

Developments in Geoarchaeological Research, Methodologies and Applications in Harbour Maritime Archaeology

Jean-Philippe Goiran, Winnie May Chan, Christophe Benech, Quentin Vitale Vitale, Nicholas Riddick, Hugo Delile, Ferréol Salomon, Stoil Chapkanski, Christine Oberlin, Gilles Y. Brocard, et al.

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Developments in Geoarchaeological Research, Methodologies and Applications in Harbour Maritime Archaeology

Overview

Geoarchaeology or *archaeology geology*[1] applies integrative concepts and methodologies from geosciences (e. g. geophysics, sedimentology, geomorphology, and pedology) to address archaeological questions. The objectives of geoarchaeological projects may include the reconstruction of an ancient landscape and/or environment, the dating of materials to establish a chronology, and determining site formation and the provenance of artefacts. Achieving these objects can provide insight into how a social group lived and how they responded to environmental changes. For example, geoscientific data may help archaeologists understand why Group X settled in Region Y or determine whether climate change caused or contributed to the demise of Group Z. Geoarchaeological applications were first introduced in the 19th century by Scottish geologist Sir Charles Lyell (1797-1875) in his book *Geologic Evidences of the Antiquity Man*, originally published in 1863, where he applied stratigraphic laws to understand the formation of Prehistoric sites[2]. Technological advancements during the 20th and 21st centuries led to improvements in field and lab techniques as well as new analytical equipment, such as high-resolution XRF core scanners[3] and Geographical Information Systems (GIS). As a result, geoarchaeological research is now being conducted all over the world in terrestrial, coastal, and aquatic environments.

Ancient Harbour Geoarchaeology

Maritime archaeology focuses on understanding the interaction between ancient societies and the sea using material and cultural remains including, shipwrecks, harbour basins, and submerged infrastructure[4]. The development of self-contained underwater breathing apparatus (SCUBA) during the 1900s allowed marine archaeologists to access the underwater world, and lead to major discoveries (e. g. the lost city of *Heracleion* in Egypt)[5]. This development has also helped Earth scientists to better interpret the importance of sea level change and its impact on ancient coastal societies[6].

The integration of geoscientific methods in maritime archaeology expanded in the 1980s around the Mediterranean, with reconstructing harbour basins being popular today[7]. For example, Reinhardt et al.[8] and Goiran and Morhange[9] revolutionized Mediterranean maritime archaeology by applying high resolution time-series sedimentary data, micropaleontology, and geochemistry to understand the environmental and anthropogenic influences that eventually led to the abandonment and destruction of ancient Mediterranean harbour cities. Reconstructing the functionality of ports and harbours is another important aspect of ancient harbour geoarchaeology.

Goiran et al. developed a model from sediment archives from *Alexandria* (Egypt), *Avaris* (Egypt), and *Portus* (Italy), to define the different types of harbours (**fig. 1**)[10]. This model can be used to identify the type of harbour (i. e. protected, or semi-protected), the foundation and/or termination of the harbour, and it may also provide an overview of how the harbour was used when it was active (i. e., the type of boats that would enter, etc.). This model is divided into three units: (I) *pre-limenic*, (II) *limenic*, and (III) *meta-limenic*. The pre-limenic unit, or *pre-harbour* phase, represents the depositional environment before the construction of the harbour. This unit is important for revealing how harbour basins were initially excavated[11]. For instance, pre-limenic and limenic units in stratigraphic continuity indicate that the basin was deep enough to support boats and that dredging was not required for harbour construction. The limenic unit contains harbour sediments when it was fully operational. The type of sediment found in this unit varies depending on the qual-

1 Hassan, Geoarchaeology: The Geologist and Archaeology 267.
2 Pollard, Geoarchaeology: an introduction 8.
3 Delile et al., the contribution of geochemistry to ancient harbour geoarchaeology 171.
4 Gibbins/Adams, Shipwrecks and maritime archaeology 279.
5 Goddio, Topography and Excavation of Heracleion-Thonis and East Canopus.
6 Benjamin et al., Late Quaternary sea-level changes and early human societies 42-45.
7 Raban, Harbour Archaeology.
8 Reinhardt et al., Caesarea Maritima.
9 Goiran/Morhange, Géoarchéologie.
10 Goiran et al., The Geoarchaeology of ancient Mediterranean Harbours.
11 Goiran et al., The Geoarchaeology of ancient Mediterranean Harbours 292.

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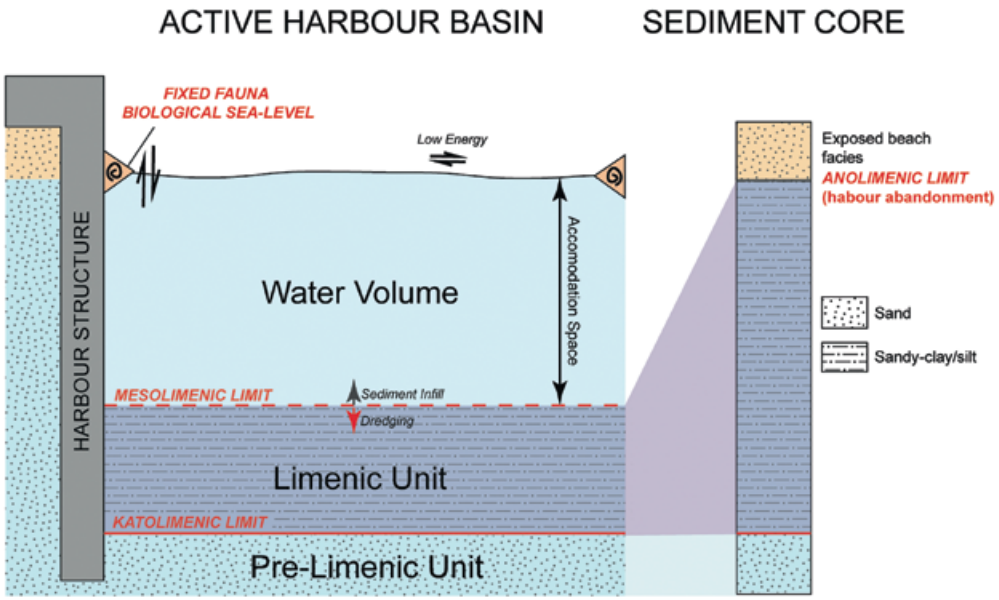


Fig. 1 Modified version of the Active Harbour Basin model originally published in Goiran and Morhange (2003), showing a typical sequence stratigraphy from a core sample.

ity of harbour infrastructure (i. e., whether the artificial basin is protected or semi-protected from marine or fluvial influence). A well-protected harbour, for example, will have a limenic unit containing silt and clay sediments which is characteristic of a confined low energy environment. A sandy limenic unit indicates an open harbour basin or an entrance of the harbour[12]. This unit may also reveal one or several dredging phases which is important for understanding how these harbours respond to various depositional environments. It also helps researchers understand how ancient societies maintained the basin while the harbour was in function as the economical/trade heart of a coastal city. The meta-limenic unit, or the inactive/post harbour phase, is often identified by a sharp contact with the limenic unit. The meta-limenic facies contains coarser sediments (e. g. similar to exposed beach or dune environments) or fine-grained silt sediment due to fluvial floods and/or deltaic progradation. Analysing this unit can determine the cause of abandonment of the harbour (i. e., whether the causes were natural or anthropogenic). Furthermore, these harbour units are divided by three limits (or boundaries): (I) *katolimenic*, (II) *mesolimenic*, and (III) *biological sea level*.

The katolimenic limit is the contact between the pre-limenic and limenic units. It is the initial limit of the harbour basin construction (i. e., the initial digging of the basin). The katolimenic unit can therefore be the foundation level or also the deepest point of harbour dredging in the basin. The latter means the initial foundation level has been destroyed by several dredging phase(s). The mesolimenic limit, or the harbour bottom, is the boundary between the ancient harbour deposits (i. e., the volume of sediment accumulated in the basin) and the water volume in the basin. It represents the upper part of sediment accumulation in the basin while the harbour was active. When the mesolimenic is closed (or reaches) the sea level, it implies that the harbour basin is infilled and near abandonment. For example, progressive abandonment is evident when there is a gradational change in facies between the limenic and meta-limenic units. A stratigraphical sharp contact implies that the abandonment process was quick (i. e., from floods, storm activity, destruction, etc.). In a stable tectonic context, the ancient biological sea level is determined using the highest measured fixed infralittoral marine fauna found on harbour quays[13]. The height of the water column (or referred to as *accommodation space* in geology) can be determined by comparing the depth of the mesolimenic limit and the biological sea level. This is useful for determining the precise depth of the harbour and can be used to construct a bathymetric profile of the basin. Once the depth of harbour is known, archaeologists can also determine which boats had access to the quay by comparing the calculated basin depth with known ancient ship draughts[14].

12 Goiran et al., Paleoreconstruction of ancient harbours of Rome 3-13.
13 Goiran et al., Découverte d'un niveau marin biologique 61. – Salomon et al., The Development and Characteristics of Ancient Harbours 7. – Vacchi et al., Multiproxy assessment of Holocene relative sea-level 177.
14 Goiran et al., High chrono-stratigraphical resolution of the harbour sequence 68-84.

Methodologies in Geoarchaeological Research

Mapping and site surveying

The initial steps in geoarchaeological research involve site surveying and mapping for excavation purposes and the understanding of the geomorphological characteristics of the study area. This is often conducted using advanced geophysical methods and spatial analysis tools such as Geographic Information Systems (GIS) and remote sensing. This section will summarize the technological developments of these methods and tools and how they are integrated into geoarchaeological research on ancient harbours.

GIS & Remote Sensing

Both GIS and remote sensing techniques are pivotal tools for spatial analysis in geoarchaeological research. Remote sensing techniques (e. g. aerial photography and satellite imagery) help researchers identify and monitor cultural and natural landscapes as well as reconstruct geomorphological changes over time[15]. Advancements in remote sensing over the past few decades including Light Detection and Ranging (LiDAR) and Interferometric Synthetic Aperture Radar (IFSAR or InSAR) technologies provide higher resolution data and have the ability to detect archaeological structures that may be covered (e. g. by vegetation)[16]. Furthermore, GIS is a computerized tool that is often used for site prospection, geo-statistics, and predictive modelling for geoarchaeological research. GIS models are used for determining research field strategies such as determining where to sample sediment cores) and for interpreting human behaviours influenced by the surrounding natural landscape by analysing the distribution of cultural remains[17]. Pourkerman et al., for example, created a model that monitors and tracks shoreline erosion in Siraf, an important port that served as one of the main hubs for trading goods (i. e., Chinese ceramics and silk) between the Persian Gulf and Asia[18]. This model enabled the researchers to localize where coastal erosions are occurring and determine the cause. These predictive models are produced through calculating, setting, and ranking various parameters based on scientific (e. g. paleoclimate, geological, and hydrological data) and available historical literature describing past human behaviours. Another advantage to GIS is it is an efficient and cost-effective tool that can add significant value to geoarchaeological research especially when funding and/or accessibility of a region is an issue[19].

