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Geoscience of ancient Mediterranean harbours

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Abstract

Although much has been written on the subject of ancient Mediterranean harbours, the relatively new area of harbour geoarchaeology remains dispersed in the geoscience and archaeological literature. Over a decade of research has amassed rich and varied datasets of anthropogenically forced coastal evolution, with a remarkable number of between-site analogies. This new research field also shows the rich potential of geoscience to reconcile important archaeological questions. No single publication, however, has yet drawn on these geological patterns to yield a detailed overview suitable for geoscientists and environmental archaeologists. The aim of this review article is to (1) discuss how ancient harbours have come to be preserved in the geological record; (2) expound the basic principles and palaeoenvironmental tools underpinning ancient harbour geoarchaeology; (3) outline some of the most significant research advances made; and (4) discuss a new chrono-stratigraphic model applicable to harbour sequences.
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1. Introduction

Maritime archaeology has for many decades been dogmatically skewed towards what Breen and Lane (2003) term 'ship-centrism', the study of boats and their architectural aspects, to the detriment of physical harbour landscapes and infrastructures (Muckelroy, 1978; Sherwood Illsley, 1996; Gould, 2000; Green, 2004; Pomey and Rieth, 2005). Indeed, the opening sentence of a 2001 article by Gibbins and Adams emphatically encapsulates this: "Maritime archaeology, the study of the material remains of human activities on the seas and interconnected waterways, is fundamentally focused on shipwrecks. Although the definition encompasses many other types of context such as harbours, submerged land surfaces and coastal settlements, shipwrecks are the most distinctive and numerous type of site studied by maritime archaeologists." Whatever the benevolent aspects of the former, and there are many, we argue that it has yielded a patchy and archaeologically biased picture that largely disregards the port area and adjacent coastal environments. Significantly, Gibbins and Adams (2001) go on to concede that "in the fields of study focused on the maritime past, the ubiquity of shipwrecks as a site type has seemed at times to promote their research profile at the expense of palaeo-landscapes, submerged settlement sites and other structures such as harbours and fish traps."

Ports were for a long time a privileged research object of classical archaeology (Grenier, 1934), focusing namely on the study of harbour infrastructure and the analysis of

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maritime commerce (Rougé, 1966). Traditionally, reconstruction of ancient palaeogeographies relied heavily on ancient texts such as Strabo and Ptolemy (Ardaillon, 1896). At the start of the 1980s, unprecedented multi-disciplinary excavations were initiated at Caesarea Maritima (Israel) and Marseilles (France), looking to overcome many of these traditional shortcomings and prioritise both large-scale and small-scale archaeological units (Raban, 1985; Raban, 1988; Hesnard, 1994; Raban and Holum, 1996; Hermary et al., 1999; Rothé and Tréziny, 2005). The resultant data are unparalleled in their scope and completeness, with mutually discrete disciplines (archaeology, history, geology, geomorphology and biology) working in tandem to produce a multifaceted basin-wide understanding of the two sites. One important and perhaps most singly pervasive advancements, both in terms of cost effectiveness and data wealth, was the exploitation of the geological record as an aid to the archaeology (Reinhardt et al., 1994; Reinhardt and Raban, 1999; Morhange et al., 2001; Morhange et al., 2003). Ancient harbour sediments were shown to be rich time-series of human impacts yielding insights into the magnitude, variability and direction of changes during antiquity. Despite this geoarchaeological 'revolution', no single publication has yet given a detailed overview suitable for earth scientists and environmental archaeologists (Goiran and Morhange, 2003).

2. Brief history of research

2.1. Ancient harbour research in archaeology

2.1.1. Early travellers and savants (seventeenth to nineteenth centuries)

Whilst maritime archaeology scarcely predates the invention of underwater breathing apparatus in the early twentieth century, scholarly interest in ancient Mediterranean harbours is a centuries-old field of inquiry stretching back to the Renaissance. Revival of the Classics around this time meant that the Grand Tour of Italy and Greece was an important rite of passage for young aristocrats looking to 'enlighten' themselves with the architecture and archaeology of antiquity's most important sites (Bourguet et al., 1998; Horden and Purcell, 2000). In the Near East meanwhile, pilgrims en route to the Holy Land extensively described the landscapes of numerous Levantine coastal sites (Pococke, Volney etc.).

Whilst interesting from a historiographical standpoint, these early works were dominated by speculative reverie void of any real scientific substratum. Numerous authors attempted to deductively translate the classic written sources and personal observations of relic landscape features into graphic representations of harbour topographies (e.g. the sixteenth century reconstruction of Portus in Braun and Hogenberg's *Civitates Orbis Terrarum*, volume IV, 1588, Fig. 1). This early corpus of antiquarian study significantly influenced scholarly research during the proceeding centuries, and idealised views of many ports continued to be produced with just slight variations (see Paroli, 2005 for Portus). Although this piecing together of the literary jigsaw yielded frail and greatly tentative results it bears testimony to the intrigue surrounding ancient harbours.

Many of these early sixteenth to eighteenth century voyagers were startled by the paradoxically small size of ancient port basins, a fact which appeared greatly enigmatic with their former maritime glories. For example, Maundrell (1703) cannot but help hide the disenchantment of his stay at Tyre: "This city, standing in the sea upon a peninsula, promises at a distance something very magnificent. But when you come to it, you find no similitude of that glory, for which it was so renowned in ancient times." Volney (1792) further compounds his predecessor's words: "Where are those fleets of Tyre, those dock-yards of Arad, those work-shops of Sidon, and that multitude of sailors, of pilots, of merchants, and of soldiers? […] I sought the ancient inhabitants and their works, and found nothing but a trace, like the foot-prints of a traveller over the sand. The temples are fallen, the palaces overthrown, the ports filled up, the cities destroyed; and the earth, stripped of inhabitants, has become a place of sepulchres." A century later, Renan reiterated his predecessor's words "I think that no other first order city of antiquity has left behind as few traces as Tyre."

During the nineteenth century a clear transition is observed away from the simple landscape descriptions of the antiquarian traditions to the employment of more rigorous scientific techniques by intellectuals. Colonialism and the fight not only for territorial but also cultural supremacy gave rise to a number of important geographical and archaeological works. Napoleon's ambitious military expedition to Egypt (1798–1801) epitomises these new scientific currents. Although the military campaign itself was a debacle, Napoleon took with him 167 of France's leading scholars: mathematicians, astronomers, naturalists, engineers, architects, draftsmen, and men of letters. Their task was to study the country in all its aspects and eventually led, some 20 yr later, to the elephantine publication the *Description de l'Egypte*.

After the fall of Napoleon I, the French looked to offset rising British influence in the Mediterranean using culture and science. In 1846, the *Ecole française d'Athènes*, the first research school of its kind was created in Greece and spawned an annex school, the *Ecole française de Rome,*

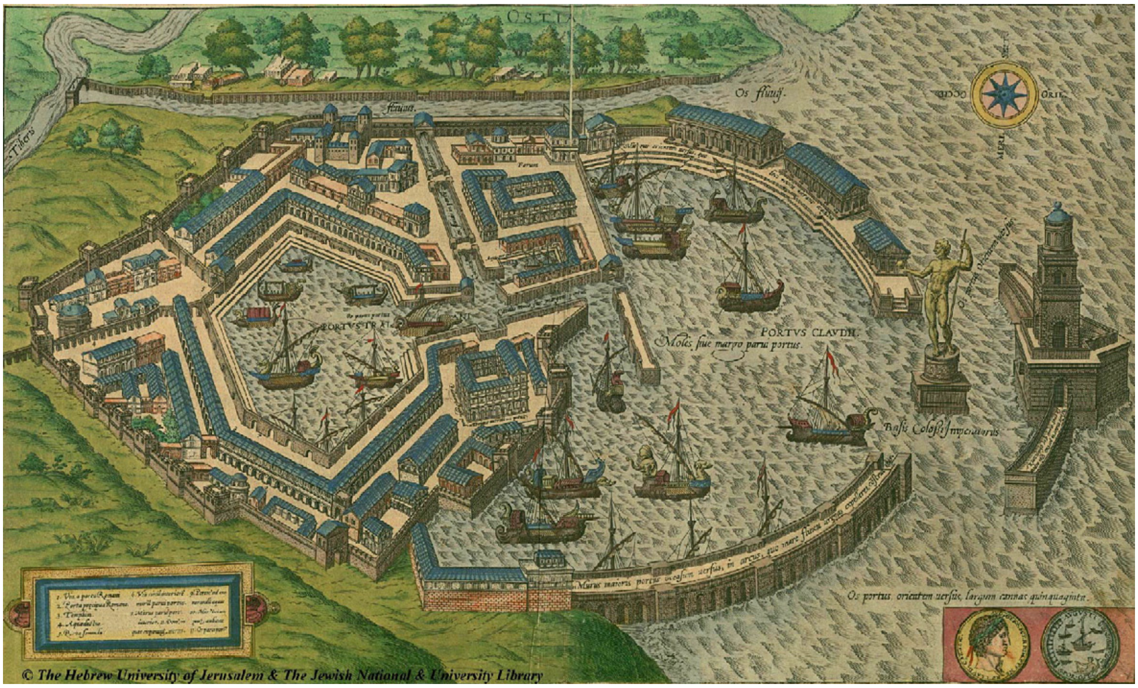

Fig. 1. Braun and Hogenberg's sixteenth century reconstruction of Portus, near Rome (volume IV, 1588). This representation is typical of the Renaissance antiquarian tradition whereby, in the absence of precise topographical information, speculative graphic reconstructions were reached.

which eventually became autonomous in 1875. The German Archaeological Institute was founded in 1871. These two schools had been preceded at Rome by a joint Franco–German venture, the *Institut de correspondance archéologique* (1829), which aimed to publish new archaeological findings from around the Mediterranean in the institution's journal. At Rome, the model was eventually followed by other European and North American nations.

In addition to the archaeological schools, a number of geographical societies, including the Royal Geographical Society, the Palestine Exploration Fund and the *Société de Géographie de Paris*, also came into being around this time. Archaeology was seen as a means of showcasing political prowess and stronghold, and was very much at the centre stage of the British, French and German colonial movements. The resulting encyclopaedic works, and the supporting institutional frameworks which accompanied them, typify the shift towards precise recording and measurement in all areas of the natural sciences and archaeology. For coastal archaeology, the most important works of this period include Renan (1864), El-Falaki (1872), Ardaillon (1896) and Georgiades (1907). Significantly, it was during this period that many scholars started to draw parallels between coastal progradation and harbour silting (Fig. 2) to explain the reduced size or isolation of many ancient port basins, notably Renan at Tyre (1864) and Canina (1830) at Portus.

2.1.2. Pre-World War II — the beginnings of underwater archaeology

While underwater archaeology was given its first major impetus in the 1850s, when low water levels exposed tracts of archaeology in Swiss lakes, it was not until the beginning of the 1900s that the technology had sufficiently caught up with the theory (Keller, 1854; Desor and Favre, 1874; Paret, 1958; Dumont, 2006). Despite cumbersome and rudimentary breathing apparatus, the discovery and partial excavation of shipwrecks at Antikythera (1900–1) and Madhia (1908–13) were archaeological firsts (Pomey and Rieth, 2005). Around the same time, a number of scholars undertook systematic surveys of submerged port structures (for example Negris, 1904a,b; Jondet, 1916; Paris, 1916; Halliday Saville, 1941). In 1923, Lehmann-Hartleben furnished one of the most comprehensive and authoritative early studies on Mediterranean port infrastructures.

During the 1930s, Poidebard pioneeringly transposed aerial photography techniques he had developed working on Syrian limes to the maritime context of the Phoenician coast (Poidebard, 1939; Poidebard and Lauffray, 1951). Like the British archaeologist Crawford (1886–1957), who also advocated the use of aerial photography in

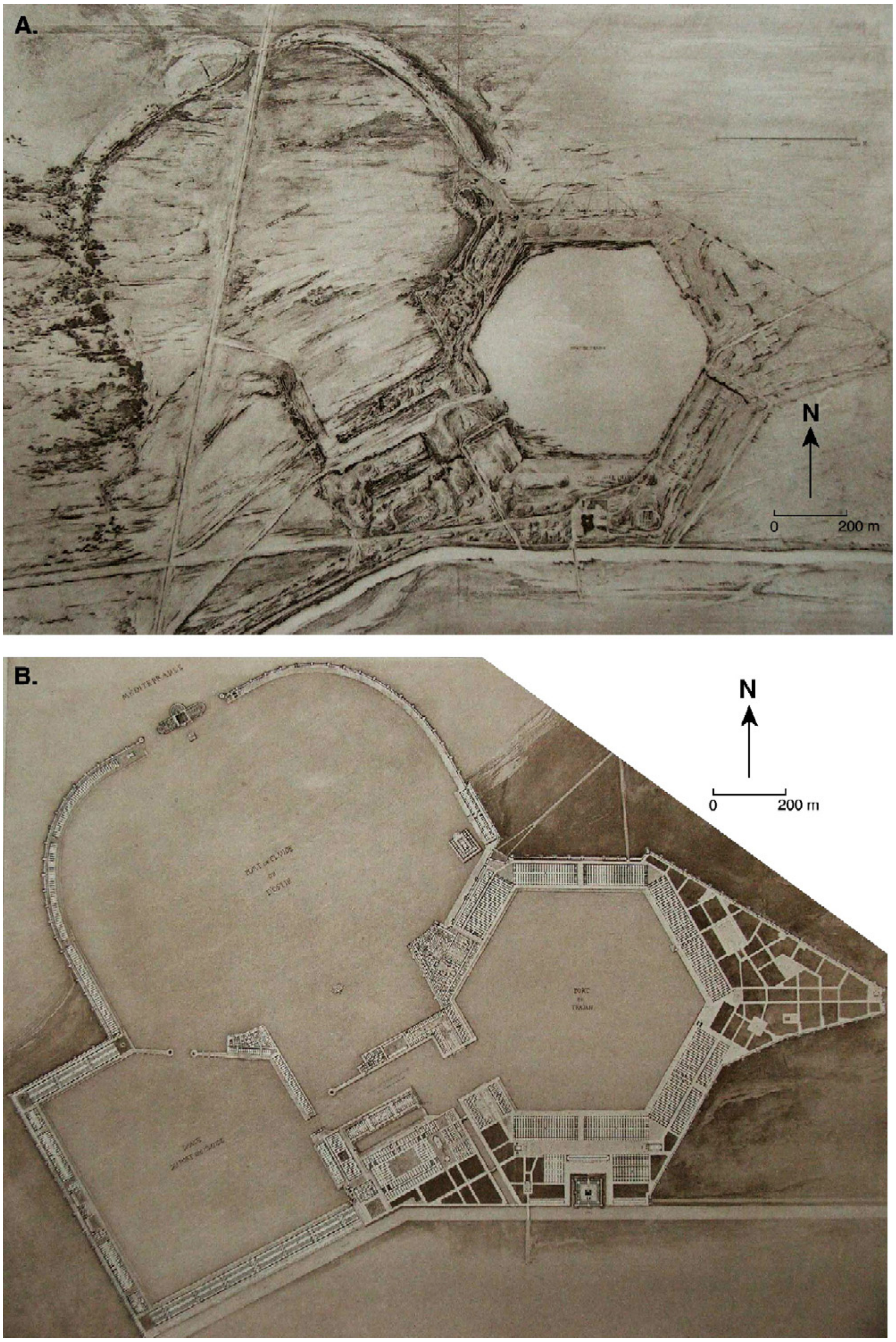

Fig. 2. A. Silting up of Portus at Ostia as represented by Garrez (1834, in d'Espouy, 1910). B. Garrez's reconstruction of the ancient port on the basis of measured topographical features. The plans were inspired by the work of Canina (1830). In general terms, the nineteenth century marked a watershed between the antiquarian tradition of the Renaissance period and modern topography. It was around this time that a number of scholars started to draw the link between harbour silting and coastal progradation to explain the demise of ancient seaports.

archaeology, Poidebard coupled this aerial reconnaissance with diving surveys to propose harbour reconstructions for numerous Phoenician city-states (Nordiguian and Salles, 2000; Viret, 2000; Denise and Nordiguian, 2004; Fig. 3). The aeroplane, symbol of technical modernity during the 1920s, offered new research avenues in archaeology and even if Poidebard was not the first to realise this, he was a pioneer in developing a clearly defined methodology. Relying on reports from 'hard-hat' divers he surveyed and mapped a number of important coastal sites including Arwad, Sidon, Tyre and Carthage. Although some of his findings have since proved erroneous (Frost, 1971; El Amouri et al., 2005) his work laid the foundations for maritime archaeology as we know it today. His methodical documentation and recording (aerial reconnaissance, cartography and underwater photography) is all the more important for modern scholars working in this region given the destruction of many remains wrought by recent building (Marriner and Morhange, 2005).

2.1.3. Post-war period

Invention of the aqualung revolutionized underwater archaeology after 1945, with a coeval shift in research loci away from the ports themselves to shipwrecks. Over the following decades, many ancient wreck sites were subsequently localized along the coasts of France and Italy (Pomey and Rieth, 2005). A minority of scholars continued to show an interest in ports and harbour infrastructure, notably at Appollonia in Libya (Flemming, 1961, 1965, 1971), Athlit in Israel (Linder, 1967), Carthage in Tunisia (Yorke and Little, 1975; Yorke, 1976; Yorke et al., 1976), Cosa (Lewis, 1973; McCann, 1979; McCann et al., 1987), Pyrgi (Oleson, 1977) and Portus in Italy (Testaguzza, 1964, 1970), Phaselis in Turkey (Blackman, 1973a), Kenchreai (Scranton and Ramage, 1967) and Porto Cheli in Greece (Jameson, 1973), and the ancient harbours of Israel (Galili et al., 2002). Underwater archaeologists such as Frost also did much for the development of aquatic survey techniques during the

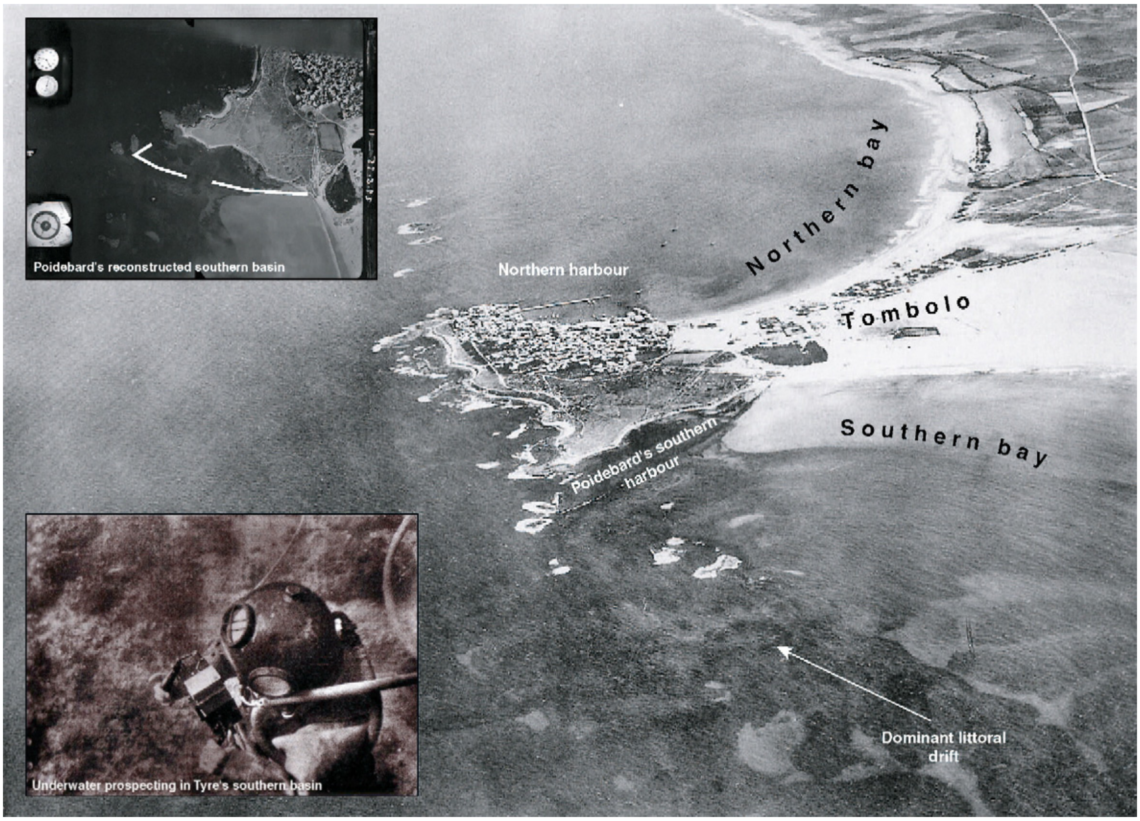

Fig. 3. Antoine Poidebard was one of the pioneers in underwater and coastal archaeology. He coupled aerial photography and underwater surveying to propose harbour locations for a number of Phoenicia's coastal sites. The oblique aerial photograph is of the Tyrian peninsula. In 332 BC, Alexander the Great linked the offshore island fortress to the continent by means of a causeway. This engineering feat profoundly influenced sediment trapping behind the island and today a tombolo, or sand spit, links the two. Poidebard diagnosed a series of harbourworks on the southern coastal fringe of Tyre. New research suggests that this area is in reality not a harbour basin but rather a drowned urban quarter, which sank into the sea during late Roman times (photographs from Poidebard (1939) and Denise and Nordiguian (2004)).

1960s and 1970s (Frost, 1964, 1966, 1971, 1973). Placing emphasis on precise observation and recording, her surveys were a continuum in the long history of inquiry on the Phoenician coast (Frost, 2000, 2002a,b, 2005).

In recent decades, progress in coastal archaeology can be attributed to the emergence of new tools (Leveau, 2005). For example, aerial photography, use of the aqualung, underwater robotics, advances in dating and geochemistry have all facilitated a revolution in traditional approaches.

2.2. History of ancient harbour geoarchaeology

In many ways, geology and archaeology have played a mutually perpetuating role in the development of one another. Stratigraphy and the processes involved in the formation of the sedimentary record have influenced archaeology since the late nineteenth century. In the absence of written documentary evidence, prehistorians turned to earth scientists in an attempt to better understand human–environment interactions. Similarly, archaeology has long been used as a temporal control in the interpretation of the Quaternary geological record (Bridgland, 2000; Westaway et al., 2006). In coastal areas it was notably the theme of sea-level changes and archaeological structures that especially focused the attentions of early natural scientists. During the nineteenth century, scholars started to recognise the importance of landscape mobility, which went against the vein of the dominant “fixist” and “catastrophist” theories that had dominated thinking in the preceding centuries (Desjardins, 1876). Lyell (1830), for example, was intrigued by marine borings he observed on pillars in the Roman market of Pozzuoli and ingeniously deduced their potential as a gauge of sea-level changes since antiquity. As attest the drowned remains of Pozzuoli’s Portus Julius, this area, which lies in the centre of an active caldera, has been subject to significant rapid sea-level changes during the past two millennia (Morhange et al., 2006a).

Lyell opined that the only way to understand the past was to assume that the earth-modifying processes which occur today also occurred in the past (Ager, 1989, 1995). To clearly illustrate this idea of uniformitarianism Lyell used the three pillars at Pozzuoli as the frontispiece to his *Principles of Geology* (1830) (Fig. 4). Lyell’s later text *Geological Evidence of the Antiquity of Man* (1863) was an even more transparent manifestation of the reciprocity between the two disciplines (Lyell, 1863).

The existence of submerged vestiges in Crete had been known since the seventeenth century, but it was not until 1865 that Spratt published a study of coastal movements on the island (Spratt, 1865). Spratt not only identified and measured the altitude of ancient coastlines at various localities around the island, but was also the first to understand, on the basis of his observations of Phalasarna harbour that uplift of the western part of the island dated to the historical period. In 1869, Raulin, having translated Spratt’s study, postulated the island had undergone uplift in its western part whilst suffering collapse on its eastern side (Raulin, 1869).

At the beginning of the twentieth century, debate opposed the Greek Negris (1903a,b, 1904a,b) and the influential French geologist Cayeux (1907, 1914), regarding the position of submerged archaeological vestiges around the coasts of the eastern Mediterranean (Delos, Leucade, Egine, etc.). For Negris observed metric submergence, such as that of Alexandria (Egypt), were not to be linked with localised phenomena but rather a ubiquitous basinwide rise in sea level (Negris, 1921). Cayeux on the other hand, greatly influenced by Suess’ fixist postulates for the historical period, affirmed that the general level of the Mediterranean had not varied significantly since antiquity. At Delos, Negris and Cayeux identified archaeological examples of sea-level fixity and instability, and Cayeux interpreted drowned structures as being the result of localised sediment compaction. The latter ignored the well-documented example of Phalasarna’s uplifted harbour (western Crete), refusing to concede the possibility of regional scale sea-level changes since antiquity. Cayeux’s conclusion is a classic example of scientific rigidness, resulting from the defence of a pre-established theory. Much of this debate subsided from the 1950s onwards, when the advent of radiometric dating techniques ushered in much greater temporal control.

