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Harbors and Ports, Ancient

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Synonyms

Haven; Port; Roadstead

Definition

Coastal areas have been used as natural roadsteads at least since prehistoric times. In the Oxford English dictionary, a harbor is "a place on the coast where ships may moor in shelter, especially one protected from rough water by piers, jetties, and other artificial structures." This safe refuge can be either natural or artificial. As a result, the term "harbor" can often be ambiguous when it refers to a premodern context because it incorporates a plethora of landing site types, including offshore anchorages, in addition to different mooring facilities and technologies (Raban 2009). Conceptions of ancient Mediterranean harbors have frequently been skewed by all-season harbor facilities such as Alexandria (Egypt), Piraeus (Greece), and Valletta (Malta) with their favorable geomorphological endowments. The archaeological record is, however, more complex. Port is derived from the Latin *portus* meaning "opening, passage, asylum, refuge." Drawing on multidisciplinary archaeological and geoscience tools, there has been a renewed interest in ancient harbors during the past 30 years, including the Indian Ocean (Rao 1988), the Atlantic, Scandinavia (Ilves 2009), the Mediterranean (Marriner and Morhange 2007), and Africa (Chittick 1979).

Introduction

Until recently, coastal sediments uncovered during Mediterranean excavations received very little attention from archaeologists, even though, traditionally, the received wisdom of *Mare Nostrum*'s history has placed emphasis on the influence and coevolution of physical geography in fashioning its coastal societies (Braudel 2002; Stewart and Morhange 2009; Martini and Chesworth 2010; Abulafia 2011). Before 1990, the relationships between Mediterranean populations and their coastal environments had been studied within a cultural-historical paradigm, where anthropological and naturalist standpoints were largely considered in isolation (Horden and Purcell 2000). During the past 20 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 wetland and waterfront archaeology (Milne and Hobley 1981; Coles and Lawson 1987; Purdy 1988; Coles and Coles 1989; Mason 1993; Van de Noort and O'Sullivan 2006; Menotti and O'Sullivan 2012). This built on the excavation of Alpine lake settlements in Switzerland and elsewhere from the 1850s onwards (Keller 1866). Because of the challenges of waterfront contexts, the archaeological community is today increasingly aware of the importance of the environment in

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understanding the socioeconomic and wider natural frameworks in which ancient societies lived, and multidisciplinary research and dialogue have become a central pillar of most large-scale excavations (Walsh 2004; Butzer 2005, 2008; Walsh 2008).

It is against this backdrop that ancient harbor contexts have emerged as particularly novel archives, shedding new light on how humans have locally interacted with and modified coastal zones since the Neolithic (Marriner and Morhange 2007). This idea is set within a wider debate on the Early Anthropocene Hypothesis (Ruddiman 2007) and human-driven changes in Holocene environments (e.g., Marriner et al. 2014). Their importance in understanding ancient maritime landscapes and societies (e.g., Gambin 2004, 2005; Tartaron 2013) makes them one of the most discussed archaeological contexts in coastal areas (Fig. 1). Around 6000 years ago, at the end of the Holocene marine transgression, societies started to settle along "present" coastlines (Van Andel 1989). Older sites were buried and/or eroded during this transgression (Bailey and Flemming 2008). During the past ~4000 years, harbor technology has evolved to exploit a wide range of environmental contexts, from natural bays and estuaries (e.g., Giaime et al. 2018) through to the completely artificial basins of the Roman and Byzantine periods. Although some of these ancient port complexes continue to be thriving transport centers, now, many millennia after their initial foundation, the vast majority have been completely abandoned, and their precise whereabouts, despite rich textual and epigraphic evidence, remain unknown. Although not the sole agent of cultural change, these environmental modifications indicate in part that long-term human subsistence has favored access to the open sea. Key to this line of thinking is the idea that societies have adopted adaptive strategies in response to the rapidly changing face of the coastal environment, and in many instances, harbor sites closely mirror modifications in the shoreline (e.g., Brückner et al. 2004; Giaime et al. 2019a). Nonetheless, it is important to emphasize that regional environmental change, although strong, must not be seen as the principal agent of cultural shifts and that site-specific explanations remain fundamental (Butzer 1982).

During the 1960s, urban regeneration led to large-scale urban excavations in many coastal cities of the Mediterranean. It was at this time that the ancient harbor of Marseille (France) was rediscovered. Nonetheless, it was not until the early 1990s that two large-scale coastal excavations were undertaken at opposite ends of the Mediterranean in Marseille (Hesnard 1994, 1995) and Caesarea Maritima in Israel (Raban and Holum 1996). Both projects placed emphasis on the harbor archaeology and their articulation within the wider landscape. The first, at Caesarea Maritima, investigated a completely artificial Roman harbor complex on the Levantine coast, active between the first and second centuries CE (Reinhardt et al. 1994; Reinhardt and Raban 1999; Raban 2009). At Marseille, meanwhile, researchers set about reconstructing the archaeology and environmental history of the city's ancient harbor since the seventh century BCE, founded in a naturally protected limestone embayment by Greek colonists from Ionia (Fig. 2).

In contrast to deltaic areas, the smaller analytical scale of harbor basins meant that coastal changes could be studied not only with greater facility but also more finitely. The research at Marseille (Morhange et al. 2003) reconstructed a rapid shift in shoreline positions from the Bronze Age onwards and demonstrated the type of spatial resolution that can be obtained when large excavation areas are available for geoarchaeological study. These studies were unique in that, for the first time in a Mediterranean coastal context, both sought to embrace a multidisciplinary methodology. Investigative fields included not only archaeology but also geomorphology, geography, sedimentology, history, and biology (Raban and Holum 1996; Hesnard 2004). The waterlogged conditions were particularly conducive to environmentally contextualized analyses, and both studies demonstrated how coastal archaeology could benefit from being placed within a broader multidisciplinary framework.

Since these projects, there has been a great proliferation of studies looking into coastal and ancient harbor geoarchaeology (see Marriner and Morhange 2007; and Giaime et al. 2019a for multiple references; Fig. 1), building on pioneering archaeological work in the first half of the twentieth century (e.g., Négris 1904a, b; Paris 1915; Jondet 1916; Paris 1916; Lehmann-Hartleben 1923; Poidebard 1939; Halliday Saville 1941; Poidebard and Lauffray 1951). Ancient harbor basins are particularly interesting because (1) they served as important economic centers and nodal points for maritime navigation (Casson 1994; Arnaud 2005); (2) there is generally excellent preservation of the material culture (Rickman 1988; Boetto 2012) due to the anoxic conditions induced by the water table; and (3) there is an abundance of source material for paleoenvironmental reconstruction (Marriner 2009; Kaniewski et al. 2018). Seaports are particularly interesting, as they allow us to understand how people "engaged with" the local environmental processes in coastal areas.

Here, we will explore the specific interest of harbor sediments in reconstructing ancient coastal landscapes and their evolution through time. In particular, we will discuss the stratigraphic evidence for these changes and set them within the wider context of coastal changes driven by various natural and anthropogenic forcing agents. We will also address present challenges and gaps in knowledge.

Harbors and Ports, Ancient, Fig. 1 Mediterranean harbor sites discussed in the text

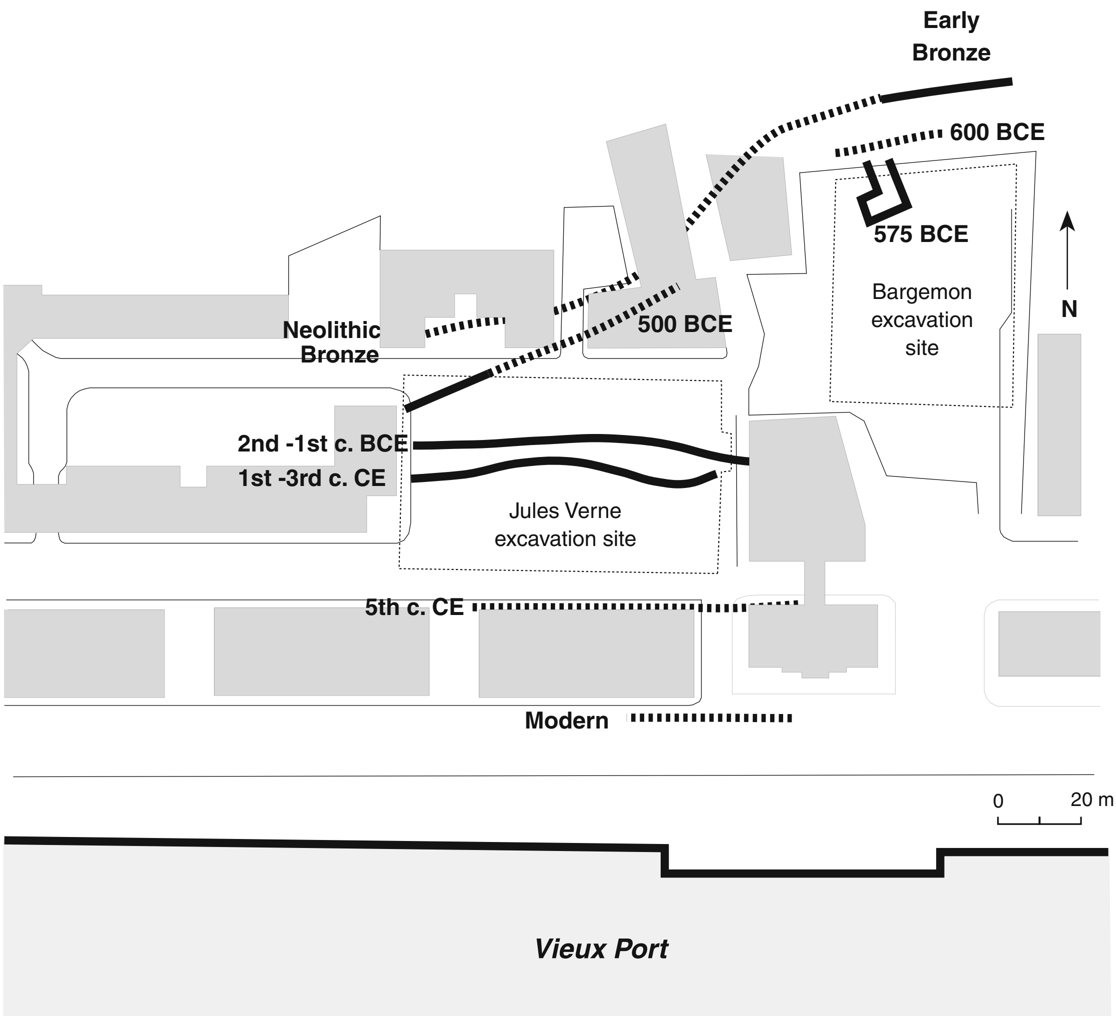
Harbor Origins

The ease of transport via fluvial and maritime routes was important in the development of civilizations. At least three areas – the Indus, China, and Egypt – played an important role in the development of harbors and their infrastructure.