Geophysics

Site surveying is often conducted using advanced geophysical methods for excavation purposes and to understand the geomorphological characteristics of a region. This involves mapping the archaeological site and identifying landscape changes. The significant development of technology in the last 20 years has made it possible to integrate geophysical methods into the geoarchaeological exploration of ancient harbours.

Geophysical methods and tools used to conduct both archaeological and environmental research depend on the type of landscape and the scale of the study area. The first step to an archaeological excavation on an ancient harbour is to conduct a geophysical survey to detect structures related to the harbour activities, such as quays and storage spaces, and to understand the context behind port infrastructures to its adjacent city. This includes understanding and identifying areas of access (i. e., traffic lanes) and/or locating site fortifications. Geophysical surveys may also lead to the discovery of new neighbourhoods and the development of urban landscapes. The technology required to conduct these surveys must be quick and detailed, as the study areas are typically thousands of square kilometres in size[20]. Although various methods are used to detect infrastructures, magnetic surveys are considered the most suitable method for a wide range of possible structures and building materials, with a reasonable survey depth up to 2 m.

The electrical methods are used less often in coastal geoarchaeology because they are notably slower and more cumbersome to implement compared to systems that give results at a reasonable time[21]. The ground penetrating radar method (GPR) is a good alternative, as towed systems are used that considerably improve the performance of this instrument and allow a depth of investigation equivalent to the magnetic method or even higher, depending on the nature of the environment. However, it should be noted that the GPR is not suitable for use in environments where clay sediments are prevalent, which can be problematic in coastal areas. The penetration depth in such environments is no more than a few tens of centimetres, which in most cases is not sufficient to detect archaeological structures. Nonetheless, the GPR remains useful in an integrated approach with other geophysical data[22]. Furthermore, there are only a few studies that use geophysical surveys and geomorphological drilling to understand the organisation of ancient harbours[23].

Geophysical methods provide additional information to contextualize the results of sediment cores and correlate them spatially to provide different scales. The magnetic method can

15 Holcomb/Shingiray, Imaging Radar 11.
16 Maktav et al., Integration of remote sensing and GIS 1667.
17 Nsanziyera et al., GIS and Remote Sensing Application 2-3.
18 Pourkerman et al., Shoreline erosion. – Shen, The China-Abbasid Ceramics Trade.
19 Nsanziyera et al., GIS and Remote Sensing Application 16.
20 Mozzi et al., The Roman City of Altinium 31-34.
21 Campana/Dabas, Archaeological Impact Assessment 145-147.
22 Neal/Roberts, Applications of ground-penetrating radar (GPR) 140-145.
23 Marriner/Morhange, Geoscience of Ancient Marine Harbours 162-165.

be useful for shallow/on surface formations, such as recording the evolution of banks or detection of paleochannels[24]. For more detailed studies on stratigraphy, electrical resistivity tomography (ERT) is the most widely used method. ERT provides large transects of vertical sections of the ground that can be directly correlated with the stratigraphic results obtained from sediment cores[25]. Electromagnetic induction (EMI) measures both electrical conductivity and magnetic susceptibility. The former is useful for detecting paleochannels or the boundaries of ancient lagoons or coastlines[26]. The latter detects the ferrimagnetic content in the top meter of the soil, which may be associated with human occupation and activities[27]. The Portus project led by the British scholar Simon Keay (University of Southampton), used these methods to show interest in an interdisciplinary approach to integrate archaeology, geophysics, and geomorphology to reconstruct the organization and operation of the harbour from an archaeological and environmental perspective[28]. Furthermore, geophysical methods can also provide insight into the evolution of harbours located in modern cities in a dense urban context.

Regarding an urban context, archaeological excavations can be achieved in the case of a temporary allotment (e. g. obtaining a permit from the government, private company, etc.) which can lead to complications in planning and executing excavations. This means non-destructive tools are essential for understanding the complexities of these environments and their extensive history. Geophysical exploration will not be able to obtain the same degree of information as in a non-urbanized environment and locations are also subjected to modern urban constraints. The integrated approach, however, remains an essential part of the study. It is essential to correlate findings to understand the exploration project. A »blind« prospection will lead to failure: a geophysical prospection will be used to validate a preliminary hypothesis but will not provide meaning without using a multidisciplinary approach considering the complexities of the subsoil. From a methodological standpoint, it is the electrostatic method[29] and GPR[30] that remain the two methods most adapted to the modern urban context. In an urban context, the depth of investigation of a geophysical method cannot be limited to the first meter and requires at least 2 m to detect surfaces undisturbed by modern occupation. The technical developments of electrostatic devices help with the range of methods that can work on the first 2 m[31]. New electrostatic systems can reach a depth of 3 to 4 m: the resolution will as a result be lower, but such systems can detect larger structures including city walls[32].

Sediment Core Analysis in Harbour Geoarchaeology

Sediment Analysis is important for (I) reconstructing the paleoenvironment and paleoclimate to understand how the environment may have influenced the construction of a harbour and (II) determining the foundation, dredging phases, and destruction/abandonment of an ancient port. Such analyses are carried out by taking surface samples or sediment cores. The research goals and the type of environment (i. e., deltaic, lacustrine, marine, etc.) determine the choice of coring method: vibration, percussion, piston, and gravity cores, augers, and large coring rid. Coring devices are summarized in **Table 1**.

Once sediment cores are collected, various analyses are conducted, such as grain size, geochemistry, mineralogy, magnetic susceptibility, and micropaleontology. The examination of bed-forms (e. g. ripples and dunes) and types of stratification is also used to determine the depositional environment. Sediment analyses helped geoarchaeologists reconstruct ancient harbours, such as identifying the foundation of the harbour (i. e., pre-limenic unit), how the basin was excavated (i. e., dredging phases) and used as identified in the limenic unit (**fig. 1**).

Micropaleontology

Micropaleontological analysis can be used for many applications including biostratigraphy, paleoenvironmental reconstruction[33], paleotempestology, tsunami/seismicity, pollution, and reservoir mapping. Reinhardt et al., for example, used micropaleontology (foraminifera) along with geochemical analysis (Sr isotopes) from sediment cores collected in Caesarea Maritima (Israel) to understand the harbour's evolution from 1st c. BC to its destruction in 2nd c. AD[34]. Microfauna is often used as a proxy for recording paleoclimate and paleoenvironmental changes because of their sensitivities to ecological changes. This section will focus on common groups of microfossils used in geoarchaeological research: I) Foraminifera, II) Ostracods, (III) Diatoms, and (IV) Palynology.

Foraminifera

Foraminifera (or forams for short) are single-celled protozoans that produce their own tests (shells) through autogenous (i. e., secrete calcium carbonate) or xenogenous processes (i. e., agglutinating foreign detritus material)[35]. Calcareous

24 Weston, Alluvium and Geophysical Prospection 266-270.
25 Wunderlich et al., The river harbour of Ostia Antica 55-65.
26 Verhegge et al., Preliminary results of an archaeological survey 166-168.
27 Tabbagh, Electromagnetic Prospecting Method 186-190.
28 Keay et al., The role of integrated geophysical survey methods 155-164.
29 Tabbagh et al., Un outil de reconnaissance géophysique en milieu urbain 6-8.
30 Conyers, Innovative ground-penetrating radar methods 139-140.
31 Panissod et al., A novel mobile multipole system 983-984. – Panissod et al., Archaeological prospecting 240-242.
32 Benech et al., Revealing the topography of the Ancient Kition (Larnaka, Cyprus) 17-19.
33 van Hengstum et al., Thecamoebians (testate amoebae) and foraminifera 305-317. – Pilarczyk/Reinhardt, Testing foraminiferal taphonomy as a tsunami indicator 133-135.
34 Reinhardt et al., Caesarea Maritima.
35 Scott et al., Monitoring in Coastal Environments 99.

Coring Device	Description
Vibracorers	Electric powered Used in terrestrial, water saturated environments (lacustrine, marshes, bogs, lagoons, deltas and some fluvial systems) or deep-water environments Penetration: ~8 m
Augers	Travel friendly (i. e. handheld and can be used in inaccessible areas and can obtain long sequences of muds, peats, soils, and sands) Easy to operate but may not provide a continuous section Penetration: up to ~10-15 m
Percussion Coring	Portable Mud, sand, peat, and minor gravel Penetration: ~10 m
Large Coring Rig	Mounted on a truck or boat Used for areas that are not easily accessible and/or difficult terrain Penetration: +10 m
Piston Corers/Gravity Corers (Russian/Gorge)	Used in water saturated fine grained muds in lacustrine environments and deep lagoons Penetration: +10 m

Tab. 1 Summary and comparison among coring devices. – (After Shuter/Teasdale, Application of drilling).

foraminifera are either benthic or planktonic and are found in marine environments where the precipitation of calcium carbonate is possible[36]. Those with agglutinated tests are found in marginal marine environments, such as estuaries and lagoons, where calcium carbonate production is limited. These microorganisms are typically collected from sediment cores and/or surface samples. They are later washed using a recommended 63 µm sieve to capture forams that are typically 0.1 to 1.0 mm, but some species can grow >10 cm in size[37]. Specimens can be observed and identified using a stereomicroscope with no less than 40× magnification and can be picked wet or dry onto a storage slide. Species assemblages are identified based on test composition and its morphological structure including, the number of chambers, coiling, aperture, and ornamentation. Once processed, foraminifera can be used for geochemical analysis and for quantitative statistical analysis which commonly requires counting a minimum of 300 specimens per sample to calculate the relative fractional abundance of each species[38].

They are often used as proxies for monitoring or reconstructing ecological changes because of their sensitivity to environmental changes (e. g. pH, temperature, salinity, and dissolved oxygen), their preservation potential, and their abundance in the geological record (first in the early Cambrian[39]), as they are easy to collect and statistically analyse[40]. For these reasons, micropaleontological analyses involving forams are commonly used in paleoenvironmental and palaeoceanographic (planktonic species) studies. They have also been proven to be a useful proxy for ancient harbour geoarchaeology, beginning with Reinhardt et al. Study in *Caesarea Maritima* (Israel)[41]. In a more recent study around the Mediterranean, Seeliger et al. were able to use foraminifera concerning transgressive contact to reconstruct the Holocene sea level curve and determine the ancient sea level from the Bay of *Elaia* (Western Turkey), the home to Pergamum's harbour dating to Hellenistic and Roman times[42].