During the 1970s, scholars such as Flemming (1969, 1971, 1978) and Blackman (1973a,b, 2005), resuscitated ancient harbour research, notably the study of sea-level change as an aid to understanding submerged settlement sites. In a similar vein, Schmiedt (1972) used Roman fish tanks to precisely reconstruct Tyrhennian sea-level changes during the past 2000 yr. Following in Poidebard’s footsteps, he coupled these data with aerial photographs and geomorphology to propose palaeogeographical reconstructions of numerous ancient harbour sites on Italy’s coastline (Schmiedt, 1970, 1975; Acquaro, 1988). These geocentric research currents, influenced by palaeoenvironmental inquiry, served as important precursors to ancient harbour geoarchaeology as it is today practiced. The latter has its origins in two research programs beginning in the early 1990s: the first at Marseilles, France and the second at Caesarea, Israel. Although geoarchaeology was not a new notion, it had rarely been applied to the rich archaeological and sedimentary contexts of ancient harbours. At Caesarea, Reinhardt et al. (1994, 1998) and Reinhardt and Raban (1999)

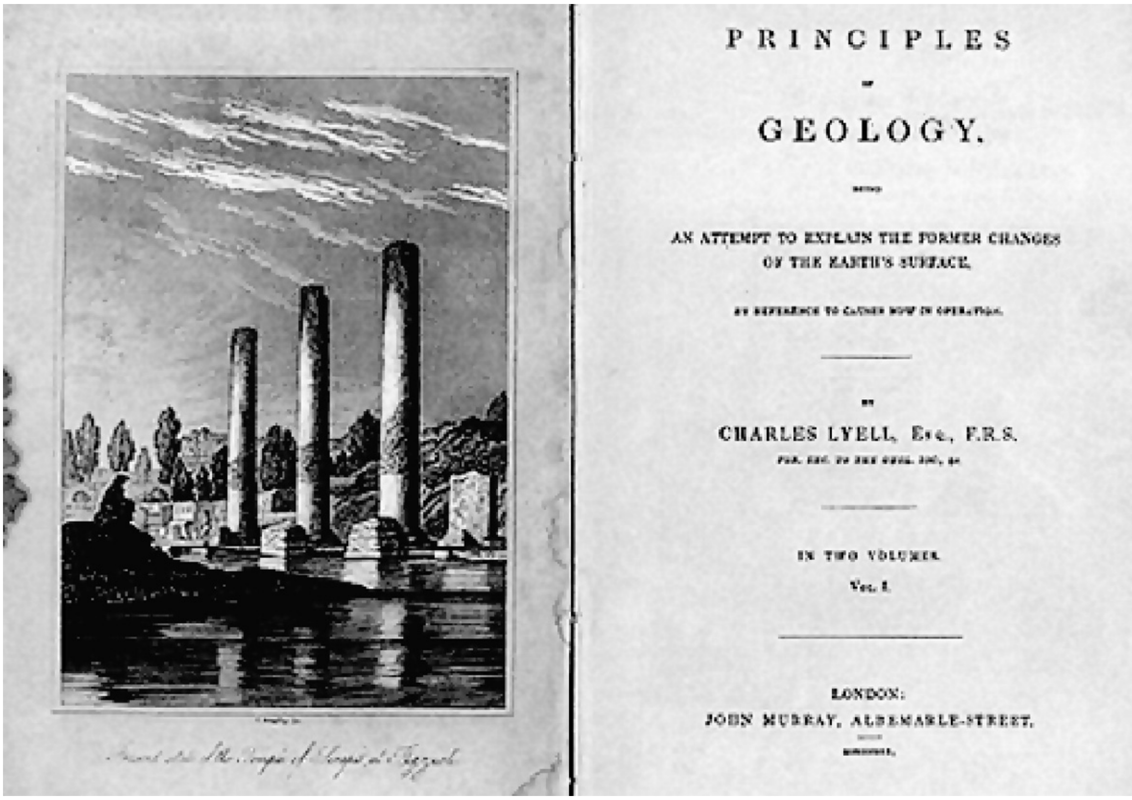

Fig. 4. The three pillars of the Roman market at Pozzuoli (southern Italy) have become a secular icon of uniformitarianism since their publication in Charles Lyell's Principles of Geology (1830). Lyell argued that the rise and fall of the coastal archaeology showed the land had undergone significant vertical movements since antiquity.

undertook micropalaeontological and geochemical studies to investigate the harbour's Roman history. Around the same period, Hesnard (1994), Morhange (1994) and Morhange et al. (2001, 2003) investigated large stratigraphic sections to probe the history of Marseilles' Graeco-Roman basin (e.g. relative sea-level rise, coastal progradation, rapid silting) and anthropogenic impacts since antiquity (Fig. 5).

The history of geoscience in ancient harbour research is nowhere better documented than at Marseilles, where construction work bordering the *Vieux Port* has revealed sandy beach facies and widespread plastic clays since the nineteenth century (Vasseur, 1911, 1914). Speculative interpretations, void of any systematic field and laboratory analyses, were produced although many of the early authors confused coastline deformation and relative sea-level changes (Vasseur, 1914; Bouchayer, 1931; Duprat, 1935). It was not until after the Second World War that the embryo of a multi-disciplinary team came into being, comprising a research quartet of Benoît (an archaeologist), Gouvernet (a sedimentologist), Mars (a malacologist) and Molinier (a botanist). Although much of their work was never fully published, Gouvernet studied beach formations around the city's ancient harbour (Gouvernet, 1948). Notwithstanding the research difficulties they faced, notably presence of the water table and absence of precise chronological constraints, the team was one of the first to recognise the scientific scope of harbour basin geology in reconstructing coastal progradation since antiquity (Morhange, 2001). In the 1960s and 1970s, new excavations led to the major discovery of the Roman harbour quays, although research was marred by fixist dogma and a notable absence of any palaeoenvironmental investigations (with the exception of Pirazzoli and Thommeret's, 1973 paper in which they describe and date biological mean sea-level indicators attached to harbour structures). Widespread excavations in the early 1990s set out to remedy many of these earlier ills, with the formulation of a multi-disciplinary research framework (Hesnard, 2004a,b).

From these two early works, a new era of coastal geoscience came to fruition with significant advances in our understanding of ancient harbour sedimentary systems (e.g. Kition-Bamboula, Morhange et al., 2000; Alexandria ad Aegyptum, Goiran, 2001, Stanley and Bernasconi, 2006; Tyre, Marriner et al., 2005; Sidon, Marriner et al., 2006a,b). These multiple studies have

Fig. 5. Jules Verne 3, a Roman dredging boat unearthed in Marseilles' ancient harbour. The vessel dates from the first to second centuries AD. The central dredging well measures 255 cm by 50 cm. The wooden hull has been preserved by the enveloping harbour clays (photograph: Morhange).

shown ancient harbours to be rich geoarchaeological records replete with information on occupation histories, human use and abuse of the Mediterranean environment, natural catastrophes (e.g. tsunami impacts) or even local tectonic mobility (Neev et al., 1987).

At a broader scale, research on deltaic systems has also been an important area of inquiry in understanding anthropogenically forced coastal change, pioneered notably by scholars such as Kraft and Rapp since the 1970s. This work has tended to focus on geomorphological research objects – deltas and their sediments – rather than archaeological layers at a given site, and has been qualified as archaeological geology by Rapp and Hill (1998). Although there is a great deal of overlap, the research can broadly be dissected into two separate *écoles*: (1) A first school has looked to validate the classical sources. For example, in Greece and Ionia Kraft et al. (1975, 1977, 1980a,b, 2003, 2005), Bousquet and Pechoux (1980), Bousquet et al. (1983), Jing and Rapp (2003), Pavlopoulos et al. (2003) have employed extensive coastal stratigraphy and palaeogeographic reconstructions as tests of the Homeric sources; (2) A second school has focused on the more geocentric themes of delta progradation and sediment failure. These notably include the work of Arteaga et al. (1988), Rapp and Kraft (1994), Riedel (1995), Schröder and Bochum (1996), Brückner (1997), Brückner et al. (2002, 2005) in Ionia, Fouache et al. (2005), Vött et al. (2006a,b) in Greece, and Wunderlich (1988), Stanley et al. (2001, 2004a,b) on the Nile delta.

Nowadays, most large-scale coastal archaeological projects look to apply a multi-disciplinary approach at different temporal and spatial scales. Since 1985, harbour archaeology and geoscience workshops have furnished important scientific arenas for multi-disciplinary discussion and debate, and attest to a clear growth in this domain as a research focal point (Raban, 1985; Euzennat, 1987; Raban, 1988; Karageorghis and Michaelides, 1995; Briand and Maldonado, 1996; Pérez Ballester and Berlanga, 1998; Leveau et al., 1999; Morhange, 2000; Vermeulen and De Dapper, 2000; Zaccaria, 2001; Berlanga and Pérez Ballester, 2003; Fouache, 2003; De Maria and Turchetti, 2004a,b; Zevi and Turchetti, 2004a,b; Fouache and Pavlopoulos, 2005; Bochaca et al., 2005; Morhange et al., 2005a).

3. Defining ancient harbours

Goiran and Morhange (2003) have formulated a tripartite definition of ancient artificial harbours, which is a practical starting point for geoscientists investigating these rich archives (Fig. 6). Although it may seem paradoxical that the earth sciences should show an interest in these peculiar archives, it is in many ways not surprising that ports have focused the attention of physical geographers. In effect, these unique base-level depocentres lie at the intersection between the natural environment and human societies. This new harbour geoarchaeology exploits the originality of these unique

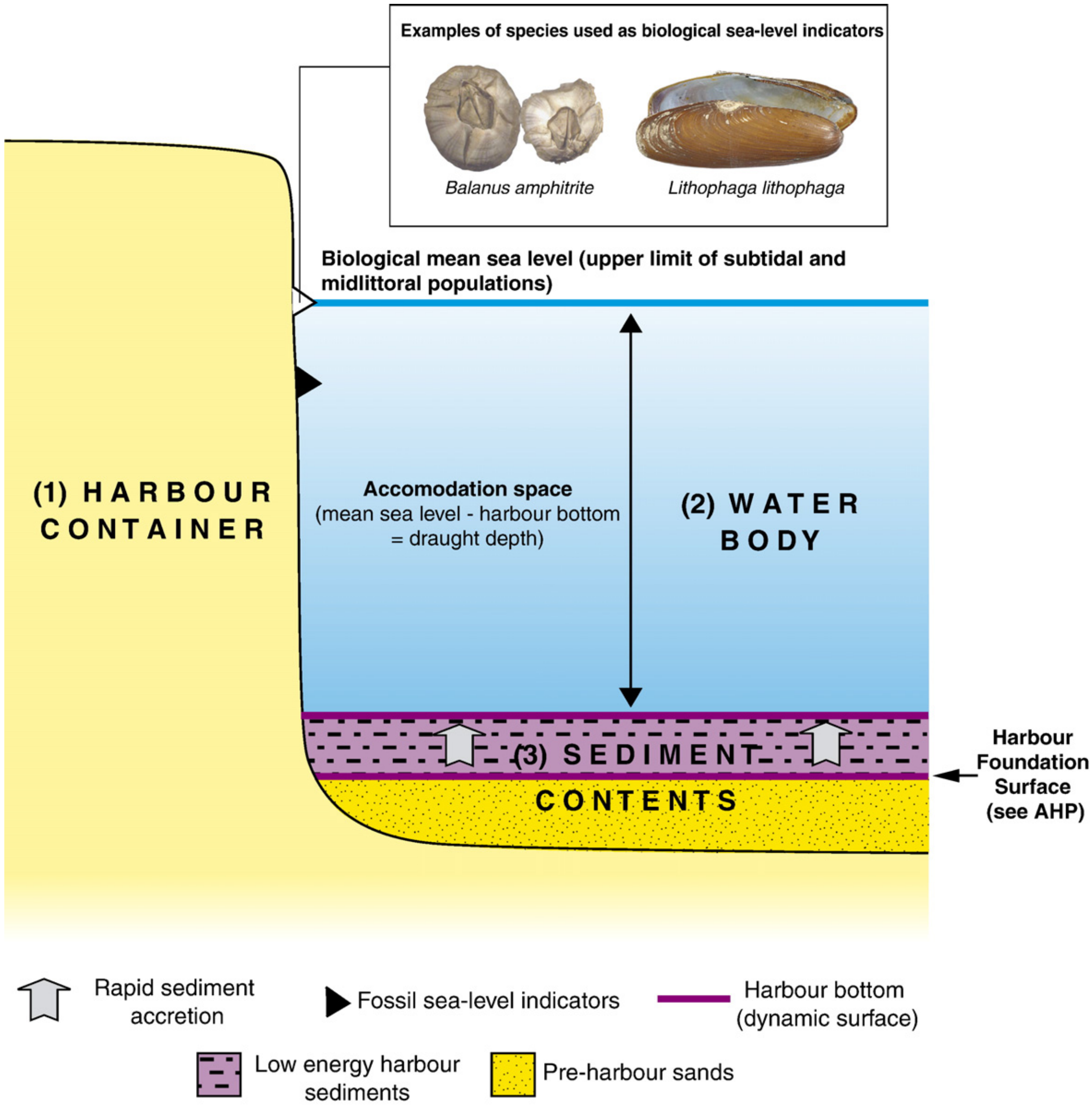

Fig. 6. Schematic representation of an ancient harbour depositional context with its three defining entities (1) the harbour container; (2) the water body; and (3) the sediment contents.

depocentres, whereby ancient environmental protection has ensured their preservation in the geological record.

3.1. The basin container

For a traditional archaeologist, an ancient harbour is defined on the basis of its physical 'man-made' attributes such as harbourworks (quays, piers, moles), shipsheds and the general satellite infrastructure which gravitates around this entity. In reality there is great diversity in the nature of these containers, be they natural low-energy environments (coves, estuaries or lagoons) used since the Bronze Age, or (semi)artificial basins resulting from human enterprise (e.g. Phoenician cothons (Carayon, 2005) or the Caesarea's concrete moles (Brandon, 1996), Portus, Cosa (Felici and Balderi, 1997) and Anzio (Felici, 1993, 2002)).

For the earth scientist, an ancient harbour incorporates not merely the physical man-made edifices – which in many cases no longer exist in a conspicuous form – but also two important geological objects: (1) the sedimentary contents of the basin; and (2) the water column.

3.2. The sedimentary contents

Ancient harbours are base-level depocentres. A harbour basin typically comprises a suite of fine-grained sediment layers which translate the low-energy conditions created by the port container. High-resolution study of this unit's bio and lithostratigraphical contents gives insights into the degree of harbour protection, confinement and degradation of local ecosystems, in addition to local occupation histories. The unique anoxic specificity of this layer also renders it important in the preservation of otherwise perishable archaeological material (leather artefacts, wood etc.).

3.3. The water column

The water column lies at the intersection between the terrestrial and marine domains. Relative changes in the position of the waterline, coupled with an understanding of sediment budgets and fluxes, are important in comprehending aggradation of the harbour bottom and coastal progradation or deformation. For human societies two reference levels, relative sea level and the harbour bottom, are therefore important in dictating the viability of a harbour basin. These reference levels are dynamic, moving up or down (more rarely) as a function of sea-level changes, tectonic isostasy, sediment fluxes and sediment compaction to dictate the total accommodation space. In the face of rapid accumulation rates, maintaining a navigable water column, or draught depth, engendered clear management strategies (Marriner and Morhange, 2006a).

4. Ancient harbour typology

Rougé (1966) was the first to propose an archaeological typology on the basis of harbour technology (natural and artificial harbours). A geoarchaeological typology has, however, never been devised. Four main aspects are important in dictating harbour location and design. (1) *Situation*. A port is not built simply anywhere. It forms an interface between the hinterland and sea and its location depends on traffic in these two areas. The margins of large deltas were often attractive locations, e.g. Marseilles for the Rhone valley and Alexandria for the Nile. (2) *Site conditions*. Two types of geological contexts, rocky and clastic coasts, were exploited. During the Iron Age, Greek and Phoenician colonists established harbour complexes in protected rocky bays and coves around the Black Sea and circum Mediterranean. Ports on clastic coasts were generally later, founded by much larger political superpowers with developed harbour technology and engineering *savoir faire* (e.g. Rome and Carthage). When large urban areas lay in inland areas, these types of coastal harbours served as *avant-ports* and operated in tandem with a fluvial port further upriver (e.g. the Ostia complex for Rome). The discovery of hydraulic concrete in the second century BC meant that the Romans were not significantly hindered by environmental constraints, as was typically the case during the Bronze and Iron Ages (Oleson, 1988; Brandon, 1996). (3) *Overall layout*. The layout of a port depends on navigation conditions (winds and waves) and on the types of ship that use it. The size of the ships defines the acceptable wave-induced disturbance and the possible need to build a breakwater providing protection against swell and storms. The number of ships using the port dictates the length of quays and the area of the basins required. (4) *Harbour structures*. The ships' draught defines the depth at the quayside and thus the height and structure of the quay. Locally available materials (wood, stone and mortar) and construction methods define the specific structures for a region and historical period.

In light of these determining factors, there is great variety in harbour types and how these have come to be preserved in the geological record. Four variables determine our chosen harbour typology: (1) distance from the present coastline; (2) position relative to present sea level; (3) geomorphology, and its role in influencing the choice of harbours; and finally (4) taphonomy, or how these ancient ports have come to be fossilised in the sedimentary record (Fig. 7). Seven groups can broadly be discerned (Figs. 8 and 9).

4.1. Unstable coasts

4.1.1. Submerged harbours

Freak of the greatly mediatised legend of Atlantis (Collina-Girard, 2001; Gutscher, 2005), drowned cities and harbours have long captured the public imagination (Frost, 1963; Flemming, 1971). Since 18,000 yr BP, glacio-eustatic sea-level rise of ~120 m has transgressed important coastal areas of the Mediterranean, submerging numerous Palaeolithic and Mesolithic sites (Shepard, 1964; Masters and Flemming, 1983; Kraft et al., 1983; Shackleton et al., 1984; Galili et al., 1993; Flemming, 1996, 1998; Collina-Girard, 1998; Petit-Maire and Vrielinck, 2005; Fig. 10). In the Aegean, many islands, such as Kerkira, Euboea and the northern Sporadhes, were connected with the mainland and most of the Cycladic islands were joined together to form a Cycladic semi-peninsula (van Andel and Shackleton, 1982). In southern France, the partially drowned

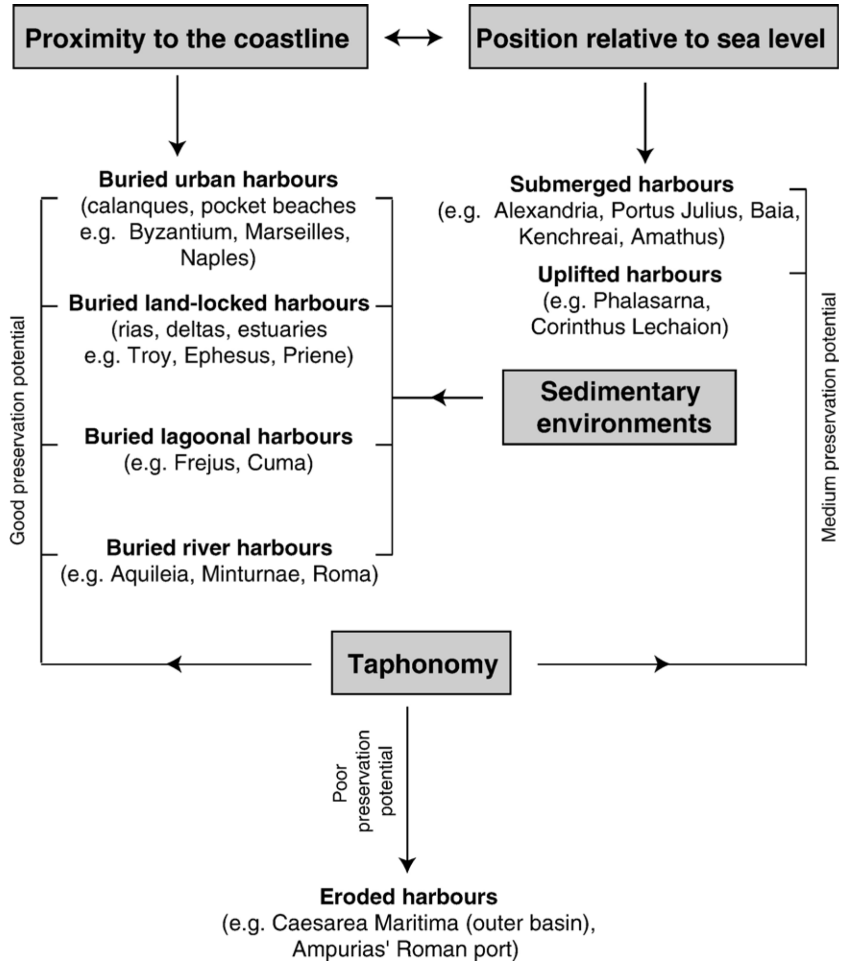

Fig. 7. Ancient harbour classification based on four variables (1) proximity to the coastline; (2) position relative to sea level; (3) sedimentary environments; and (4) taphonomy.

Unstable coasts		Stable coasts				
Submerged harbours	Uplifted harbours	Buried urban harbours	Buried landlocked harbours	Buried fluvial harbours	Buried lagoonal harbours	Eroded harbours
- Alexandria - Baia - Eastern Canopus - Egnazia - Helike - Herakleion - Megisti - Miseno - Pozzuoli	- Aigeira - Kenchreai - Lechaion - Phalasarna - Seleucia Pierea	- Acre - Beirut - Byzantium/Istanbul - Cartagena - Kition Bamboula - Marseilles - Naples - Olbia - Piraeus - Sidon - Toulon - Tyre	- Enkomi - Ephesus - Kalopsidha - Leptis Magna - Miletos - Malta - Priene - Troy - Salamina	- Antioch - Aquileia - Gaza - Minturnae - Narbonne - Naucratis - Ostia (Sardinia) - Pelusium - Rome - Sevilla - Schedia - Thebes - Valencia - Zaragoza	- Coppa Nevigata - Cuma - Frejus - Lattara	- Ampurias - Caesarea (outer harbour)

Fig. 8. Non-exhaustive list of harbours classed into seven groups.

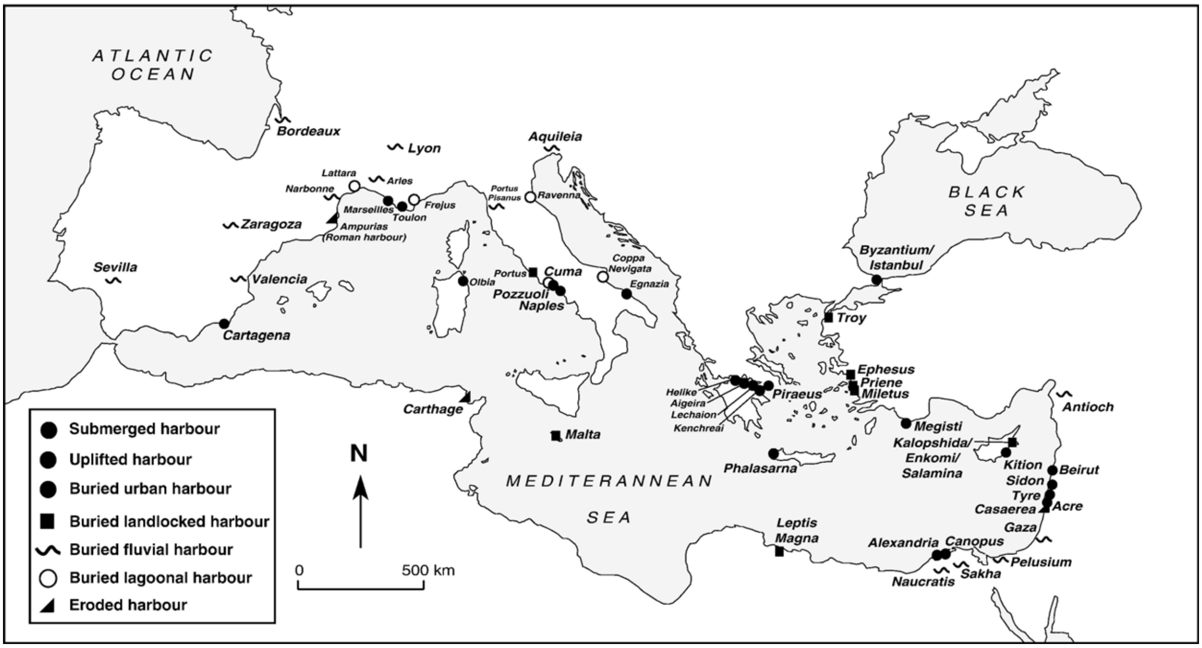

Fig. 9. Non-exhaustive map of the Mediterranean's ancient habours, grouped according to how they have been preserved in the geological record.

Palaeolithic cave of Cosquer is one of the best Mediterranean examples of human occupation of the continental margin and post-glacial sea-level rise (Fig. 11). Painted horses dated ~18,000 BP have been partially eroded at current sea level testifying the absence of any sea-level oscillation higher than present. Transgression of the continental platform gradually displaced coastal populations landwards until, around 6000 BP, broad sea-level stability meant that human societies started to sedentarise along present coastlines (van Andel, 1989).