Egypt

It has been suggested that the Egyptians were one of the earliest Mediterranean civilizations to engage in fluvial and maritime transportation. Evidence for the use of boats in ancient Egypt derives from deepwater fish bones found at prehistoric hunter/gatherer campsites (Shaw et al. 1993). The earliest boats were probably rafts made of papyrus reeds, which enabled these societies to navigate between camps. It is speculated that wooden boats were adopted during Neolithic times, around the same time as the introduction of agriculture and animal husbandry. The rise of chiefdoms during the Egyptian Predynastic period (3700–3050 BCE) was accompanied by the widespread adoption of boats as attested by art and pottery depictions (Fabre 2004–*2005*). North of the First Cataract in Egypt, ships could travel almost anywhere along the Nile. On the delta, the then seven branches served as navigable waterways into the Eastern Mediterranean (Tousson 1922; Stanley 2007; Khalil 2010). The Eastern Mediterranean was also a natural communications link for the major cultural centers of the Levant, Cyprus, Crete, Greece, and North Africa. In light of this, it is unsurprising that the works along the fluvial banks and coastlines of the Red Sea and Mediterranean were many and varied. Overlooking the west bank of the Nile, the pyramids of Giza – Khufu, Khafre, and Menkaure – were built during 2686–2160 BCE by engineers who used a now-defunct arm of the river to transport building materials to the harbor complex in the Giza plateau (Fabre 2004–*2005*; Butzer et al. 2013; Lehner 2014). A study by Sheisha et al. (2022) examined the environmental conditions that enabled transport along this former branch of the Nile using pollen grains extracted from cores drilled from the floodplain. Their reconstruction suggests that a drop in water levels following the end of the African Humid Period, in response to the gradual aridification of East Africa (Marriner et al. 2012; Williams 2019), rendered the branch an attractive conduit for freight transport during the fifth millennium, facilitating monumental construction in the pyramid complex through its fluvial port complex (Fig. 3). Quays were also commonly established along the Nile, for instance, at fourteenth century BCE Amarna, boats have been depicted parallel to shoreside quays equipped with bollards (Blackman 1982a, b). An artificial quay dating to the second millennium BCE is attested at Karnak, on the Nile (Lauffray et al. 1975; Fabre 2004–*2005*). High sediment supply and rapid changes in fluvial systems mean that few conspicuous remains of these early riverine harbors are still visible, particularly on the delta (Blue and Khalil 2010). In Mesopotamia, a similar evolution is attested (Heyvaert and Baeteman 2008).

Navigation in the Red Sea during pharaonic times is a theme that has attracted renewed interest during the past

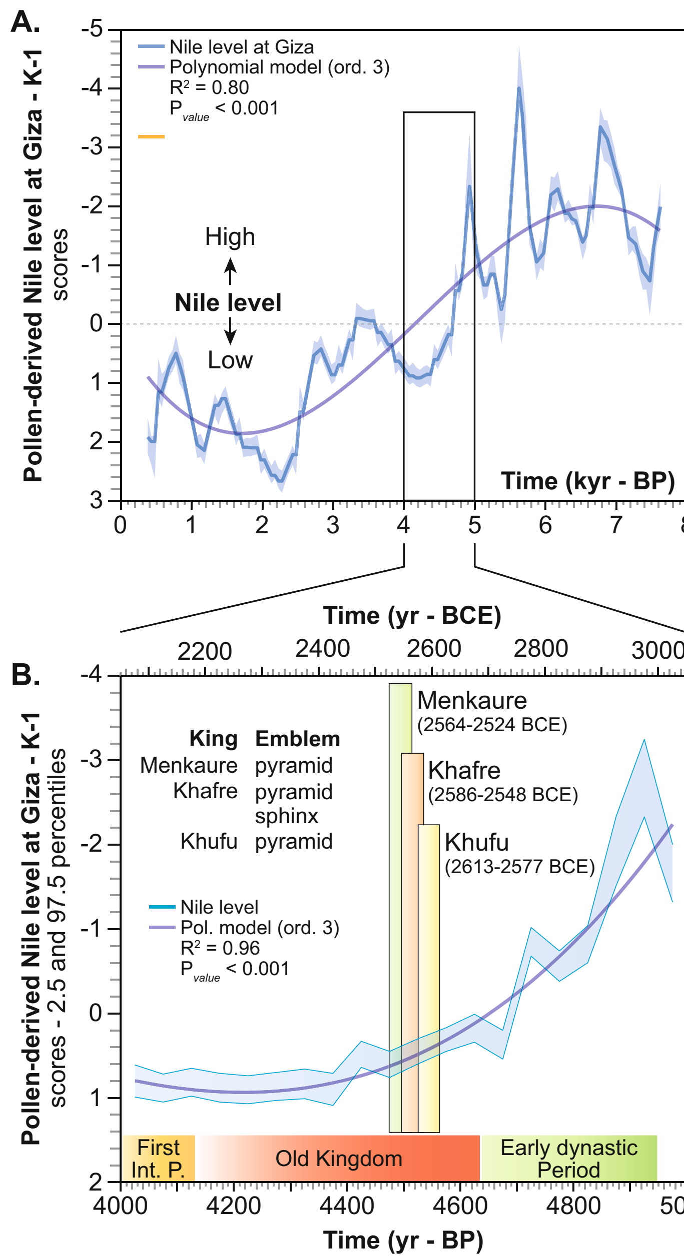


Harbors and Ports, Ancient, Fig. 2 Coastal progradation in the ancient harbor of Marseille since Neolithic times. Chronostratigraphy and marine fauna fixed upon archaeological structures document a steady 1.5 m rise in relative sea level during the past 5000 years. Sea level was broadly stable around the present datum between CE 1500 and the last century

30 years, underpinned notably by the discovery of a number of exceptional coastal sites, shedding new light on the extent and chronology of human impacts in maritime areas. Extending for over 2000 km from the Mediterranean Sea to the Arabian Sea, the Red Sea was a major communications link. Egyptian seafarers traveled along its shorelines during the Predynastic period and were probably the first to contact the peoples living on the Sudanese coast and around the Horn of Africa. Since the discovery of remains at Mersa/Wadi Gawasis in 1976, new findings have been made more recently at Ayn Soukhna, El-Markha, and Wadi al-Jarf (Tallet 2009). In the absence of harbor excavations, much of the data available remains preliminary. At Mersa/Wadi Gawasis, archaeological data have documented evidence for some of the world's earliest long-distance seafaring, including bundled ropes, ships, and remnants of storage boxes used for the transport of goods. The site was used extensively during the Middle Kingdom (around 4000–3775 years ago) when seafaring ships departed from the harbor for trade routes along the African Red Sea coast (Bard and Fattovich 2010; Hein et al. 2011).

The Indus Valley

On the Indian subcontinent, archaeological explorations during the past century have brought to light a large number of structures related to ancient harbor works and maritime activities (Rao 1988). The Indus valley in particular has been a key focus of research, where high sediment supply in a context of rapidly changing deltaic environments is responsible for the landlocking of many ancient port sites (Gaur and Vora 1999). The oldest reference to a harbor in India derives from a mid-third millennium Mesopotamian text mentioning boats from Meluhha that were anchored in Agade harbor (Kramer 1964). Nonetheless, despite rich textual evidence, the exact location



Harbors and Ports, Ancient, Fig. 3 (**a**) 8000 years of Nile-level variations on the Giza floodplain, derived from pollen-derived vegetation assemblages. (**b**) Nile levels (2.5 and 97.5 percentiles) during the construction of the pyramids of kings Khufu, Khafre, and Menkaure

of many of these ancient harbor sites is equivocal. Most would have exploited riverbanks that served as natural harbors. Many of the best-studied examples derive from the region of Gujarat, which attests to significant paleo-shoreline changes during the past 4500 years (Gaur and Vora 1999).

Archaeological sites of Harappan age (3000–1500 BCE), including Lothal, Padri, and Bet Dwarka, have yielded particularly interesting archaeological records consistent with maritime activity (Gaur and Vora 1999). Lothal, on the paleo-banks of the river Sabarmati, is one of the best-studied examples of a Harappan harbor city. The site presently lies 35 km from the coast at the head of the macrotidal Gulf of Cambay and is believed to have been an important trade center during the Harappan period (Rao 1991). A number of Egyptian and Mesopotamian imports have been recovered from the site. Excavations have brought to light a brick basin of trapezoidal shape that measures 214 × 36 m and is 3.3 m deep. It has tentatively been labeled as the world's first dockyard (Rao 1979), although these interpretations are not without contention (e.g., Gaur 2000), and the basin presents striking similarities with water storage basins used throughout the region. Based on present knowledge, it is difficult to confirm that Lothal's basin was used as a harbor. Elsewhere in the Indus valley, Chalcolithic/Harappan landing platforms attributed to harbor works have been identified at Kuntasi and Inamgaon. Paleoenvironmental changes are seen as important causes of harbor abandonment.

China

Between 7000 and 5000 BCE, agricultural villages and towns began to emerge and grow along the Yellow and Yangtze River basins and coasts. Research has focused on this transitional period because it corresponds to the onset of deltaic sedimentation and the emergence of agriculture and early complex societies (Zong et al. 2007; Chen et al. 2008). Ancient Chinese history is marked by three successive dynasties that became the roots of Chinese culture: the Xia Dynasty (2200–1766 BCE), the Shang Dynasty (1766–1122 BCE), and the Zhou Dynasty (1122–256 BCE). Despite the importance and continuity of Chinese civilization, understanding of its harbors is relatively limited in western academic circles due to obvious language barriers. Nonetheless, the recent rediscovery of Hepu harbor of the Western Han Dynasty (206 BCE to 25 CE) is particularly promising in shedding new light on this question. Now located within Beihai City in south China's Guangxi Zhuang Region, recent archaeological work suggests that Hepu harbor – probably the oldest seaport in China – served as a very important "marine silk road." This navigation link allowed western goods to be transported into the vast continental interior of Asia.

Early Mediterranean Harbors

Our understanding of early harbors is poor. In the Mediterranean, the first artificial structures appear to date to the Middle/Late Bronze Age. For example, submerged boulder piles are attested at Yavne-Yam, a Middle Bronze Age site on the coast of Israel; these suggest premeditated human enterprise to improve the quality of the natural anchorage (Ezra Marcus, personal communication). Recent geoarchaeological work in Sidon (Lebanon) has tentatively dated the presence of a semi-protected cove beginning around 4410 ± 40 BP (2750–2480 cal BCE; Marriner et al. 2006b; Marriner 2009; Marriner et al. 2014). This sedimentological unit has been interpreted as a Middle Bronze Age to Late Bronze Age proto-harbor, with possible reinforcement of the shielding sandstone ridge improving the quality of the natural anchorage. It is suggested that small boats were beached, with larger vessels being anchored in the outer harbor of Zire (Frost 1973; Carayon 2008; Fig. 4).

