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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, Piraeus, and Valletta 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 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; Butzer, 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

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and Morhange, 2007). Their importance in understanding ancient maritime landscapes and societies (e.g., Gambin, 2004; Gambin, 2005; Tartaron, 2013) makes them one of the most discussed archaeological contexts in coastal areas (Figure 1). Around 6,000 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 ~4,000 years, harbor technology has evolved to exploit a wide range of environmental contexts, from natural bays and estuaries 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). 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; Hesnard, 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 AD (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 BC, founded in a naturally protected limestone embayment by Greek colonists from Ionia (Figure 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 for multiple references; Figure 1), building on pioneering archaeological work in the first half of the twentieth century (e.g., Negris, 1904a; Negris, 1904b; 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). 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.

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 BC) 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. 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 (Fabre, 2004–2005; Butzer et al., 2013). Quays were also commonly established along the Nile, for instance, at fourteenth century BC Amarna, boats have been depicted parallel to shoreside quays equipped with bollards (Blackman, 1982a; Blackman, 1982b). An artificial quay dating to the second millennium BC 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 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 2,000 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 remain 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 transport of goods. The site was used extensively during the Middle Kingdom (around 4,000–3,775 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 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 4,500 years (Gaur and Vora, 1999).

Archaeological sites of Harappan age (3000–1500 BC), 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 BC, 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 BC), the Shang Dynasty (1766–1122 BC), and the Zhou Dynasty (1122–256 BC). 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 BC to 25 AD) 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 BC; Marriner et al., 2006b; Marriner, 2009). 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; Figure 3).

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 BC, 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 BC 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 AD. 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, a total width of over 20 m. Radiometric dating of wood fragments constrains this Phoenician structure to the ninth century BC (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 BC age (Braidwood, 1940).

Depending on the time and culture, different variations are noted in the use of headers. From the fifth century BC, 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 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, 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 AD, 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 BC (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; Brandon et al., 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 BC) 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 (Figure 4; 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; Blackman, 1982b), 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 BC onwards, the most extensive enterprises were undertaken during the first century AD, at which time huge volumes of sediment were extracted. At the excavations of Naples, absence of pre-fourth century BC layers has been linked to extensive dredging between the fourth and second centuries BC (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 AD. They are characterized by an open central well that is inferred to have accommodated the dredging arm.

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 2 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).

Ancient harbors are both natural and constructed landscapes and, from a geoarchaeological perspective, comprise three elements of note.

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; Marcus, 2002b), through the first Phoenician mole attributed to around 900 BC (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). 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.

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.

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 into 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 (Figure 5). 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; Keay et al., 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, 1971–72). 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 of 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 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 BC 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 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; Marriner et al., 2006b). 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 (Figure 6).

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 is 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.

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).

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; Yanko-Hombach et al., 2007b; 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 AD (Tousson, 1922; Stanley et al., 2001; Stanley et al., 2004a; Stanley et al., 2004b).

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; Figure 7). Since Roman times, tectono-volcanism inside this collapsed volcanic cone has led to significant shoreline mobility and is responsible for 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 BC, to high seismic activity in the eastern Mediterranean between the fourth to sixth centuries AD (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 BC (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 AD and 250 AD (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 AD (Stiros, 1998; Stiros, 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; Kayan, 1999). For example, the Menderes floodplain has prograded by ~60 km during the past 7,000 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.

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 BC 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, 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). Despite excavations at a number of sites on the Nile Delta, e.g., Tell El-Daba/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 BC until the fifth century AD. 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 AD following a large and rapid influx of Nile river sediment in the ninth century AD. This discharge in sediment led to the avulsion of a new distributory to the west, probably the Damietta branch.

Aquileia in northeastern Italy is a well-studied example of a Roman fluvial harbor. A series of important waterways characterized the Aquileia deltaic plain during antiquity. These were channelized during the Roman period so as to ensure favorable conditions for navigation and to mitigate against the impact of floods (Arnaud-Fassetta et al., 2003). 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 AD. 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 AD (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.

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 AD 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 AD 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; Figure 8). The lagoon presently extends for 70 km on a - SW-NE axis with a maximum width of $\sim$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 8,000 years (Flaux, 2012; Flaux et al., 2012; Flaux et al., 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. 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 AD).

Lagoonal systems were particularly conducive to endolagoonal 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.

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. 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.