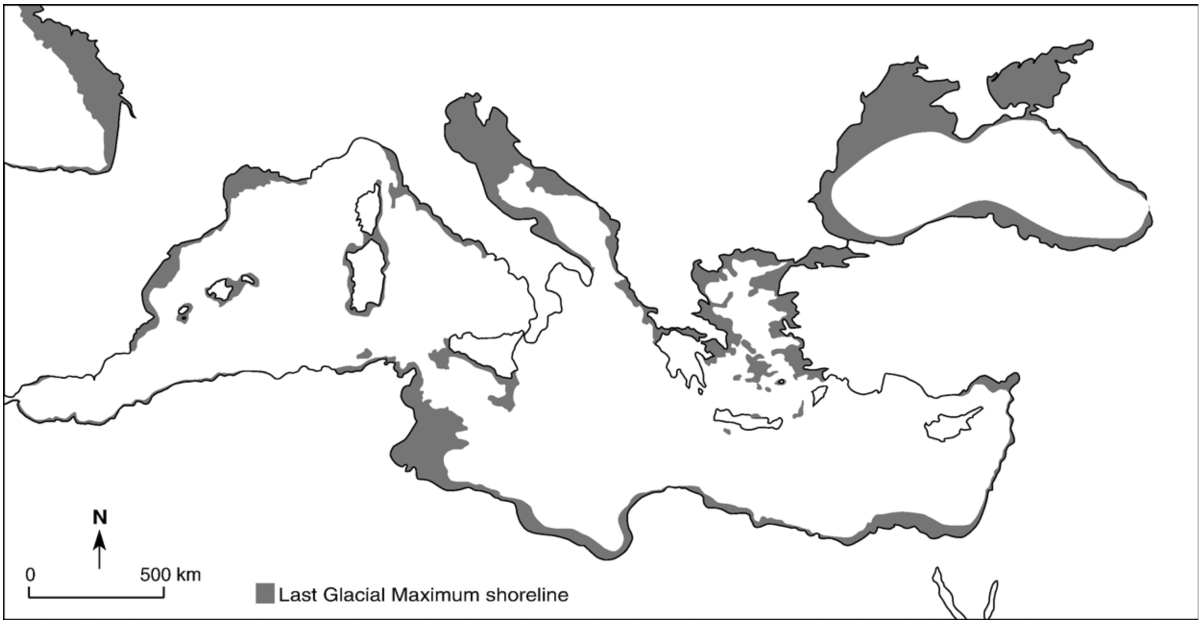

Fig. 10. Last Glacial Maximum shoreline and transgression of the Mediterranean's coastal margin since 18,000 BP, when sea level was around 120 m below present (after Bracco, 2005). The drowning of a great number of Palaeolithic sites means that our understanding of coastal prehistoric human groups in the Mediterranean is relatively poor.

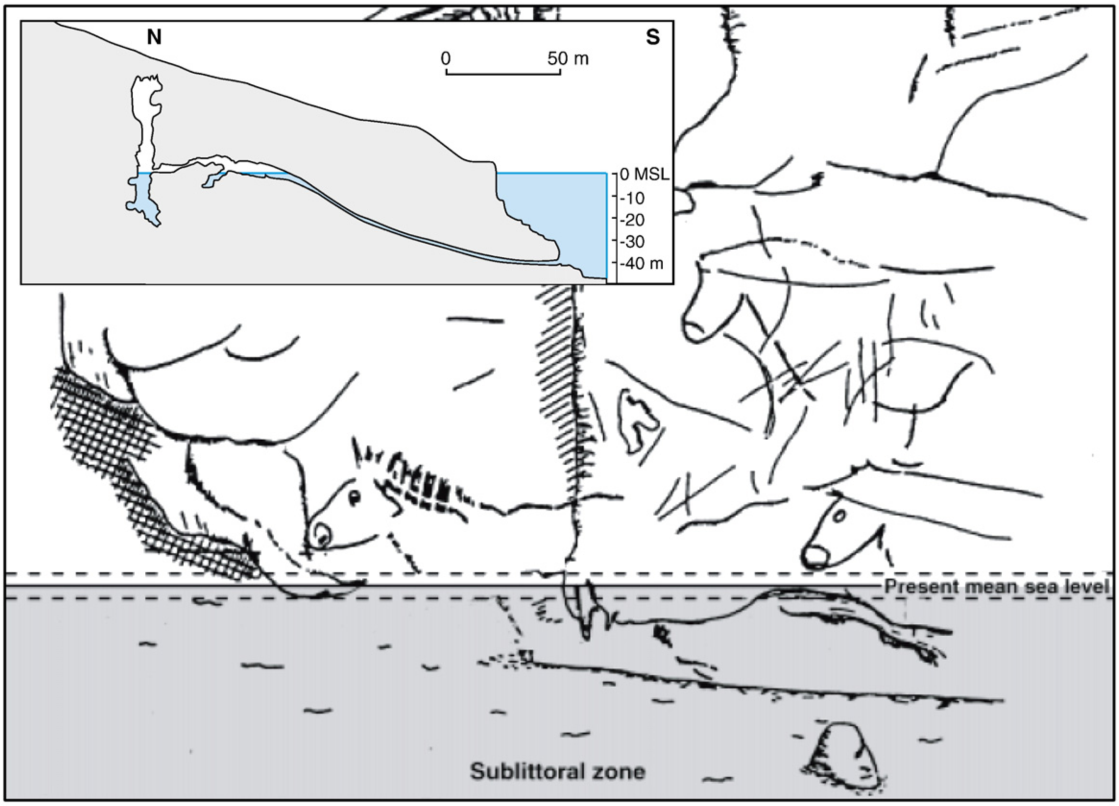

Fig. 11. Cosquer is a French Palaeolithic painted cave (27,000–18,500 BP). The partially drowned cavern has formed in the Urgonian limestones of Cap Morgiou, near Marseilles. The entrance, 37 m below sea level, was submerged around 7000 BP (Sartoretto et al., 1995). Archaeological studies indicate that the cave was used as a refuge around 27,000 and 18,000 BP. The partially eroded cave paintings demonstrate there has been no sea level higher than present during the Holocene (adapted from Vouvet et al., 1996).

Since this time, coastal site and port submersion can be linked to two different geological factors: (1) tectonic mobility (e.g. subsidence in eastern Crete); and/or (2) sediment failure (e.g. Alexandria, Menouthis and Herakleon at the margin of the Nile delta).

At Alexandria, public interest was roused in the mid-1990s with the spectacular images of J.-Y. Empereur's team surfacing statuary and megalithic blocks, many of them attributed to Pharos' celebrated lighthouse (Empereur and Grimal, 1997; Empereur, 1998; Hairy, 2006). Concomitant underwater research by Goddio et al. (1998) and Goddio and Bernand (2004) brought to light drowned harbourworks in the city's eastern harbour, ~5 m below present MSL and covered by a thin layer of sand (Fig. 12). The coastal instability of the Alexandria sector has been attributed to seismic movements (Guidoboni et al., 1994), destructive tsunami waves (Soloviev et al., 2000; Goiran, 2001) and Nile delta sediment loading (Stanley et al., 2001; Stanley and Bernasconi, 2006). Following an opulent Graeco-Roman apogee, recent research suggests that the demise of Alexandria's ports was centred on the eighth to ninth centuries AD, during which time tsunami impacts and dramatic sea-level rise severely damaged harbour infrastructure (Goiran et al., 2005).

To the east of Alexandria, in the Abu Qir Bay area, Stanley et al. (2001, 2004a) have elucidated the submergence of two ancient Greek cities, Herakleion and Eastern Canopus, after the eighth century AD (Stanley et al., 2004a,b). The two seaport cities, which lay at river mouths on the delta coast, have been submerged and drowned by ~8 m during the past 2500 yr. The team attributes this subsidence to (1) 4–5 m of RSL rise (eustasy and sediment compaction), and (2) 3–4 m of episodic land failure by sediment loading.

The southwestern coast of the Gulf of Corinth, Greece, lies in a region of rapid tectonic uplift and extension. In 373 BC, the Greek city of Helike and its harbour, built on a Gilbert-type fan delta, were destroyed by an earthquake and submerged (Kiskyras, 1988; Soter and Katsonopoulou,

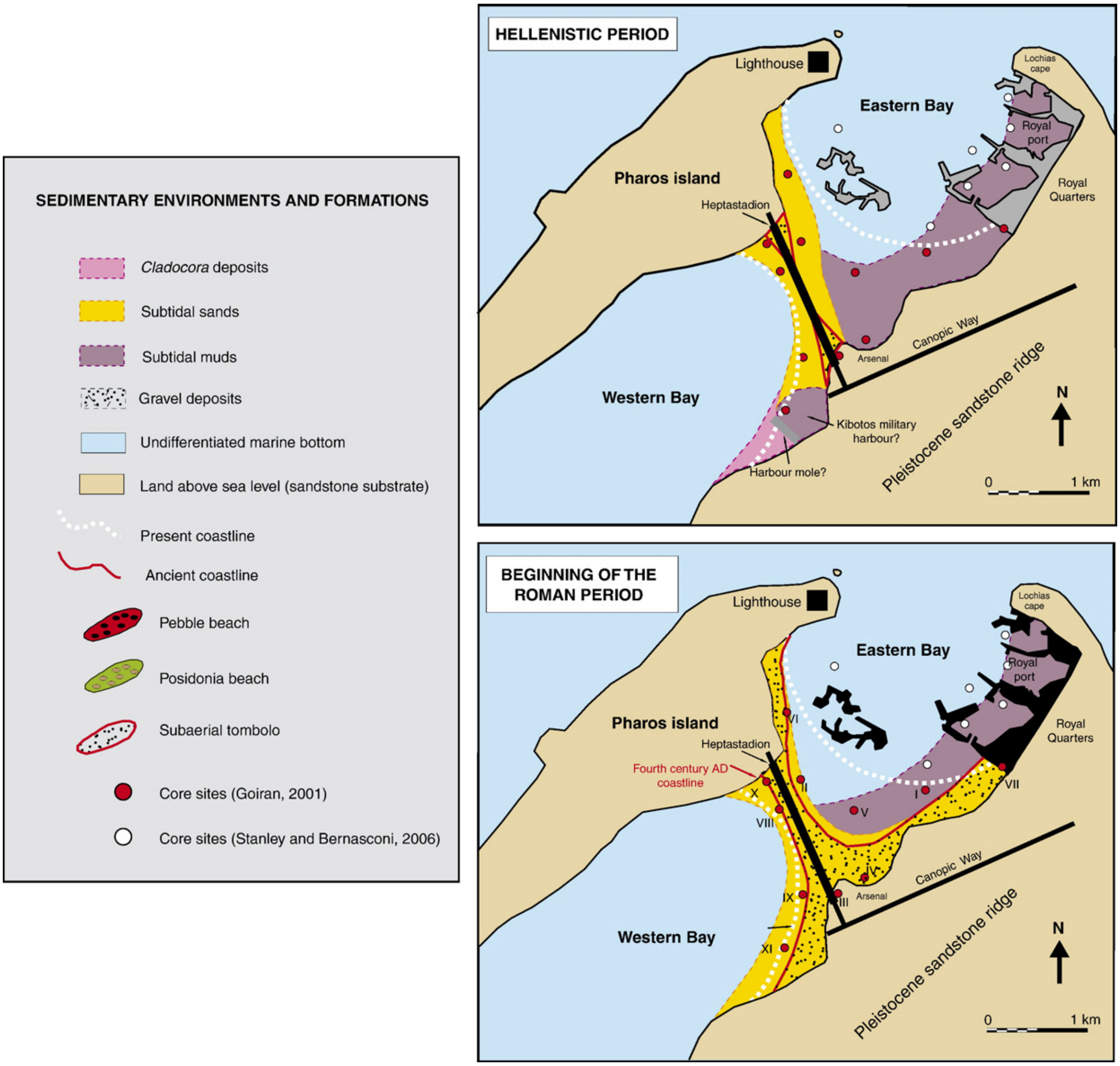

Fig. 12. Geomorphological reconstruction of Alexandria's ancient harbour by Goiran et al. (2005). The Heptastadion, constructed by Alexander the Great in 331 BC, separated Alexandria's bay into two separate coves. The Eastern Bay shielded a number of discrete port basins. The Royal port is presently drowned ~5 m below present sea level. Goiran (2001) has reconstructed the Holocene history of Alexandria's ancient harbours using coastal stratigraphy and numerous geoscience tools. Corings by Stanley and Bernasconi (2006) from the centre of the Eastern Bay show no diagnostic harbour sediments, suggesting that this area lay outside the main artificial basins.

1998). Using bore-hole datings, Soter (1998) estimates that Helike delta subsided by at least 3 m during the earthquake. The opposition between gradual regional uplift (the Gulf of Corinth rift) and local co-seismic subsidence apparently resulted in a relatively small absolute displacement of the delta during the Holocene.

The Phlaegrean Fields volcanic complex in southern Italy presents a very different crustal context. The ancient ports of Miseno, Baia and Portus Julius (Pozzuoli) are presently drowned ~10 m below mean sea level (Dubois, 1907; Gianfrotta, 1996; Scognamiglio, 1997; Fig. 13). These sites are located inside a caldera and are good examples of shoreline mobility attributed to volcanism and faulting. Recently, scholars have reconstructed a complex history of post-Roman relative sea-level changes evidencing three metric scale crustal oscillations at both Pozzuoli (Morhange et al., 2006a) and Miseno (Cinque et al., 1991) between the fifth and fifteenth centuries AD. Research suggests that inflation–deflation cycles are linked to a complex interplay of deep magma inputs, fluid exsolution and degassing (Todesco et al., 2004) that have profoundly influenced the position of the coastal archaeology. The Roman harbour of Egnazia is another good example of a drowned seaport on the south-eastern coast of Italy. During the past 2600 yr a RSL rise of 6 m has been measured using the archaeology, although the exact mechanisms behind this subsidence remain unclear (Auriemma, 2004).

On Castellorizo island, Greece, the ancient city and harbour remains of Megisti have been drowned −2.5 to −3 m below present MSL. Pirazzoli (1987a) has linked this to a gradual 1.5 to 2.0 mm/yr subsidence of the Lycian coast since antiquity. This trend continues today as attest recently abandoned houses on the fringe of the Mandraki basin.

4.1.2. Uplifted sites

By contrast, uplifted harbours resulting from crustal movements are much rarer. The best geoarchaeological evidence for this harbour type derives from the Hellenic arc, an area long affected by the complex tectonic interplay of the African and Anatolian plates (Stiros, 2005).

In western Crete, Pirazzoli et al. (1992) have ascribed a 9 m uplift of Phalasarna harbour, founded in the fourth century BC, to high seismic activity in the eastern Mediterranean between the fourth to sixth centuries AD (Stiros, 2001). Sometimes referred to as the Early Byzantine Tectonic Paroxysm (Pirazzoli, 1986, Pirazzoli et al., 1996), this episode is concurrent with a phase of Hellenic arc plate adjustment. Synchronous uplift (1–2 m) has been observed in Turkey (the uplifted harbour of Seleucia Pierea, Pirazzoli et al., 1991), Syria (Sanlaville et al., 1997) and sectors of the Lebanese coastline (Pirazzoli, 2005; Morhange et al., 2006b). Phalasarna's ancient harbour sediment archive is of particular interest for the geosciences as it has trapped and archived tsunami deposits inside the basin (Dominey-Howes et al., 1998).

The Gulf of Corinth is a deep inlet of the Ionian Sea separating the Peloponnese from western mainland Greece. It is one of the most tectonically active and rapidly extending regions in the world (6–15 mm/yr), and surface features (uplifted shorelines, reversal of drainage patterns, earthquake-induced landslides) and archaeology are clearly associated with seismic activity (Papadopoulos et al., 2000; Koukouvelas et al., 2001;

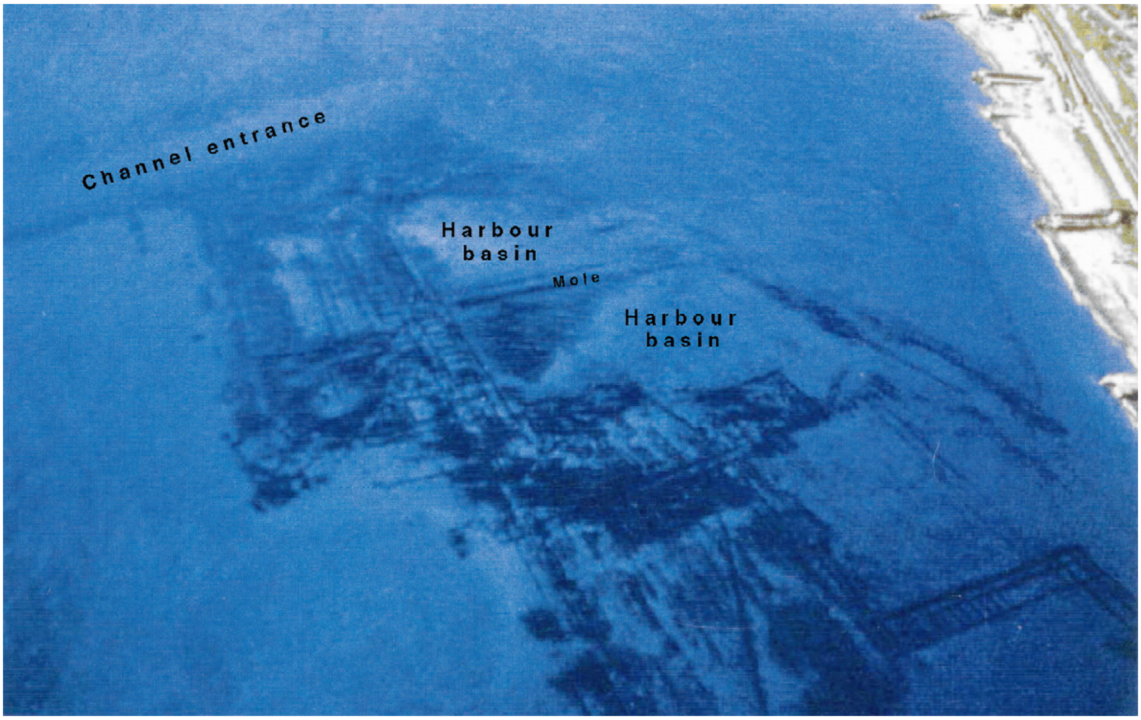

Fig. 13. Pozzuoli's drowned harbour remains presently ~10 m below mean sea level. The site lies inside a caldera, where shoreline mobility is attributed to volcanism and faulting. Recently, scholars have reconstructed a complex history of post-Roman relative sea-level changes evidencing three metric crustal oscillations at both Pozzuoli (Morhange et al., 2006a) and Miseno (Cinque et al., 1991) between the fifth and fifteenth centuries AD. Research suggests that inflation–deflation cycles are linked to a complex interplay of deep magma inputs, fluid exsolution and degassing (photograph: CNRS, CJB, Naples).

Kokkalas and Koukouvelas, 2005). Several ancient harbours are known from inside this deep inlet, including Helike (submerged, see above), Aigeira and Lechaion (both uplifted).

At Aigeira, an artificial Roman harbour was built ~100 AD to 250 AD (Papageorgiou et al., 1993). The southern Gulf of Corinth is void of any natural roadstead due to shoreline regularisation by coastal progradation. Stiros (1998, 2005) has described archaeological sea-level indicators attesting to an uplift of ~4 m. Biological and radiometric evidence indicate that this relative sea-level drop was co-seismic in origin and associated with an earthquake around 250 AD.

Interest in Lechaion's harbour organisation and environments, the western seaport of ancient Corinth, dates back to the work of Paris (1915). The harbour was particularly active during Archaic times, a period of Corinthian expansion to the Ionian Sea and southern Italy. Crustal uplift led to the rapid silting up of the harbour basins (Stiros et al., 1996). Bioconstructions (upper limit of *Balanus* sp. or *Lithophaga lithophaga*) on quays at ~1 m above present MSL have been dated to 2500 BP (400–100 cal. BC).

The archaeological data from subsided and uplifted coasts contrast with stable tectonic contexts where harbour infrastructure lie just a few centimetres below present sea level (Pirazzoli, 1976; Morhange et al., 2001). These are the result of relatively minor millennial-scale sea-level rise in response to regional glacio-hydroisostasy. A good example of this derives from the Tyrrhenian coast of Italy, where Roman fish ponds lie ~50 cm below present mean sea level (Schmiedt, 1972; Leoni and Dai Pra, 1997; Antonioli and Leoni, 1998). Lambeck et al. (2004) revised these measured data and corrected them on the basis of modelled glacio-hydroisostatic adjusment; they obtain 135±7 cm of sea level change since the Roman period. Compared to direct measurements made on fossil bio-indicators, these modelled adjustments appear to over-estimate RSL changes during the past 2000 yr. For example, well-studied mid-littoral fossil algal ridges in the south of France fit tightly with the 50 cm sea-level rise since Roman times (Pirazzoli, 1976; Laborel et al., 1994; Vella and Provansal, 2000).

4.2. Buried harbours

After 6000 BP, slowdown in sea-level rise allied with high sediment supply led to accelerated coastal progradation. Over many millennia, this progradation explains the burial and loss of countless ancient harbours. Human modification of fluvial watersheds (deforestation, agriculture) from the Neolithic period onwards accelerated soil erosion of upland and lowland areas; since the beginning of the Christian era, research has identified three important detritic crises during the Augustean period (~2000 yr ago), late Antiquity and the Little Ice Age, translated geologically by pronounced periods of coastal and deltaic progradation (Provansal et al., 1995; Arnaud-Fassetta and Provansal, 1999; Vella et al., 2005). Four different types of buried harbours can be identified.

4.2.1. Buried urban harbours

Beirut, Byzantium/Istanbul, Cartagena (García, 1998; Del Carmen Berrocal Caparrós, 1998), Kition Bamboula, Marseilles, Naples, Olbia, Piraeus, and Toulon are examples of buried urban harbours *par excellence*. Whilst the cities' port areas are still fully functional today, the heart of the ancient hubs lay beneath the modern city centres. Rapid rates of sediment accumulation of 10–20 mm/yr during the Roman and late Roman periods have led to the silting-up of the basin fringes, which have been gradually dislocated seawards. Two processes are important in explaining these coastal deformations: (1) high sediment supply linked to fluvial inputs, erosion of clay buildings, urban runoff and use of the basin as a waste deposit (cultural inputs); and (2) human activity has also directly accentuated coastal progradation with a regularisation of coasts since the Bronze Age (Figs. 14–16).

On the Phoenician coast, good examples of buried harbours include Sidon and Tyre (Marriner et al., 2005; Marriner et al., 2006a,b). Although the present basins are still in use today, some 5000 yr after their foundations, their surface areas have been reduced by almost half. Such a geomorphological evolution offers a great multiplicity of research possibilities in areas where, paradoxically, very little is known about the maritime history.

Although not seaports *sensu stricto*, the artificial spits (tombolos) of Tyre and Alexandria are unique geological examples of anthropogenically forced sedimentation (Fig. 17). These rare coastal features are the heritage of a long history of natural morphodynamic forcing and pluri-millennial human impacts. In 332 BC, following a long and protracted seven-month siege of Tyre, Alexander the Great's engineers cleverly exploited the city's atypical geological context to build a causeway and seize the island fortress; this edifice served as a prototype for Alexandria's Heptastadium built a few months later. Both causeways profoundly and pervasively deformed the natural coastline and entrained rapid progradation of the spits (Nir, 1996; Goiran et al., 2005). These two examples underline the impact of human societies in accentuating

Fig. 14. Greek and Roman port remains were discovered in the Bourse area of Marseilles during the 1960s. These vestiges, in the heart of the modern city, have since been converted into museum gardens. The preserved port buildings date from the end of the first century AD, although these were preceded by earlier constructions in an area known as "the Port's Horn". Prone to silting, the area was abandoned from late antiquity onwards. The modern *Vieux Port* is clearly discerned in the background and attests to progradation of the coastline landlocking the ancient seaport (photograph: CNRS, CCJ, MMSH, Aix-en-Provence).

coastal deformation since the Bronze Age. Other examples of anthropogenically forced tombolos include Clazomenae (Ionia), Apollonia Pontica (Sozopol, Bulgaria) and possibly Orbetello (Italy).