At Kommos, in southern Crete, a large building with six galleries (Puglisi 2001) has been interpreted as a hangar for the dry-docking of Minoan ships during the winter months. This building, dated to the fifteenth century BCE, is an illustration of Minoan harbor construction even though, in this instance, it had no direct impact upon the quality of the anchorage haven.

After this period, the maritime harbors of the ancient Mediterranean evolved in four broad technological leaps.

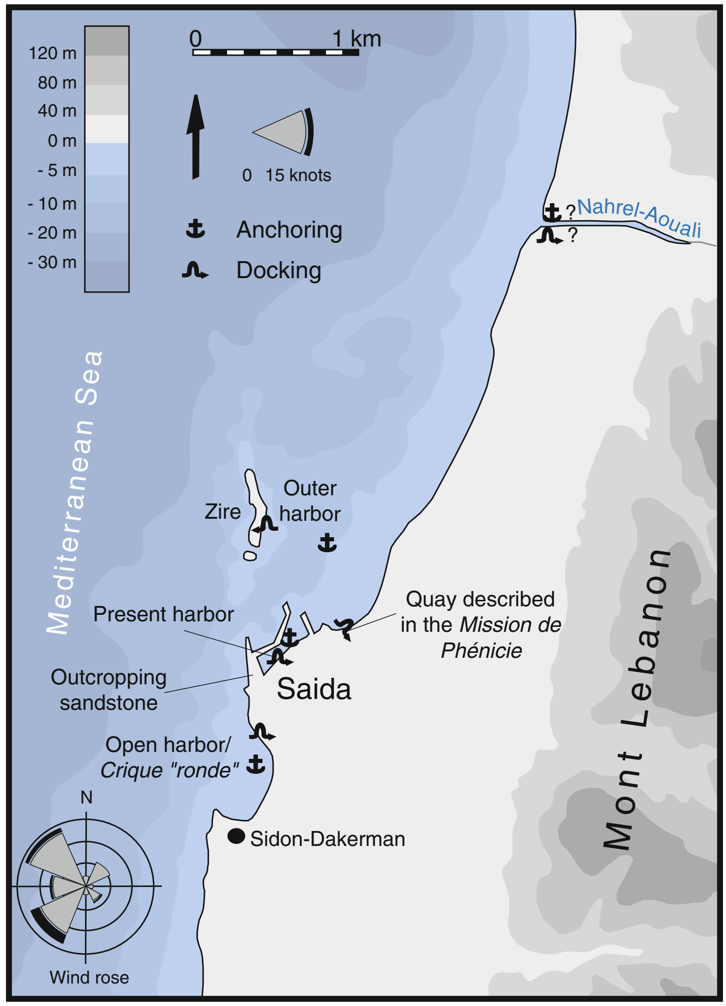
Bronze Age to Early Iron Age Ashlar Header Technology

A double ashlar wall infilled with stones is a harbor construction method common to the Phoenicians; it is known as the pier-and-rubble technique (Raban 1985). This system has been noted in an eleventh century BCE layer at Sarepta, Lebanon (Markoe 2000). Van Beek and Van Beek (1981) have suggested that this technique is Levantine in origin and that it spread from the Late Bronze Age Levant to the western Punic colonies, Greece, and Roman North Africa, where it can be found as late as the sixth century CE. The use of ashlar techniques is well attested in the Persian period harbor of Akko (Israel), the Hellenistic harbor at Amathus in Cyprus (Empereur and Verlinden 1987), and the Roman quay at Sarepta, Lebanon (Pritchard 1978), Dor, and Athlit (Israel). Iron Age Athlit is one of the best-studied Phoenician harbors (Haggi 2006; Haggi and Artzy 2007). The northern harbor's mole extends about 100 m into the sea. It is about 10 m wide and constitutes two parallel ashlar headers that are 2–3 m in width. A fill of rubble and stones was placed between the ashlar walls. This form of construction improved the stability of the mole against high-energy waves. The mole was placed on a foundation of ballast pebbles of various sizes. Underwater excavations have revealed that the layer of pebbles extends more than 5 m beyond the outer side of each wall, with a total width of over 20 m. Radiometric dating of wood fragments constrains this Phoenician structure to the ninth century BCE (Haggi 2006), although paradoxically there is very little pottery dating from this period (Michal Artzy, personal communication). A similar example is also known from the Syrian coast at Tabbat el-Hammam, where the archaeological evidence supports a ninth/eighth century BCE age (Braidwood 1940).

Depending on the time and culture, different variations are noted in the use of headers. From the fifth century BCE, metal links were used to reinforce blocks (e.g., Sidon and Beirut). At Amathus (Cyprus) during Hellenistic times, the header masonry was built upon a ballast base of disorganized blocks.

Cothons

Archaeologists refer to the sites of Carthage (Tunisia), Mahdia (Tunisia), Phalasarna (Crete), Jezirat Fara'un (Egypt), and Lechaion (Greece) as "cothon" harbors. The Greek term was applied to the harbor at Carthage by Strabo and Appian, the harbor's U shape suggesting the original meaning of "drinking cup," which is metaphorically appropriate to the protected harbor basin. Carthage is the only site that has been referred to as a "cothon" in ancient texts, although a Punic etymology has not yet been supported, meaning it is difficult to propose that the concept was Carthaginian in origin or that all harbors built into the shoreline in the same manner were felt to be variations on a "cothon" (John Oleson, personal communication). Nowadays,



Harbors and Ports, Ancient, Fig. 4 Sidon's ancient harbor areas. (Adapted from Carayon (2008) and Marriner (2009))

specialists agree that the term can be associated with an artificially dug harbor basin linked to the sea via a man-made channel (Carayon 2005). The design solves some of the problems involved in building a harbor along a shallow, featureless coastline, or on the bank of a river, and a number of cultures appear to have adopted this solution, from the Bronze Age onwards. Some authors have suggested that Trajan's basin at Portus also qualifies as a cothon, in addition to some of the proposed Etruscan harbor basins associated with river mouths (John Oleson, personal communication). It would appear that the carving of a cothon is a simple but energy-consuming technique used to create a particularly well-sheltered basin. This type of infrastructure poses three problems: (1) rapid silting up in a confined environment; (2) the carving of a basin in rocky outcrops or clastic coastlines, which is energy consuming; and (3) maintaining a functional channel outlet to the sea in a clastic coast context. Despite these shortcomings, the cothon persisted for many centuries (Carayon 2008). A Latin author, writing in the fifth century CE, noted that this type of harbor was common at this time: "*ut portus scilicet faciunt*" (Deutero-Servius, *Aeneidos*, I, 421).

Hydraulic Concrete

Pre-Roman ashlar block methods continued to be used throughout the Roman era. Nonetheless, another technique was introduced during the second century BCE (Gazda 2001) that completely revolutionized harbor design and construction – the use of hydraulic concrete. This technological breakthrough meant that natural roadsteads were no longer a prerequisite to harbor loci, and completely artificial ports, enveloped by imposing concrete moles, could be located on open coasts (Hohlfelder 1997). The material could be cast and set underwater. Roman architects and engineers were free to create structures in the sea or along high-energy shorelines (Brandon et al. 2005, 2010). Pozzolana facilitated the construction of offshore basins such as Claudius's harbor at Portus of Rome (Testaguzza 1970). The Roman author Vitruvius (first century BCE) provided an inventory of harbor construction techniques (Vitruvius, De Architectura, V, 12).

Romano-Byzantine Harbor Dredging

Vitruvius gave a few brief accounts of dredging, although direct archaeological evidence has, until now, remained elusive. The ancient harbors of Marseille and Naples have both undergone widespread excavations (Fig. 5; Hesnard 1995; Giampaola et al. 2004), and extensive multidisciplinary datasets now exist for the two sites. At Tyre and Sidon, geoarchaeological research has led to the extraction of 40 cores that have facilitated a chronostratigraphic reconstruction of basin silting (Marriner et al. 2005; Marriner and Morhange 2006a; Morhange and Marriner 2010a). Why were ancient harbors dredged? On decadal timescales, continued silting induced a shortening of the water column. De-silting infrastructure (Blackman 1982a, b), such as vaulted moles, 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 draft depth and ensuring long-term harbor viability. At Marseille, although dredging phases are recorded from the third century BCE onwards, the most extensive enterprises were undertaken during the first century CE, at which time huge volumes of sediment were extracted. At the excavations of Naples, absence of pre-fourth century BCE layers has been linked to extensive dredging between the fourth and second centuries BCE (Carsana et al. 2009). Unprecedented traces 165–180 cm wide and 30–50 cm deep attest to powerful dredging technology that scoured into the volcanic substratum, completely reshaping the harbor bottom. Notwithstanding the scouring of harbor bottoms, this newly created space was rapidly infilled and necessitated regular intervention. Repeated dredging phases are attested up until the late Roman period, after which time the basin margins were completely silted up. At Marseille, three dredging boats have been unearthed (Pomey 1995). The vessels were abandoned at the bottom of the harbor during the first and second centuries CE. They are characterized by an open central well that is inferred to have accommodated the dredging arm. A further example of widespread dredging in a high sediment-supply context derives from the Ostia-Portus seaport complex on the Tiber Delta (Lisé-Pronovost et al. 2019).

It was not until the Industrial Revolution in England that cement and iron structures were developed on a large scale (Palley 2010). In 1756, Smeaton made the first modern concrete (hydraulic cement) by adding pebbles as a coarse aggregate and mixing powdered brick into the cement. In 1824, Aspdin invented Portland cement by burning ground limestone and clay together. The Frenchman Monier invented reinforced concrete in 1849 using imbedded steel. It can withstand heavy loads because of its tensile and compressional strengths. Reinforced concrete was widely used in railway ties, pipes, floors, arches, bridges, and ports.

Geoarchaeology of Harbor Basins: Tools and Methods

Over the past two decades, ancient harbors have attracted interest from both the archaeological and earth science communities. 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 (Milne 1985; Leveau et al. 1999; Milne 2003; Walsh 2004; Leveau 2005). The growing corpus of sites and data demonstrates that ancient harbors constitute rich archives of both the cultural and environmental pasts. Ancient harbor sediments are particularly rich in research objects (archaeological remains, bioindicators, macrorests, artifacts, etc.), and they yield insights into the history of human occupation at a given site, coastal changes, and the natural processes and hazards that have impacted these waterfront areas (Reinhardt et al. 2006; Bottari and Carveni 2009; Morhange and Marriner 2010b; Bony et al. 2012).