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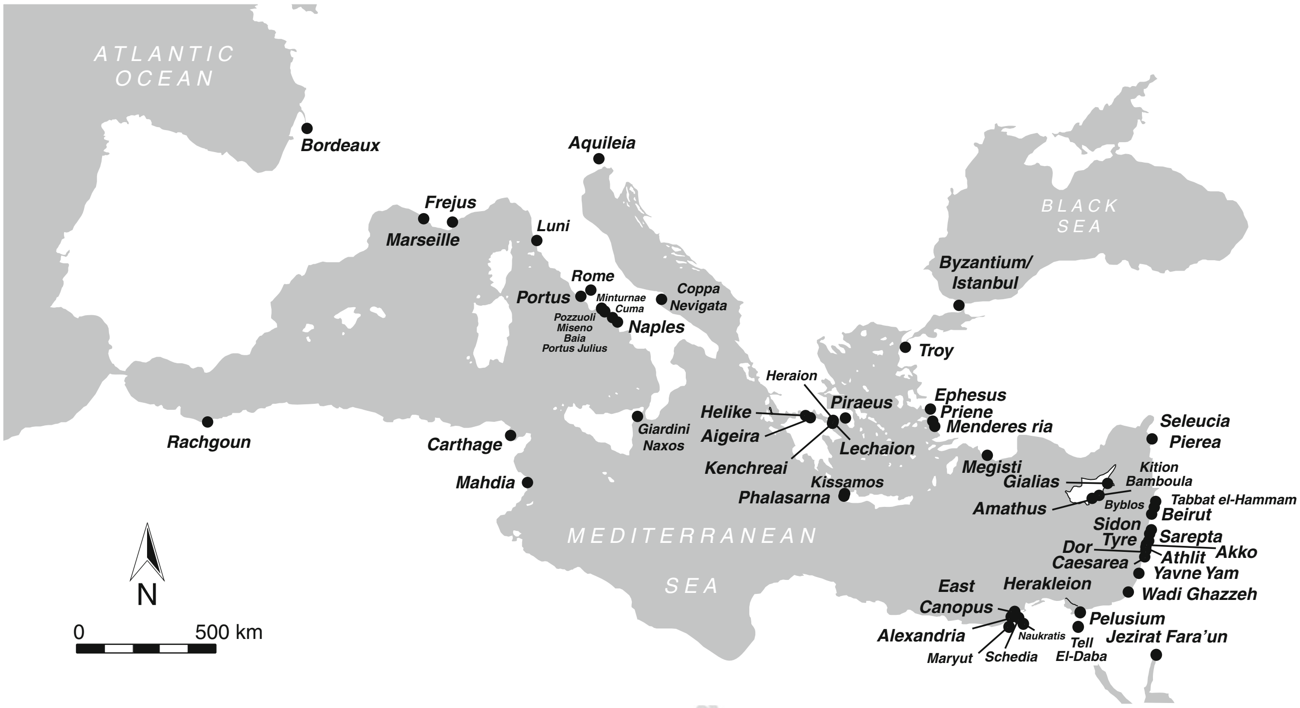