The amount of sediment transported by river systems is important in dictating the scale of coastal progradation. At Marseilles, Toulon or Kition-Bamboula, coastal deformation has been relatively minor, in the order of a few hundred

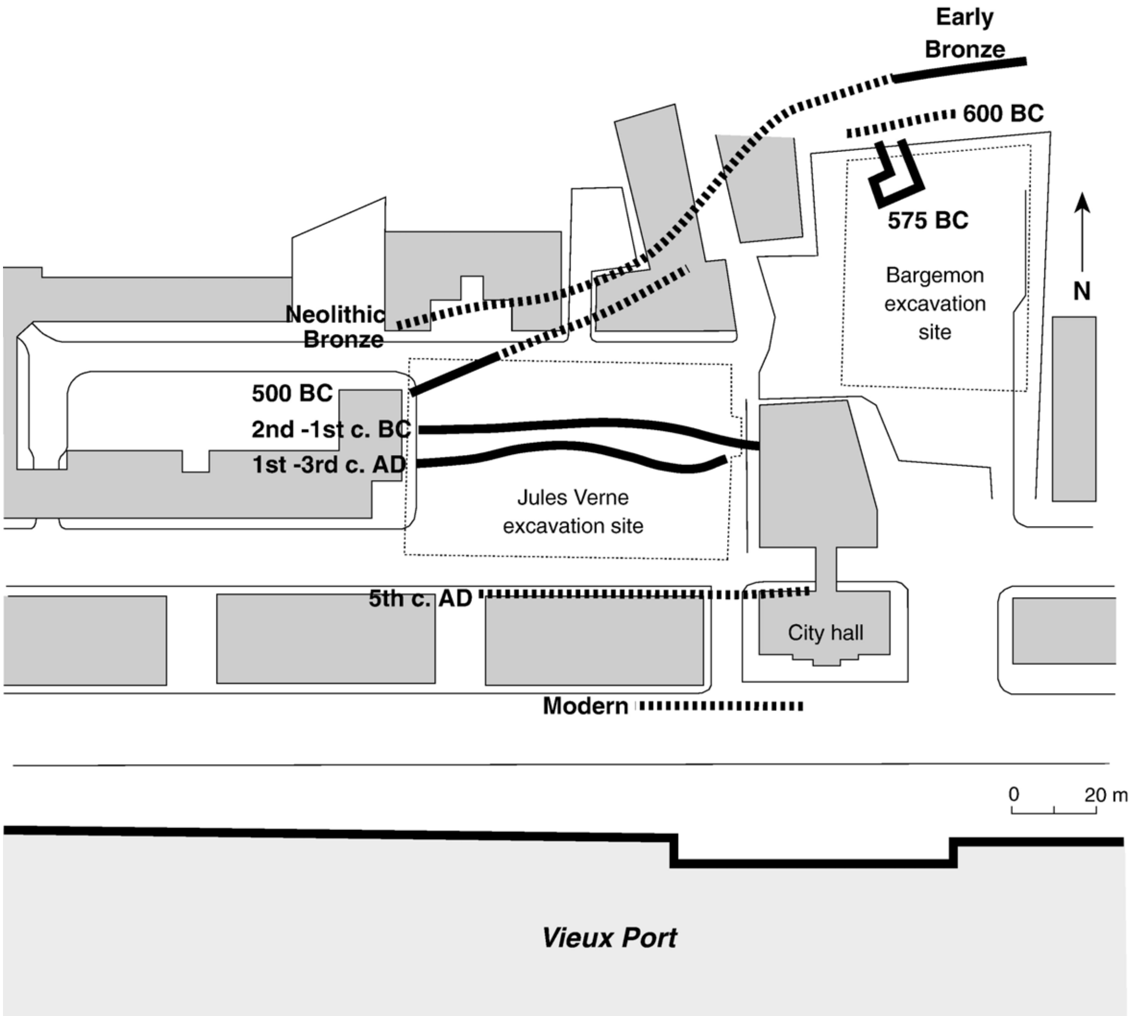

Fig. 15. Progradation of Marseilles' northern harbour coastline since the Neolithic. The coastlines were studied in section during archaeological excavations and each historic coastline was defined on the basis of its archaeological remains (quays, jetties). Note the progressive regularisation of the coastline. After Morhange et al. (2003).

metres. In the Bosporus strait, modest sedimentary inputs have resulted in the long-term viability of Istanbul (Byzantium/Constantinople), an important crossroads between Europe and Asia (Dark, 2004). Modest sediment inputs means that many partially silted up ancient seaports have remained important trade centres since their foundations during antiquity. This harbour type is contrasted by our next group, buried landlocked harbours.

4.2.2. Buried landlocked harbours

The buried landlocked harbour type is characterised by kilometric coastal progradation, as epitomised for example by Ionia's ancient ports (Troy, Miletus, Priene or Ephesus; Brückner, 1997). Such rapid deltaic progradation is linked to two factors (1) broad sea-level stabilisation around present level since 6000 BP (Fig. 18) and (2) the unique morphology of these palaeo-rias, which correspond to narrow, transgressed grabens with limited accommodation space (Kayan, 1996, 1999). For example, the delta front of the Menderes ria has prograded by ~60 km since the maximum marine ingression at 7000 BP (Schröder and Bochum, 1996; Müllenhoff et al., 2004; Fig. 19).

The best studied examples include Troy (Kraft et al., 2003), where the harbour areas were landlocked by 2000 BP, and also Ephesus, Priene and Miletos (Brückner, 1997). Brückner's research at Ephesus provides a good illustration of harbour displacement, or 'race to the sea', linked to rapid shoreline progradation. The ancient city's first artificial harbour, near Artemision, silted up as early as the sixth century BC, during a period of rapid delta growth. A second harbour

Fig. 16. Cartagena's buried urban seaport (from García, 1998). Cartagena was founded ∼230 BC by Carthaginian general Hasdrubal. Coastal stratigraphy and archaeology indicate that the heart of the ancient seaport is presently located beneath the city centre.

was subsequently built to the west in the fifth century BC, before relocation of the landlocked city at the end of the third century BC.

In Cyprus, Devillers (2005) has elucidated the marine flooding of the Gialias ria around 8000 BP and its ensuing deltaic progradation after ∼6000 BP. Using

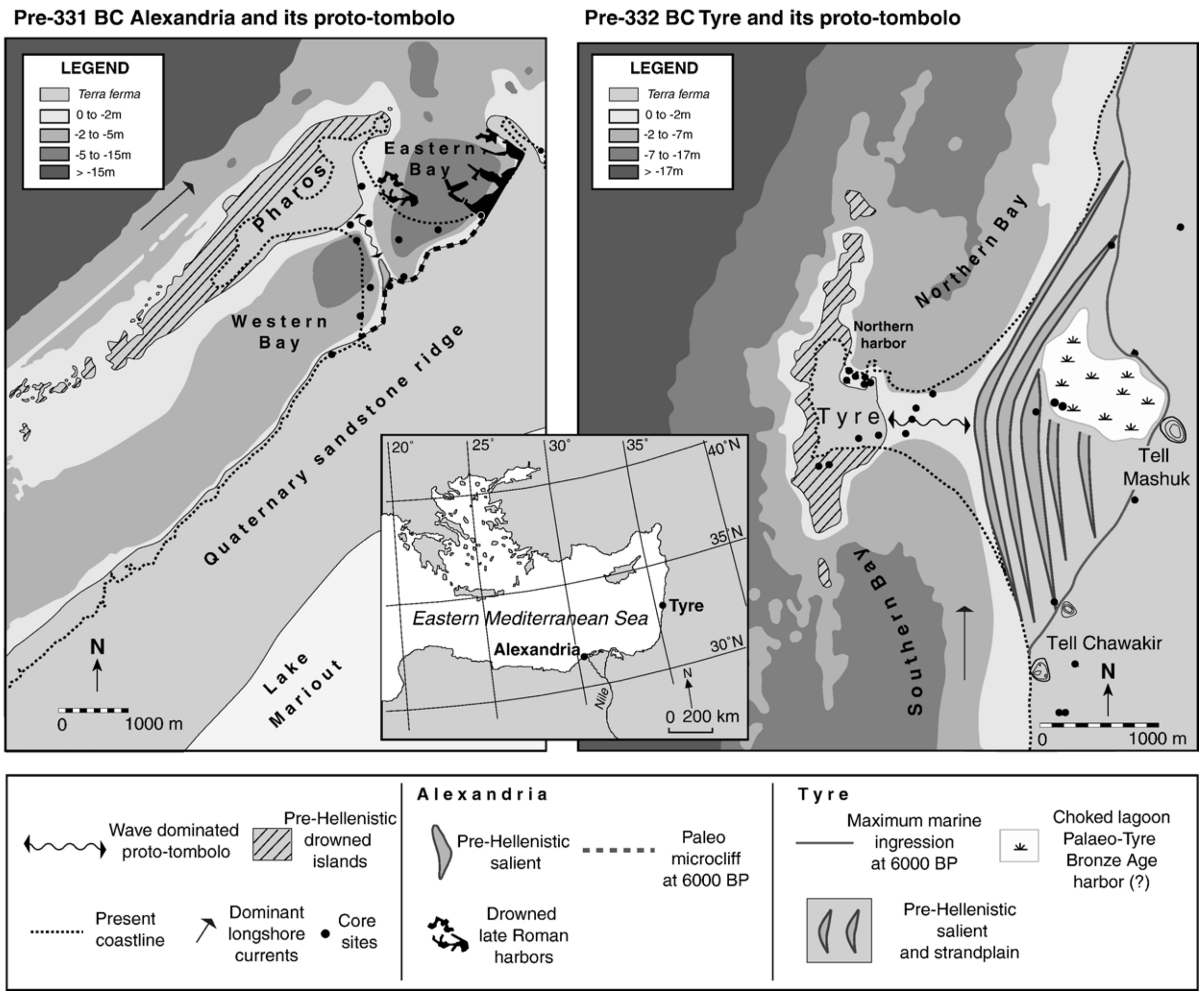

Fig. 17. Morphodynamic evolution of Alexandria and Tyre's isthmuses since antiquity. Research at both sites has elucidated a proto-tombolo phase within 1–2 m of sea level by Hellensitic times (Goiran, Marriner and Morhange, unpublished data). This proto-tombolo phase greatly facilitated the construction of the two artificial causeways.

coastal stratigraphy, geomorphology and teledetection, he links a suite of coastal environments (alluvial plain, lagoons, coastal ridges) with an easterly migration of the coastline. Human societies constantly adapted to this changing coastal environment as illustrated by the geographical shift of four ancient harbours: Early/Middle Bronze Age Kalopsidha, Middle/Late Bronze Age Enkomi, Graeco-Roman Salamina and Medieval Famagusta.

Many of the southern Levant's Bronze Age proto-harbours have been investigated by Raban (1987, 1988) and Marcus (2002). Raban elucidated a series of natural estuarine harbours along the presently rectilinear coast of Gaza and Israel. This natural but short-lived protection was eventually compromised by coastal progradation and barrier accretion on the wave-dominated coast to the east of the Nile delta (Raban, 1990). After 2000 BC, many of the coast's Bronze Age tells were no longer viable, eventually abandoned due to silting up of their transport hubs and isolation from maritime trade routes.

The landlocked harbours of the Maltese islands are an example of partially infilled rias (Gambin, 2004). Coastal progradation explains the landlocking and dislocation of many anchorage havens.

Around 6000 BP, the maximum marine ingression created an indented coastal morphology throughout much of the Mediterranean. Over the next few millennia, these indented coastlines were gradually infilled by fluvial sediments reworked by longdrift currents, culminating in a regularised coastal morphology. This process was particularly intense at the margin

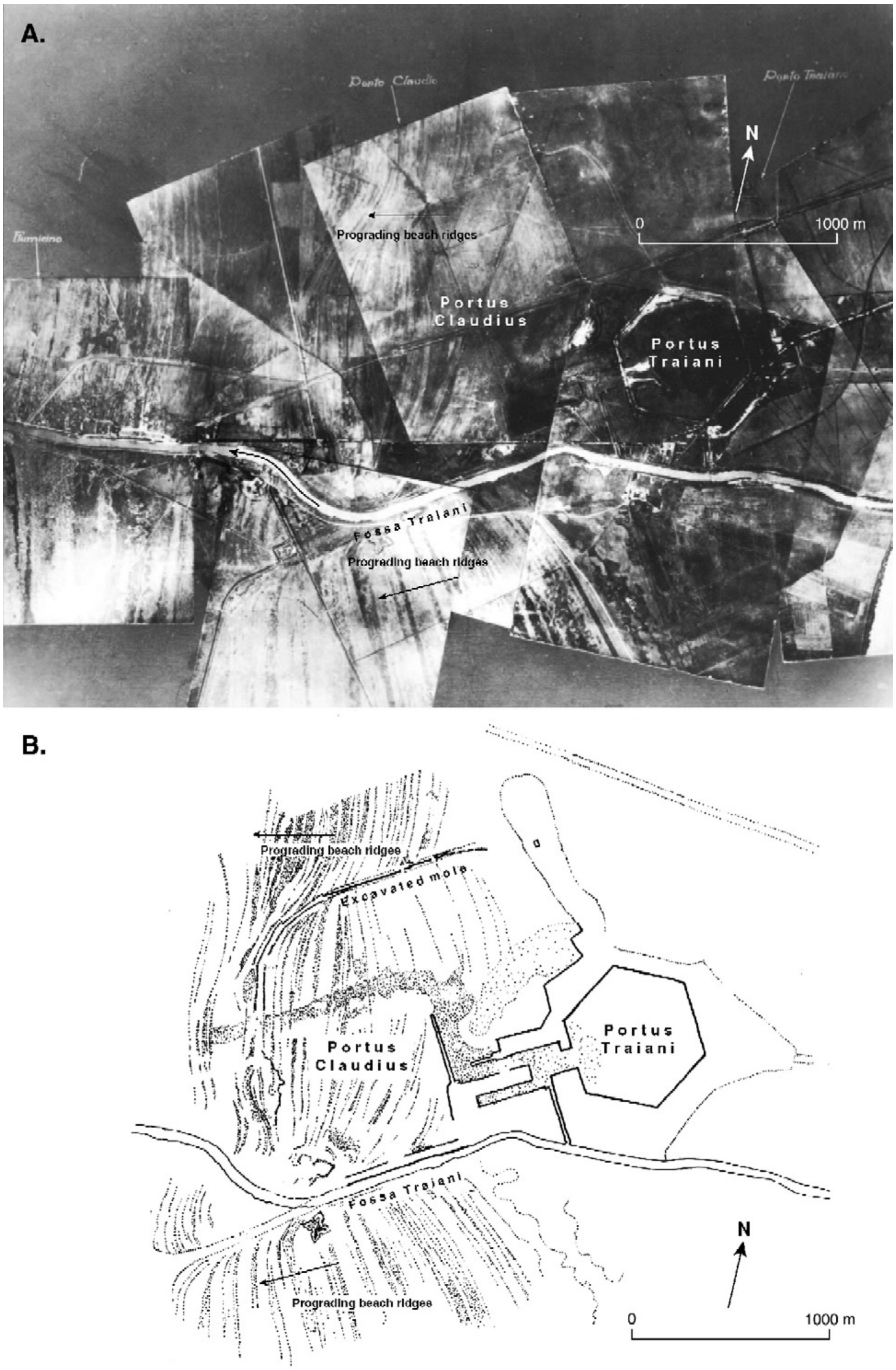

Fig. 18. A. Early twentieth century photographic mosaic of Portus. B. Geoarchaeological interpretation of the site (after Giuliani, 1996). Portus Claudius has completely silted up since antiquity, whilst the artificial Portus Traiani today comprises a freshwater lake. Progradation of the beach ridges is clearly evidenced by the aerial photography.

of major deltas. The coast of Sinai and Palestine, for example, was indented during the Bronze Age before being transformed into a rectilinear shoreline in recent millennia (Stanley, 2002; Morhange et al., 2005b). The attractive proto-historic coves served as anchorage havens for early coastal societies but were rapidly

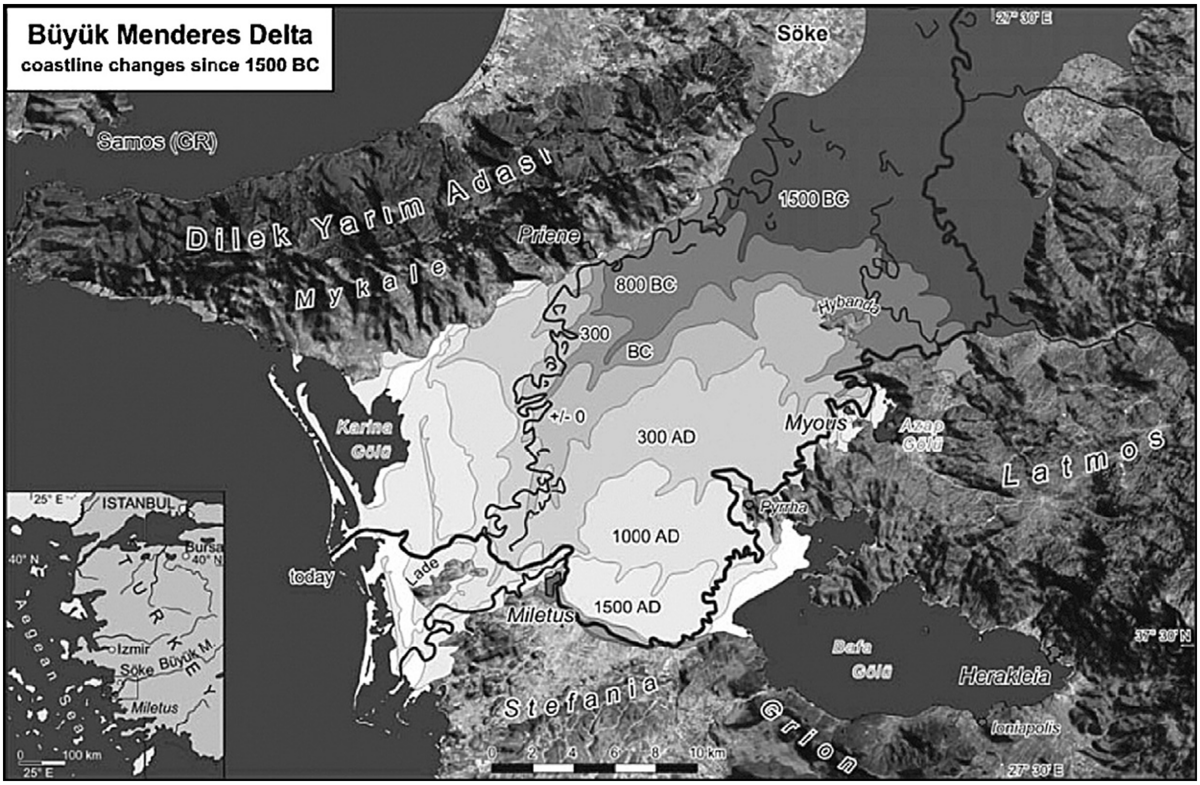

Fig. 19. Coastal progradation of the Menderes delta and the landlocking of Priene, Miletus and Heracleia's ancient seaports (from Müllenhoff et al., 2004).

transformed into base-level depocentres and eventually abandoned.

Along the Black Sea shore, peculiar ancient rias known as limans have not progaded. For example in southern Bulgaria, the Roman harbour of Deultum lies inside such a liman. The ria has been transformed into an estuary presently disconnected from the open sea by coastal spits. In eastern Crimea (Ukraine), the harbour of the Greek colony Nymphaion is probably located inside a liman (Ménanteau and Geffray, 2003).

4.2.3. Buried fluvial harbours

River harbours are not subject to the same geomorphological and sedimentary processes, and therefore diagnostic harbour sediment signatures are different. Geoarchaeological study of such contexts has been relatively limited until now, but 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).

The Egyptians and Mesopotamians were the earliest western civilizations to engage in fluvial transportation and primeval Bronze Age harbourworks are known from the banks of the Nile at Memphis and Giza (Fabre, 2004/2005). These inevitably served as precursors for coastal anchorages, which were much more demanding environments stretching engineering knowledge far beyond primitive river infrastructure (Wachsmann, 1998; Fabre, 2004/2005). Unfortunately, high sediment supply and rapid changes in fluvial geomorphology mean that few conspicuous remains of these early fluvial harbour centres have survived to present. In Mesopotamia, docking basins were excavated and enclosed within the city walls of late third millennium Ur. A small dock dated 700 BC, built with mud-brick and bitumen is also known from alongside a bank of the Euphrates at Assyrian Til-Barsib (Blackman, 1982a,b). In Egypt, the works were many and varied. In the third millennium, for instance, canals were excavated from the Nile to the valley temples of the Giza pyramids so that building materials could be transported. Quays were also commonly established along the Nile, for instance at fourteenth century BC Amarna, boats have been depicted parallel to shoreside quays equipped with bollards. A large basin has also been reported from near fourteenth century Thebes (Blackman, 1982a,b).

Despite extensive excavations at numerous sites on the Nile delta (e.g. Tell El-Daba, Tell el-Fara'in; Shaw,

2000) the exact location of many of the river ports is not known. The port city of Pelusium, located on the delta's northeast margin near the mouth of the former Pelusiac branch, was active during the Late Dynastic Kingdom and is a good example of settlement demise forced by geological changes and sedimentary inputs (Goodfriend and Stanley, 1999). At present, Pelusium is partially buried beneath tracts of deltaic sediments, and lies 3 km south of the present coast, separated from the sea by extensive beach ridges and salt flats. This site was suddenly cut-off during the ninth century AD from the Nile Pelusiac branch and the sea as a result of floods. These floods induced rapid blockage of the Pelusiac branch and the avulsion of a new branch west of Port Said, most likely the Damietta branch (Stanley, 2005).

Stanley and his team have also worked extensively on the Canopic branch of the Nile delta coast (Stanley and Jorstad, 2006). They have combined geological and archaeological data to show that the Ptolemaic Roman city of Schedia once lay directly on the Canopic channel which was active between the third to second centuries BC until the fifth century AD. Abandonment of the site occurred when Nile waters were displaced to the east via the Bolbitic and later Rosetta branches.

Excavations and geological surveys at Greek Naucratis have revealed a series of active and abandoned channels during antiquity. These channels served as transport pathways for the ancient site, however the site's fluvial port has never been precisely located (Villas, 1996).

Our knowledge of later periods is much better (Berlanga and Pérez Ballester, 2003). The durability of Roman construction works means that well-known buried river harbours are known from Aquileia (Arnaud-Fassetta et al., 2003; Rosada, 2003), Rome (Casson, 1965; Segarra Lagunes, 2004), Portus Ostia (Mannucci, 1996; Keay et al., 2005a), Minturnae (Ruegg, 1988), London (Milne, 1982, 1985; Milne and Bateman, 1983), Bordeaux (Gé et al., 2005), Lyon, Sevilla (Ordóñez Agulla, 2003), Roman and Islamic Valencia (Carmona and Ruiz, 2003) and Zaragoza (Aguarod Otal and Erice Lacabe, 2003). Other studies have yielded less convincing geoarchaeological results as for example at ancient Narbonne (Ambert, 1995).

The main problem of this harbour type is bank instability due to flood erosion and sedimentary accumulation. Two geological processes are important in explaining the archaeology of fluvial ports: (1) *Canalisation and funnelling of the river bed.* In London, for example, Milne (1985) describes a 100 m shift in the port's waterfront between AD 100 and today (Fig. 20). Under a mesotidal fluvial regime, this funnelling of the waterbody has led to a positive increase in tidal amplitude. (2) *The vertical accretion of river banks by flooding.* At Bordeaux, the staircasing of numerous quays and platforms has been described at two sites in the Garonne estuary (Gé et al., 2005). Rapid sediment accumulation during palaeoflood events is indicated by fine-grained organic lithofacies intercalated between the stepped platforms. There is significant scope to translate the waterfront archaeology techniques developed in northern Europe to the rich historical context of the Mediterranean.

4.2.4. Buried lagoonal harbours

Since 6000 BP, spit accretion on clastic coasts has disconnected a number of palaeo-bays from the open sea. The resulting low-energy depocentres formed lagoons that have gradually infilled since this time to form rich geological archives. Lagoons offer natural protection and their use as anchorage havens has been widespread since early antiquity. At Coppa Nevigata, for example, a palaeo-lagoon connected to the sea by several entrances was deep enough for navigation between the third and first millennia BC (Caldara et al., 2002). Caldara et al. (2003) have gone on to draw parallels between the nature of the lagoon environment and the development modes of the settlement.

Three main geoarchaeological problems are connected with lagoonal harbour types: (1) Because these anchorages lie at or near river mouths, access to the inlet is hindered by underwater coastal bars which can render navigation treacherous (e.g. the inlet at Licola lagoon near Cuma, Italy (Stefaniuk et al., 2003) or Lattara lagoon, southern France (Garcia and Vallet, 2002)). (2) The limited draught depth of the lagoon water body: during the Bronze Age and early Iron Age shallow draught boats meant that lagoons could be widely used (Ambert and Chabal, 1992). The shallow nature of the water column meant, however, that none of the early lagoon ports evolved into large scale seaports. It was not until Roman times that technological advances facilitated artificial remodelling and overdeepening of the basins. Carthage and the basin of Claude at Ostia are the most grandiose examples of these large-scale works. At these two sites, the lagoons had to be repeatedly dredged in order to maintain a navigable water column. (3) Also during Roman times, the ancient lagoons lining the Tyrrhenian and Adriatic seas were used as important intra-lagoonal waterways.