Harbors and Ports, Ancient, Fig. 5 Harbor dredging in Naples. (Photograph by D. Giampaola, Archaeological Superintendence of Naples)

Ancient harbors are both natural and constructed landscapes and, from a geoarchaeological perspective, they comprise three elements of note (Salomon et al. 2016).

The Harbor Basin

In architectural terms, the harbor basin is characterized by its artificial structures, such as quays, moles, and sluice gates (Oleson 1988; Oleson and Branton 1992). Since the Bronze Age, there has been a great diversity in harbor infrastructure in coastal areas, reflecting changing technologies and human needs. These include, for instance, the natural pocket beaches serving as proto-harbors (Frost 1964; Marcus 2002a, b), through the first Phoenician mole attributed to around 900 BCE (Haggi and Artzy 2007), to the grand offshore constructions of the Roman period made possible by the discovery of hydraulic concrete (Oleson et al. 2004).

In their study of harbor landscapes, geoarchaeologists are also interested in the sedimentary contents of the basin and relative sea-level changes.

Ancient Harbor Sediments

Port basins constitute unique coastal archives. Shifts in the granularity of these deposits indicate the degree of harbor protection, often characterized by a rapid accumulation of heterometric sediments following a sharp fall in water competence brought about by the installation of artificial harbor works. The harbor facies is characterized by three poorly sorted fractions: (1) human waste products, especially at the base of quays and in areas of unloading (harbor depositional contexts are particularly conducive to the preservation of perishable artifacts such as leather and wood); (2) poorly sorted sand; and (3) an important fraction (>90%) of silt that signifies the sheltered environmental conditions of the harbor. They are also particularly pertinent archives for reconstructing the history of heavy metal pollution at coastal settlements (e.g., Véron et al. 2006; Delile et al. 2015b, 2016; Véron et al. 2018). Harbor basins are characterized by rapid accumulation rates. For instance, sedimentation rates of up to 20 mm/year have been recorded in undredged areas of the Graeco-Roman harbor of Alexandria (Goiran 2001). High-resolution study of the bio- and lithostratigraphical fractions can help shed light on the nature of ancient harbor works, such as at Tyre (Marriner et al. 2008) or Portus (Goiran et al. 2010). Recent research has sought to characterize and date these chronostratigraphic phases using the unique sedimentary signature that each technology brings about (Marriner and Morhange 2007; Marriner 2009). In the broadest sense, these are characterized by an evolution from natural roadsteads before the Bronze Age towards completely artificial seaport complexes from the Roman period onwards.

Relative Sea-Level Changes, the Paleo-Water Column, and Ship Circulation

Nowadays, most ancient harbors are completely infilled with sediments – e.g., the Roman harbor of Luni at the mouth of the river Magra (Bini et al. 2009) or the Roman harbor of Aquileia (Arnaud-Fassetta et al. 2003). Harbor sediments are particularly conducive to the preservation of biological remains. 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 paleo-water column to be estimated (Laborel and Laborel-Deguen 1994; Morhange et al. 2013). Such relative sea-level data are critical in understanding the history of sedimentary accretion in addition to estimating the draft depth for ancient ships (Pirazzoli and Thommeret 1973; Morhange et al. 2001; Boetto 2012). Archaeological work undertaken upon ancient wrecks suggests that the largest fully loaded ships during antiquity required a draft of less than 3 m (Casson 1994; Pomey and Rieth 2005). These two reference levels, the paleo-sea level and sediment bottom, are mobile as a function of crustal movements – e.g., local-scale neotectonics (Stiros et al. 1996; Stiros 1998; Evelpidou et al. 2011), regional isostasy (Lambeck et al. 2004), sediment budgets (Vött et al. 2007; Devillers 2008), and human impacts such as dredging (Marriner and Morhange 2006b). All these factors can potentially impact the available accommodation space for sediment accretion (Goiran et al. 2018). For example, Vacchi et al. (2020) have shown how progressive silting of Naples's harbor made it impossible to safely navigate within the basin after the second century CE, leading to its progressive decline.

Sediments Versus Settlements

As outlined above, one of the key problems posed by artificially protected harbors relates to accelerated sediment trapping. In the most acute instances, it could rapidly reduce the draft depths necessary in accommodating large ships (Pomey and Rieth 2005). From a cultural perspective, therefore, harbors were important "economic landscapes," and many changes in harbor 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 dislocation derives from Aegean Anatolia (Brückner et al. 2005). Delta areas in particular serve as excellent geo-archives to understand and analyze the impacts of rapidly evolving settlement phases.

It is important to set these geoarchaeological results within a wider spatiotemporal framework using archaeological data from coastal and hinterland valley areas. Changes in sediment supply at the watershed scale are particularly important in understanding base-level changes in deltaic and coastal contexts, as is the case of the Gialias in Cyprus (Devillers 2008) or the paleo-island of Piraeus (Goiran et al. 2011). Probing the rates of progradation is also key to understanding the timing, origin (climate or human forcings), and rhythm of local and basin-scale erosion (Anthony et al. 2014).

Ancient Harbor Stratigraphy, Terminology, and Research Goals

During the past 20 years, multidisciplinary inquiry has allowed a better understanding of where, when, and how ancient Mediterranean harbors evolved. This is set within the wider context of a new "instrumental" or "quantitative revolution" towards the environment. A battery of research tools is available, tools that broadly draw on geomorphology and the sediment archives located within this landscape complex (Marriner and Morhange 2007).

Where?

The geography of ancient harbors constitutes a dual investigation that probes both the location and the extension of the basins. Biostratigraphical studies of sediments, married with a GIS investigation of aerial photographs and satellite images, can be used to reconstruct coastal evolution and identify possible anchorage areas (Ghilardi and Desruelles 2009). Traditionally, urban contexts have been particularly problematic for accurate archaeological studies because the urban fabric can hide many of the most important landscape features. In such instances, chronostratigraphy can be particularly useful in reconstructing coastal changes (Morhange et al. 2003). For example, litho- and biostratigraphical studies of cores drilled in the city center of Tyre attest to a well-sheltered port basin between the Hellenistic and Byzantine periods, today buried beneath the modern market by thick sediment tracts. The chronostratigraphy demonstrates that during antiquity, the harbor was approximately twice as large as present (Fig. 6). This approach helps not only in reconstructing ancient shorelines and changes through time (e.g., as at Ephesus, Priene, Frejus, Alexandria, or Pelusium on the Nile Delta) but can also aid in relocating ports for which no conspicuous archaeological evidence presently exists, as in the case of Cuma (Stefaniuk and Morhange 2005) or Byblos (Stefaniuk et al. 2005).

Geophysical techniques can also 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 (Nishimura 2001). Because geophysical techniques are nondestructive, they have been widely employed in archaeology and are gaining importance in coastal geoarchaeology (Hesse 2000) and ancient harbor contexts (Boyce et al. 2009). Very rapid and reliable information can be provided on the location, depth, and nature of buried archaeological features before excavation. At Alexandria, geophysical surveys have allowed Hesse (1998) to propose a new hypothesis for the location of the Heptastadium. Hesse suggests that the causeway linking Pharos to the mainland was directly tied into the city's ancient road network. In this instance, the findings have since been corroborated by sedimentological data from the tombolo area (Goiran 2001). Stratigraphic data are therefore critical in providing chronological insights into environmental changes and coastal processes. Such a dual approach has also been successfully employed at Portus, one of the ancient harbors of Rome. Large areas of the seaport and its fringes have been investigated using coastal stratigraphy (Bellotti et al. 2009; Giraudi et al. 2009; Goiran et al. 2010; Di Bella et al. 2011; Mazzini et al. 2011; Salomon et al. 2012), geophysics, and archaeological soundings (Keay et al. 2005, 2009; Keay and Paroli 2011), yielding fresh insights into the harbor's coastal infrastructure and functioning. On the Tiber delta, geophysics has also been used to accurately map the progradation of the coastal ridges. Bicket et al. (2009) have demonstrated that the Laurentine ridge, ~1 km inland from the modern coastline, constitutes the Roman shoreline of the Tiber delta.

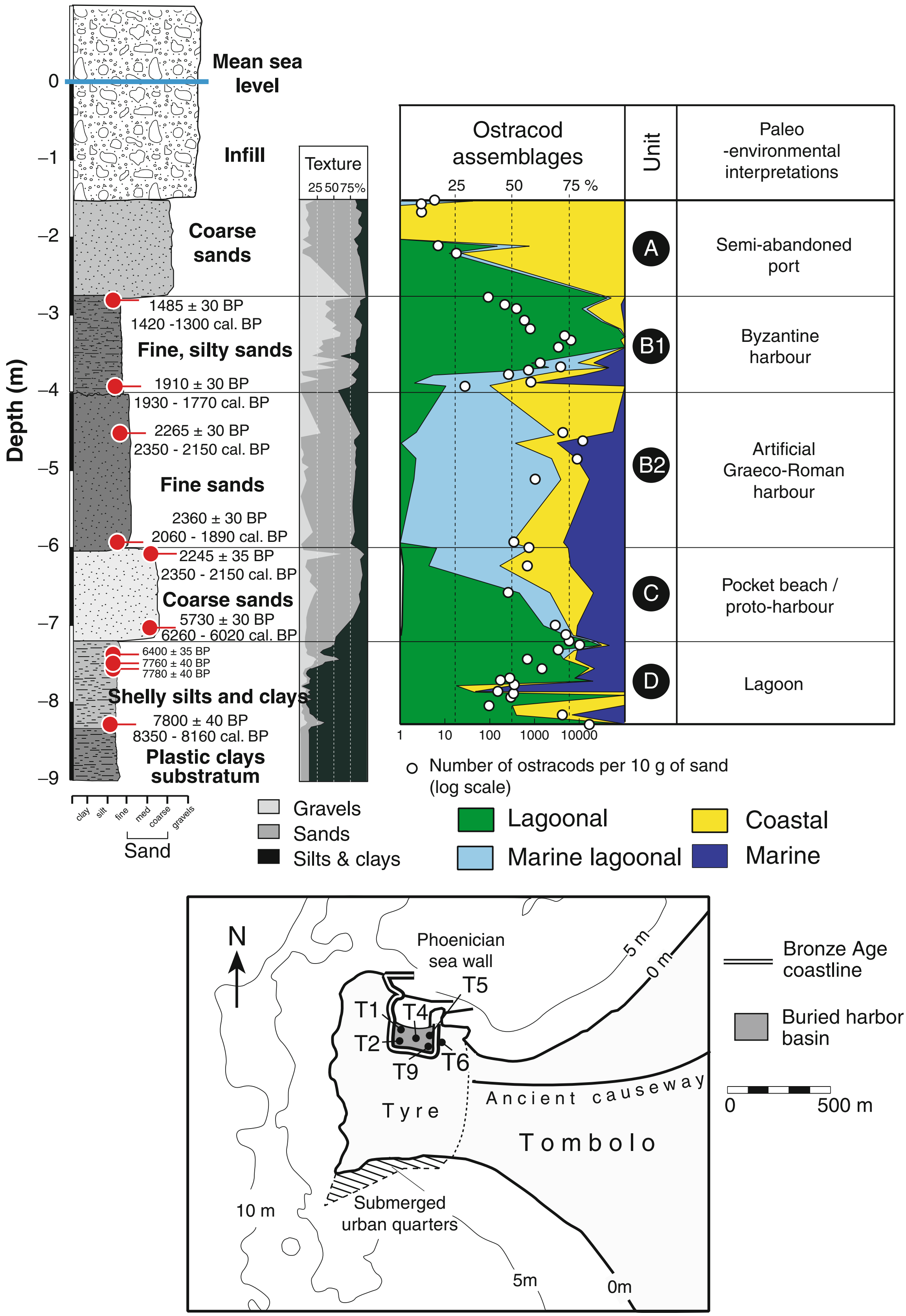
When and How?