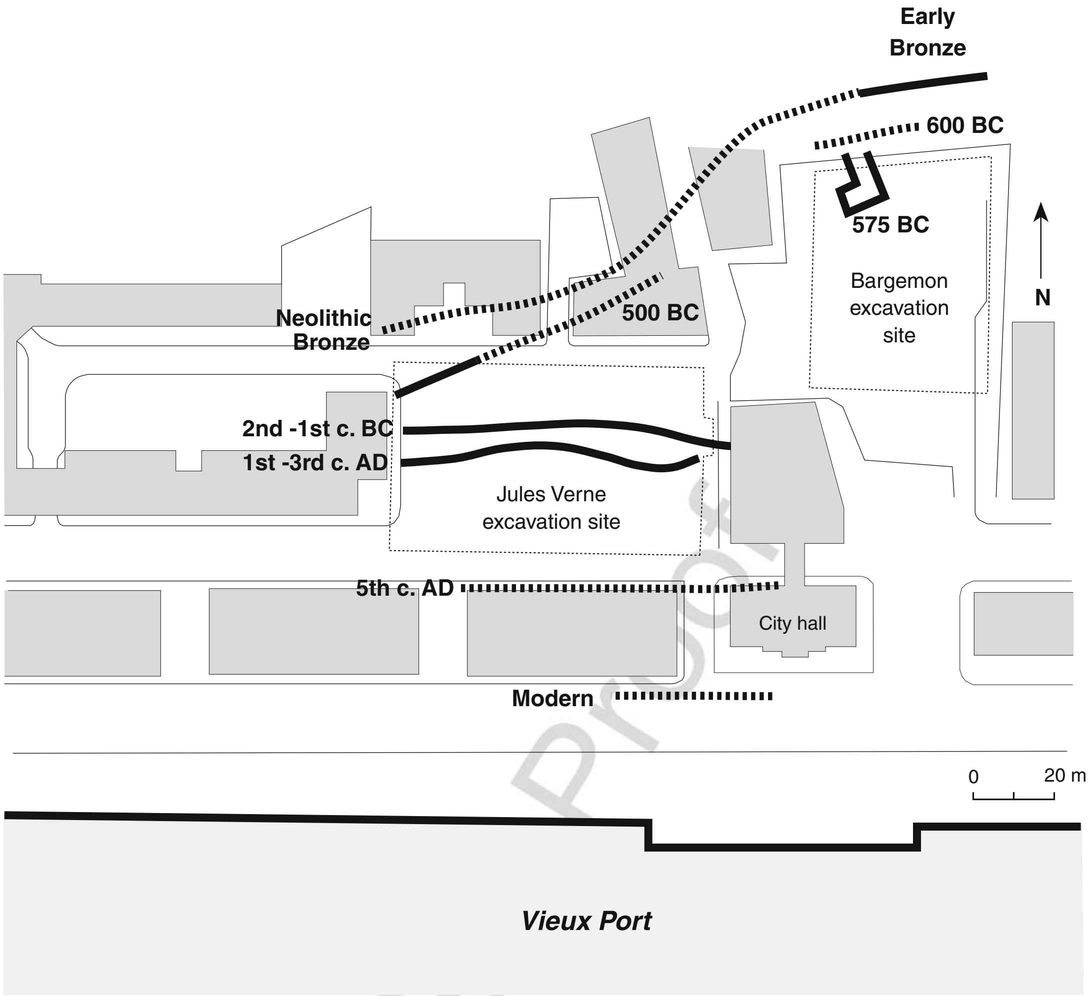
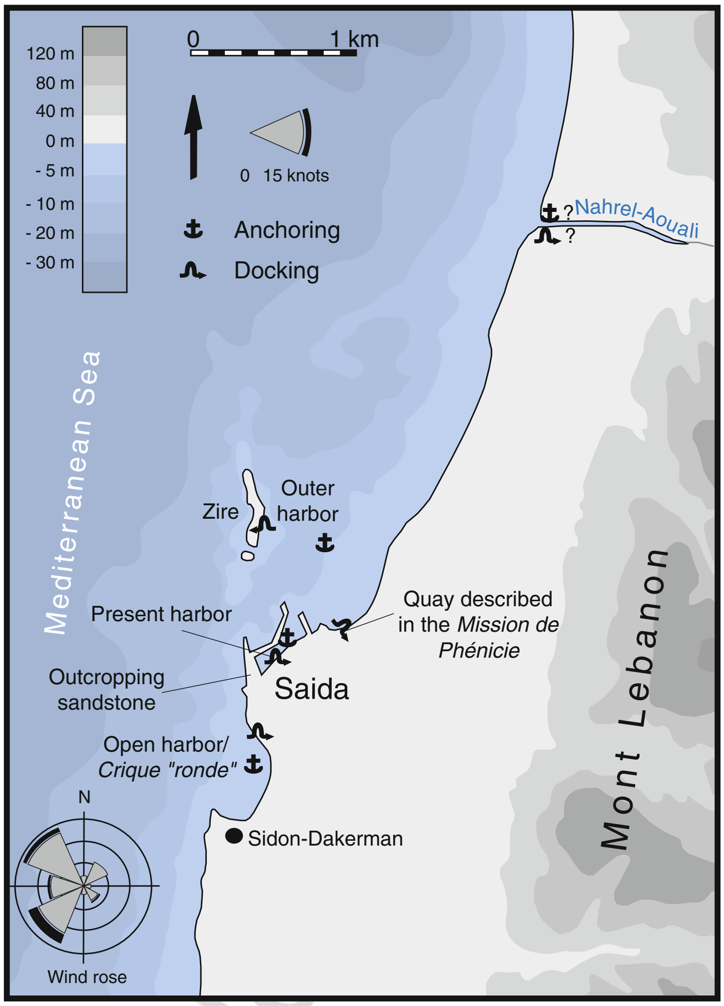