Reconstructing harbour histories using classic bio-sedimentological techniques (see below) has not been wholly conclusive (Melis, 2000; Lespez et al., 2003; Caldara et al., 2003; Pasquinucci, 2004; Stefaniuk and

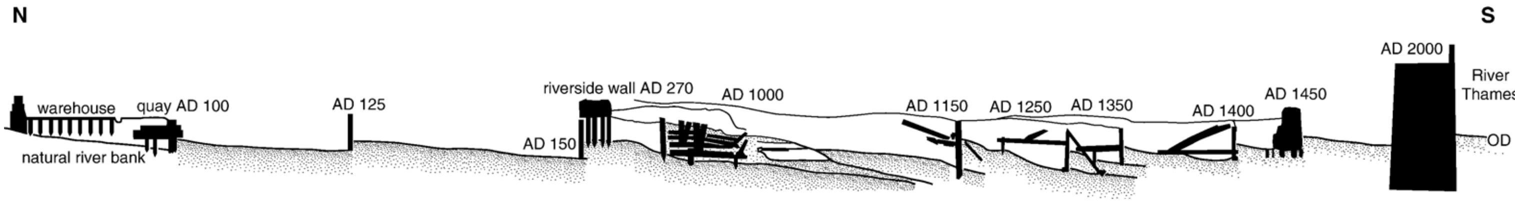

Fig. 20. London's fluvial harbour, showing a gradual shift in the river bank and quays between the Roman period and today (after Milne, 1985). Marrying archaeological and stratigraphic data facilitates an understanding of sedimentary variations on the fluvial plain linked to the cities installed on the river banks. As in coastal areas, a deformation of the river bank is observed since antiquity.

Morhange, 2005). Very little human modification of the lagoon is required and therefore precisely discerning the presence of man can be difficult on purely bio and lithostratigraphical grounds. On the contrary, geochemistry offers interesting avenues for future research.

4.2.5. Eroded harbours

Eroded harbours can result from two complementary geological processes: (1) a fall in sediment supply to the coastal zone; and/or (2) the destruction of harbourworks in areas exposed to high energy coastal processes. The best examples of eroded harbours date from the Roman period, when natural low-energy roadsteads were no longer a prerequisite for harbour location. At many high to medium energy coastal sites across the Mediterranean, the Romans constructed large enveloping moles to shelter an anchorage basin on its leeward side. Good examples of eroded ancient harbours include Carthage, Caesarea Maritima and the Roman port of Ampurias (Nieto and Raurich, 1998).

Although the location of Punic Carthage has never been lost to memory, academic speculation has persisted concerning the location, shape and number of its harbours during the Late Punic period (Little and Yorke, 1975; Hurst and Stager, 1978). Gifford et al. (1992) cross-correlated brackish-lagoon stratigraphies to reconstruct the coastline and harbour areas of Carthage. The work shows a shallow (4–5 m below MSL) artificial harbour dug down into a Quaternary aeolianite sandstone and flooded by marine waters in the third century BC. The team elucidate two interlinked basins: (1) a commercial port; and (2) a shallower, circular military harbour. Eventual erosion of the harbour is indicated by overlying anthropogenic and high energy beach facies, consistent with the hub's abandonment (Paskoff et al., 1985).

Eroded outer harbour remains at Caesarea Maritima are still clearly visible. During the first century BC, King Herod ordered the construction of a royal harbour of the size of that of Piraeus. Roman engineers employed pozzolan concrete to build free-standing moles

Fig. 21. Ampurias' Roman harbour. Exposed wave conditions coupled with avulsion of the river Fluvia to the north of the settlement have led to a fall in sediment supply and a gradual erosion of the harbour infrastructure during the past two millennia. The ancient Greek harbour had to be abandoned due to silting up of the basin (photographs: Marriner).

and create a closed offshore harbour (Raban, 1992a). Unlike Early Bronze and Iron Age harbours, which exploited natural roadsteads, Caesarea's outer harbour, also known as Sebastos, lay completely exposed to the high energy dynamics of the Levantine coast (Raban and Holum, 1996). Raban and Holum's team have described a short-lived protected outer harbour, eroded and exposed after 200 AD. Coastal erosion of the harbour remains induced Mart and Perecman (1996) into identifying a 5–8 m neotectonic collapse of the western Caesarea area. However, more recent geological research using seismic profiles has found no evidence of any faults, attesting neotectonic stability for at least the past 2500 yr (Gill, 1999). These local data are corroborated by regional sea-level data and coastal archaeology, which indicate the Israeli coast has been stable during the past 6000 yr (Sivan et al., 2001, 2004).

Ampurias on the Catalonian coast of Spain had several ancient harbour basins during antiquity. A natural cove/lagoon served as an anchorage during the Greek occupation of the site. Problems of harbour silting mean that this basin was eventually abandoned and superceded by an outer artificial basin during the Roman period. The exposed wave conditions coupled with the avulsion of the Fluvia river to the north have led to a fall in sediment supply and a gradual erosion of the harbour infrastructure during the past two millennia (Fig. 21). Very few remains of the port have survived to the present, rendering a precise reconstruction difficult. Geophysical investigations are presently underway in an attempt to solve many of these geoarchaeological problems (Nieto et al., 2005). Other examples of eroded harbours include Caulonia in Italy (Lena and Medaglia, 2002).

Unlike traditional archaeological typologies that grouped harbours on the basis of chronology and technology, this geoarchaeological classification looks to classify ports using earth science techniques. Sediment supply and RSL changes (neotectonics) are the two most important geological factors in accounting for the position of ancient harbours in relation to the present coastline. Understanding how these two processes have interacted at centennial and millennial timescales is critical to a transparent comprehension of the archaeological record, notably in coastal areas where very little such information is presently available.

5. Research methodology

A suite of research tools is available to the geoarchaeologist investigating ancient harbour sequences. These can be ordered into various field and laboratory phases. The onus of recent ancient harbour geoarchaeology has been on the application of a multi-disciplinary research approach to derive accurate palaeoenvironmental and archaeological reconstructions.

5.1. Field techniques

Broadly speaking, coastal geoarchaeologists draw their information from two areas, (1) geomorphology; and (2) the sediment archives located within this landscape complex.

5.1.1. Geomorphological surveying

In the absence of any conspicuous archaeology, an initial geomorphological prospection and mapping of the coastal landforms aids in identifying those areas of greatest archaeological significance. Geomorphological surveying can yield information on the morphology, genesis and age of key coastal landforms including dune ridges, infilled lagoons, estuaries, fluvial morphology, beach ridges and fossil cliffs. The approach is twofold and consists in (1) identifying key landscape features using a suite of cartographic, iconographic and photographic archives; and (2) verifying and detailing these interpretations in the field.

This terrestrial research can also be coupled with underwater prospections and mapping looking to better comprehend the evolution of near-shore landscapes and relative sea-level variations, using both morphological (marine notches and erosion benches) and biological indicators. For the latter, precise vertical relationships between species ecology and sea level have been shown to exist for a number of marine taxa, including *Balanus* sp., *Lithophyllum* outgrowths and boring *Lithophaga* (Laborel and Laborel-Deguen, 1994). Understanding these relative sea-level movements is not only critical in comprehending landscape evolution but also human occupation within this landscape complex (Morhange et al., 2001).

Urban contexts are particularly problematic for accurate geomorphological studies because the urban fabric hides many of the most important landscape features. In such instances, a study of the urban tissue and microtopography has been shown to be particularly useful in reconstructing coastal progradation after the Byzantine period at Acre, Alexandria, Sidon and Tyre.

Some degree of caution must however be exercised in the geomorphological approach – hence the importance of multi-disciplinary research – and the dangers of blindly extrapolating present to past geomorphology can create ambiguity and misinterpretation. The technique is also subject to a great deal of subjectivity, which can vary between researchers. For example, at Kition-Bamboula in Cyprus, Morhange et al. (2000) questioned landscape

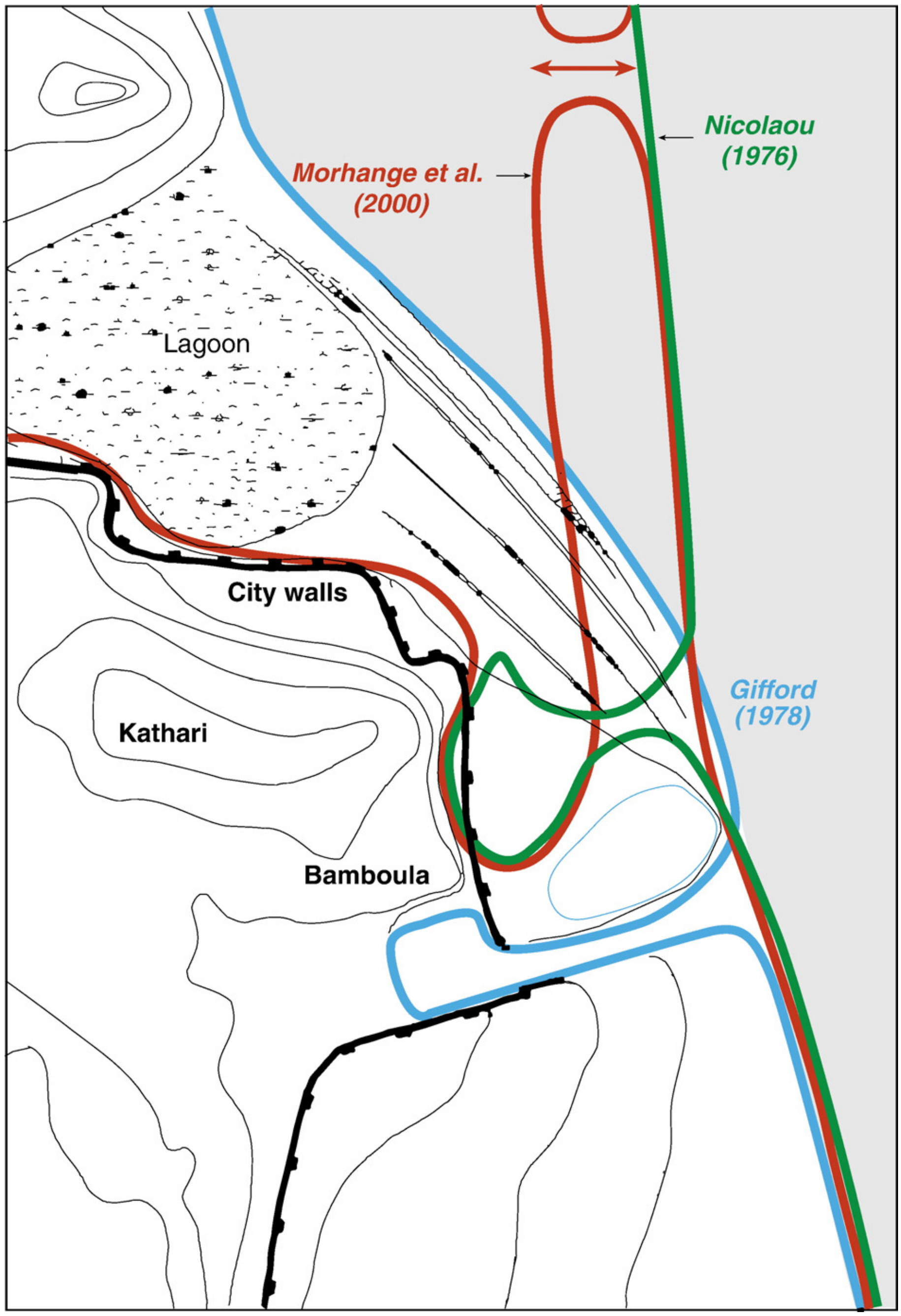

Fig. 22. Coastal reconstruction of Kition-Bamboula (Cyprus) according to various authors. Nicolaou (1976) and Gifford (1978) speculated the presence of a cothon harbour based on modern engravings showing a lagoon. Morhange et al. (2000) demonstrated that Bamboula basin was in fact a small cove within a larger lagoon. The work reinforces the idea that recent landscape patterns should not be extrapolated to antiquity.

interpretations proposed by Nicolaou (1976) and Gifford (1978). Although recent seventeenth to nineteenth century engravings indicate a lagoon environment, the cothon harbour speculated by the latter authors was shown to be erroneous. In reality, Bamboula basin comprised a small cove within a much larger lagoon (Fig. 22).

5.1.2. Geophysical surveying

Geophysical research techniques also provide a great multiplicity of mapping possibilities, notably where it is difficult to draw clear parallels between the archaeology and certain landscape features (Nishimura, 2001). The method assumes that subterranean conditions can be

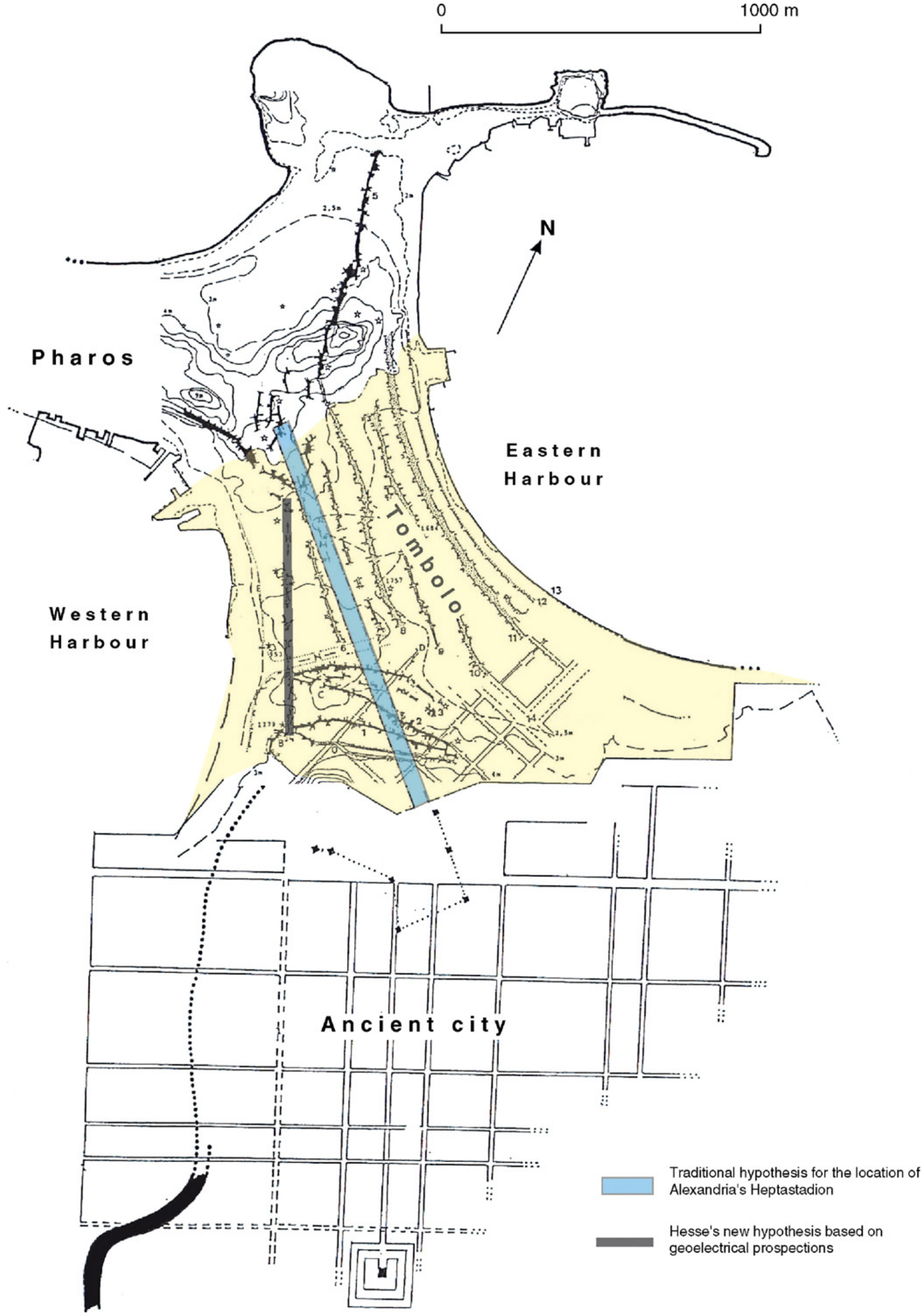

Fig. 23. Hesse's new hypothesis for the location of Alexandria's causeway, based on geoelectrical prospections (modified from Hesse, 1998).

elicited via differences in physical properties. Geophysical techniques detect subsurface archaeological features that contrast with the surrounding soils in terms of electrical resistance, magnetic, or other properties (Clark, 1990; Scollar et al., 1990; Conyers and Goodman, 1997). Factors that can create a geophysical contrast include soil compaction, particle size, organic content, artefact content, burning, and moisture retention (Neal, 2004).

The non-destructive nature of geophysical techniques means that they have been widely employed in terrestrial archaeology, and increasingly so in coastal geoarchaeology (Hesse, 2000). At Ampurias (Nieto et al., 2005) and Cuma (Stefaniuk et al., 2003) resistance profiles have been processed to produce geophysical profiles that can be interpreted both in stratigraphic and geoarchaeological terms. Significantly, profiles can be grouped together to produce a three dimensional cartography. By searching out the sizes, shapes and extents of differences it has been possible to yield insights into (1) the progradation of the ancient coastlines and the maximal extension of the former water body; and (2) information on coastal infrastructures. At Alexandria, Hesse (1998) has used geophysical prospection to propose a new hypothesis for the location of the ancient city's Heptastadium. Since the nineteenth century and the work of El-Falaki (1872), it was widely accepted that the Heptastadion occupied an axial position on the tombolo. Hesse now suggests that the causeway lay further to the west (see Fig. 23) and was directly linked to the city's grid layout. These findings have since been corroborated by sedimentological data from the area (Goiran, 2001).

Since 1997 a geophysical survey has been completed at Portus, covering ~178 ha of the ancient port complex (Keay et al., 2005b). Large areas of the seaport's fringes have been investigated to gain new insights into the harbour's coastal infrastructure and functioning during the Roman period. This technique has also accurately mapped the progradation of coastal ridges on the delta plain.

The main advantages of geophysical techniques are that (1) they are non-destructive (therefore particularly useful at sensitive sites and in urban contexts); and (2) rapid and reliable information can be provided on the location, depth and nature of buried features without the need for excavation. Unfortunately, there are no chronological constraints on the stratigraphy and archaeological features observed. Also, as with geomorphological mapping, there is an element of subjectivity involved in the interpretation of geophysical maps.

5.1.3. Coastal stratigraphy

Direct observation of the geological record is one of the key methods used to locate, characterise and reconstruct the physical evidence of past human activity (Kraft et al., 1977). The most ideal means by which to observe coastal stratigraphy, including sedimentary structures, is using excavated sections. In the absence of large scale excavation works, such working conditions are frequently unrealisable and the geoarchaeologist must rely on coring techniques to elucidate the sedimentary column. Cross-correlation and core networking can yield detailed spatial and chrono-stratigraphic information on a given area's sedimentary geometry and key surfaces (e.g. the Harbour Foundation Surface etc.).

For a coastal geoarchaeologist two fundamental scales of analysis can be differentiated: (1) the delta or ria scale (Kraft et al., 1977; Brückner, 1997); and (2) the harbour basin scale (Morhange, 2001). Both sedimentary systems are characterised by a general progradation since 6000 BP, which is critical in comprehending landscape deformation and the changing occupation history of the coastal plain.

The smaller analytical scale of harbour basins means that coastal deformation can be studied more finitely. The work of Morhange et al. (2001) at Marseilles, elucidating a rapid shift in shoreline positions from the Bronze Age onwards (Fig. 15), demonstrates the type of spatial resolution that can be obtained when large excavation areas are available for study. Given the relatively limited accommodation space, ancient harbour basins are particularly sensitive to changes in sediment supply. For many years, researchers advocated rapid rates of sedimentation as being conducive to the creation of high-resolution geoarchives of human occupation and impacts. However, recent work from Marseilles and Naples suggests that this premise should be moderated (Hesnard, 1994; Giampaola et al., 2004). Not surprisingly, the dual phenomenon of limited accommodation space and high sediment yields necessitated human management responses to ensure the viability of the harbour basin.

5.2. Laboratory techniques

The use of multi-disciplinary research techniques is essential in precisely reconstructing coastal palaeoenvironments and shoreline deformation. Integration of multiple proxies ensures the most robust research conclusions possible (Fig. 24). Be the sediments from an excavation section or core sequence, a short sampling interval (<5 cm) facilitates high-resolution reading of the coastal stratigraphy and harbour history. The laboratory techniques employed can be divided into a series of sedimentological, biostratigraphical and geochemical proxies.

5.2.1. Sedimentology

After an initial description of the main facies units and sedimentary structures, the section or core is divided into a series of sub-samples. Depending on the nature of the sediments and the coring equipment employed the sampling interval will vary. High-resolution (centimetric) sampling facilitates very precise reconstruction of harbour

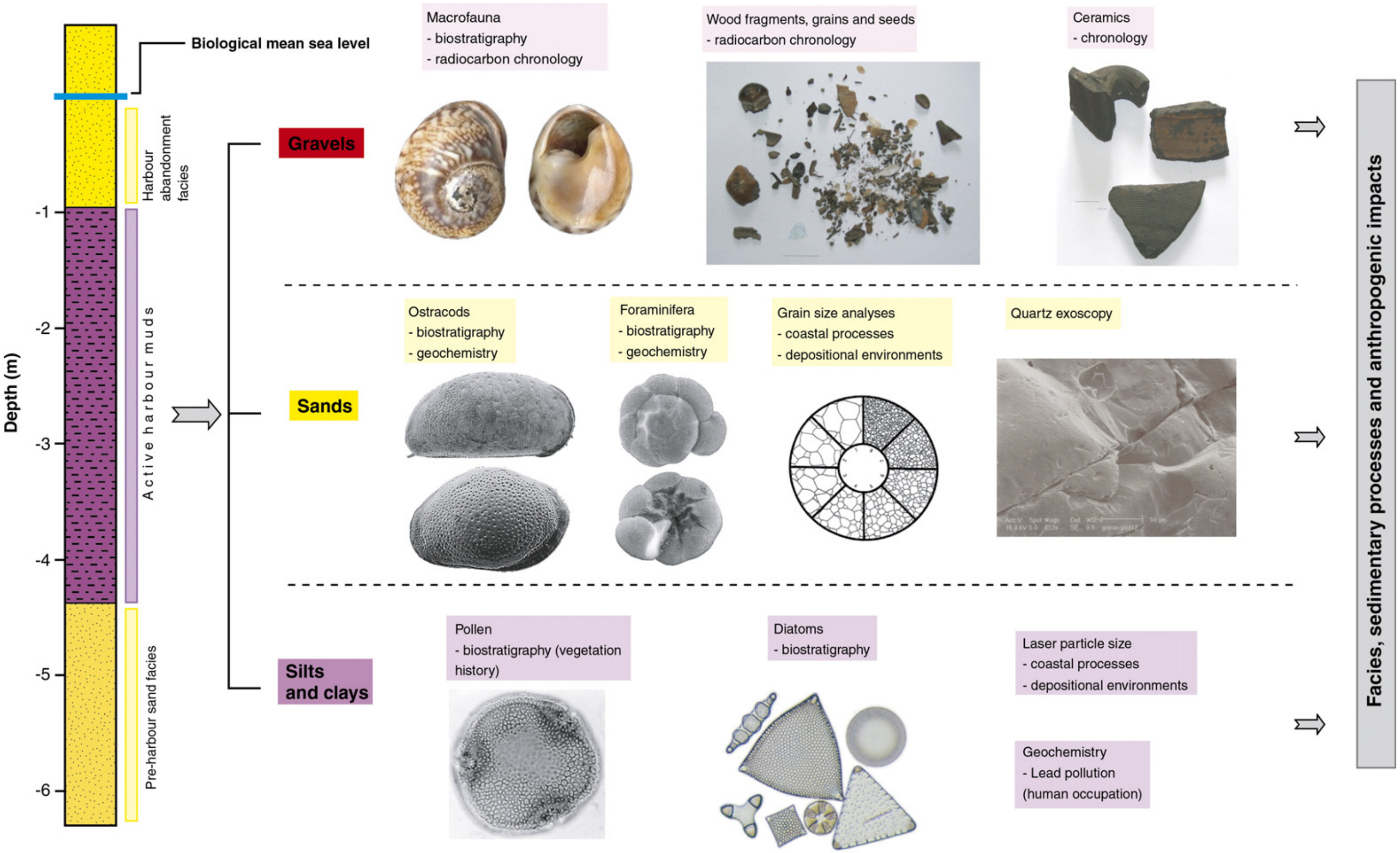

Fig. 24. Facies, sedimentary processes and anthropogenic impacts: research tools used in the study of ancient harbour sequences.

history and chronology. In reality, very few geoarchaeological teams engage in high-resolution laboratory studies due to their time-consuming nature.

5.2.1.1. Colour. Once the sediment samples have been dried they can be described using the Munsell colour scheme. Developed jointly by Munsell and the USDA Soil Conservation Service, these charts were initially used to classify soil colours but are now commonly used in all areas of the earth sciences and archaeology. The Munsell colour system specifies colours based on three dimensions, hue, lightness (called Value by Munsell), and chroma (difference from grey at a given hue and lightness). Although subjective, the charts provide a practical international standard for the communication and specification of sediment colour.