Chronostratigraphy is essential in understanding modifications in harbor technology and the timing of human impacts, such as lead pollution from the Bronze Age onwards (Véron et al. 2006) or ecological stresses demonstrated by changes in faunal assemblages (Leung Tack 1971–1972). The overarching aim is to write a "sedimentary" history of human coastal impacts and technologies, using quantitative geoscience tools and a standardized stratigraphic framework (e.g., sequence stratigraphy). Research in the eastern and western Mediterranean attests to considerable repetition in ancient harbor stratigraphy, both in terms of the facies observed and their temporal envelopes. There are three distinct facies to note: (1) middle-energy beach sands at the base of each unit (e.g., the proto-harbor), (2) low-energy silts and gravels (e.g., the active harbor phase), and (3) coarsening up beach sands or terrestrial sediments which cap the sequences (e.g., post-harbor facies). In the broadest terms, this stratigraphic pattern represents a shift from natural coastal environments to anthropogenically modified contexts, before a semi- or complete abandonment of the harbor basin.

There are a number of stratigraphic surfaces that are key to understanding the evolution of ancient harbor basins.

The Maximum Flooding Surface (MFS)

Ancient harbors form integral components of the highstand parasequence (aggradational to progradational sets). For the Holocene coastal sequence, the maximum flooding surface (MFS) represents the lower boundary of the sediment archive. This surface is broadly dated to around 6000 cal BP and



Harbors and Ports, Ancient, Fig. 6 Chronostratigraphic evolution of Tyre's ancient northern harbor since the Bronze Age (core T9) marks the maximum marine incursion (Stanley and Warne 1994). It is associated with the most landward position of the shoreline. In the eastern Mediterranean, it is contemporaneous with the Chalcolithic period and the Early Bronze Age. Indeed, the MFS along the Levantine coast clearly delineates the geography of early coastal settlements from this period (Raban 1987).

Natural Beach Facies

The MFS is overlain by naturally aggrading beach sands, a classic feature of clastic coastlines. Since around 6000 cal BP, relative sea-level stability has impinged on the creation of new accommodation space, leading to the aggradation of sediment strata. This is particularly pronounced in sediment-rich coastal areas such as deltas and at the margins of fluvial systems. Where this sedimentation continued unchecked, a coarsening upward of sediment facies is observed, consistent with high-energy wave dynamics in proximity to mean sea level. For example, Gaza bears witness to important coastal changes since the Bronze Age. During the mid-Holocene, the coast comprised estuaries at the outlets of major wadi systems. This indented coastal morphology spawned important maritime settlements such as Tell es-Sakan and Tell al-‘Ajjul at the outlet of Wadi Ghazzeh, which probably served as a natural harbor. During the same period, the rate of sea-level rise slowed, leading to the formation of the Nile Delta and small, local deltas along the coasts of Sinai and Palestine. From the first millennium BCE onwards, the coast was regularized by infilling of the estuaries, and the harbor sites became landlocked. In response, new cities, such as Anthedon, were founded on a Quaternary ridge along the present coastline (Morhange et al. 2005).

The Harbor Foundation Surface (HFS)

This surface marks important human modification of the sedimentary environment, characterized by the transition from coarse beach sands to finer-grained harbor sands and silts (Marriner and Morhange 2007). This surface corresponds to the construction of artificial harbor works and, for archaeologists, is one of the most important surfaces to date in the foundation of the harbor.

The Ancient Harbor Facies (AHF)

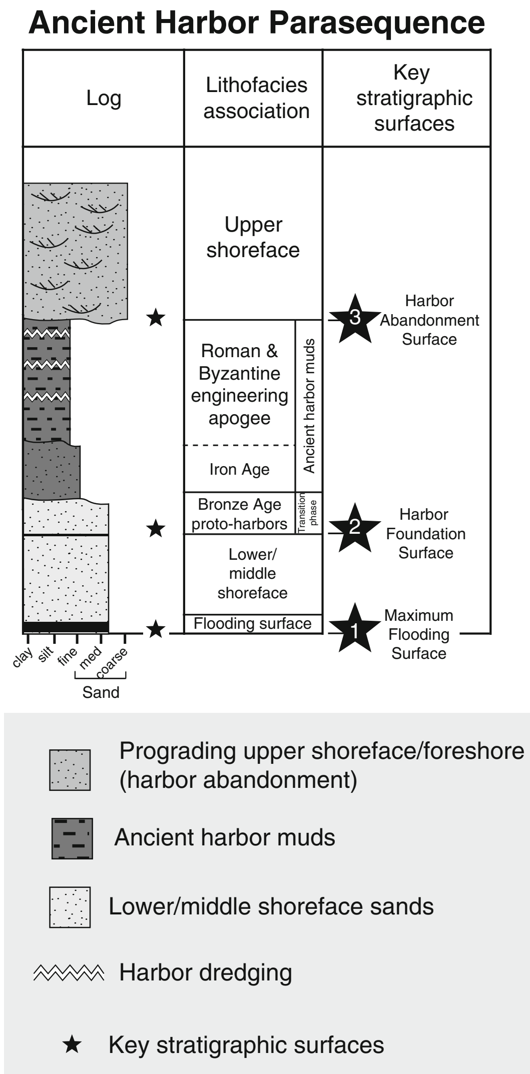
The AHF corresponds to the active harbor unit. This artificialization is reflected in the sedimentary record by lower-energy facies consistent with a barring of the anchorage by artificial means. Harbor infrastructure (quays, moles, and jetties) accentuated the sediment sink properties by attenuating the swell and marine currents leading to a sharp fall in water competence. Research has demonstrated that this unit is by no means homogeneous, with harbor infrastructure and the nature of sediment sources playing a key role in shaping facies architecture. Of note is the granulometric paradox of this unit consisting of fine-grained silts juxtaposed with coarse gravels made up of ceramics and other urban waste.

In some rare instances, a proto-harbor phase (PHP) precedes the AHF. Before the major changes characteristic of the AHF, biosedimentological studies have elucidated moderate signatures of human presence when societies exploited natural low-energy shorelines requiring little or no human modification. For instance, coastal stratigraphy has demonstrated that the southern cove of Sidon, around Tell Dakerman, remained naturally connected and open to the sea throughout antiquity (Poidebard and Lauffray 1951; Marriner et al. 2006a, b). The PHP interface is by no means transparent, particularly in early Chalcolithic and Bronze Age harbors, and the astute use of multiproxy data is required (Fig. 7).

During the Late Bronze Age and Early Iron Age, improvements in harbor engineering have been recorded by increasingly fine-grained facies. Plastic clays tend to be the rule for Roman and Byzantine harbors, and sedimentation rates 10–20 times greater than naturally prograding coastlines are recorded. The very well-protected Roman harbors of Alexandria, Marseille, and Frejus (Gébara and Morhange 2010) all comprise plastic marine muds consisting of 90% silts and a coarse gravel fraction of human origin. Significant increases in sedimentation rates can also be attributed to human-induced increases in the supply term, for example, anthropogenic changes in the catchments of supplying rivers (deforestation, agriculture), erosion of mudbrick urban constructions (Rosen 1986), and finally, use of the basins as waste dumps. This underlines the importance of an explicit source-to-sink study integrating both the coastal area and the upland hinterland. Such high rates of harbor infilling were potentially detrimental to the medium- to long-term viability of harbor basins and impinged on the minimum 1 m draft depth.

The Harbor Abandonment Surface (HAS)

This surface marks the “semi-abandonment” of the harbor basin. Recent studies have focused upon the role of natural hazards in explaining the decline or destruction of ancient Mediterranean harbors. While these factors may have had a role to play, it seems that the financial weight of maintaining harbor works in the face of the Mediterranean’s shifting political and economic makeup was simply too burdensome (Raban 2009). A relative decline in harbor works after the late Roman and Byzantine periods are characterized by a return to “natural” sedimentary conditions, comprising (1) coarse-grained sands and gravels in a coastal context and (2) terrestrial facies in fluvial environments. Following hundreds to thousands of years of artificial confinement, reconversion to a natural coastal parasequence is sometimes expressed by high-energy upper shoreface sands. This shoreline progradation significantly reduced the size of the basins, often landlocking the heart of the anchorages beneath thick tracts of coastal and fluvial sediments.



Harbors and Ports, Ancient, Fig. 7 Chronostratigraphic evolution of ancient Mediterranean harbors in coastal areas

Ancient Harbor Case Studies: From Natural to Artificial Ports

Today, it is recognized that harbors should be studied within broader regional frameworks using a multidisciplinary methodology (Carayon 2008; Blackman and Lentini 2010). There is great variety in harbor types, and, broadly speaking, three areas or physical processes are important in influencing harbor location and design: (1) geographical situation, (2) site and local dynamics, and (3) navigation conditions dictated by the wind and wave climate. The diversity of contexts investigated during the past 20 years 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 (Marriner and Morhange 2007). Ancient harbors can be divided into six non-exhaustive types on the basis of preservation. Sediment supply, human impacts, crustal changes, and coastal energy dynamics are significant in explaining how ancient harbors have been preserved in the geological record (Bony 2013). The majority of the examples outlined herein derive from the Mediterranean region, which has a long history of ancient harbor research.