Ostracods

The ostracods (or *ostracodes*) are microcrustaceans that are ubiquitous in marine and non-marine aquatic environments (**fig. 2, 1**); additionally, there are some semi-terrestrial species[43]. These organisms secrete a low-Mg calcium bivalved carapace typically 0.5 to 2.0 mm in size[44] and are well-preserved in the sedimentological record[45]. Ostracods are useful proxies commonly applied in ecological monitoring as well as in paleoenvironmental and paleoclimate research[46]. Similar to foraminifera, they are sensitive to variations in their biotope, such as changes in temperature, salinity, dissolved oxygen, hydrochemistry, water depth, substrate, and productivity[47]. They are excellent bioindicators in brackish marginal marine environments[48], where they are more abundant and diversified than foraminifera[49], and in freshwater ecosystems[50]. The study of these microorganisms involves the analysis of the species assemblages of the samples, the population structure (i. e., age, sex, and valve ratio) of the species and the intraspecific morphological (i. e. size, shape, ornamentation) and chem-

36 Scott et al., Monitoring in Coastal Environments 3.
37 Saraswati/Srinivasan, Micropaleontology 12-14. – Scott et al., Monitoring in Coastal Environments 10-16.
38 Patterson/Fishbein, Re-examination of the statistical method 245.
39 Pawlowski et al., The evolution of early Foraminifera 11494-11498.
40 Scott et al., Monitoring in Coastal Environments 3-4.
41 Reinhardt et al., Caesarea Maritima.
42 Seeliger et al., Foraminifera as markers of Holocene sea-level fluctuations.
43 Smith et al., Class Ostracoda 769-770.
44 Smith et al., Class Ostracoda 758. – Reeves, Ostracods 339.
45 Smith et al., Class Ostracoda 760.
46 Boomer et al., Ostracods 164-167. – Reeves, Ostracods 347-350.
47 Boomer/Eisenhauer, Ostracod faunas as paleoenvironmetal indicators 137. – Smith et al., Class Ostracoda 770-773. – Reeves, Ostracods 341. – Frenzel/Boomer, The use of ostracods 74-82.
48 Boomer/Eisenhauer, Ostracod faunas as paleoenvironmetal indicators 135-142; Frenzel/Boomer, The use of ostracods.
49 Frenzel/Boomer, The use of ostracods 74. – Barbieri/Vaiani, Benthic foraminifera or ostracoda 217.
50 Ruiz et al., Freshwater ostracods as environmental indicators.

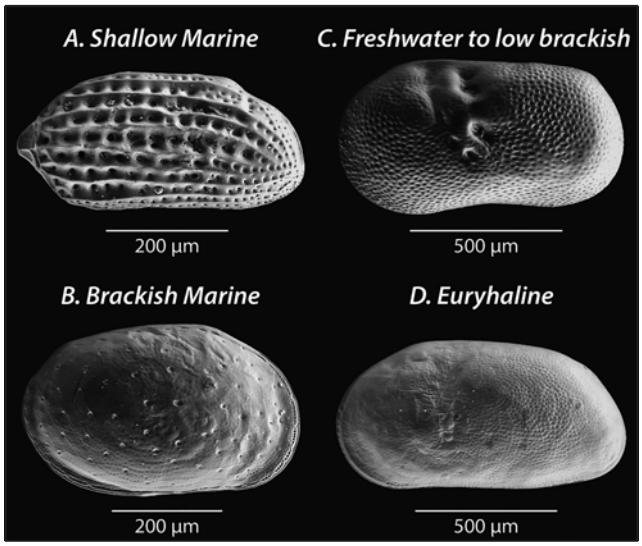


Fig. 2 Example of ostracod valves according to the ecological/environmental groups defined by Mazzini et al., Ostracods in archaeological sites along the Mediterranean coastlines 127-128 and table 1) for geoarchaeological studies: **A** shallow marine: *Semicytherura sulcata*, right valve, external view. – **B** brackish marine: *Loxoconcha elliptica*, male, right valve, external view. – **C** freshwater to low brackish: *Ilyocypris gibba*, left valve, external view. – **D** euryhaline: *Cyprideis torosa*, female, smooth valve, left valve, external view.

ical valve variations[51]. Commonly for core samples, only a few grams of dry sediment are processed using a 125 µm sieve or a finer 63 µm sieve to capture the smallest juvenile stage ostracods[52]. The ostracods are later picked dry under a binocular microscope with a fine brush and placed onto a black slide with a grid for counting and identification[53]. The most commonly used statistical threshold is 300 specimens per sample, but fewer individuals may suffice, especially for core samples requiring more samples to improve spatial and chronological resolution[54].

The ostracods are commonly used in archaeological and geoarchaeological research, especially to (1) determine the origin of ceramics and limestone and identify related quarries; to (2) reconstruct paleoclimates near human settlements and to study their impact on environments (i. e., soils erosion, pollution); and to (3) study paleoenvironmental changes in wetlands, such as lakes, lagoons, estuaries, and river deltas[55]. As such, they are excellent proxies for ancient harbour geoarchaeology in coastal (e. g. Portus in the Tiber Delta or Tyre in Lebanon), lagoon (e. g. Pisa in Tuscany), fluvial (e. g. Ostia in the Tiber Delta), or in limnological contexts (e. g. Magdala in Israel[56]). In these studies, the ostracods are used to identify harbour deposits based on the degree of isolation (i. e., in relation to the sea, rivers, and lakes) of the biotopes[57] and salinity variations that could indicate a connection with the sea, freshwater or marine inputs or evaporation periods concerning harbour infrastructures and management activities[58].

Diatoms

Diatoms are a diverse group of photosynthetic unicellular microalgae (phytoplankton) with a resilient silica-rich (SiO_2) cell wall called *frustules*[59]. There are ~200 000 species of diatoms found in aquatic environments around the world ranging from freshwater, brackish, to photic zones of marine water as well as moist terrestrial environments including soils and plants[60]. They come in many different shapes and sizes, from few micrometres to millimetres, and have two modes of life (i. e., benthic, living on the sea floor of submerged terrains or planktonic, floating in the photic zone)[61]. Diatoms, for example, are often classified into three groups: acidobiontic (pH <7), acidophilus (pH~7), and alkaibionic[62]. Their sensitivity to the pH of water makes them useful climate proxies in paleoliminological studies. In a marine environment, diatoms thrive in the photic zone and high upwelling zones. Diatoms are excellent proxies and are often used in paleoenvironmental research because of their preservation potential, abundance in the sedimentological record, as well as sensitivity and rapid response to changes in the environment (i. e., changes in pH, nutrient, temperature, salinity, etc.)[63]. The use of diatoms in geoarchaeological research is not a new phenomenon and has been practised for over 40 years[64].

Palynology

Palynology is the study of acid-resistant, organic-walled microfossils (palynomorphs); pollen, fungal spores, acritarchs and the remains of organic-walled algae, such as dinoflagellates and desmids. Palynomorphs can be found in sediments collected from freshwater and marine environments and

51 Boomer et al., Ostracods 158-164. – Reeves, Ostracods 342-347.
52 Horne/Siveter, Collecting and processing fossil ostracods 5. – Reeves, Ostracods 342. – Danielopol et al, Techniques for collection and study of ostracoda 72-73.
53 Horne/Siveter, Collecting and processing fossil ostracods 5-6.
54 Danielopol et al, Techniques for collection and study of ostracoda 75-77.
55 Mazzini et al., Ostracodological studies in archaeological settings 326-327. – Ruiz et al., Marine and brackish-water ostracods 94.
56 Marriner et al., Coastal and ancient harbour geoarchaeology 23. – Mazzini et al., Late Holocene palaeoenvironmental evolution of the Roman harbour of Portus 251-255. – Goiran et al., Paleoreconstruction of ancient harbours of Rome 10-12. – Mazzini et al., Ostracods in archaeological sites along the Mediterranean coastlines 134-138. – Goiran et al., Geoarchaeology confirms location of the ancient harbour basin of Ostia 395-397. – Rossi et al., New insights into the palaeoenvironmental evolution of Magdala ancient harbour 368-370.
57 Mazzini et al, Ostracods in archaeological sites along the Mediterranean coastlines 134-138. – Rossi et al., New insights into the palaeoenvironmental evolution of Magdala ancient harbour 368-369. – Marriner et al., Coastal and ancient harbour geoarchaeology 23.
58 Goiran et al., Paleoreconstruction of ancient harbours of Rome 12. – Mazzini et al., Late Holocene palaeoenvironmental evolution of the Roman harbour of Portus 255. – Goiran et al, Geoarchaeology confirms location of the ancient harbour basin of Ostia 395. – Rossi et al., New insights into the palaeoenvironmental evolution of Magdala ancient harbour 369-370.
59 Smith/Flocks, Environmental investigations using Diatom 1. – Chepurnov et al., Experimental studies on sexual reproduction in diatoms 91-154.
60 Bathurst et al., Diatoms as bioindicators of site use 2920-2921. – Armbrust, The life of diatoms in the world's oceans 185.
61 Bathurst et al., Diatoms as bioindicators of site use 2920. – Armbrust, The life of diatoms in the world's oceans 185-187.
62 Saraswati/Srinivasan, Micropaleontology 128.
63 Gasse et al., Diatom-inferred salinity in paleolakes 548.
64 Ognjanova-Rumenova, Paleoenvironment and archaeology 293.

represent a large group of organisms with varied environmental preferences (e. g. nutrient levels, acidities, salinities) and life modes (e. g. benthic, planktonic, autotrophic, heterotrophic)[65]. While providing information on terrestrial and aquatic environments, these microfossils can also yield insight into human activities. For example, the presence of cultivar pollen can infer agriculture/diet practices, increases in grass and other upland weed pollen may indicate land clearing by humans, and changes in aquatic palynomorph assemblages may reflect human-induced eutrophication[66]. Typical palynological processing involves the removal of non-organic constituents from a sample, usually with acids (hydrochloric to dissolve carbonates and hydrofluoric to dissolve silicates), and the addition of a known number of marker particles (e. g. *Lycopodium* spores; **fig. 3**[67]). The remaining residue is the acid-resistant, organic component that can be mounted on microscope slides and analysed for palynomorphs.

The relationship between archaeology and palynology goes back nearly a century, before the advent of radiocarbon dating, where pollen assemblages from archaeological sites were compared to the assemblages of nearby lakes and bogs[68]. Marriner and Morhange state that the use of palynology for harbour geoarchaeology has been limited, despite the presence of fine-grained harbour mud being suitable for palynomorph preservation[69]. They cite previous harbour studies where palynological analysis was inconclusive. Contamination caused by the transport of pollen in large water bodies is considered a limiting factor in harbour/coastal studies[70]. Recent harbour geoarchaeological studies employing palynology have been more successful. In studying the ancient Roman port of Ostia, Sadori et al. were able to infer phases of human impact and phases of increased siltation[71]. Respectively, the palynological signatures included relatively high pollen concentration with the presence of cultivar pollen (e. g. olive, cereals and grape) and relatively low pollen concentration with the presence of non-pollen palynomorphs like *Glomus* and *Pseudoschizaea* (**fig. 3**). More significantly, it was reported that algal remains were very scarce, and pollen was often poorly preserved in this study. Shumilovskikh et al., while completing a palynological analysis in the harbour of Elaia (Western Turkey), observed the dinoflagellate cyst *Peridinium ponticum* (**fig. 3**), a species endemic to the Black Sea[72]. This species has been observed several times, its first appearance coinciding with the Mithridatic Wars in the 1st century BCE, and has been taken as evidence of maritime trade. Recurrence of *P. ponticum* is thought to be due to repeated introduction into the harbour environment, the establishment of a population in the harbour, or both.