5.2.1.2. Sediment texture and granulometry. Particles or 'clasts' are the basic element of any sediment and therefore separating these clasts into discrete fractions is a key *inceptum* for geoarchaeologists. In order to extract the maximum amount of palaeoenvironmental information held within the coastal sediments, the sediment aggregates are wet sieved through two separate meshes (usually 2 mm and 50 μm) to separate out the gravels, sands and silts and clays fractions. The resulting dry fractions are subsequently weighed and data plotted against stratigraphic logs in percentages. The gravels fraction in ancient harbour sediments comprises a suite of interesting material, from marine molluscs, seeds, and grains to ceramic shards. These all attest to the harbour basin being used as a base-level waste dump by human societies.

The sand fraction can be subjected to mechanical sieving to establish various grain size parameters including histograms, fractiles and graphical indices (Folk and Ward, 1957; Folk, 1966). A column of sieves descending in size from 1.6 mm to 0.063 mm is employed and the separated sand fractions accordingly weighed. Results are subsequently statistically analysed, in concordance with various grain size parameters. The silts and clays fraction can also be investigated using laser particle sizing.

The granulometry of port sediments has traditionally interested engineers and not sedimentologists *sensu stricto* (Caldwell, 1939). Breakwaters, groins and jetties are all structures that act in a similar manner in that they impose a physical barrier in the nearshore zone and block the flow of littoral drift. Harbour sediments tend to be characterised by a strong granulometric heterometry, juxtaposing fine-grained silts and sands against coarse grained gravels constituting ceramics, marine macrofauna, wooden fragments etc. Harbour beach faces are generally characterised by a coarser granulometry which contrasts with the predominant silts and clays (50 to 90%) from within the heart of the basin itself (Morhange, 2001). Unfortunately, although grain size analysis can yield information on the nature of the sedimentary dynamics, marine currents and coastal processes, it is a relatively weak palaeoenvironmental tool when used in isolation.

5.2.1.3. Exoscopic indicators. Clastic sediments can also be studied for their grain shape, and traces of surface dissolution and shocks. Sphericity and roundness can yield insights into the nature of the depositional environment and coastal processes. Precise investigation of the sand fraction is now possible using Scanning Electron Microscope (Prone, 2003), and within this context a methodology to characterise ancient harbour quartz grains has been developed by a number of researchers (Georges and Prone, 2000; Goiran, 2001). This particular technique is especially useful in differentiating between sedimentary environments.

In ancient harbour sequences two types of quartz signature can be identified: (1) Quartz grains from low energy harbour muds are characterised by pyritospheres indicative of a confined marine environment. Surface shock marks induced by wave action tend to be polished by low-energy marine processes. Grains can also manifest traces of marine dissolution, characterised by anatomising surface patterns. (2) Quartz grains deriving from midlittoral beaches are marked by shock traces (cupules and croissants) indicative of breaking waves and the higher energy context. The position of the deposits within the intertidal zone is also indicated by traces of aeolian processes, subsequently reworked and polished by marine action.

Palaeo-lagoons are a case apart and research by Georges and Prone (2000) and Georges (2004) has established a typology of lagoon quartz grains which they qualify as Evolved Non-Eroded. Such low energy quartz signatures contrast with recent work at Alexandria, Egypt where paradoxical high-energy deposits present within the harbour muds have been used to establish a typology of tsunami trace shocks (Goiran, 2001; Fig. 25). These have been compared and contrasted with modern analogues from around the globe and provide a preliminary referential with which to corroborate palaeo-tsunami facies. Palaeo-tsunami layers are notoriously difficult to differentiate from storm surge deposits (Dawson, 1994; Dawson, 1999, Dawson et al., 2004).

5.2.2. Biostratigraphy

Biostratigraphy is the study of the temporal and spatial distribution of fossil organisms (Jenkins, 1993;

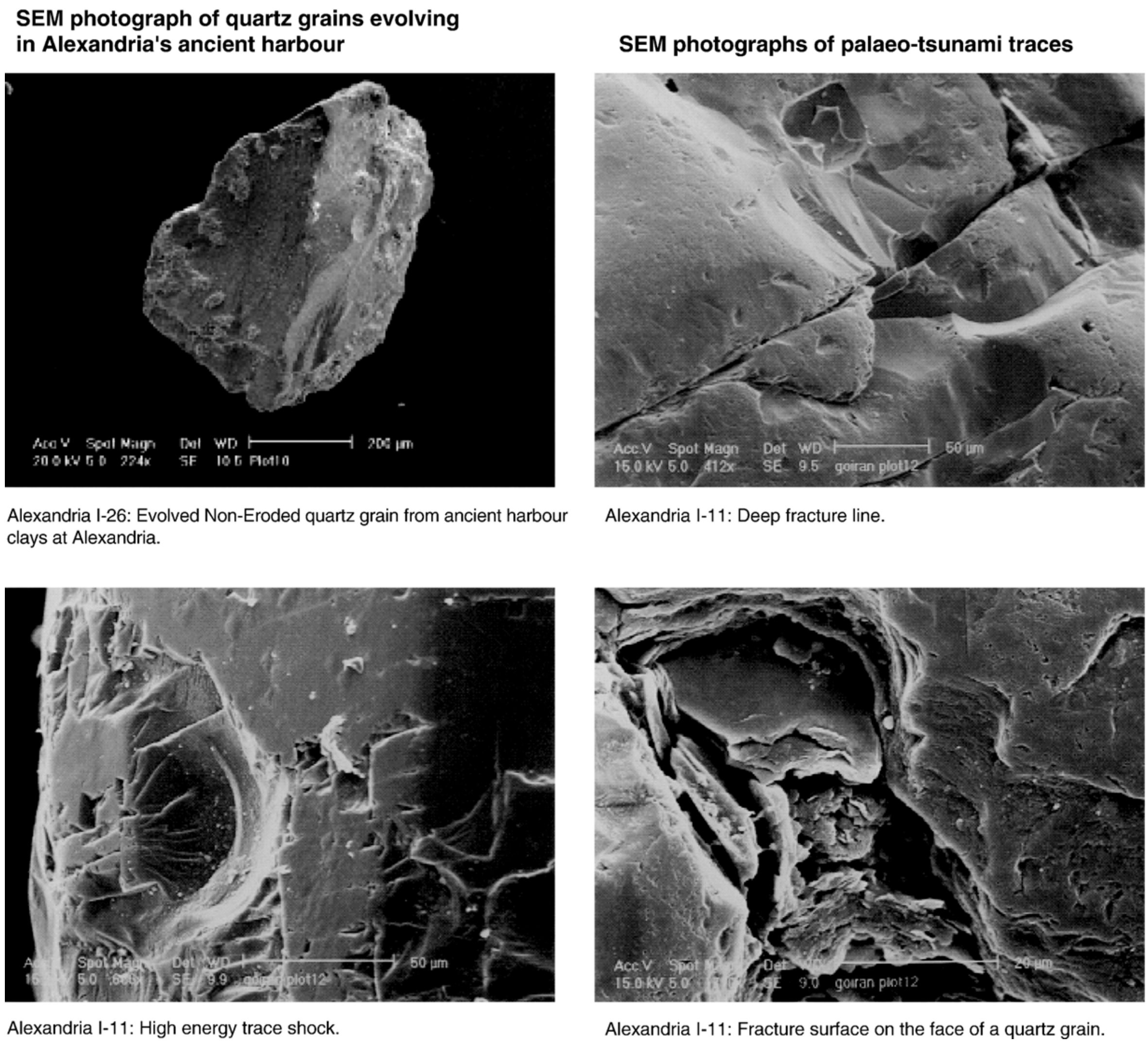

Fig. 25. Harbour and palaeo-tsunami quartz grains from Alexandria's ancient harbour (from Goiran, 2001). Goiran has shown that tsunami leave traces of high energy shocks on the quartz grains. This technique appears particularly useful in the study of palaeo-tsunami.

Haslett, 2002). In coastal geoarchaeology, it is an important tool in precisely reconstructing depositional environments, the evolution of coastal biocenoses and the impact of human societies upon these ecosystems (pollution, harbourworks etc.). An essential prerequisite for this approach is a good taxonomic framework, and understanding of both the ecology and geographical ranges of species encountered.

5.2.2.1. Malacology. Mediterranean malacology has a long history of research and since work on the *Vieux Port* at Marseilles marine molluscs have proved a powerful tool in reconstructing ancient harbour palaeoenvironments, where their fossil shells are found in abundance (Leung Tack, 1971–72). During the 1960s, Péres and Picard (1964) were eminent figures in developing a molluscan classification system that assigned Mediterranean species to well-defined ecological groups (see also Péres, 1982). Refined versions of this classification system are presently used. The most important workable identification frameworks for the Mediterranean include d'Angelo and Gargiullo (1978), Barash and Danin (1992), Poppe and Goto (1991, 1993), Bellan-Santini et al. (1994), Doneddu and Trainito (2005).

Both *in situ* and *extra situ* taxa can be identified on the basis of core lithology and shell taphonomy. This approach can be useful in establishing the degree of harbour confinement/exposure. For example, at Alexandria malacological work on a tsunami layer juxtaposes a great diversity of *in situ* and *extra situ* molluscan tests,

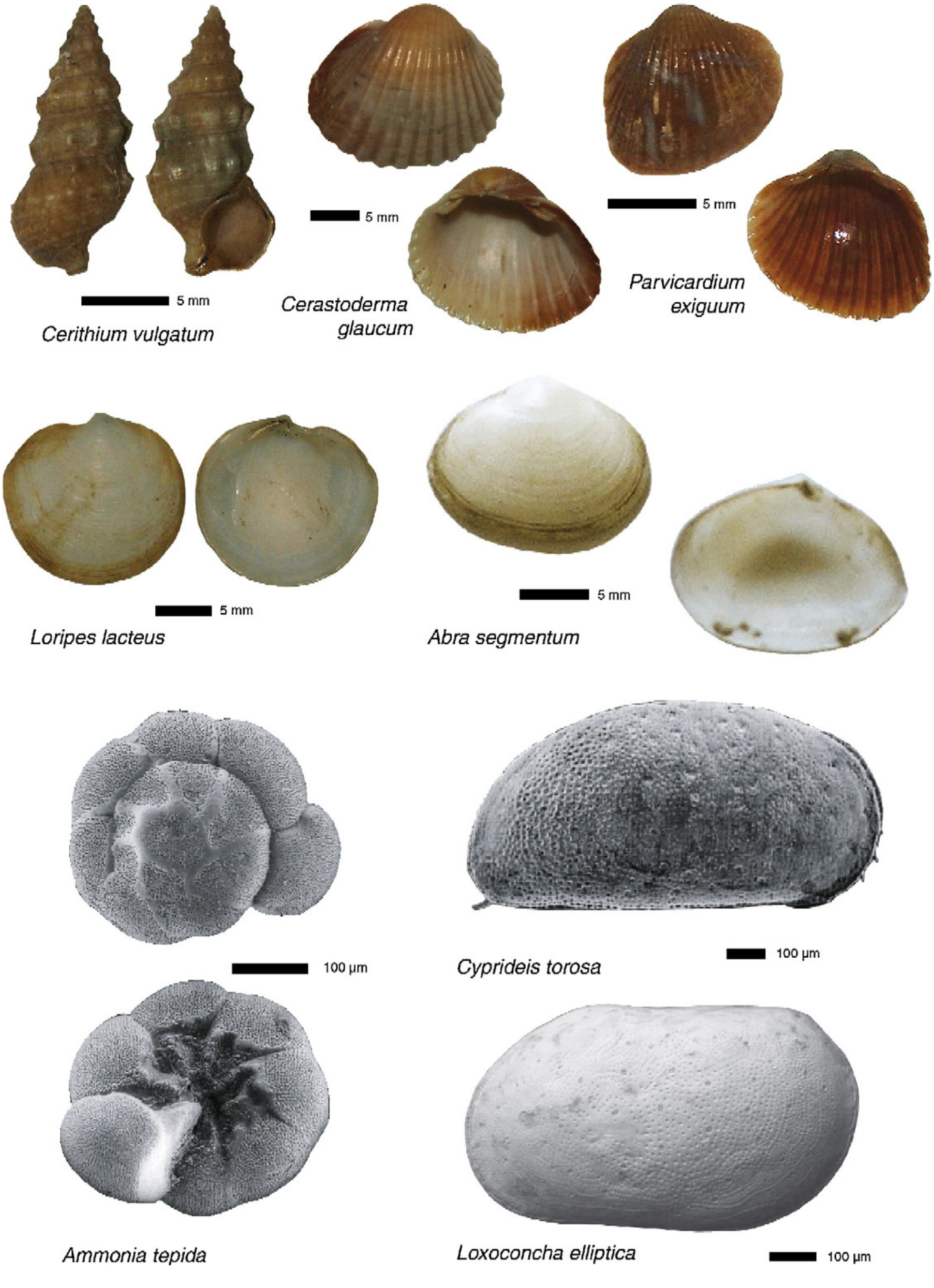

Fig. 26. Biostratigraphic indicators of confined harbour conditions.

consistent with powerful offshore waves reworking biocenoses from deeper bathymetric depths (Goiran, 2001; Stanley and Bernasconi, 2006). Ecological stresses and harbour pollution can also be evidenced by the presence of certain taxa (Fig. 26). Typical ancient harbour taxa include *Parvicardium exiguum*, *Cerastoderma* *glaucum*, *Loripes lacteus*, *Abra segmentum* and *Cerithium vulgatum*. These species are all consistent with either lagoonal environments or sheltered areas rich in fine-grained sands and silts. Given that marine shells are frequently used to radiocarbon date harbour sequences, it is imperative to understand the ecology of observed taxa and whether or not these are *in situ*.

5.2.2.2. Ostracods. Ostracods are microcrustaceans comprising soft body parts enclosed in a low-Mg calcite bivalve (Athersuch et al., 1990). They are typically around 1 mm in size but can vary between 0.2 and 30 mm. As with all crustaceans, ostracods grow by moulting. The carapace has numerous morphological characters which allow taxonomic and phylogenetic studies to be made on living and fossil specimens (Holmes and Chivas, 2002). Ostracods have a long and well-documented fossil record from the Cambrian to the present day, and have been particularly useful for the biozonation of marine strata on a local or regional scale.

Ostracods are excellent indicators of palaeoenvironments because of (1) their ubiquity in both fresh and marine waters; (2) their small size; and (3) their easily-preservable carapaces. Their faunal composition, population density and diversity vary in time and space as a function of numerous environmental factors including water temperature, salinity, water depth, grain size, and anthropogenic impacts (Boomer and Eisenhauer, 2002). In many coastal and nearshore marine areas, human activities can significantly modify the natural coastal system (construction works, pollutants) leading to severe alterations in the different trophic levels of the ecosystems (Ruiz et al., 2005). Ancient anthropogenic activities can affect ostracods in three ways: (1) impact on the densities and diversities of the assemblages; (2) strongly influence the abundance and distribution of selected species; and (3) affect the chemistry of their carapaces.

Although slightly different preparation techniques exist, ostracoda are generally extracted from the dry sand fraction (>150 μm). A minimum of 100 valves is preferred to ensure statistical robustness. Identified taxa are most commonly assigned to five assemblages on the basis of their ecological preferences: freshwater, brackish lagoonal, marine lagoonal, coastal and marine (Müller, 1894; Breman, 1975; Bonaduce et al., 1975; Carbonel, 1980, 1982; Morhange et al., 2000). These clearly discrete ecological groups render ostracods one of the best biostratigraphical markers in ancient harbour sequences. Potential research avenues include the application of ostracod test geochemistry to reconstruct ancient harbour salinity patterns and pollution levels (Ruiz et al., 2005).

5.2.2.3. Foraminifera. Foraminifera are single-celled organisms (protists) with tests that have been abundant as fossils for the last 540 million years (Murray, 1991). Foraminiferal tests are commonly divided into chambers that are added during growth, though the simplest forms are open tubes or hollow spheres (Sen Gupta, 2002). Based upon their composition, the tests can be divided into three categories: organic (membranous or tectinous), agglutinated, and calcareous. The agglutinated shells are composed of foreign sediment particles glued together with an organic cement, while the calcareous shells are formed from secreted calcium carbonate. The calcareous shells can be further subdivided into hyaline, porcellaneous, and microgranular types which differ in their calcite crystal arrangement. Fully grown individuals range in size from about 100 μm to almost 20 cm long.

Foraminifera are among the most abundant and ubiquitously spread shelled organisms in marine environments. Their distribution range comprises the intertidal zone to the deepest ocean trenches, and from the tropics to the poles. Although a few species are found in brackish environments, foraminifera do not occur in freshwater environments.

Foraminifera are particularly useful in ancient harbour geoarchaeology because: (1) they are abundant in most marine and marginal marine environments, with a living population density often exceeding one million individuals per square metre; (2) they have a mineralized shell and thus have a high preservation potential in the sedimentary record; (3) only small sediment samples are needed to obtain fossil populations large enough for statistical treatment; (4) being single celled they respond rapidly to environmental changes (Samir, 2000; Pascual et al., 2002); and (5) foraminiferal species characterise very specific environments.

Workable taxonomic frameworks for the Mediterranean region include Cimerman and Langer (1991) and Sgarrella and Moncharmont Zei (1993). In northern Europe and North America, marsh and intertidal foraminifera have been widely used to develop high-resolution sea-level transfer functions (Horton and Edwards, 2006), although studies in the Mediterranean have tended to focus upon establishing broad depth ranges for benthic taxa (Basso and Spezzaferri, 2000). Whilst foraminiferal test geochemistry has long been used in palaeoclimatology (Bard, 1999) to study temperature, salinity, carbonate chemistry, diet, and nutrient conditions, it is only very recently that these principles have been applied to ancient harbour contexts (Reinhardt et al., 1998).

5.2.2.4. Diatoms. Diatoms are a major group of eukaryotic algae, and are one of the most common types of phytoplankton (Round and Crawford, 1990; Battarbee et al., 2001). Most diatoms are unicellular, although some form chains or simple colonies. Diatoms cells are contained within an intricate siliceous frustule comprised of two separate valves, the morphology of which forms the basis for their taxonomy. They are a widespread group and can be found in the oceans, freshwater, soils and on damp surfaces. Most live pelagically in open water, although some live as surface films at the water-sediment interface (benthic), or even under damp atmospheric conditions. They are especially important in oceans, where they are estimated to contribute up to 45% of the total oceanic primary production (Mann, 1999).

Unlike many other algal groups, diatoms are readily identifiable to species level and beyond (Round, 1991), and this has made them particularly useful in palaeoenvironmental and palaeoclimatological studies. They manifest a consistent tolerance with a wide range of environmental parameters such as light, moisture, current velocity, pH, salinity, oxygen and inorganic and organic nutrients (Battarbee et al., 2001). Whilst their identification remains difficult, numerous comprehensive taxonomic texts and floras dealing with taxonomy are now readily available.

Their ubiquity in diverse types of waterbodies means that they are also increasingly being used in geoarchaeology (Battarbee, 1988). Although not widely employed in ancient harbour basins until now, recent preliminary studies suggest that diatoms could be rich palaeoenvironmental indicators in these unique archives (Vecchi et al., 2000). Their greatest geoarchaeological scope appears to lie in lagoon and fluvial harbour environments, where coastal geoarchaeological methods are not sensitive enough to accurately reconstruct port history.

5.2.2.5. Palynology. Palynology is the science that studies contemporary and fossil palynomorphs, including pollen, spores, dinoflagellate cysts, acritarchs, chitinozoans and scolecodonts (Nair, 1985). Palynomorphs are broadly defined as organic-walled microfossils between 5 and 500 μm in size, and have been widely used in the earth and plant sciences since the 1940s (Moore et al., 1991). They are extracted from rocks and sediments both physically, by wet sieving, often after ultrasonic treatment, and chemically, by using chemical digestion to remove the non-organic fraction.

Pollen are the most commonly employed type of palynormorph fossil in archaeology, where they have been used to reconstruct regional vegetation landscapes and human impacts (Bottema and Woldring, 1990; Atherden et al., 1993; Dumayne-Peaty, 2001). The Mediterranean basin has experienced intensive human development and impact on its ecosystems for thousands of years (Bottema et al., 1990). The greatest impacts of human civilization have been deforestation, intensive grazing and fires, and infrastructure development, especially on the coast. There is a growing body of literature on the use of pollen and plant remains at underwater sites (Weinstein, 1996; Gorham and Bryant, 2001).

The use of pollen in ancient harbour geoarchaeology has been more limited, where abundant and easily-identifiable fossil types such as molluscs, ostracods and foraminifera yield more pertinent information relating to the coastal history. Although fine-grained harbour muds are ideally suited to the preservation of palynomorphs, the most recent studies undertaken upon this type of archive have not proved conclusive (Marriner et al., 2004). Sediments transported and deposited by coastal processes can contain pollen 'contamination'. Differentiating this background noise from 'economic' pollen resulting from local cultural processes at the site can be problematic. On the other hand, plant macrofossils can provide information on (1) the identification of botanical cargoes, provisions, and dunnage; and (2) the identification of plant fibres used to make rope, baskets, matting, and caulking (Gorham and Bryant, 2001).

5.3. Geochemistry

The association of trace metal anomalies are increasingly being used to reconstruct ancient pollution levels during the historical period and antiquity (Gale and Stos-Gale, 1982; Nriagu, 1983; Sayre et al., 1992; Yener et al., 1991; Renberg et al., 1994; Hong et al., 1994, 1996; Nriagu, 1998; Shotyk et al., 1998, 2005; Martínez-Cortizas et al., 1999; Pyatt et al., 2000; Aberg et al., 2001; Bränvall et al., 2001; Cundy et al., 2006). Within this context, it has been demonstrated that lead (Pb) isotopes in harbour sediments are particularly powerful tools in retracing the history of metallurgic activities at coastal sites (Véron et al., 2006). There are a number of reasons why port sediments are particularly conducive to geochemical analyses: (1) ancient seaports comprise low-energy depocentres. Urban and coastal contaminants are thus concentrated in the basins, and have the potential to yield long time series of human-environment interactions; (2) trace metals (e.g. copper, lead), have been used by ancient societies since the end of the Neolithic (Mellaart, 1967). Covariation in the geochemical suites of harbour sediments can therefore be linked to changes in metallurgical *savoir faire* (e.g. copper during the Chalcolithic, copper, tin and lead during the Bronze Age etc.); (3) although small amounts of metals are found in relatively pure form, most must be extracted from more complex ores by removing

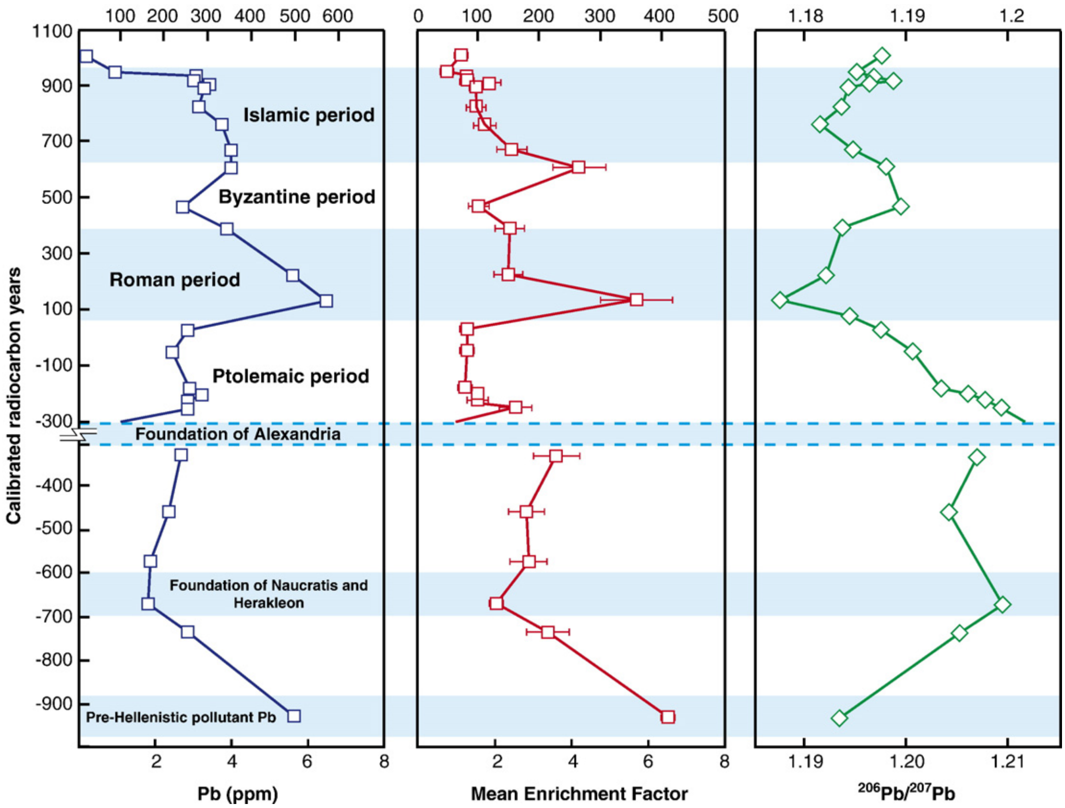

Fig. 27. Pollutant lead at Alexandria during the past 3000 yr (adapted from Véron et al., 2006). The use of lead geochemistry has elucidated pre-Hellenistic pollutants at Alexandria, suggesting an advanced settlement at the site before the arrival of Alexander the Great in 331 BC.

the 'impurities' (non-metal or other metal) from the combination ore. For example, natural lead is very rare in the earth's crust, therefore when it is found at an archaeological site its presence can invariably be attributed to a mineral fusion. This renders lead and other trace metals particularly powerful tools in reconstructing anthropogenic contaminations (Shotyk et al., 1998, 2005; Martínez-Cortizas et al., 1999); (4) the majority of trace metals are well-preserved in the fossil record, with relatively low levels of degradation over the Holocene timescale; (5) finally, the geochemical composition of some metals means that they can be provenanced. Lead, for example, is a chemical element that possesses three stable radiogenic isotopes ^{206}Pb, ^{207}Pb and ^{208}Pb. These three isotopes vary as a function of the geological source area which means that lead samples can invariably be linked back to a well-constrained mining area.