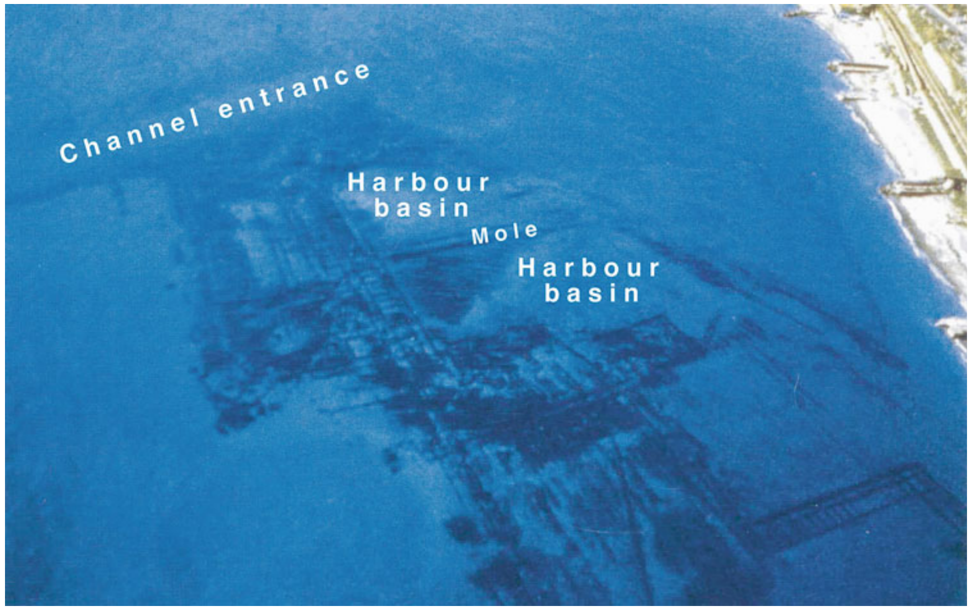
Drowned Harbors

Drowned cities and harbors have long captured the public imagination and inspired research (Marinatos 1960; Frost 1963; Flemming 1971; Bailey and Flemming 2008), fueled by mediatized legends such as Atlantis (Collina-Girard 2001; Gutscher 2005) and the "biblical flooding" of the Black Sea (Yanko-Hombach et al. 2007a, b; Ravilious 2009; Buynevich et al. 2011).

After the Last Glacial Maximum, when global sea level lay around 120 m below present, transgression of the continental platform gradually displaced coastal populations landwards until broad sea-level stability led to a sedentarization of populations along present coastlines (Van Andel 1989). The continental shelf between Haifa and Atlit (Israel) is one of the best-studied examples (Galili et al. 1988; Sivan et al. 2001). A series of submerged archaeological sites dating from the Pre-Pottery Neolithic B (8000 BP) and late Neolithic (~6500 BP) were found at depths of 12 to 8 m and 5 to 0 m, attesting to the postglacial transgression of the Levantine coastline. Since 6000 cal BP, coastal site and port submersion can be attributed to crustal mobility (e.g., historical subsidence in eastern Crete and uplift on the western coast) and/or sediment failure in deltaic contexts.

For example, on the western margin of the Nile Delta of Egypt, the coastal instability of the Alexandria area is responsible for a ~ 5 m drowning of archaeological remains since antiquity (Empereur and Grimal 1997; Goddio et al. 1998; Goiran 2001; Fabre 2004–*2005*). The subsidence has been variously attributed to seismic movements (Guidoboni et al. 1994) and Nile Delta sediment loading (Stanley et al. 2001; Stanley and Bernasconi 2006). Approximately 22 km east of Alexandria, around Abu Qir bay, an ~8 m collapse of the former Canopic lobe of the Nile is responsible for the drowning of two ancient seaport cities, Herakleion and East Canopus, during the eighth century CE (Tousson 1922; Stanley et al. 2001, 2004a, b).

Italy's Phlegraean Fields volcanic complex testifies to a very different crustal context that has led to a series of yo-yo land movements during the late Holocene. The ancient ports of Miseno, Baia, and Portus Julius are located inside a caldera (Gianfrotta 1996; Scognamiglio 1997; Fig. 8). Since Roman times, tectono-volcanism inside this collapsed volcanic cone has led to significant shoreline mobility and is responsible for



Harbors and Ports, Ancient, Fig. 8 Pozzuoli's drowned harbor remains presently ~10 m below mean sea level. The site lies inside a caldera, where shoreline mobility is attributed to volcanism and faulting; photograph: Centre Jean Bérard, Naples

a 10 m submergence of the Roman harbor complexes (Dvorak and Mastrolorenzo 1991). The pattern of movement inside the bay is spatially contrasted because, around the fringes of the caldera, the columns of the Roman market attest to an upper limit of marine bioerosion at 7 m above present sea level. Recent research suggests a series of post-Roman inflation-deflation cycles at both Pozzuoli (Morhange et al. 2006a) and Miseno (Cinque et al. 1991) linked to the interplay of deep magma inputs, fluid exsolution, and degassing (Todesco et al. 2004), all acting as drivers of rapid coastal change. Other studied examples of drowned cities include Helike and Kenchreai in the Gulf of Corinth, Greece (Kiskyras 1988; Soter 1998; Soter and Katsonopoulou 1998; Rothaus et al. 2008) and Megisti on the island of Castellorizo, Greece (Pirazzoli 1987).

Uplifted Harbors

The best geoarchaeological evidence for uplifted harbors derives from the Hellenic arc, one of the most seismically active regions in the world (Stiros 2005).

In western Crete, Pirazzoli et al. (1992) have ascribed a 9 m uplift of Phalasarna harbor, founded in the fourth century BCE, to high seismic activity in the eastern Mediterranean between the fourth and sixth centuries CE (Stiros 2001). This episode is concurrent with a phase of Hellenic arc plate adjustment linked to uplift (1–2 m) in Turkey, e.g., the uplifted harbor of Seleucia Pieria (Pirazzoli et al. 1991), Syria (Sanlaville et al. 1997), and parts of the Lebanese coastline (Pirazzoli 2005; Morhange et al. 2006b). Phalasarna's ancient harbor sediment record is of particular interest because its rapid uplift has possibly trapped tsunami deposits inside the basin (Dominey-Howes et al. 1998).

The Gulf of Corinth constitutes a neotectonic graben separating the Peloponnese from mainland Greece (Moretti et al. 2003; Evelpidou et al. 2011). It is one of the most tectonically active and rapidly extending regions in the world (6–15 mm/year), with a marked regional contrast between its subsiding northern coast and an uplifting southern flank borne out by its geomorphological features and archaeology (Papadopoulos et al. 2000; Koukouvelas et al. 2001). Biological and archaeological proxies attest to pronounced spatial disparities in the amplitude of uplift. The position of the gulf's ancient harbors can help to refine the recent tectonic history. The harbor of Heraion on the gulf's northern coast is, for instance, modestly uplifted by around 1 m (Pirazzoli et al. 1994).

The western harbor of Corinth at Lechaion is also uplifted. Emerged *Balanus* fossils indicating a former biological sea level 1.2 m above the basin surface have been dated to around 2470 ± 45 BP, i.e., 375 ± 120 cal BCE (Stiros et al. 1996). The location of the port basin in a well-protected depression suggests silting was already a problem during its excavation and not favorable to the basin's long-term viability as a seaport (Morhange et al. 2012). At Aigeira, an artificial Roman harbor was functional between ~100 CE and 250 CE (Papageorgiou et al. 1993). Biological and radiometric evidence from the city's harbor structures attests to ~4 m of uplift tentatively attributed to an earthquake around 250 CE (Stiros 1998, 2005).

In a different geodynamic context, Holocene evolution of Etna's coastline is associated with subduction of the African plate under the Eurasian plate. It presents a number of uplifted harbors, such as the neoria of the military harbor of Giardini-Naxos (Blackman and Lentini 2010). This category of harbor is often poorly represented due to destruction by modern urbanization, e.g., the harbor of Kissamos, northwestern coast of Crete (Stefanakis 2010).

Landlocked Harbors

Around 6000 cal BP, the maximum marine ingression, created an indented coastal morphology throughout the Mediterranean. During the ensuing millennia, these indented coastlines were gradually infilled by fluvial sediments reworked by longshore currents, culminating in a regularized coastal morphology. This process was particularly intense at deltaic margins.

Coastal progradation as a driver of settlement and harbor changes is best represented by Ionia's ancient ports in Turkey (Brückner 1997), many of which are located inside infilled ria systems. Such rapid coastal change is linked to two factors: (1) broad sea-level stability since 6000 cal BP; and (2) the morphology of these paleo-valleys, which correspond to narrow, transgressed grabens with limited accommodation space (Kayan 1996, 1999). For example, the Menderes floodplain has prograded by ~60 km during the past 7000 years (Schröder and Bay 1996). The best-studied examples include Troy (Kraft et al. 2003), where the harbor areas were landlocked by 2000 cal BP, and also Ephesus, Priene, and Miletos in Turkey (Brückner et al. 2005; Kraft et al. 2007).

In Cyprus, Devillers (2008) has elucidated the infilling of the Gialia's coastal embayment. The sedimentary archives attest to an easterly migration of the coastline. Human societies constantly adapted to this changing coastal environment as illustrated by the geographical shift of at least four ancient harbors: Early/Middle Bronze Age Kalopsidha, Middle/Late Bronze Age Enkomi, Graeco-Roman Salamina, and Medieval Famagusta. The latter is located on a rocky coast outside the paleo-ria. In a similar vein, the ancient harbor of Utica on the Mejerda Delta in Tunisia is today landlocked 10 km inland. Delile et al. (2015a) have reconstructed rapid environmental changes that probably isolated the harbor complex before the end of the Punic period.

Environmental changes on small deltaic systems also shaped the evolution of harbor systems and maritime access. At Tel Akko, the settlement's southern anchorage was located in the river mouth of the Na′aman until the early Persian period. Due to infilling of the Na'aman, this anchorage shifted to the "open" western coast of the tell during the Persian period before its subsequent relocation to the rocky promontory of Akko in Hellenistic times, in a semi-protected pocket beach at the western foot of the promontory (Morhange et al. 2016; Giaime et al. 2018).

Despite the ecological attraction of estuaries and fluvial mouths for harbor location, ancient engineers were aware of the longer-term hazards to survival. Greek settlers, for instance, founded Marseille around 600 BCE at the distal margin of the Rhone delta in order to avoid the problems of rapid siltation. It is only in instances of absolute necessity that artificial ports were located inside deltaic systems. The Imperial harbors of Portus on the Tiber delta are a classic example (Goiran et al. 2010).