Harbors and ports, ancient, Figure 1 Mediterranean harbor sites discussed in the text.

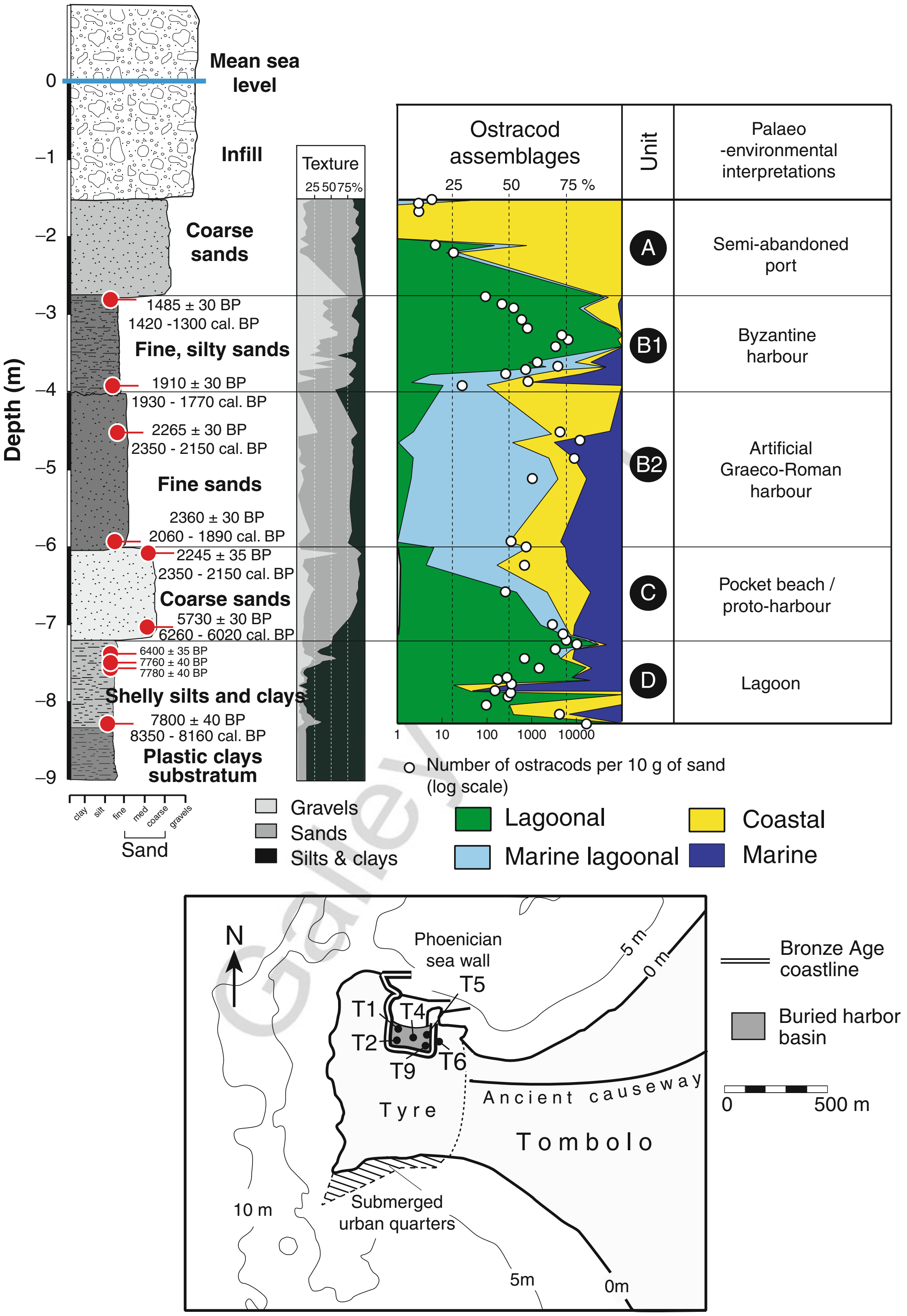


Harbors and ports, ancient, Figure 2 Coastal progradation in the ancient harbor of Marseille since Neolithic times. Chronostratigraphy and marine fauna fixed upon archaeological structures document a steady 1.5 m rise in relative sea level during the past 5,000 years. Sea level was broadly stable around the present datum between AD 1500 and the last century.