To date, four ancient harbours have undergone geochemical analyses of this nature. At Alexandria, Véron et al. (2006) evidenced Bronze Age human occupation of the site calling into question the Alexandria *ex nihilo* hypothesis (Fig. 27). The Graeco-Roman apogee of the city is indicated by lead pollution levels twice as high as those measured in contemporary ports and estuaries. Graeco-Roman pollution peaks have also been evidenced at Marseilles (Le Roux et al., 2005), Sidon (Le Roux et al., 2003; Fig. 28) and Tyre (Elmaleh, unpublished data).

6. The ancient harbour: stratigraphy and geological principals

Fig. 29 sets out the type stratigraphy for some of the Mediterranean's best studied examples. Be it in the eastern or western Mediterranean, the stratigraphic similarities are striking, with three distinct facies of note: (1) a middle energy beach sands at the base of each unit, (2) low energy silts, and (3) coarsening up beach sands which cap the sequences. In very general terms this stratigraphic pattern translates a shift from natural coastal environments to anthropogenically modified environments, eventually culminating in a semi or complete abandonment of the harbour basin.

On the basis of these observed stratigraphic patterns, we have attempted to understand ancient harbour basins within the ordered framework of sequence stratigraphy.

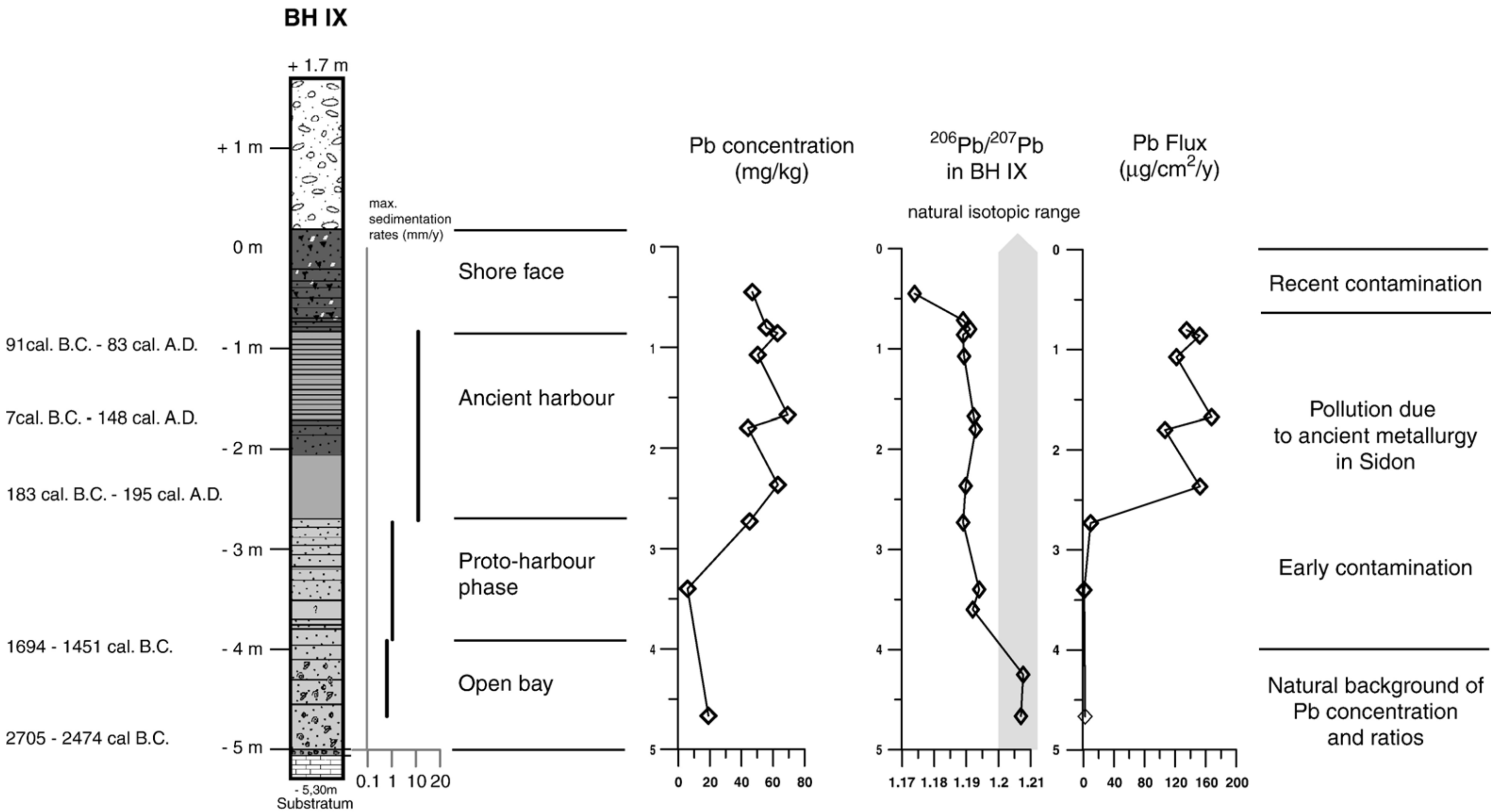

Fig. 28. Pollutant lead contamination at Sidon's ancient harbour (adapted from Le Roux et al., 2003).

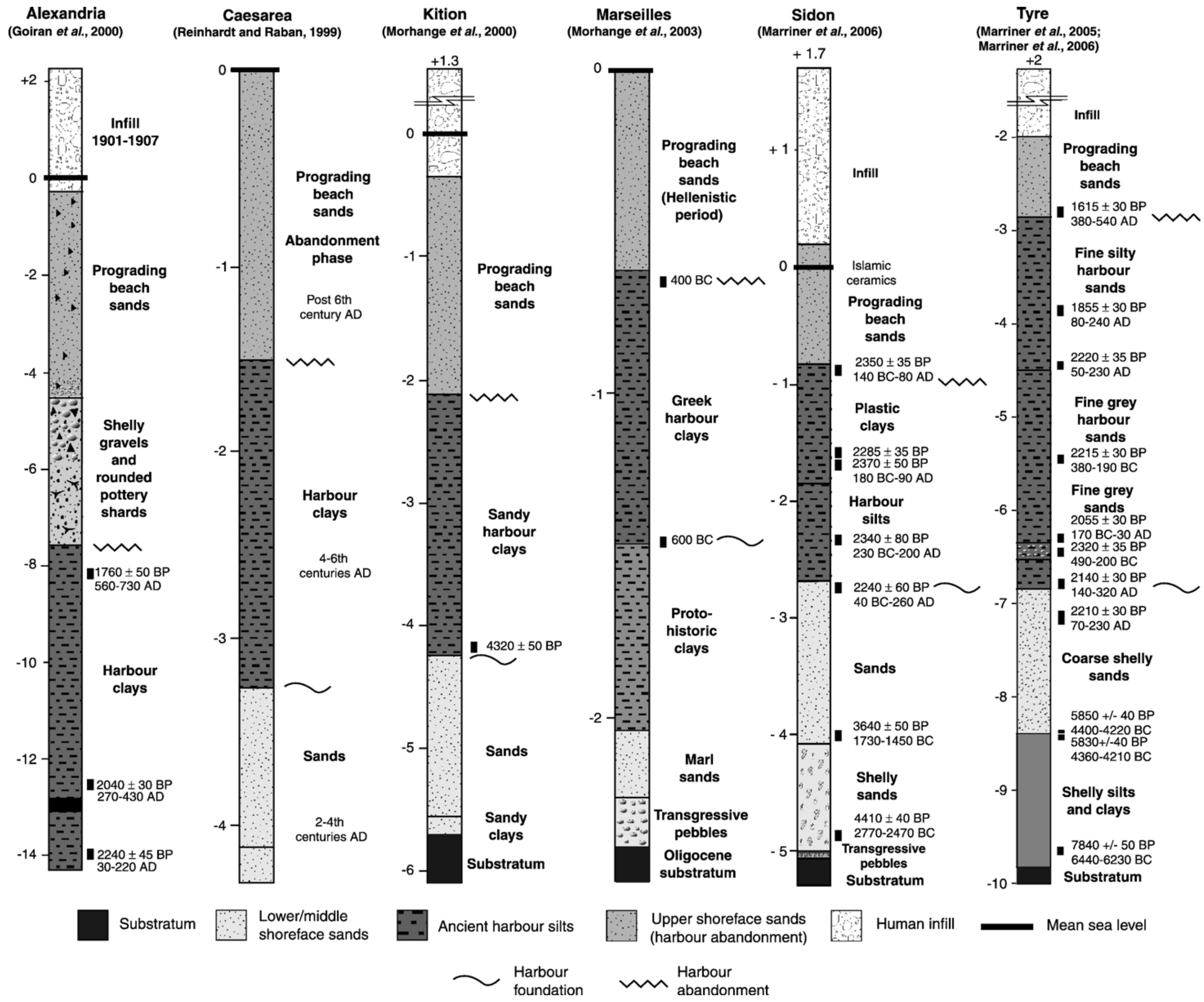

Fig. 29. Lithostratigraphy of the Mediterranean's best studied ancient harbours. This highstand anthropogenic facies comprises uncharacteristically high levels of fine-grained material (Marriner and Morhange, 2006a,b).

Human agency, in addition to modest sea-level variations and overriding sediment supply forcings, are easily incorporated into this conceptual approach that has revolutionised the study of sedimentary formations in geology since the 1970s (Catuneanu, 2002, 2005; Coe, 2003).

There are a number of reasons why sequence stratigraphy provides a robust framework for this new coastal geoarchaeology. (1) Firstly, it is a holistic means of examining the mid to late Holocene stratigraphic record, in that it considers not only the empirical record but also those parts which are missing. (2) Secondly, evolving palaeogeographies can be studied in their wider contexts and ancient harbours linked into the source to sink sedimentary conveyor. (3) It facilitates different harbour sites to be compared and contrasted with relative ease, whereby relative sea-level variations are correlated with lateral facies changes. (4) Finally, this approach focuses on the mechanisms and processes driving coastal deformation, namely climatic, eustatic, tectono-isostatic and anthropogenic factors (Morhange, 2001). Mankind, as we will go on to demonstrate, has had a greatly distorting role to play within this forcing complex.

6.1. Basic principles

Ancient harbours are base-level depocentres that owe their origins to Bronze Age human agency and mid-Holocene sea-level deceleration, stability which brought terrigenous accumulation to certain low-energy littoral zones. The basins form integral components of the Highstand Systems Tract (HST) and their sediment strata comprise aggradational to progradational sets. The Maximum Flooding Surface (MFS) represents the lower boundary of the sediment archive. This surface, dated ~6000 yr BP, marks the harbour basin's maximum marine incursion and is broadly contemporaneous with the Chalcolithic period and the Bronze Age. Indeed, strong links have been found between the position of the MFS and early coastal settlement patterns along the Levantine coast (Raban, 1987).

Early Bronze Age societies preferentially concentrated around geomorphologically endowed sites, namely small coves, pocket beaches, estuaries and wadis, which formed natural anchorage havens in little need of human enterprise. It is no coincidence therefore that many of the earliest seafaring communities originated in the central and eastern Mediterranean. The rocky and convoluted coasts of the Aegean islands were, for example, ideally suited to protect early mariners and their vessels. The presence of man in and around low-energy sediment sinks, allied with relatively continuous rates of sedimentation, has culminated in the formation of rich geoarchaeological archives.

Although environmental determinism was the rule, societies in the Aegean and the Levant started modifying their natural anchorages during the Middle to Late Bronze Age and Early Iron Age. Two dated examples derive from the Levant coast. Firstly, submerged boulder piles have been evidenced at Yavne-Yam, a Middle Bronze Age site on the coast of Israel; these attest to premeditated human enterprise to improve the quality of the natural anchorage (Marcus, personal communication). Secondly, radiometric dating of wood fragments held between courses of the artificial mole at Atlit constrains this Phoenician structure to the ninth century BC (Haggai, 2006). 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).

This artificialisation is translated in the sedimentary record by lower energy facies which chronicles a barring of the anchorage by artificial means. Harbour infrastructure (quays, moles and jetties) accentuated sediment sink properties and this, coupled with important changes in land use and cultural inputs, engendered rapid rates of sedimentation culminating in coastal progradation. By Roman times, harbour engineering had reached its zenith and accumulation rates 10 to 20 times greater than naturally prograding coastlines are recorded. High sediment supply resulted in the deposition of thick beds of fine-grained harbour muds that provide a multiplicity of research possibilities (see below).

6.2. Key facies belts and sequence boundaries

Research shows there to be considerable repetition in ancient harbour stratigraphy, both in terms of the facies observed and their temporal envelopes. Much of the data can be correlated on various spatial scales, locally (e.g. Alexandria, Marseilles, Tyre) and regionally (Phoenicia, the Black Sea, Magna Graecia). In light of this, we believe the stratigraphic ensemble of harbour basins to be sufficiently unique as to merit a separate epithet, the Ancient Harbour Parasequence (Marriner and Morhange, 2006b). Although AHPs can vary slightly in thickness and character, a number of key facies belts and sequence boundaries can be identified (Figs. 30 and 31).

(1) Around 6000 BP, the MFS marks the basal inception of the AHP and invariably comprises trangressive sands or pebbles. It constitutes the marine flooding of the depocentre and is associated with the most landward position of the shoreline within the basin.

(2) This surface is overlain by naturally aggrading beach sands, a classic feature of clastic coastlines since 6000 BP. After this time, the rate of increase in accommodation space (the space separating the water surface from the basin

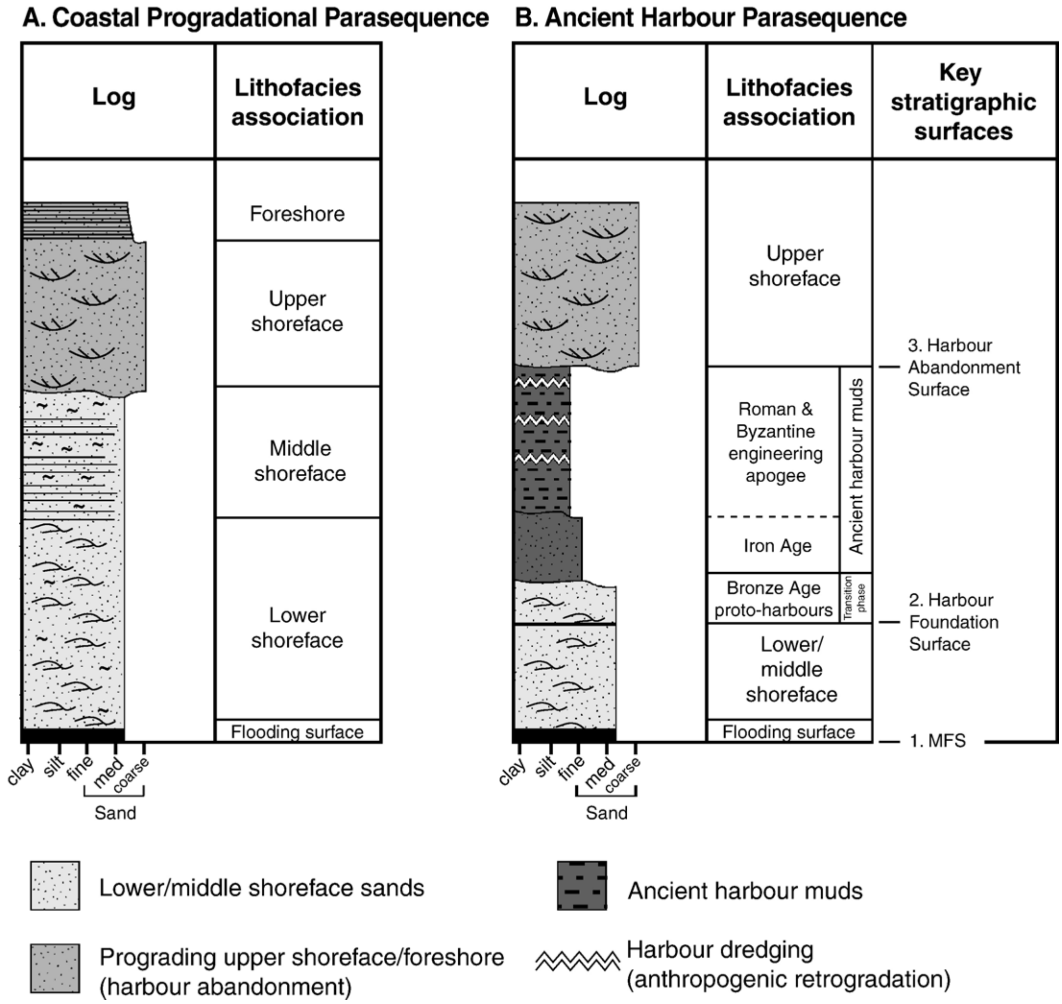

Fig. 30. Lithofacies and key stratigraphic surfaces of (A) the Coastal Progradational Parasequence and (B) the Ancient Harbour Parasequence. Adapted from Marriner and Morhange (2006b).

bottom) became outbalanced by sediment supply. Relative sea-level stability impinged on the creation of new accommodation space, leading to the aggradation of sediment strata. At this time, the coves were completely natural. Where this sedimentation continued unchecked, a coarsening upward of sediment facies is observed, translating high energy wave dynamics in proximity to mean sea level.

(3) The Harbour Foundation Surface (HFS) is one of the most important stratigraphic surfaces in ancient harbour geology. It marks early human modification of the basin, namely the transition from coarse beach sands to fine-grained harbour silts and clays, and corresponds to the construction of protective harbourworks (Goiran and Morhange, 2003).

(4) The Ancient Harbour Facies (AHF) is by no means a uniform unit of plastic clays. Stratigraphic impacts are intrinsically linked to harbour technology. The most moderate signatures of human presence are dated to the Bronze Age, when societies used natural low-energy basins needing little or no human modification. For example, the southern cove of Sidon in the vicinity of Tell Dakerman remained naturally connected and open to the sea throughout antiquity (Poidebard and Lauffray, 1951). The natural to semi-artificial interface is thus by no means transparent on purely granulometric grounds and the astute use of biological indicators, notably molluscan macrofauna and microfauna assemblages, is a much more effective means of establishing this surface. Net transition to fine-grained sands and silts is observed, good examples being those of Tyre and Sidon (Marriner et al., 2006a). During the Late Bronze Age and Early Iron Age, expanding trade forced many Levantine societies to embrace maritime engineering and build artificial harbourworks

Facies/surface name	Definition	Diagnostic sedimentology	Diagnostic biostratigraphy	Geochemical imprint
Harbour Abandonment Facies (HAF)	- Degradation of harbourworks and exposure of the basin	- High to middle energy aggradational and progradational sets - Coarsening-up sequence	- Juxtaposition of diverse ecological groups (translate the exposed nature of the depositional environment)	- Weak
Harbour Abandonment Surface (HAS)	- (Semi)abandonment of the basin	- Transition from fine-grained harbour silts and clays to coarse sands and gravels		
Ancient Harbour Facies (AHF)	- Anthropogenically forced low-energy sedimentary environment	- Transition from coarse beach sands to fine-grained harbour silts and clays - Rapid fine-grained sedimentation rates (10-20 mm/yr) - Granulometric heterometry	- Ostracods = *Cyprideis torosa Loxoconcha* spp., *Xestolebris* spp. - Foraminefera = *Ammonia* spp. - Mollusc = *Parvicardium exiguum Loripes lacteus, Cerithium vulgatum*	- Strong
Harbour Foundation Surface (HFS)	- Natural to artificial interface	- Abrupt change from coarse beach sands to fine-grained harbour silts and clays		
Proto-harbour sands / Pre-harbour sands	- Natural beach sediments	- Aggradational coarse to medium grained sands - Coarsening-up sequence	- Coastal and semi-protected sub-tidal taxa	- Weak
Maximum Flooding Surface (MFS)	- Marine flooding of the coastal sequence (ca. 6000 BP)	- Transgressive sands and pebbles	- Coastal and semi-protected sub-tidal taxa	- None

Fig. 31. Definitions of the AHP's key facies and surfaces.

(Frost, 1995; Raban, 1995). Gradual improvements in harbour engineering are recorded by increasingly fine-grained facies, up until the Roman period when pozzolan concrete marked a revolution in maritime infrastructure (Oleson et al., 2004). Natural roadsteads were no longer a prerequisite to harbour loci and completely artificial ports, enveloped by imposing concrete moles, could be located on open coasts (Hohlfelder, 1997). Plastic clays tend to be the rule for this period.

(5) Harbour Abandonment Surface (HAS). The HAS marks the semi-abandonment of the harbour basin, invariably after the late Roman period. This surface lies at the intersection between the AHF and an exposed beach facies. It corresponds to coastline progradation, culminating in the partial silting or landlocking of the basin heart.

(6) Often, the exposed beach facies comprises coarse grained beach-face sands and is consistent with degradation of harbourworks. This phenomenon can be linked to a number of historical events: (a) settlement demise (e.g. Islamic expansion in the eastern Mediterranean); or (b) natural catastrophes including seismic uplift (e.g. Phalasarna harbour in western Crete), volcano-tectonic subsidence (e.g. Portus Julius in Pozzuoli caldera), or tsunami impacts (e.g. Alexandria). In the absence of clear management strategies, port basins rapidly infilled with thick tracts of coastal and fluvial sediments.

On 'tectonically stable' coasts, sediment supply, whether it be environmentally or anthropogenically forced, has been the chief controlling factor in determining ancient harbour stratigraphy and facies organisation.

6.3. Ancient harbour stratigraphy: a geological paradox?

The presence of man has significantly impacted upon the stratigraphic record, to such a degree that we define the AHP as a geological paradox. Anthropogenic forcing of the stratigraphic record is juxtaposed against the classic Coastal Progradational Parasequence (CPP). Under natural conditions, the MFS is overlain by increasingly coarse sediments consistent with an aggradation of the marine bottom. In the AHP model, only the lower portion of this natural stratigraphy is observed; it is overlain by facies presenting a number of stratigraphic aberrations.

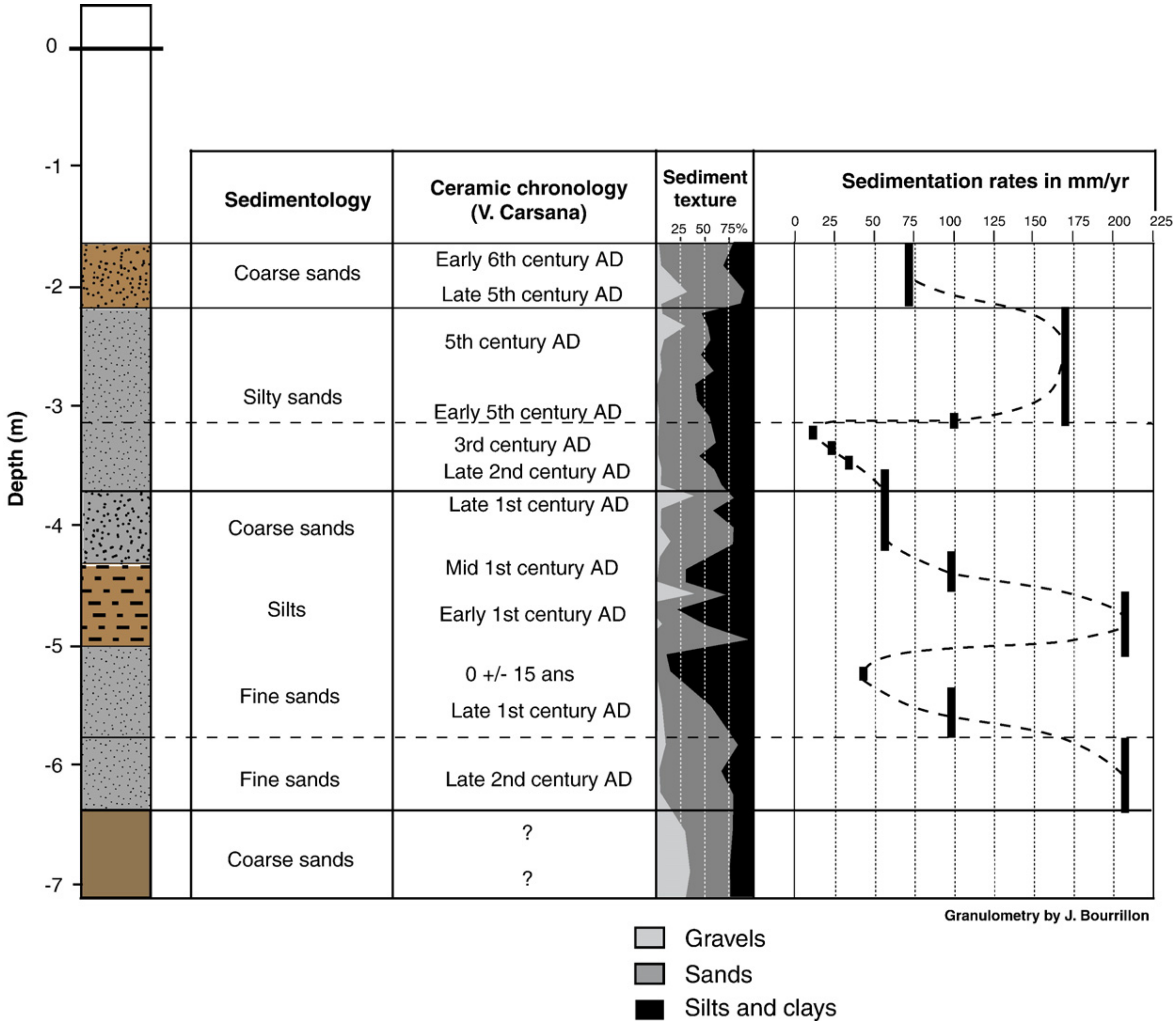

Fig. 32. Stratigraphic section from Naples' port (Piazza Municipio) showing the high variability of sedimentary fluxes. Anthropogenic impact is fundamental in explaining the harbour silting up. Excavations directed by D. Giampaola (Archaeological Superintendence of Naples) and assisted by V. Carsana.