Geochemical applications

While harbour geoarchaeology emerged as a discipline at the beginning of the 1980s, geochemical methods were not applied until the mid-2000s. Its first application was to determine human impact based on traces of ancient metal, such as lead (Pb), copper (Cu), nickel (Ni), silver (Ag), tin (Sn), etc. More specifically, anthropogenic impact using Pb isotopes as a tracer has been used extensively in the ancient harbours of Alexandria[73], Sidon[74], Marseilles[75]. Rome[76], Naples[77], Ephesus[78], Cala Francese[79], and Fréjus[80]. Measuring Pb isotopes from sediment cores obtained in an ancient port, for example, help to solve archaeological questions including understanding human activities prior to the foundation of cities[81]. Moreover, some studies have combined the study of Pb concentrations and isotopic compositions in harbour sediments to understand water supply systems (i. e., Pb pipes, sinter deposits taken from aqueduct channels). Results have shown that Pb constitutes a proxy for the evolution of drainage systems (e. g. extension vs. contraction), connectivity, and engineering during the active period of the ancient city (e. g. Rome[82], Naples[83], Ephesus[84]). Anthropogenic Pb isotope signals trapped in harbour basins will be compared to those of known Pb ores supply sources (i. e., from mining resources), and insights into trade routes and sea roads from production centres (i. e., mining districts) to consumption centres (i. e., urban areas) can be deduced[85]. More recently, geochemistry has been used in geoarchaeology for paleoenvironmental reconstructions.

In some cases, classic environmental markers cannot be used for paleoenvironmental reconstruction due to low quantity/abundance, hiatus in the sedimentary deposits, and/or the cost of analysis permit the production of high-resolution

65 van Geel, Non-pollen palynomorphs. – de Vernal, Palynology.
66 See Iversen, Landnam. – Krueger/McCarthy, Lagerstätten. – Sadori et al., Palynology and ostracodology. – McCarthy et al., Algal palynomorphs.
67 Fægri/Iversen, Textbook of pollen analysis 294.
68 Bryant/Holloway, Archaeological palynology 913-917.
69 Marriner/Morhange, Geoscience of ancient Mediterranean harbours.
70 Marriner/Morhange, Geoscience of ancient Mediterranean harbours 171. – Sadori et al., Palynology and ostracodology 1508.
71 Sadori et al., Palynology and ostracodology.
72 Shumilovskikh et al., The harbour of Elaia.
73 Véron et al, Pollutant lead reveals the pre-Hellenistic occupation 1-3. – Véron et al., A 6000-year geochemical record 141-143. – Stanley et al., Alexandria 5-8.
74 Le Roux et al., Geochemical evidences 115-119.
75 Le Roux et al., Lead pollution in the ancient harbours of Marseilles 31-35.
76 Delile et al., Lead in ancient Rome's city waters 6594-6599. – Delile et al., Rome's urban history 1-6.
77 Delile et al., A lead isotope perspective on urban development in ancient Naples 3-6.
78 Delile et al., Demise of a harbour 205-211.
79 Fagel et al., Record of human activities in the Pb isotopes 770-781.
80 Véron et al., Fréjus, France 242-249.
81 Le Roux et al., Geochemical evidences 115-119. – Véron et al, Pollutant lead reveals the pre-Hellenistic occupation 1-4. – Véron et al., A 6000-year geochemical record 138-147.
82 Delile et al., Lead in ancient Rome's city waters 6594-6599.
83 Delile et al., A lead isotope perspective on urban development in ancient Naples 6148-6153.
84 Delile et al., Demise of a harbour 202-213.
85 Le Roux et al., Geochemical evidences 115-119. – Le Roux et al., Lead pollution in the ancient harbours of Marseilles 31-35. – Delile et al., Lead in ancient Rome's city waters 6594-6599. – Delile et al., A lead isotope perspective on urban development in ancient Naples 6148-6153. – Véron et al., A 6000-year geochemical record 138-147. – Véron et al., Fréjus, France 242-249.

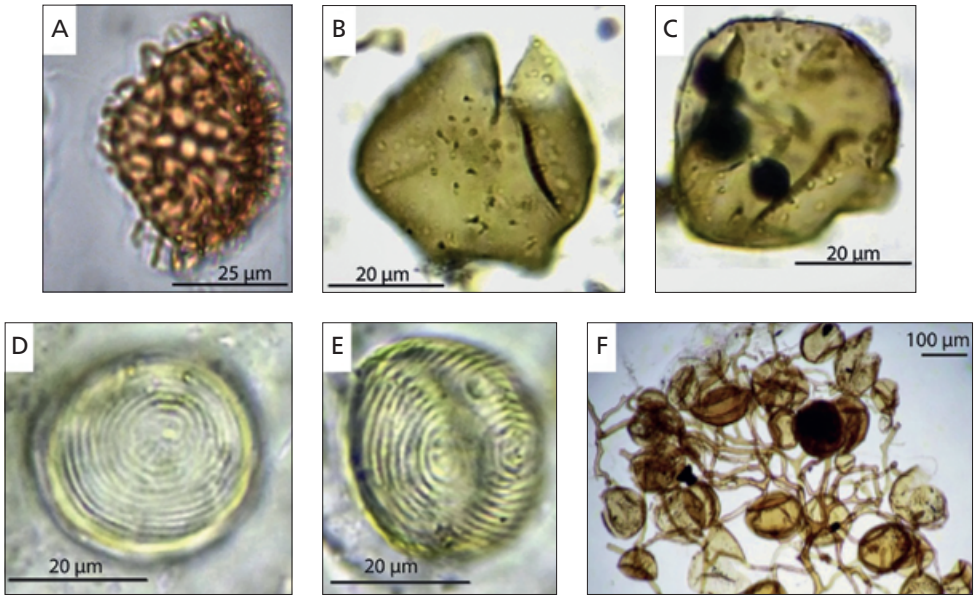


Fig. 3 Plate showing examples of Palynomorphs: **A** *Lycopodium* spore (photo by Andrea Krueger) which can be used as marker particle. – **B-C** Dinoflagellate cyst *Peridinium ponticum* (photo from Sadori et al., Palynology and ostracodology). – **D-E** Acritarch *Pseudoschizaea circula* (photo from Sadori et al., Palynology and ostracodology). – **F** cluster of fungal spore *Glomus* (photo modified from Revelles et al., Pollen and non-pollen palynomorphs).

results. To remedy these shortcomings, and to complement the more commonly used proxies, elemental geochemistry has been added to the toolkit of geoarchaeology. Only recently, research teams have used elemental geochemistry to improve the paleoenvironmental reconstructions in archaeological contexts, as in Corinth (Greece)[86], Magdala (Israel)[87], Elaia (Turkey)[88], and Alkinoos (Greece)[89]. This recent expansion of geochemistry into geoarchaeological research is a direct result of the widespread use of micro x-ray fluorescence (µXRF) core scanners during the last decade[90]. To extract as much information as possible from the elementary geochemistry data, it is recommended to link them to a factor analysis that can discriminate the main environmental factors leading to the formation of the harbour basin deposits[91]. Based on five different ancient harbour deposits, a recent study by Delile et al.[92] classified these environmental variables in order of importance as (I) current velocity, (II) biogenic production, (III) water column ventilation, (IV) anthropogenic flux, and (V) seawater versus freshwater influence. The association and coupling of these control factors have demonstrated its robustness for detailed paleoenvironmental reconstructions in numerous cases[93].

X-Ray Fluorescence (XRF) Spectrometry

XRF is a non-destructive analytical tool that has been increasingly popular in archaeology and geosciences due to its ability to offer high resolution semi-quantitative and qualitative elemental data, often with little preparation. The data produced by XRF analysis help researchers to interpret the provenance of material (archaeometry) and paleoenvironmental reconstruction (relevant for geoarchaeological studies). There are many types of XRF including both laboratory XRF and portable handheld XRF, the latter being useful for rapid analysis in the field[94]. This section introduces and summarises two types of XRF techniques commonly used by archaeologists and geoarchaeologists: energy-dispersive XRF (EDXRF) and wavelength-dispersive XRF (WDXRF).

Each technique uses x-rays to excite and displace the electrons of the inner shell of the atom. The electrons from the outer shell then fill the void, which emits x-ray photons that can be counted to identify the elements present in the material and/or sediment core. Archaeologists commonly rely on these XRF techniques for obsidian studies and more recently, analysing archaeological basalts[95]. The operating principle behind EDXRF and WDXRF are similar, however, WDXRF detects one element at a time and as a result, takes longer to process than EDXRF which is more efficient with the ability to detect groups of elements simultaneously and process within a few minutes. The spectral resolution of WDXRF is higher (i.e., ~5 eV to 20 eV) than EDXR (~150 eV-600 eV; this depends on the detector) which means there are fewer spectral overlaps of elemental data in WDXRF than in EDXRF.

86 Hadler et al., Harbour of ancient Corinth (Peloponnese, Greece) 139-180.
87 Rossi et al., New insights into the palaeoenvironmental evolution of Magdala ancient harbour 356-373.
88 Shumilovskikh et al., The harbour of Elaia 167-187.
89 Finkler et al., Tracing the Alkinoos Harbour 24-42.
90 Croudace/Rothwell, Ch. 1 Micro-XRF Studies of Sediment Cores 14-19.
91 Delile et al., Geochemical investigation of a sediment core 34-45. – Delile et al., Demise of a harbour 202-213. – Delile et al., Neapolis harbour 84-97. – Delile et al., The contribution of geochemistry to ancient harbour geoarchaeology 170-187.
92 Delile et al., The contribution of geochemistry to ancient harbour geoarchaeology 170-187.
93 Delile et al., Geochemical investigation of a sediment core 34-45. – Delile et al., Demise of a harbour 202-213. – Delile et al., Neapolis harbour 84-97.
94 Shackley, Ch. 1 X-Ray Fluorescence Spectrometry 12-15.
95 Shackley, Ch. 1 X-Ray Fluorescence Spectrometry 1-2. – Lunbald et al., Non-destructive EDXRF Analyses of Archaeological Basalts 65-77.