Eroded Harbors

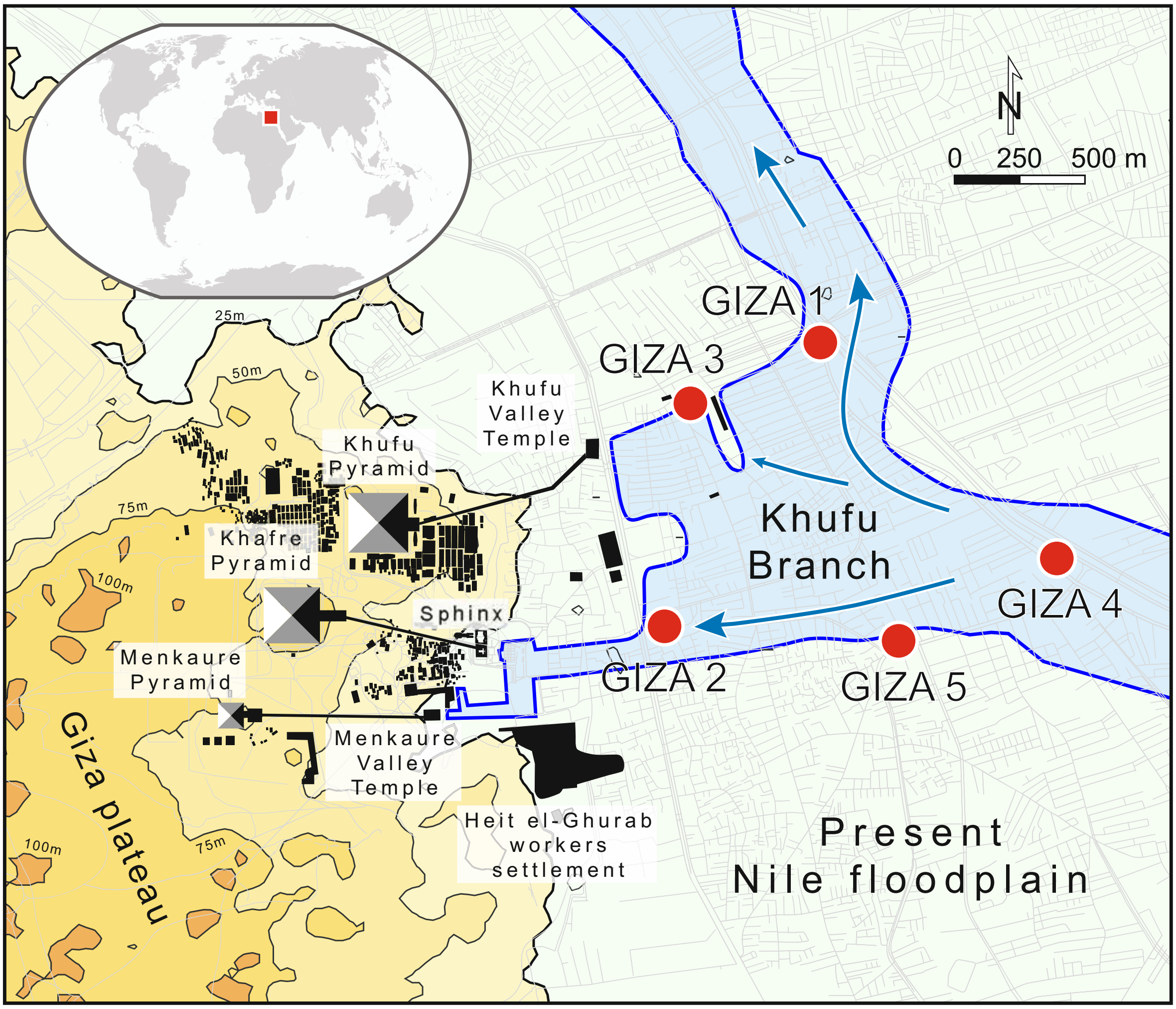
Eroded harbors can result from two complementary geological processes: (1) a fall in sediment supply to the coastal zone and/or (2) the destruction of harbor works in areas exposed to high-energy coastal processes. The best examples of eroded harbors date from the Roman period, when natural low-energy roadsteads were no longer a prerequisite for harbor location. At many high- to medium-energy coastal sites across the Mediterranean, the Romans constructed large enveloping moles to accommodate mooring facilities and interface installations such as fishponds and industrial saltpans. Good examples of eroded ancient harbors include Carthage and the outer Roman basin of Caesarea Maritima (Raban 2009).

Fluvial Harbors

River harbors are not subject to the same geomorphological and sedimentary processes as coastal seaports, and therefore diagnostic harbor sediment signatures can be markedly different. Unfortunately, geoarchaeological study of such contexts has been relatively limited until now. It is nonetheless an interesting avenue for future research and provides opportunities with which to compare and contrast the coastal data (Milne and Hobley 1981; Good et al. 1991; de Izarra 1993; Bravard and Magny 2002; Arnaud-Fassetta et al. 2003). In particular, current research has focused upon the relationships between fluvial settlements, including their harbors, and flood hazards (Arnaud-Fassetta et al. 2003).

The environmental challenges of fluvial harbors are linked to: (1) seasonal and exceptional flood episodes (Stewart and Morhange 2009); (2) river mouth access and rapidly shifting longshore bar development; and (3) the lateral instability of riverbanks (Bruneton et al. 2001; Brown 2008).

The Egyptians and Mesopotamians were among the earliest western civilizations to engage in fluvial transportation, and primeval Bronze Age harbor works are known from the banks of the Nile at Memphis and Giza (Fabre 2004–*2005*). The Wadi el-Jarf Papyri, discovered at a Khufu-age port on the Red Sea coast (Tallet 2013, 2017; Tallet and Lehner 2021a*,* b), attest to the existence of Giza's harbor complex, called Ro-She Khufu ("Entrance to the Lake…" or "…Basin of Khufu"). The Journal of Merer, a large corpus of these papyri, describes the transport of limestone from Tura, ~17 km from the Giza Plateau, to the construction site of the Great Pyramid of Khufu. A striking parallel exists between the names of the basins and waterways in the papyri and the spatial organization of Giza's Fourth Dynasty waterscape (Fig. 9), as reconstructed by archaeologists (Lehner 2014).



Harbors and Ports, Ancient, Fig. 9 Simplified paleogeography of the Giza area and its Pyramid Complex (Lehner 2014). (Adapted from Sheisha et al. (2022))

Despite excavations at a number of sites on the Nile Delta, e.g., Tell el-Dabʿa/Avaris and Tell el-Fara'in (Bietak 1996; Shaw 2000), the exact location of many of the river ports is equivocal. There has been extensive research looking at the Canopic branch of the Nile Delta coast (Stanley and Jorstad 2006; Stanley 2007). Geoarchaeological data show that the Ptolemaic and Roman city of Schedia (Egypt) once lay directly on the Canopic channel, which was active from the third to second centuries BCE until the fifth century CE. Abandonment of the site resulted from the avulsion of Nile waters to the Bolbitic and later Rosetta branches in the east. The discovery of a series of active and abandoned channels around the Greek city of Naukratis (Egypt) attests to significant fluvial mobility during antiquity. These channels served as transport pathways for the ancient settlement, although the site's fluvial port has never been precisely located (Villas 1996). In the northeastern part of the Nile Delta, a number of sites on the now-defunct Pelusiac branch (Sneh and Weissbrod 1973) have attracted geoarchaeological interest. Goodfriend and Stanley (1999) have shown that Pelusium, an important fortified city located at the mouth of the Pelusiac branch, was abandoned during the twelfth century CE following a large and rapid influx of Nile river sediment in the ninth century CE. This discharge in sediment led to the avulsion of a new distributary to the west, probably the Damietta branch.

Aquileia in northeastern Italy is a well-studied example of a Roman fluvial harbor. The Roman colony was founded in 181 CE and lay on the border between the Friuli plain and the edges of the Grado lagoon. The site is located in a highly dynamic natural environment shaped by fluvial activity (Arnaud-Fassetta et al. 2003; Kaniewski et al. 2022). Fresh, brackish, and sea waters alternatively presented opportunities and risks for local communities. During the Roman period, Aquileia was the focus of a communication network, consisting of terrestrial routes through a system of natural and artificial waterways, which provided access to the sea and maritime trade routes (Cottica and Ventura 2019). A similar evolution is attested at Minturnae (Italy), which controlled the bridge on the Appian Way over the Liris River. It occupied a prime location that allowed the Roman colony to evolve into a flourishing commercial center until its final abandonment around 590 CE. Recent geoarchaeological work undertaken at the mouth of the Tiber delta, around the ancient site of Ostia, has probed the evolution of the city's ancient harbor, which serviced ancient Rome around 32 km upriver (Goiran et al. 2012). Problems of basin silting meant that the harbor had already experienced an important phase of sediment infilling by the first century CE (Goiran et al. 2014). Continued late Holocene progradation dynamics have isolated ancient Ostia, which is now about 4 km from the present coastline. The silting of the harbor basin probably acted as a precursor to the construction of Rome's new port basin at Portus, although Ostia and the fluvial banks of the Tiber continued to accommodate smaller, shallow-draft vessels.

On the Danube Delta, the Roman fortress of Halmyris was founded in the late first century CE. At this time, the Danube Delta had already prograded several kilometers to the east of Halmyris, comprising a deltaic plain with numerous lakes and fluvial channels. Halmyris was protected from flooding due to its location atop a paleo-cliff, but it had direct access to the river. A secondary channel of the Saint George, which flowed to the north of the site, has been elucidated between the seventh century BCE and the seventh century CE and could have been used as a natural harbor (Giaime et al. 2019b).