(1) *Fining-upward sequence*. The AHP comprises a fining-upward granulometry characterised by coarser-grained transgressive deposits at the base, overlain by increasingly fine-grained deposits up-sequence. The very well protected Roman harbours of Alexandria, Marseilles and Naples all comprise plastic marine muds consisting of >90% silts.

(2) *Accelerated accretion rates*, at least ~10 times greater than nearby naturally prograding coasts, are archetypical of these depocentres (Fig. 32). On natural coasts, sediment was resuspended from the seabed due to energetic wave processes and transported by currents in the water column. In ancient harbour basins, harbour infrastructure attenuated the swell and perturbed marine currents, accounting for a sharp fall in water competence (Inman, 1974). Whilst watershed geomorphology and climate are first-order controls on sediment production and delivery to the ocean, the presence of man also increased the potential for subaerial erosion in coastal watersheds (Horden and Purcell, 2000; Devillers, 2005). Significant increases in the supply term are recorded from the Neolithic period onwards including, for example, anthropogenic changes in the catchments of supplying rivers, erosion of adobe urban constructions (Rosen, 1986) and finally use of the basins as *ad hoc* waste dumps. Even though the qualitative impact of human activity seems obvious, quantitative evaluation of the impact of land use is complicated by coeval variations in other independent environmental factors (e.g. the incidence of intense rainstorms).

Fig. 33. (A–B) Tufa substratum scour marks resulting from Roman dredging of the harbour bottom at Piazza Municipio, Naples. Excavations directed by D. Giampaola (Archaeological Superintendence of Naples) and assisted by V. Carsana.

(3) *Frequent chrono-stratigraphic inversions* are observed from the Roman period onwards. Rapid aggradation of marine bottoms impinged on the 1 m minimum draught depth required for ancient shipping, a problem which grew so acute that it necessitated a management response (Hesnard, 2004a,b). Harbour dredging phases have been unequivocally evidenced in a number of ancient harbours, characterised by the removal of great tracts of Bronze Age and Iron Age sediments (Marriner and Morhange, 2006a). This can create an important archive loss in certain areas of the basin (Fig. 33). Recognising these hiatuses is significant in estimating the archaeological importance of the archive in question.

(4) *Granulometric paradox*. Roman facies are diagnosed by a granulometric paradox juxtaposing plastic clays, indicative of the prevailing low-energy hydrodynamic processes, and a coarser gravel fraction comprising seeds, charcoal, wood fragments, molluscan shells

and a plethora of archaeological artefacts. This latter cultural input attests to the basin being used as a huge waste dump by ancient societies.

A relative decline in harbourworks after the late Roman and Byzantine periods is manifest in a return to 'natural' sedimentary conditions comprising coarse-grained sands and gravels. Following thousands of years of accelerated anthropogenic confinement, reconversion to a natural coastal parasequence is typified by high-energy upper shoreface sands. A change in geometry is also observed with transition from aggradational to progradational strata. This progradation significantly reduced the size of the basins, burying the heart of the anchorages beneath thick tracts of coastal and fluvial sediments.

7. The ancient harbour: an archaeological paradigm?

Traditionally, poor archaeological layers were overlooked as data voids, however an increasing body of literature suggests that the judicious use of litho and biostratigraphies can yield extensive data in apparently homogeneously sterile strata. In opposition with traditional research approaches to port complexes we posit that the outlined geological processes have created an important archaeological archive that has the potential to significantly advance the study of coastal archaeology.

The latter has traditionally been dominated by architectural approaches to the study of boats, to the detriment of supporting port infrastructure and settlement. Although potentially rich archives in terms of, for example, patterns of consumption, shipwrecks relate to a single event in time and therefore remain relatively modest in spatial and temporal terms. Whilst shipwrecks and their 'sunken treasures' have captured the public imagination (Ballard, 1987; Goddio et al., 1998; Ward and Ballard, 2004) from a holistic perspective they are relatively marginal pieces of the maritime record, given priority over and diverting resources from the local and regional coastal pictures.

Despite the promising beginnings of maritime archaeology in the 1930s and 1940s, our understanding of ancient harbours has actually advanced very little compared to other aspects of the science (Poidebard, 1939). Until the 1990s, and to a great extent even today, it is striking that technological advancements (underwater coring, side-scan sonar, geophysical cartography etc.) are paradoxically contrasted against multi-disciplinary research stagnation. In effect, traditional approaches can only have a limited effect on the future development of this subject whilst the pioneering multi-disciplinary projects at Caesarea and Marseilles show the scope of a theoretically informed landscape approach. Areas as culturally complex and dynamic as the coast require flexible multifaceted research strategies. Use of the geological record allows three types of information to be teased out:

(1) *Where?* Geoscience techniques can be used to spatially locate ancient harbour basins. Diagnostic litho- and biostratigraphies, consistent with human modified basins, are clearly translated in the geological record. At locations where the approximate location of the former basins is known, geoarchaeology facilitates a high-resolution reconstruction of the harbour history (e.g. Alexandria, Caesarea and Marseilles). In areas where the basins are not spatially constrained, reconstruction of the Holocene coastal history can aid in advancing informed hypotheses concerning their location (e.g. Cuma, Tyre's southern harbour). (2) *When?* The transition from natural to anthropogenic environments recorded in the stratigraphy can be dated using either radiometric or ceramic dating techniques. (3) *How?* How did local populations modify their coastal environment? Either (a) indirectly, through the production of increased sediment yields; and (b) directly, by modifying their natural environment to produce low energy basins. Recent work from the Levantine coast indicates that these impacts were relatively moderate during the Bronze Age and reached their apogee during the Roman period.

Harbour basins are also appropriate for the analysis of archaeological data at three scales. (1) Basin scale: an informed geoarchaeological approach can yield insights into the harbour basin topography, its functioning, spatial organisation, and coeval infrastructure through time. (2) Urban scale: information pertaining to the site's occupation history, notably using geochemistry and geophysics, is made possible due to high rates of sedimentation through time. (3) Regional scale: typological data can be derived on how these individual maritime sites interacted as regional economic complexes.

The unique geological specificity of ancient harbours means that former marine environments can be probed over large areas using terrestrial or submarine survey methods. We outline six areas relevant to coastal archaeology at present:

7.1. Logistic difficulties of excavating in heavily urban contexts

The logistic difficulties of excavating in heavily urban contexts are significant, for example at Alexandria (Goiran et al., 2005), Naples (Giampaola et al., 2004) and London (Milne, 1982; Milne and Bateman, 1983; Milne, 1985; see De Maria and Turchetti, 2004a, b; Zevi and Turchetti, 2004a,b for other examples).

Evidence is quintessentially fragmentary and difficult to integrate into wider spatial and temporal archaeological pictures.

Coastal archaeology is significantly linked to the whims of the construction industry, whose planning delays are invariably incompatible with scientific agendas. A major challenge is therefore to extract the maximum amount of data over relatively short time periods. Grounding this in a robust intellectual framework is a major challenge. The protected site of Caesarea is an excellent example of meticulous research undertaken over the long-term with an aim not only to expound but also to preserve the site's cultural heritage. At the majority of urban sites such minutiae are not possible and the geosciences have a key role to play in identifying and rapidly delimiting those areas of greatest research potential. At Sidon and Tyre, recent geoarchaeological research has allowed the ancient harbour areas to be precisely delimited, showing that the heart of the ancient basins lie beneath the modern urban centres and constitute areas of immense archaeological importance (Franco, 1996; Marriner and Morhange, 2005). Future construction must consequently be undertaken in close collaboration with the archaeological authorities. At Marseilles, the precise reconstruction of shoreline progradation is a good example of how urban planning and geoscience can be reconciled (Morhange et al., 2003).

7.2. Difficult working conditions below the water table

Notwithstanding the considerable advances made in coastal archaeology since its beginnings, working conditions remain difficult and often prohibitively expensive. For example, it is not usually possible to excavate vertical cross sections below sea level, or the water table line, because sand and silt do not hold an appreciable wall. This renders the systematic recording of stratigraphy at best difficult and at worst impossible. Consequently, stratigraphy at coastal sites has in the past often been ignored or not properly examined. Casing and coring techniques can overcome these problems and rapidly expound the coastal and archaeological stratigraphies with a view to precisely directing resources.

7.3. High-resolution archaeological data

That some objects survive well in certain depositional contexts but not others has been acknowledged by archaeologists since the nineteenth century (Caple, 2001). This paradox has greatly skewed interpretation of the archaeological record and led early antiquarians to define prehistory on the basis of what was preserved: stone, bronze and iron. The only opportunity to gain a holistic view of the past is when we find remains in frozen (e.g. Ötze the ice man), desiccated or waterlogged anoxic conditions which preserve organic and other materials.

Large-scale urban excavations such as those at Marseilles and Naples have shown the considerable research scope of ancient harbour geoarchives. The unique preservation potential of fine-grained silts and sands (low-energy anoxic environment), is one of the key defining elements of the harbour geological paradox and is significant in probing the artefactual record. Enveloping sediments, coupled with the presence of the water table, have the potential to preserve otherwise perishable archaeological artefacts such as wood, leather etc. (Holden et al., 2006). The most impressive archaeological findings to date include numerous shipwrecks (yet again!) and well-preserved wooden harbourworks (Pomey, 1995). The density of both vertical and horizontal information is exceptional.

7.4. Sea-level studies

The analysis of harbourworks and the fixed and boring fauna attached to structures has long been recognised as a potential source of sea-level data (Pirazzoli and Thommeret, 1973; Laborel and Laborel-Deguen, 1994; Morhange et al., 2000). Such data, fundamental to understanding the vertical distribution of coastal remains, had traditionally derived uniquely from the geological and geomorphological record (note that Lyell, Negris and Cailleux were all exceptions to this). Where precise vertical relationships can be established between archaeological structures and biological palaeo-sea levels it has been possible to accurately reconstruct relative sea-level trends since antiquity at a number of Mediterranean sites (Pirazzoli, 1976, 1979–1980, 1980, 1987b, 1988). Three groups of structures have traditionally been used (Blackman, 1973b; Flemming, 1978; Flemming, 1979–1980; Flemming and Webb, 1986; van Andel, 1989; Stanley, 1999; Blackman, 2003): (1) emerged vestiges (dwellings, stock houses, walls); (2) partially emerged structures (quays, mooring-stones, slipways, channels; coastal wells can also give insights into sea-level tendencies (Sivan et al., 2001)); and (3) submerged structures (shipwrecks). Unfortunately, the technique tends to be marred by large altitudinal errors, where the envelope of imprecision is often as important as the absolute sea-level change, and dating uncertainties, in addition to the interpretative vagaries of certain structures. Another problem is linked to the geological meaning of these data.

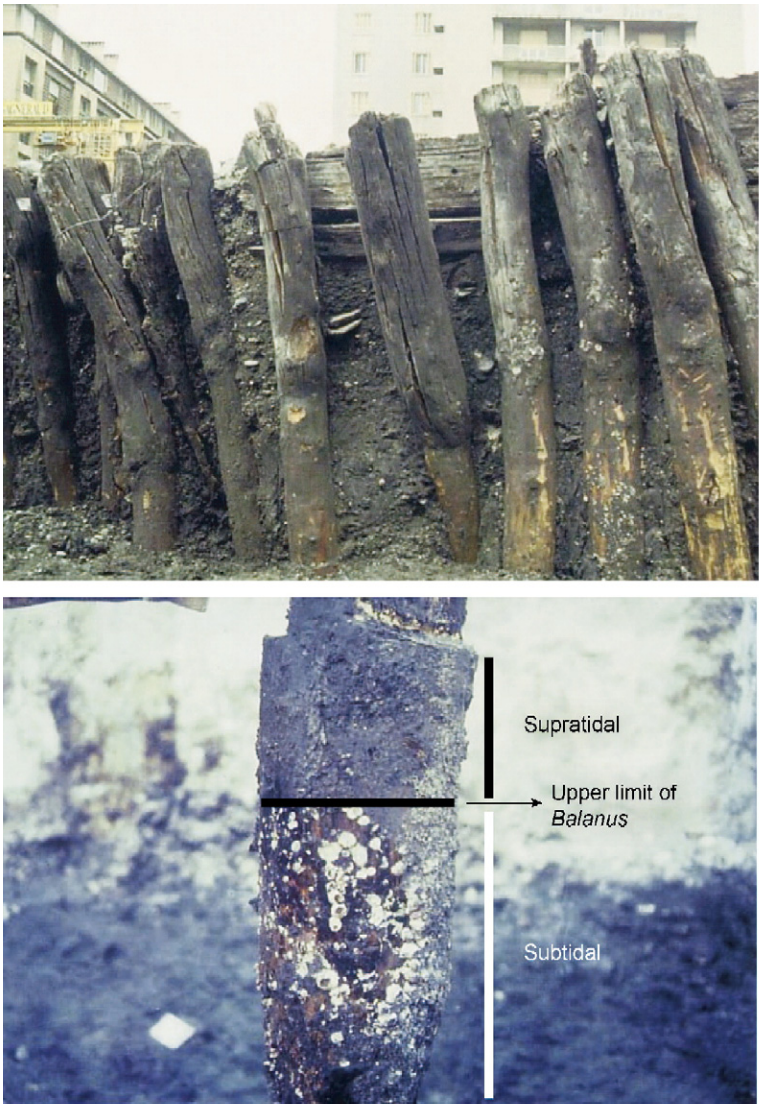

Fig. 34. Top: Marseilles excavations, Place Jules Verne. Bottom: the upper limit of fixed fauna on stakes from the harbour's Roman quays. By measuring the upper altimetric difference between fossil and contemporary populations it is possible to accurately infer palaeo-sea levels during antiquity (photographs: Morhange).

Pioneering work in the 1970s demonstrated that these shortfalls could be overcome using biological fossil remains attached on or in certain interface harbour structures (e.g. quays and jetties). By transposing the techniques developed on rocky coasts (Pirazzoli, 1988; Stiros et al., 1992; Laborel and Laborel-Deguen, 1994) to the ancient harbour context, precise sea-level datasets have become a possibility. Not only do biological remains yield organic material for radiocarbon dating but the biological zonation of certain species (e.g. the upper limit of *Balanus* spp., *L. lithophaga*, *Vermetus triqueter*, *Chama griphoides* populations) is empirically and precisely linked to biological mean sea level (Péres, 1982; Laborel and Laborel-Deguen, 1994). By measuring the upper altimetric difference between fossil and contemporary populations low vertical error margins of ±5 cm can be obtained (Figs. 34–35).

7.5. Long-term archives of anthropogenic impacts

Relationships between man and his environment have long been considered in quasi-isolation, either from a human perspective or an environmental stance, rather than a coevolution where both are complementary. In our opinion, harbours can be used to write the history of man and his interactions with the environment since prehistory.

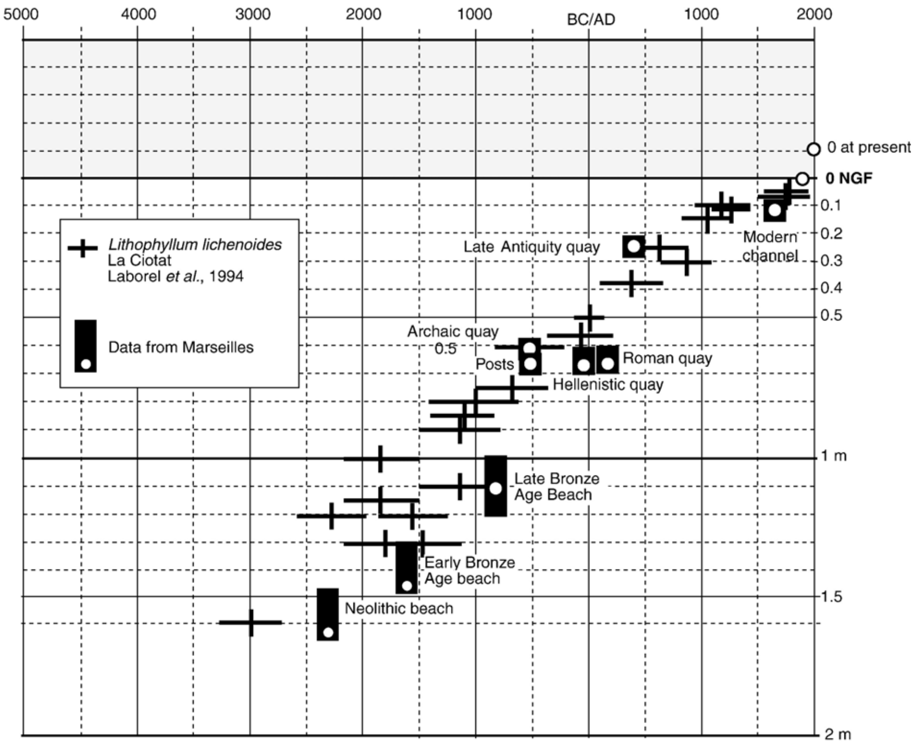

Fig. 35. In the ancient harbour of Marseilles (southern France), marine fauna fixed upon archaeological structures, allied with bio-sedimentary data, document a steady 1.5 m rise in relative sea level during the past 5000 yr. A near stable level, at present datum, prevailed from 1500 yr AD to the last century. This trend is similar to the one previously documented on the rocky coasts of Provence, southern France. Field observations inside and outside the harbour confirm that no sea-level stand higher than present occurred during the study period. Since Roman times, relative sea level has risen by ~50 cm (after Morhange et al., 2001).

The presence of man is manifested by a number of proxies that cumulatively have significant historical scope. (1) *Granulometric impacts*: the construction of harbourworks is at the origin of a unique fine-grained facies. This lithoclastic signature facilitates a delimitation of the ancient basin topography. (2) *Morphological impacts*: the rapid aggradation of harbour bottoms leads to accelerated coastline progradation. The precise study of accumulation rates and sedimentary fluxes yields insights into the erosional system, notably landscape use at both the urban and watershed scales. (3) *Biological pollution*: modification in faunal assemblages translates local anthropogenic inputs such as increases in turbidity and use of the basin as a waste depocentre over many thousands of years. (4) *Geochemical impacts*: lead has proved to be a powerful tool in recognizing ancient industrial activities (Shotyk et al., 1998; Véron et al., 2006).

7.6. Cultural heritages

It is now widely recognised that archaeological remains are a finite resource endangered by modern encroachment (Galili and Sharvit, 2000). At present, ancient harbours are disappointingly neglected in coastal preservation policy. The paradox of underwater sites today buried on land provides a potentially unique opportunity to showcase these cultural heritages to the general public. Outgrowth ideas for coastal parks have been advanced by a number of authors but very few have in reality come to fruition, be it for financial and/or logistic constraints (Franco, 1996). Unlike their drowned counterparts (e.g. Pozzuoli's Portus Julius, Alexandria's eastern harbour), with their problems of visibility and access, buried harbours are unique in that they can be preserved on land allowing visitors to walk freely amongst the vestiges. Married with modern forms of museum exhibition and harbour reconstructions the didactical and tourism potentials are far-reaching. Such parks also have a role to play in the preservation of sites.

Very few well-preserved examples actually exist, and Marseilles is at present a rare exception. At Caesarea, an underwater archaeological park for divers was trialled during the 1990s (Raban, 1992b) and in 2006 became the first park of its kind. Visitors are furnished with plastic guidebooks and maps and follow cable guidelines to explore the submerged remains and harbourworks. Divers view some 36 different sign-posted sites along four marked trails in the sunken harbour covering an area of ∼73,000 m^2. For less-experienced divers, one trail is also accessible to snorkelers. The others, ranging from 2 to 9 m below the surface, close to the beach, are appropriate for any beginner diver.

One of the potentially best sites is that of Portus, near Rome Ostia, a site which has long captured the public imagination and scholarly interest. Presently buried beneath thick tracts of coastal and fluvial sediments, the harbour remains are still clearly visible. Although a small museum does presently exist at the site, the rich archaeological potential is not exploited to the full (Mannucci, 1996) and Rome's international airport and large urban agglomeration are pressures on the preservation of the site.

In collaboration with local, national and international (e.g. UNESCO World Heritage) organisations a major challenge facing maritime archaeology is to develop a robust conservation framework at the Mediterranean's most important sites. Many ancient ports raise numerous coastal management issues which need addressing in order to ensure the harmonious development of human activities while protecting the submerged remains of the ancient cities. Issues such as urban expansion and environmental problems have increased significantly in recent years. For example at Alexandria, a site of worldwide significance in terms of its coastal archaeology, problems of wastewater pollution are a major obstacle to an underwater archaeological museum.

8. Conclusion

It would be wrong to engage in a scientific discourse of the archaeological positives of this new ancient harbour geoscience without exposing some possible shortfalls. Whilst use of the geological record must by no means be seen as a talisman by which to heal all ills, a number of fallibilities remain, often not relating specifically to the overriding discipline itself but rather the tools used. From the perspective of the archaeologist, the new field could be criticised as being overly geocentric. This is to some extent reflected in the propensity for much of the recent literature to feature in specialised geological journals. Thus far, it would appear that a fair *terrain d'entente* has been found whereby geological data is being correctly tied into the archaeological context and vice versa. Progress must be made on two key questions:

(1) Can ancient harbours document historical events? Whilst ancient harbours have been shown to be replete with archaeological information, accurately pinpointing precise historical events can be problematic. Ancient harbours are not annual archives and although considerable advances have been made, discrepancies remain in the relationship between calendrical and radiometric chronologies. At sites where whole sections can be investigated archaeological material can provide good decadal temporal resolution. Where this information is not readily available (e.g. core stratigraphies), radiocarbon chronologies can produce broad bands of dates (centennial resolution), although these are never capable of precisely reconciling certain events, such as harbour construction, with any great degree of precision. This problem is further accentuated in the coastal domain by the vagaries of marine calibration (Reimer and McCormac, 2002). A great deal of recent research has sought to establish local site-specific reservoir ages, although this can be subject to significant variation (Siani et al., 2000). There is therefore a manifest paradox between high-resolution geological data, capable of recording rapid cultural change, and the dating resolutions used to constrain this narration.

(2) Until recently, harbour sediment archives were taken to be relatively continuous records of anthropogenic and coastal change since antiquity. However, a mounting body of evidence elucidating Roman and post-Roman dredging practices suggests that this premise should now be moderated. At sites such as Marseilles, Naples, Sidon and Tyre, significant dating discrepancies coupled with unique sedimentologies provide widespread evidence of repeated dredging from the third century BC to the fifth century AD (Marriner and Morhange, 2006a). Such practices were of course logical management responses to the silting problem and ensured harbour viability. In many ports therefore, significant tracts of Bronze Age and Iron Age strata are missing. Precisely constraining this loss of space and time is fundamental in assessing the archaeological scope of the harbour basin. It also suggests the need for core networking to yield the most complete stratigraphic record possible and identify those areas of missing and complete record.

Although ancient harbour geology is a paradigm thus far little known in archaeology we believe it represents a significant shift from dogmatic to pragmatic research which opens up new interpretative possibilities. It is an innovative means of integrating various scales and types of data with potentially profound and pervasive implications for maritime archaeology as a whole. Traditional disciplinary studies have been shown to be largely inadequate when considered in isolation and a geoarchaeological approach is particularly useful in areas of data paucity.

Whilst paradigm shifts are often slow to reach wider acclaim we believe it is fundamental to link wreck archaeology with the coastal, and notably harbour research, to formulate a more holistic picture of maritime landscapes in antiquity. The benefits of a geoscience approach, both in terms of cost effectiveness and data wealth, are arguably unparalleled. We deem it important to develop new scientific arenas, integrating this new approach with an interpretative archaeology.

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