The interpretation of the elemental compositions in sediment cores for geoarchaeological research is site-specific. Therfore, it is imperative to understand the geochemical properties related to the ecological setting of the study area. Mistakes are often made when elements are placed in relation without considering external parameters, such as the climatic, hydrologic, and geologic context of the region[96]. Moreover, technological advancements in recent years, such as the development of micro-XRF (µXRF), can provide rapid and continuous high spatial resolution elemental records (~200 µm) than conventional XRF[97].

µXRF core scanners, such as AVAATECH/CORTEX and ITRAX are the most popular instruments used in palaeoceanography and paleolimnology studies today[98] and are becoming more widely used in geoarchaeology research for reconstructing paleoenvironments and paleoclimates. For example, depending on sediment accumulation rates in the core, µXRF can identify seasonal to multi-decadal scale changes in geochemical signatures associated with environmental change over time. Some core scanners, such as the *Cox Analytical ITRAX XRF scanner*, can also produce radiographic and optical images that can be useful for studying spatial heterogeneities, sedimentary structures, and sediment accumulation from the recorded film density of the core[99].

Dating (Relative vs. Absolute dating)

Dating is essential for geoarchaeologists to establish a chronology of their research area. There are two different types of dating methods: I) Absolute dating and II) Relative dating. Absolute dating provides a fixed date set on a chronological scale (i. e., calendar years and calibrated years) and can be determined by referencing a known printed date (e. g. a coin) or using scientific methods, such as radiometric (e. g. radiocarbon, uranium series, and single-crystal laser fusion Argon-argon dating) and trapped charged dating (e. g. thermo-luminescence, cosmogenic exposure dating, and electron spin resonance). Relative dating is arbitrary where objects are put into chronological order and geologic time series are wiggle-matched to reference curves or using a point of reference, such as an artefact or known event. Table 2 provides a summary of some of the most common absolute and relative dating methods used in geoarchaeology today. This section on dating methods will focus on the use of radiocarbon and cosmogenic isotopes (absolute dating), and palaeomagnetism (relative dating).

Radiocarbon Dating

Radiocarbon dating (^{14}C) is the most used dating technique in archaeological studies to estimate the age of carbon materials. The principle behind ^{14}C dating is simple: atmospheric carbon dioxide (CO_2) contains small proportions of ^{14}C, a naturally occurring radioactive element created in the upper atmosphere through the reaction of neutrons from cosmic rays and Nitrogen (^{14}N) in the air. The ^{14}C atom is rapidly oxidized to carbon dioxide ($^{14}CO_2$) and mixed with carbon dioxide in the atmosphere. This is passed from the atmosphere to oceans through dissolution or assimilation by plants via photosynthesis and enters the food chain, therefore marking all living organisms with carbon 14.

The production of atmospheric ^{14}C is continuous without accumulation – it spontaneously disintegrates to provide a nitrogen atom. The production of ^{14}C and its decay equilibrate around a low ^{14}C content conferring natural radioactivity to the carbon dioxide of the atmosphere. As long as the organisms remain in exchange with this carbon dioxide, ^{14}C is stored. Since ^{14}C is unstable, it will decay over time when an organism dies and is no longer exchanging carbon with the biosphere or during the precipitation of carbonate minerals. Age estimates can therefore be calculated by measuring the residual rate of ^{14}C left in a carbon sample after its death.

All carbon materials less than 50 000 years old are theoretically datable. The most common material used for this dating method is of vegetable origin (e. g. charcoal, wood, seeds, etc.) and bones. Marine organisms, such as fish, shells, and Posidonia, are special cases that will be discussed later. Samples must be treated to avoid contamination[100]. There are two principal techniques for measuring residual ^{14}C in a sample: 1) liquid scintillation counters and 2) counting the remaining ^{14}C atoms using an Accelerator Mass Spectrometry (AMS). The choice of method depends on the sample mass. For example, the first technique requires a large sample mass weighing 20-300 g, depending on the nature of the sample, while AMS requires smaller samples weighing a few 10 µg to 5 g. ^{14}C dates obtained using these tools are given in years B.P. (Before Present, i. e., before 1950) with a margin of uncertainty. A correction curve is used to convert these dates into a calendar date interval, depending on the accuracy of the measurement and the sequence of the calibration curve used, where the age of the dated sample has a confidence interval of 95[101].

In geoarchaeological studies, sampling is generally carried out by obtaining sediment cores from the study area. For this reason, samples that are selected for ^{14}C is usually small, e. g. in plant macro-remains, diffuse organic matter, and/or marine shells in coastal environments. The oceans receive ^{14}C from atmospheric CO_2 and the deep ocean from radioactive decay occurring at these depths and mixing of surface wa-

96 Delile et al., The contribution of geochemistry to ancient harbour geoarchaeology 171.
97 Croudace/Rothwell, Ch. 1 Micro-XRF Studies of Sediment Cores 24.
98 Croudace/Rothwell, Ch. 1 Micro-XRF Studies of Sediment Cores 3.
99 Croudace/Rothwell, Ch. 1 Micro-XRF Studies of Sediment Cores viii. – Axelsson, The use of X-ray radiographic methods 65.
100 Brock et al., Current Pre-treatment methods for AMS Radiocarbon 103-112.
101 Reimer et al., IntCal13 and Marine13 Radiocarbon Age Calibration Curves 1869-1887.

Dating Method	Age Range	Materials	Summary
Radiocarbon dating	1 - 50 000 years	Organic material (e. g. bones, shells, charcoal, wood, and peat)	Measures the radioactive decay of ^{14}C in carbon materials
Argon-Argon Ar-Ar	1000s - several billions of years	Volcanic material (e. g. igneous rocks) and early human artefacts	Measures the decay of the ratio 40Ar/ 39Ar in sediments/rocks containing argon
Potassium- Argon K-Ar	1000s - several billions of years	Volcanic material (e. g. igneous rocks), early human artefacts	Measures the decay of 39K and 40Ar in sediments/ rocks containing minerals with potassium
Uranium Series (U-Series)	Several thousand - 1 million years*	Minerals containing uranium (e. g. silicates and carbonates)	Measures the radioactive decay of 238U and 235U
Luminescence (OSL and TL)	1000 - several billions of years	Fired material (e. g. ceramics, pottery, burnt flint, etc.)	Measures radioactivity accumulated in the sediment and/or tool since the last time it was exposed to heat and/or light
Electron Spin Resonance (ESR)	1000 - 5 million years	Tooth enamel, carbonates (e. g. speleothems, shells, etc.), rocks/sediment containing quartz, etc.**	Determines the age of burial via measuring the concentration of free radicals in the material due to exposure to natural radiation***
Tephrochronology	100 - few billion years	Volcanic material/deposits	Measures age of volcanic material to determine the age of stratigraphic material
Paleomagnetism	Several hundreds - billions of years	Fired material (e. g. ceramics), sediments, and rocks (sedimentary and igneous)	Measures the fossilized Earth's magnetic field and compare to reference curves for relative dating

Tab. 2 Summary of common dating methods used in geoarchaeology (from Peppe/Deino, Dating rocks). – * Schwarcz, Uranium series dating 7-17. – ** Rink, Electron Spin Resonance 975-1025. – *** Skinner, Electron Spin Resonance.

ters. Marine organisms absorb ^{14}C dissolved in the water (as CO_2). Seawater, however, contains less ^{14}C compared to CO_2 in the atmosphere. Exchange between the surface of the ocean and the atmosphere is quicker than in deep waters. This is called the *Marine Reservoir Effect* which ages the estimated dates of marine organisms. This ageing (or apparent age) is estimated at 400 years[102]. In addition, the magnitude of the marine reservoir effect varies depending on the marine species and environmental conditions[103]. A marine calibration curve is used to calibrate the dates of these materials with regard to this correction[104]. The dating of shells is not used to determine absolute dates but are used to serve as chronological markers for geoarchaeological interpretation.

Incipient use of terrestrial cosmogenic isotopes in geoarchaeology

Absolute dating provides an estimated numerical age in sediments, rocks, and/or fossils. The most commonly used absolute dating method is radiometric dating, which uses the natural radioactive decay of some of Earth's most dominant elements including carbon, uranium, and potassium. Cosmogenic isotopes are produced through the interaction of high energy cosmic rays with atoms of the Earth's atmosphere and land surface. Cosmic ray fluxes are composed predominantly of protons and muons emitted during supernova explosions. They are considerably more energetic than the most energetic sun rays – whereas sun rays can overcome chemical bonds and split molecules, cosmic rays can overcome atomic bonds and split atoms. The isotopes produced by these reactions can be stable, but many are radioactive and decay after being produced. Those used in Earth Sciences are often radioactive with typical half-lives of several days to several millions of years. Meteoric cosmogenic isotopes are produced in the atmosphere and transferred to the ground through dry (e. g. dust, aerosols, gas) or wet (e. g. rain) deposition. The best known of these is ^{14}C. Others, such as Beryllium (^{10}Be), are used for their propensity to accumulate in soils by adsorption to organic matter, iron oxides and clays[105]. Terrestrial in-situ produced cosmogenic isotopes are generated directly in the lattices of minerals, within the topmost few metres of the Earth's surface. Average production rates have only been firmly calibrated for a few isotopes, in compositionally simple minerals, such as ^{10}Be, ^{14}C and ^{26}Al in quartz, or ^{36}Cl in calcite. In cases where such minerals are not available, more complex analyses can be conducted, for example on cosmogenic ^{21}Ne and ^{3}He in pyroxenes, olivine, and amphiboles.

The concentration produced by isotopes within mineral particles or adhering to their surface of ground particles can be used in three main ways: (I) to date the duration of exposure of a surface to cosmic rays or atmospheric fallout; (II) to quantify the rate at which a rock surface or soil is eroded, and (III) to date the burial and shielding of material from cosmic rays. Studies most commonly use one or some combination of these fundamental approaches.

Due to very low production rates (a few atoms per gram of mineral per year), measurements require the use of acceleration mass spectroscopy (AMS). Therefore, terrestrial cosmogenic isotopes initially found applications in geology, where time scales of a few thousand years to several million years allow concentrations to reach measurable levels[106]. They

102 Stuiver/Brazinius, Modelling atmospheric ^{14}C influences and ^{14}C ages 137-189.
103 Marchand et al., Entre »effet reservoir« et »effet de plateau« 307-335.
104 Reimer et al., IntCal13 and Marine13 Radiocarbon Age Calibration Curves 1869-1887.
105 Boschi/Willenbring, The effect of pH, organic ligand chemistry and mineralogy 711-722.
106 Granger et al., A cosmic trip: 25 years of cosmogenic nuclides in geology 1379-1402.

have been used to date glacial landforms, river terraces, fault scarps, caves, paleosols, and the natural rate of erosion of rocks and soils[107]. The use of terrestrial cosmogenic isotopes in geoarchaeology as a dating technique has been hindered by the slow build-up of isotope concentrations[108], such that most successful applications have been obtained in the field of palaeoanthropology[109]. The improvement of AMS detection limits, the strong momentum of this dating technique, and the use of novel minerals and isotopes will certainly soon result in breakthroughs in the field of geoarchaeology. Fluxes of atmospherically derived isotopes are higher, allowing for measurements over time-scales more relevant to geoarchaeology, but the mechanisms of accumulation/flushing of isotopes in soils are complex and poorly constrained, making interpretations less straightforward[110]. Its highest current potential lies in the field of erosion rate measurements, in particular, to assess the effects of anthropogenic perturbation to background environment levels[111], or as a tracer of sediment sources[112].