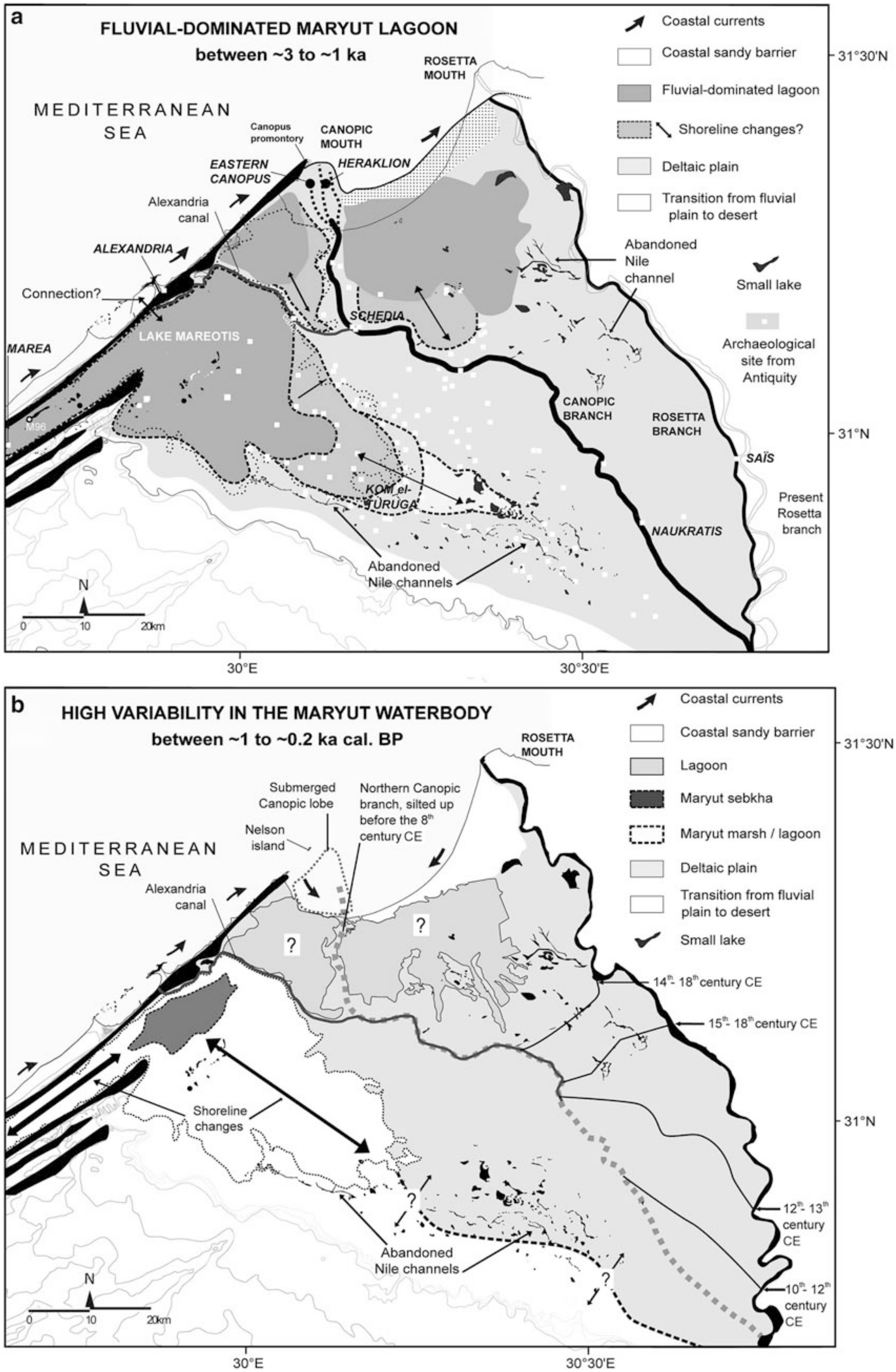
At a number of sites, the excavation of ancient harbor quays has facilitated the precise reconstruction of fluvial bank mobility since antiquity. This can be linked to the vertical accretion of riverbanks by flooding and the gradual funneling of fluvial waters by human activities. In London, for instance, Milne (1985) has described a 100 m shift in the port's waterfront between CE 100 and today. Under a mesotidal fluvial regime, funneling of the waterbody has led to a positive increase in tidal amplitude. A similar evolution is also attested at Bordeaux (France), where the staircasing of numerous quays and platforms has been described at two sites in the Garonne estuary (Gé et al. 2005). Three ancient and medieval platforms attest to a positive change in tidal amplitude of around 1.1 m during the twelfth to fourteenth centuries CE that can probably be linked to human impacts on the fluvial system.

Lagoonal Harbors

Since 6000 BP, spit accretion on clastic coasts has disconnected a number of paleo-bays from the open sea. This process formed lagoons that have gradually infilled to yield rich geological archives. Lagoons offer natural protection, and their use as anchorage havens has been widespread since early antiquity. Nevertheless, lagoons pose a number of challenges that explain why these contexts were largely avoided as harbors during later periods: (1) difficult accessibility, namely, the mobility of the outlet channel that was particularly problematic for navigation, and (2) seasonal fluctuations in lagoon level, especially in the case of large waterbodies at the margins of fluvial systems.

Maryut lagoon lies at the northwestern margin of the Nile Delta, in a depression between two consolidated sandstone ridges of Pleistocene age (Flaux et al. 2011; Fig. 10). The lagoon presently extends for 70 km on an SW-NE axis with a maximum width of ∼10 km. During antiquity, Nile inflow into the Maryut was supplied by the Canopic, the westernmost branch of the Nile. The Maryut's location at the intersection between the Mediterranean Sea and a major fluvial system has driven important paleoenvironmental changes during the past 8000 years (Flaux 2012; Flaux et al. 2012, 2013). It is also responsible for significant seasonal variations in lagoon levels, driven by annual Nile flood cycles. There has been renewed interest in the Maryut because mounting archaeological evidence suggests that the lagoon was an important waterway during antiquity, with a densely occupied shoreline and numerous harbors and mooring sites (Blue and Khalil 2010). Recent work by Flaux (2012) has demonstrated that the lagoon's Hellenistic and Roman harbors present a steplike mooring architecture to accommodate these seasonal fluctuations. Ancient Alexandria also had a lacustrine harbor on the Maryut, in addition to its maritime ports (Goiran 2001). This dual waterfront was praised by the ancient geographer Strabo in the first century BCE, because its geomorphological configuration opened Alexandria to Mediterranean trade, and also the Nile delta and Egypt. Flaux et al. (2017) have proposed a location for Portus Mareoticus, which had at least three ancient jetties, perpendicular to the shoreline and several hundred meters long to accommodate the seasonal, Nile-driven variations in lake levels. This waterfront was disconnected from the city during the ninth century CE, due to the desiccation of the Maryut Lake, concomitant with the drying-up of the Canopic branch. Alexandria canal subsequently became the sole waterway linking the city to the Nile.

Similar annual variations of around 1.4 m are also attested in the Dead Sea and the Sea of Galilee (Hadas 2011). Reinforced landing quays at the Roman harbor of Magdala (Israel) comprise a comparable architecture to offset such variation and avoid erosional undercutting (De Luca 2009). Recent work has unearthed a well-preserved harbor structure, extending for more than 100 m, which was functional during the Hellenistic and Roman periods (Sarti et al. 2013). Chronostratigraphic investigations have demonstrated that the harbor basin silted up and was abandoned during the Middle to Late Roman period (270–350 CE). At Kursi, also on the shores of the Sea of Galilee, Giaime and Artzy (2022)



Harbors and Ports, Ancient, Fig. 10 Evolution of the Maryut lagoon during the past 3000 years (From Flaux 2012). The general aridification trend described during this period appears to be linked to the gradual decline of the Canopic branch of the Nile, which supplied the Maryut lagoon with freshwater used waterfront archaeology to reconstruct lake-level variations of around 6 m between the Iron Age II and the Crusader period. Their reconstruction demonstrates that water levels were around −212 to −210 m mean sea level (msl) during the Iron Age II period. Lake levels rose to −208/−209 m msl during the Late Hellenistic/Early Roman period, before falling (<−213/−214 m msl) from the Byzantine to the Crusader period (from fifth to twelfth centuries CE). These data are consistent with a paleoclimate records from within the watershed (Kaniewski et al. 2017), characterized by a long-term aridification of Levantine climate (Marriner et al. 2022).

The rapid evolution of deltaic systems in high sediment-budget contexts means that the paleoenvironments of lagoonal harbors changed rapidly. For example, on the Arno Delta, the lagoonal harbor of Portus Pisanus evolved in a number of different phases mediated by relative sea level, sediment supply, long-term environmental dynamics, and coastal/delta geomorphology. Around 200 BCE, a naturally protected lagoon developed and hosted Portus Pisanus until the fifth century CE (Kaniewski et al. 2018). The decline of the protected lagoon started at ~1350 CE. By the seventeenth century CE, the rapid accretion of arcuate beach ridges led to the siltation of the lagoon, which was transformed into a wetland, physically detached from the Ligurian Sea.

Lagoonal systems were particularly conducive to endo-lagoonal harbor circulation. A number of lagoon strings were exploited in the Mediterranean during Roman times, most famously the Fossa Neronis (Italy) in the direction of Rome (Cuma, Campania), Narbonne in southern France (Sanchez and Jézégou 2011), and the upper Adriatic lagoons between Istria and the Po (Degrassi 1955). New archaeological data from the Maryut lagoon in Egypt also suggest that the basin possessed a series of harbor complexes and mooring sites during Hellenistic and Roman times (Blue and Khalil 2010). At present, the archetype of a harbor lagoon is medieval Venice which operated very successfully as a port up until recent modification of its marginal marine system.

Conclusions and Future Research Directions

The impact of ancient harbor geoarchaeology on our understanding of the archaeological record in waterfront areas is clear and explicit. We have presented methods for reconstructing ancient harbor landscapes at a wide range of temporal and spatial scales, drawing on geoscience techniques, paleoecology, and archaeology. With particular emphasis on the Mediterranean region, we have concentrated on the description and illustration of selected case study examples drawn from different geomorphological contexts. These lay the foundations for more geographically extensive studies, integrating the archaeological record with sediment archives for many Holocene time periods.

Some of the main advances made during the past 20 years include (1) the precise characterization of harbor facies in coastal contexts, using a variety of sedimentological, geochemical, and paleoecological proxies; (2) the characterization and intensity of human impacts in coastal areas (e.g., Véron et al. 2006); and (3) the scope to derive high-resolution RSL data (e.g., Morhange et al. 2001). Ancient harbor research is a rapidly evolving offshoot of geoarchaeology, and there is reason to be optimistic about its future prospects and applications. For the Mediterranean, as geographical gaps are gradually being filled and new research methods developed, more finite, regional-scale interpretations are becoming possible at a variety of temporal scales. Within the context of current debate on the role of the Anthropocene in shaping environments, one major cause for concern is the vulnerability of waterfront archaeology, particularly ancient harbor infrastructure, to coastal hazards due and sea-level rise. These impacts have been accentuated by falling sediment supply (drought, sediment retention in watersheds due to fluvial damming) to coastal areas, which are driving accelerated erosion (Pourkerman et al. 2018). For instance, for 49 World Heritage Sites in low-lying coastal areas of the Mediterranean, Reimann et al. (2018) have estimated that, at present, 37 sites are at risk from a 100-year flood and 42 from coastal erosion.

Current gaps in knowledge relate to the chronostratigraphic characterization of harbor facies in fluvial contexts that, in the absence of archaeological structures, renders the precise localization of harbor basins particularly challenging. Furthermore, our understanding of ancient harbor geoarchaeology is biased towards later periods, particularly Greek and Roman ports. Major gaps remain with regard to the Bronze Age, and future studies must look to probe these earlier periods (Kaniewski et al. 2014). While our understanding of Mediterranean harbors continues to improve, it seems important to extend research to new geographical regions such as China, the Red Sea, and the Persian Gulf. One area of concern is the rise in catastrophic research in harbor contexts that mirrors the growth of neocatastrophic research during the past 20 years (Marriner et al. 2010; Marriner and Morhange 2013). We advocate for the adoption of more nuanced approaches to the study of high-energy episodic events such as tsunamis and earthquakes (Marriner et al. 2017; Delile and Salomon 2020). It is also important for future research to better integrate internal and external vulnerabilities (Salomon et al. 2018).

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