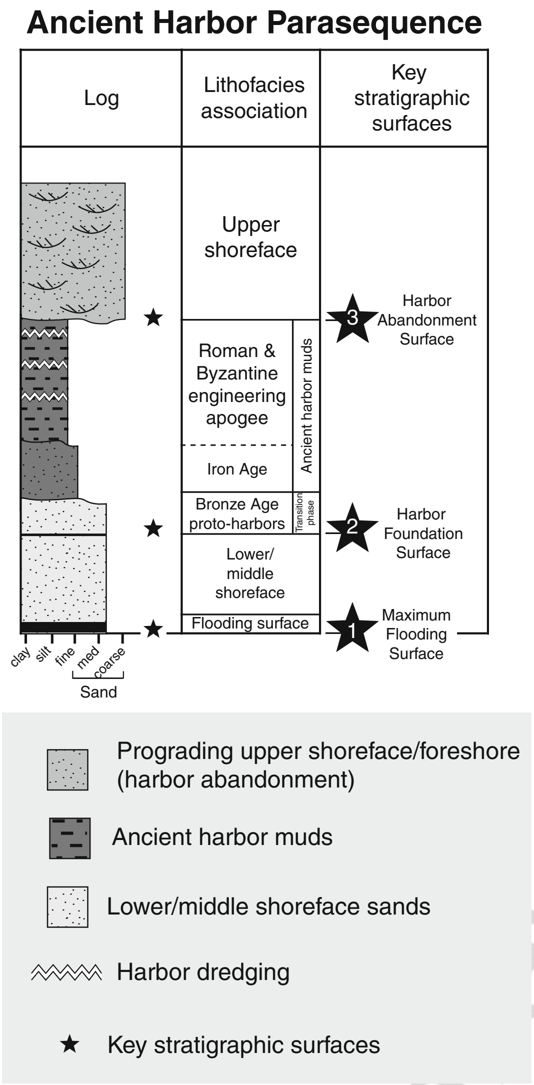


Harbors and ports, ancient, Figure 3 Sidon's ancient harbor areas (Adapted from Carayon (2008) and Marriner (2009)).

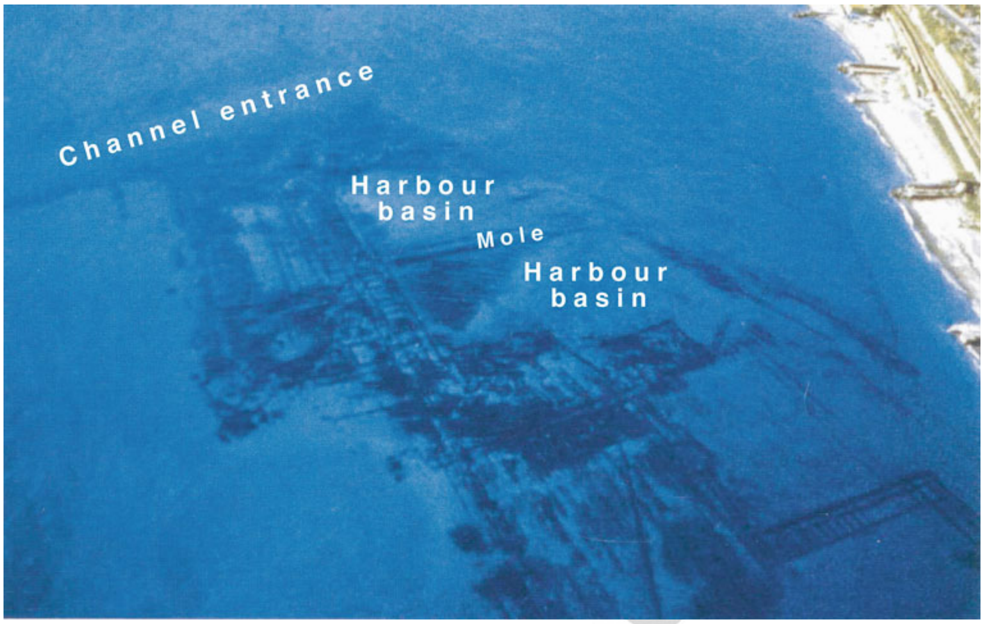
Harbors and ports, ancient, Figure 4 Harbor dredging in Naples (Photograph: D. Giampaola, Archaeological Superintendence of Naples).