Palaeomagnetism

The Earth's magnetic field can be used for relative dating of historical and archaeological sites. This is done by comparing the fossilized magnetism in sediment or fired artefacts to regional reference curves and magnetic field models. Paleomagnetic dating is based on the fact that the Earth's magnetic field changes over time and that certain minerals can enclose the ambient magnetic field. The reference curves include measurements made by mariners[113], paleorecords from well-dated geological and archaeological archives (e. g. MagIC database[114]; GEOMAGIA50 database by Brown et al.[115], and geomagnetic field models (e. g. CALSxk by Korte and Constable)[116]. Paleomagnetic dating is most powerful when using the full magnetic vector (paleointensity, inclination and declination), in a region and period a priori well-documented with quality reference curves, and as a part of a multiproxy dating strategy. Paleomagnetic dating has the potential to provide good precision in periods of large radiocarbon calibration uncertainties, such as the Early Medieval Period[117]. Sampling material for paleomagnetism includes: (I) Fired material such as hearths, ceramics, bricks, and iron sledge. The magnetic minerals record a thermal remnant magnetisation (TRM) at the time of cooling through their Curie temperature; (II) Sediment deposited in a natural (e. g. lake, sea) or artificial basin (e. g. harbours). The magnetic minerals encase a detrital remnant magnetisation (DRM) at the time of deposition. The typical sample size is 8 cm³ (8 mℓ) cubes or discrete cylinder samples for analysis in a spinner magnetometer or a cryogenic magnetometer. Sedimentary sequences can also be sampled with U-channels (core-length plastic boxes with cross-section 2 cm × 2 cm) and analysed using a cryogenic magnetometer for U-channels.

Data interpretation:
The Paleoenvironmental Age-Depth Model

The *Paleoenvironmental Age-Depth Model* (PADM) is an interpretative chart created to characterise harbour potential and operability[118] (**fig. 4**). This chart provides a useful tool for reconstructing navigability, accessibility of a water body through time, but also for visualising the degree of closure of the palaeoenvironments considered. Based on a classic age-depth model, the PADM chart combines (I) stratigraphic and paleoenvironmental data, (II) sedimentation curve, (III) reconstructed relative local sea level curve, (IV) fully laden ancient ship or boat draughts – depending on the period and the culture considered, and (V) all relevant chronological and/or altitudinal data that can possibly be collected.

PADM was initially developed and applied for the interpretation of the canals of Portus[119]. These navigable canals were excavated during the Roman period between the Imperial harbour of Rome and the Tiber River. It was then developed and improved in the context of the ERC-funded RoMP PortusLimen project to interpret different Roman harbours in coastal, lagoon or fluvial contexts in the same way[120]. Additionally, this chart was standardized for comparing different harbours and their suitability for ships and boats of varying sizes. In parallel, 2D interpretative cross-sections were built for visualising the evolution of the water column available over time with different ships[121]. Finally, a similar diagram was also applied in the harbours of Halmyris[122] (Dobrogea, Romania) and Elaia[123] (W. Turkey) using microfossil, foraminifera associations for reconstructing the water columns available over time.

To produce a PADM chart, a precise stratigraphic representation of the studied sequence is required. Paleoenvironmental analyses have to be performed for reconstructing the degree of closure of a harbour in terms of the hydrodynamism (i. e., grain-size analysis and geochemical

107 Brocard et al., Effects of a tectonically-triggered wave.
108 Akçar et al., Cosmogenic 36Cl in limestone 533-540.
109 Granger et al., New cosmogenic burial ages for Sterkfontein 85. – Philipps et al., Maximum ages of the Côa valley 100. – Verri et al., Flint mining in prehistory 7880-7884.
110 Boschi/Willenbring, Beryllium desorption 52-58.
111 Brown et al., Determination of predevelopment denudation rates 723-728. Valette-Silver et al., Detection of erosion events using ^{10}Be profiles 82-90.
112 Reusser/Bierman, Using meteoric 10Be to track fluvial sand 47-50.
113 Jonkers et al., Four centuries of geomagnetic data from historical records 2.
114 https://Earthref.org/MagIC.
115 Brown et al., GEOMAGIA50.v3: 1. Brown et al., GEOMAGIA50.v3: 2.
116 Korte/Constable, Geomagnetic field.
117 Batt et al., Advances in archaeomagnetic dating in Britain 66.
118 Salomon et al., The Development and Characteristics of Ancient Harbours 5-8.
119 Salomon et al., The Canale di Comunicazione Traverso in Portus 84-87. Lisé-Pronovost et al., Dredging and canal gate technologies in Portus.
120 Salomon et al., The Development and Characteristics of Ancient Harbours 1. – Salomon et al., Un modèle âge-profondeur paléoenvironnemental 1.
121 Salomon et al., A harbour–canal at Portus 31-49. – Goiran et al., High chrono-stratigraphical resolution of the harbour sequence of Ostia 68-84.
122 Giaime et al., Halmyris: Geoarchaeology of a Fluvial Harbour on the Danube Delta.
123 Seeliger et al., Foraminifera as markers of Holocene sea-level fluctuations 21-27.

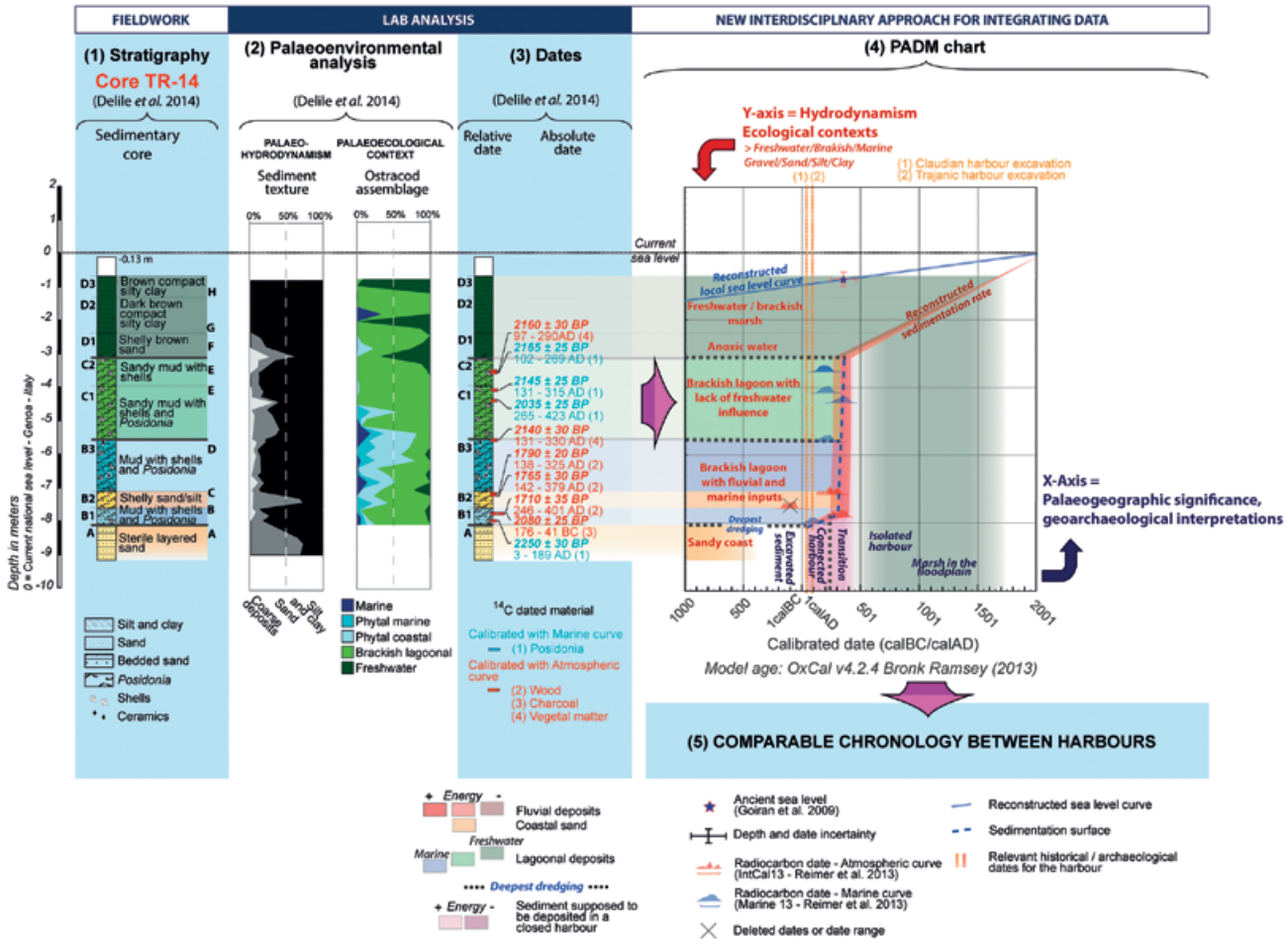


Fig. 4 An example of a Palaeoenvironmental Age-Depth Model (PDAM) Chart used to characterise harbour potential and operability. – (From Salomon et al., The Development and Characteristics of Ancient Harbours).

analysis) and the water oxygenation, connection to the sea considering the marine/freshwater balance (bioindicators – macrofauna, ostracods, foraminifera, geochemical analyses etc.). In addition, a reliable chrono-stratigraphy based on radiocarbon dating, optically stimulated luminescence dating (OSL), and archaeological dating methods (i. e., ceramics) must be established. For the reconstruction of relative sea level, the PADM requires local or regional data. Draughts of fully laden ancient boats and ships, levels of archaeologically dated quays, historical data about the use of a harbour, its foundation etc. can allow the researcher to refine the PADM.

Successive steps are taken in the construction of the Paleoenvironmental Age-Depth Model (PADM) chart:

1. Construction of an age-depth model or sedimentation curve based on absolute dates;
2. The stratigraphic sequence, the hydrodynamism, and the paleoecological context are drawn on the vertical axis (Y-axis);
3. The stratigraphic layers are transposed on the horizontal axis (x-axis) through the reconstructed sedimentation curve – interpretations relate to this axis (paleogeographical interpretation and operability of the harbour);
4. The reconstructed relative sea level curve is reported on the age-depth model – the area between the reconstructed sedimentation and the relative sea level curves correspond to the changing paleo-bathymetry;
5. The draught of a fully laden boat and ship at a given period and culture are compared to the paleo-bathymetries.

