82] Véron et al. 2006.
[83] Le Roux et al. 2005.
[84] Le Roux et al. 2002; 2003.

Nicolas Carayon
CNRS UMR 5140 Archéologie des sociétés méditerranéennes
390 avenue de Pérols, F-34970 Lattes-Montpellier
nicocara@hotmail.com

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