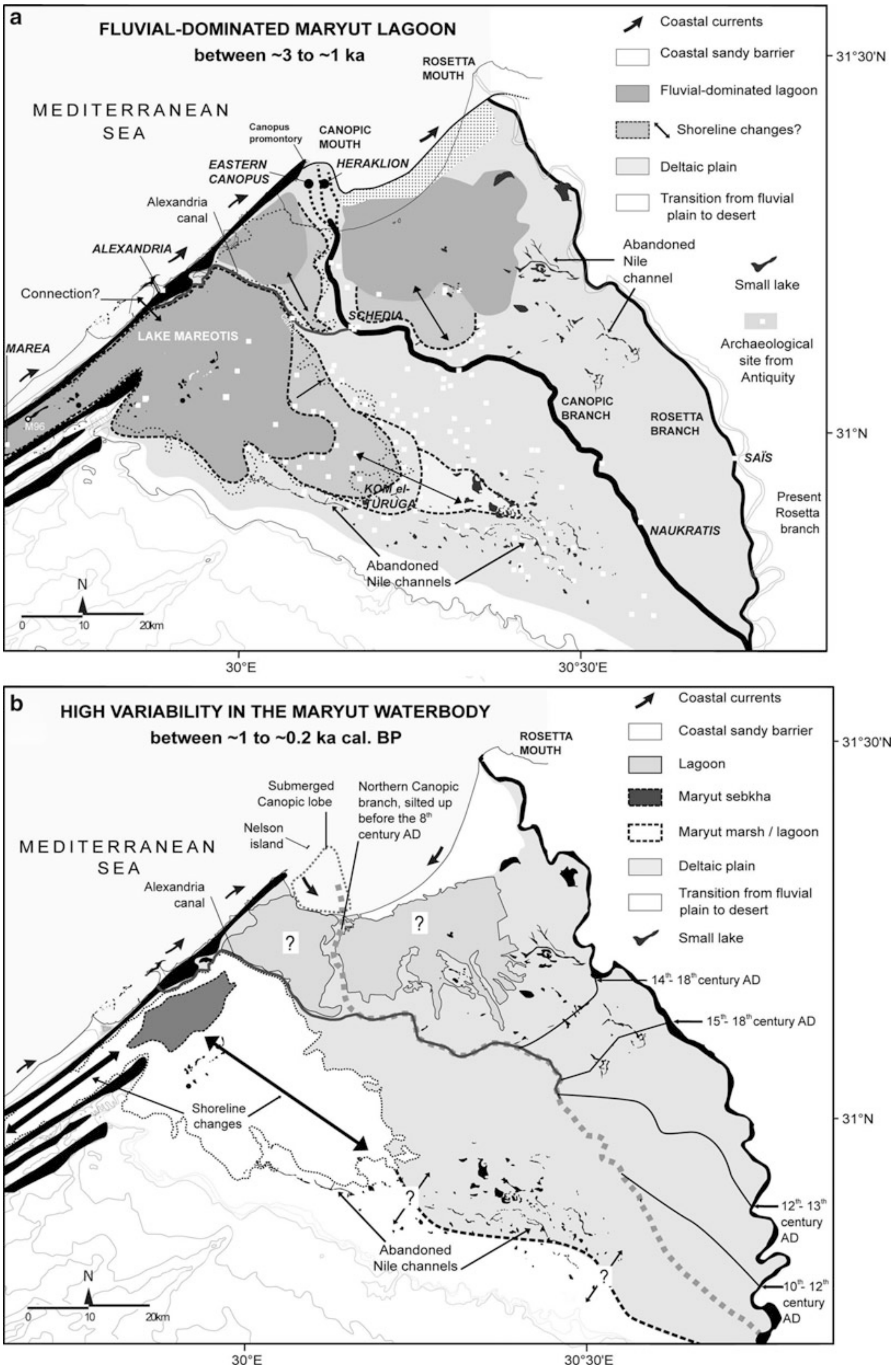
Harbors and ports, ancient, Figure 5 Chronostratigraphic evolution of Tyre's ancient northern harbor since the Bronze Age (core T9).



Harbors and ports, ancient, Figure 6 Chronostratigraphic evolution of ancient Mediterranean harbors in coastal areas.



Harbors and ports, ancient, Figure 7 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).



Harbors and ports, ancient, Figure 8 Evolution of the Maryut lagoon during the past 3,000 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.

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