Additional elements of control can be added to the PADM chart such as complementary dates, or the reconstruction of the compaction correction. Alternatively, water depth can be inferred from bio-indicators trapped in the sediments, such as foraminifera. Multiple-core analysis and a combination of sediment curves provide a better understanding of the evolution of the different parts of the harbour[124]. This method can be applied to sedimentary sequences in a built harbour as well as in any water body (e. g. coastal area, river, lake, palaeolagoon, etc.). Archaeological evidence enables better identification of the limits of a harbour area (i. e., moles, quays, settlement location, etc.).

124 Salomon et al., The Development and Characteristics of Ancient Harbours 10.

Case Studies: Reconstructing Ancient Harbours

Alexandria (Egypt)

In 331 BC, Alexander the Great led his army to Northern Africa to defeat the Persians for their rule over Egypt and founded the ancient city of Alexandria behind the island of Pharos on the western margin of the Nile Delta. The Greek geographer Strabo described an approximately ca. 1300 m long Heptastadion (causeway) that connected the mainland to Pharos, where the famous lighthouse of Alexandria once stood. The connexion divided Alexandria's coastline into two ports located on the east and west side of the Heptastadion. The eastern port of Alexandria, called *Magnus Portus*, was one of the busiest harbours in the ancient world and served as a one of the most important trading ports between Egypt and the Greco-Roman cities around the Mediterranean. The *Magnus Portus* was better protected than the western port (known as the Eunostos harbour) which was open to the sea and more susceptible to coastal processes such as strong winds and sea swells[125].

Alexandria is exposed to north-easterly winds in summer and north-westerly winds in winter. These intense seasonal wind patterns can produce storm waves with heights of ca. 1.2-2.1 m, with the strongest ocean swells occurring between June-August[126]. The magnitude of these waves is predominantly responsible for coastal erosion and sediment transportation. Over time, sediment accumulated on both sides of the Heptastadion subsequently filling up the harbours and creating a tombolo (sandbank). About the 15th and 16th centuries AD, the city expanded to the tombolo and is still a densely urbanized centre today. Consequently, urbanization on the tombolo has made it difficult for archaeologists to precisely locate the Heptastadion. Mahmoud El Falaki (1872) hypothesized that the Heptastadion was orientated NW/SE, which was widely accepted throughout most of the 21st century[127]. However, this hypothesis was refuted in 1997 by Albert Hesse (CNRS, UMR 7619 Sisyphe) through geophysical analysis[128]. Hesse argued that the Heptastadion continued the city's ancient road network. A multidisciplinary study combining geophysical, archaeological, and geomorphological methods was later performed to understand the landscape evolution of Alexandria's coastline during the last 8000 years of the Holocene.

Hesse demonstrated how the tombolo was formed and proposed a new hypothesis for the location of the Heptastadion[129]. The results from this study indicated that urban development followed the evolution of the coastline. During the geophysical survey, most of the methods were tested including Electrostatic, EMI, GPR, and seismic. Despite the extensive geophysical survey, the original structure of the Heptastadion could not be detected, but the surveys revealed and confirmed the location of the anchorage points of the ancient causeway and the evolution of the tombolo. The electrostatic survey provided the clearest results showing the evolution of the tombolo with decreasing resistivities towards the east. This decrease can be interpreted as the difference between a hard rock resistant infrastructure (the Heptastadion) and the progradation due to more conductive sediments. Despite the metallic disturbances due to the urban environment, the EMI survey successfully confirms the results obtained from the electrostatics.

Pyrgi (Italy)

The Etruscans were an ancient civilization from the Italian Peninsula renowned for their wealth and urban development. Etruscan cities were established at the end of the Final Bronze Age (12th-10th c. BC) to the Early Iron Age (i. e., the Villanovian period from 10th-8th c. BC). In the 9th century BC, the Etruscans had occupied territories around the Tyrrhenian coast extending from modern-day Tuscany, Lazio, and Umbria. They were known for engineering extensive hydraulic structures including, canals for transport and drainage systems. According to ancient texts, the Etruscans were a Thalassocratic society since they relied on the use of commercial harbour basins and naval bases. However, despite numerous archaeological studies along the Tyrrhenian coastline, no evidence of Etruscan harbour activity has been discovered[130]. Benvento Frau (1989), an Italian archaeologist known for his research in ancient Etruscan ports of Tarquinia (Lazio, Italy), believed that Etruscan settlements in Pyrgi could have used former inland lagoons to support their waterway projects instead of large maritime harbour basins[131]. This assumption was based on analysing aerial photographs of the region which appeared to reveal buried archaeological structures linked to the harbour activities (i. e., tower structures and jetties; **fig. 5a**)[132]. To test Frau's hypothesis, a geoarchaeological expedition in 2017 was conducted in the ancient city of Pyrgi (modern-day Santa Severa) located ca. 52 km north of Rome on the Lazio coast of Italy (**fig. 5b**). The purpose of this study is to identify the structures of the Etruscan harbour of Pyrgi and to verify the findings discussed by Frau[133].

125 Lotft/Badr, Long-term relief deformation and sediment characteristics 267-268.
126 Goiran et al., Geoarchaeology of Alexandria (Egypt) 730.
127 Falakī/Ḥamdī, Mémoire sur l'antique Alexandrie.
128 Hesse, Arguments pour une nouvelle hypothèse 21-33.
129 Hesse et al., L'Heptastade d'Alexandrie 191-273.
130 Enei, Pyrgi sommersa. – Boitani, Il territorio: l'emporion di Gravisca 125-136. – McCann, The Roman Port and Fishery of Cosa. – Keay/Paroli, Portus. – Goiran et al., Paleoreconstruction of ancient harbours of Rome 3-13. – Goiran et al., Geoarchaeology confirms location of the ancient harbour basin of Ostia 389-398.
131 Frau, I porti ceretani di Pyrgi e Castrum Novum 319-327.
132 Enei, Pyrgi sommersa. – Boitani, Il territorio: l'emporion di Gravisca 125-136. – McCann, The Roman Port and Fishery of Cosa. – Keay/Paroli, Portus. – Goiran et al., Paleoreconstruction of ancient harbours of Rome 3-13. – Goiran et al., Geoarchaeology confirms location of the ancient harbour basin of Ostia 389-398.
133 Frau, I porti ceretani di Pyrgi e Castrum Novum 319-327.

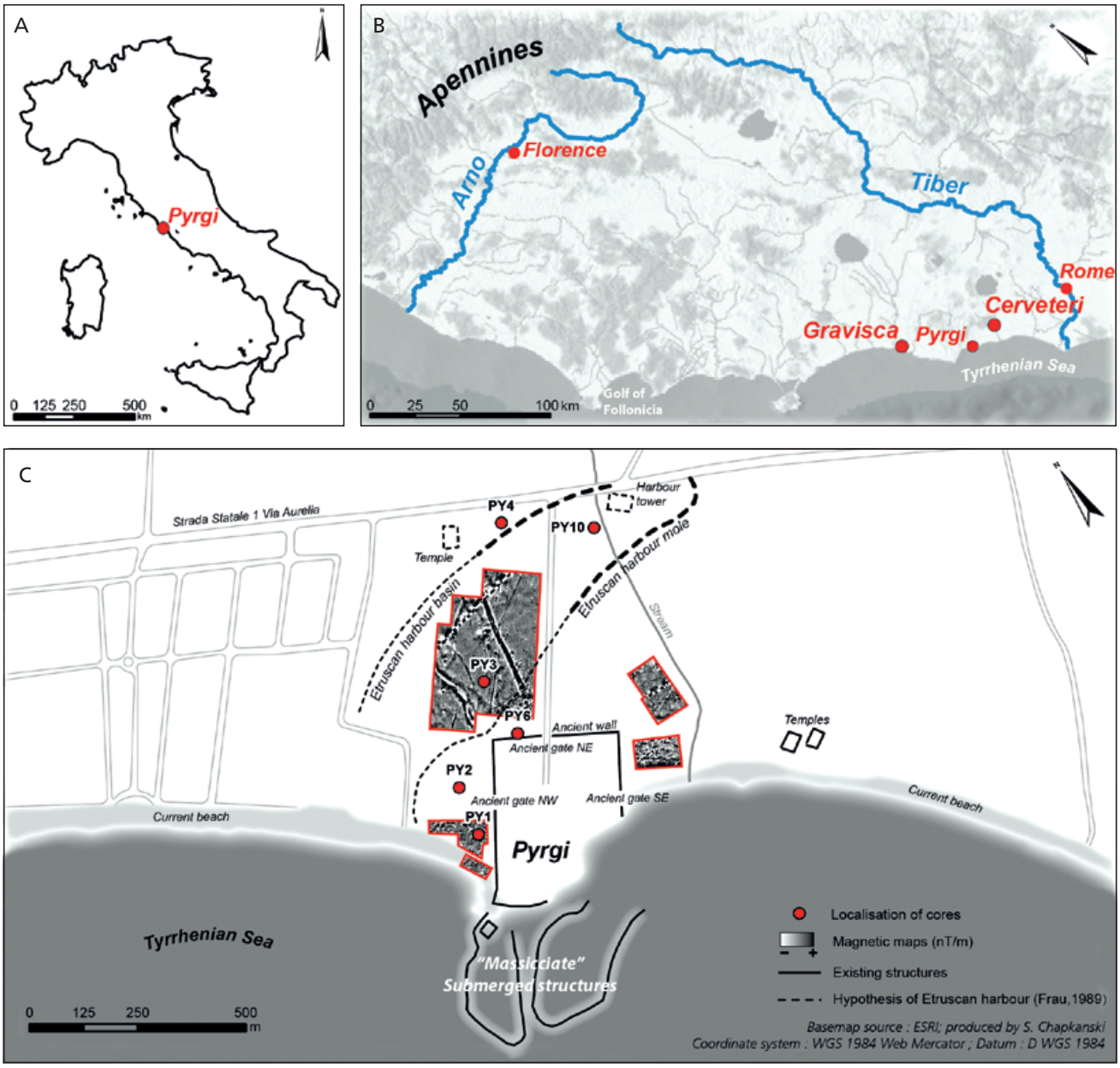


Fig. 5 Study Area: **A** Pyrgi (Italy along the Tyrrhenian Sea. – **B** Map of Pyrgi. – **C** Coring locations. This figure reveals the hypothesis of Frau, I porti ceretani di Pyrgi e Castrum Novum, suggesting the harbour of Pyrgi as well as the locations of cores and the preliminary results of magnetic maps (C) – (After Goiran et al., Recherche).

A multidisciplinary approach involving geophysical surveys and sedimentological analysis was performed. Six sedimentary cores were obtained and >8 ha of the area was investigated by geophysical prospections (**fig. 6c**). A sedimentary description of the cores revealed major stratigraphic layers, specifically silt-clay deposits overlying a sandstone bedrock (**fig. 6**). Silt-clay sediments are characteristic of a low energy depositional environment, such as a lagoon or a protected harbour. After correlating the cores (**fig. 6**), the sandstone bedrock in this area appears to be higher than the relative sea level during the Roman epoch[134]. This means that the existence of a Holocene lagoon located North-West of Pyrgi is not possible. As such, these preliminary results disagree with Frau's hypothesis regarding an inland lagoon related to Etruscan harbour settlements. These findings, however, are not conclusive as it only covers one area of Pyrgi, and radiocarbon dates are yet to be added. Future research is also needed to establish a higher spatial resolution for a more detailed paleoenvironmental reconstruction of the region. Furthermore, geophysical surveys were performed outside the ancient city walls to 1) identify a lagoon environment related to ancient harbour settlement, 2) locate the harbour's

134 Rovere et al., Relative sea level change at the arcaehological site of Pyrgi 89-90.

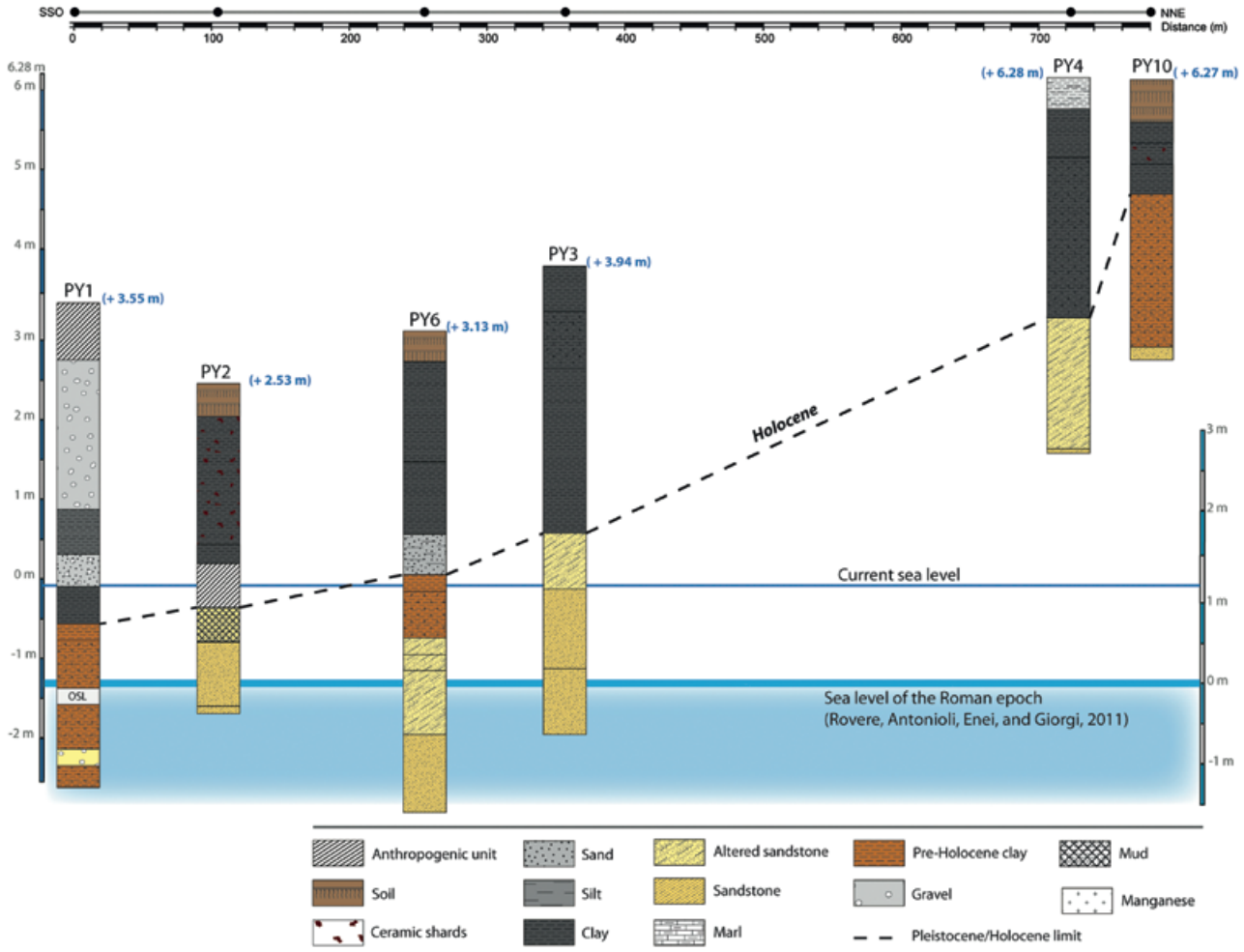


Fig. 6 Stratigraphic description of the cores in Pyrgi. Current and ancient sea-levels are marked in the figure. – (After Goiran et al., Recherche).

infrastructures, and 3) determine urban network outside the city walls (if applicable).

Magnetic surveys have been carried out in 2017 in the fields around the ancient city walls. Although the geophysical cover of the site contains several gaps and is yet to be completed, it has revealed interesting preliminary results (fig. 7). The magnetic survey (i. e., mapping the local geomagnetic field variations) highlighted road elements and buildings features within the proximity of the ancient city walls, proving that the ancient urban network continues beyond known city limits. Thus, an access road to the northern city gate as well as what appears to be an eastern neighbourhood have been identified on the magnetic map. The geophysical survey, however, is not fully completed at this stage and no harbour structures have been identified in any of the geophysical maps thus far. The contrasting electrical resistivity makes it possible to follow the clay-sandstone interface in which the clay thickness can be estimated (data is not available at this stage). This clay thickness provides insight into the size and the evolution of the alluvial plain associated with the highlighted sedimentary deposits. More research is needed,

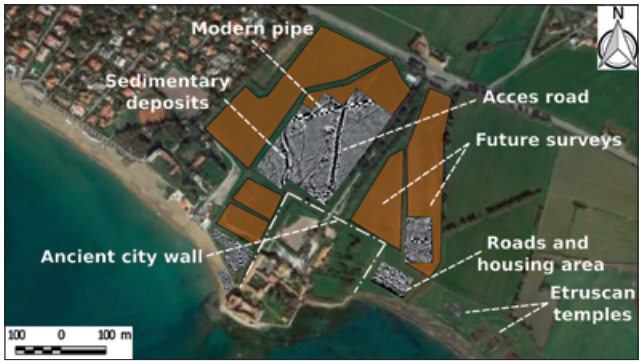


Fig. 7 Preliminary magnetic survey results for Pyrgi. – (After Goiran et al., Recherche).

however, the preliminary results presented in this section reveal promising information concerning the urban network and the ancient landscape of Pyrgi. Once the magnetic survey and a number of complementary methods, including electrical resistivity tomography cross-sections, have been completed, it will be possible to fully reconstruct the geomorphological landscape.

Conclusion

The application of geoscience provides a plethora of knowledge for harbour archaeological research. The technological advancements in geoscientific tools have made data collection more efficient and cost-effective as manifested in the introduction of non-destructive and rapid geochemical analyses using µXRF core scanners and GIS for digital modelling and spatial analyses. Such innovations have permitted geoarchaeologists to pursue further research questions and have broadened the interest in harbour maritime archaeology overall. As can be seen in Alexandria, multidisciplinary approaches have allowed researchers to gain insight into how ancient societies reacted to the natural landscape and coastal evolution. There are, of course, limitations to the methods and tools summarized in this paper. Further technological innovation is therefore needed to overcome some of these obstacles. Nonetheless, geoarchaeological research helps to understand the past but also for monitoring and preparing for the future with the use of predictive modelling.

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Summary / Zusammenfassung

Developments in Geoarchaeological Research Methodologies and Applications in Harbour Maritime Archaeology

Maritime archaeology is a popular discipline in archaeological research with a primary focus on understanding ancient societies and their connection to the sea. Over the years, the inclusion of geoscientific methods and analyses in this field has helped solve some of the largest challenges in archaeology including investigating environmental impacts on human behaviours and site formation. Technological advancements of geoscientific tools in the 20th century have allowed researchers to uncover and explore ancient ports and harbours through the detection of collapsed structures and/or land alteration, such as those found in the great Egyptian city of Alexandria. This paper provides a review of common methods used in harbour maritime geoarchaeology today including various geophysical, spatial modelling, sedimentological, geochemical, and micropaleontological analyses as well as relative and absolute dating methods. The last section of this review will focus on how these methods are executed in the field and in the laboratory based on two harbour studies from the ancient world including the famous *Alexandria* in Egypt and the Etruscan harbour of *Pyrgi* situated on Italy's Tyrrhenian coastline. The paper is written collaboratively by researchers with various geoscientific backgrounds who are working on geoarchaeological projects in various parts of the world.

Entwicklungen von geoarchäologischen Forschungsmethoden und -anwendungen in der Hafenarchäologie

Die maritime Archäologie ist eine wichtige Subdisziplin der archäologischen Forschung, deren Hauptaugenmerk auf dem Verständnis von Gesellschaften der Vergangenheit und ihrer Verbindung zum Meer liegt. Im Laufe der Jahre hat die Einbeziehung geowissenschaftlicher Methoden und Analysen in diesem Bereich dazu beigetragen, einige der größten Herausforderungen in der Archäologie zu lösen, einschließlich der Untersuchung der Auswirkungen der Umwelt auf das menschliche Verhalten und die Standortbildung. Der technologische Fortschritt geowissenschaftlicher Werkzeuge im 20. Jahrhundert hat es Forschern ermöglicht, alte Häfen zu erkunden, indem eingestürzte Strukturen und/oder Landveränderungen entdeckt wurden, wie etwa in der großen ägyptischen Stadt Alexandria. Dieser Beitrag bietet einen Überblick über gängige Methoden der heutigen maritimen Geoarchäologie, einschließlich verschiedener geophysikalischer, räumlicher, sedimentologischer, geochemischer und mikropaläontologischer Analysen sowie relativer und absoluter Datierungsmethoden. Der letzte Abschnitt konzentriert sich darauf, wie diese Methoden vor Ort und im Labor durchgeführt werden, basierend auf zwei Hafenstudien für die Antike, das berühmte Alexandria in Ägypten und den etruskische Hafen von Pyrgi an der tyrrhenischen Küste Italiens. Der Beitrag wurde gemeinsam von Forscherinnen und Forschern mit unterschiedlichen geowissenschaftlichen Hintergründen verfasst, die an geoarchäologischen Projekten in verschiedenen Teilen der Welt arbeiten.