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The contribution of geochemistry to ancient harbor geoarcheology: The example of Ostia Antica

H. Delile [a, *], J.P. Goiran [a], J. Blichert-Toft [b]

[a] Maison de l'Orient et de la Méditerranée, CNRS UMR 5133, 69365, Lyon Cedex 7, France
[b] Ecole Normale Supérieure de Lyon, Université Claude Bernard-Lyon I, CNRS UMR 5276, 69007, Lyon, France

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ABSTRACT

Once trapped in ancient harbor basins, sediments form environmental archives that have been widely studied by geoarcheologists in recent decades, especially to help reconstruct fluvio-marine landscapes of the last millennia. In some cases, classic environmental markers cannot be used for this purpose either because of their scarcity in the sedimentary deposits, or because analytical costs limit the resolution that can be achieved. In order to remedy these shortcomings, and to complement the more commonly used proxies, elemental and isotopic geochemistry has been added to the geoarcheological toolkit. Here we show how to "read" the evolution of the paleo-environmental dynamics in the water column of Ostia Antica (Rome's first maritime harbor) using the geochemical and isotopic record of a 3000-year-old sediment core drilled in the ancient harbor basin. A comparison of the results obtained from Ostia Antica with those of other ancient Mediterranean harbors reveals the nature of the main environmental processes operating during the formation of sedimentary deposits in harbor basins. From this comparative approach, it appears that the respective weight of each control factor is dependent on the coastal geomorphological context of the sites where the harbors were established. Since the discovery of the harbor of Ostia Antica in 2014, this method has provided the means, for the first time, to identify two distinct harbor basin regimes; an initial marine-dominated regime from the middle of the 4th c. BC to ~ the 3rd c. BC, and a later freshwater-dominated regime up to the 2nd c. BC. More generally, we observe the effects of the dynamics of the deltaic progradation of the Tiber, which very early on was subject to a hydro-climatic component, on the processes of alluviation of the harbor basin. Additionally, and also for the first time in harbor geoarcheology, Pb isotope compositions measured specifically on uncontaminated sediments demonstrate their utility for both identifying the geological sources of the sediments of the Tiber delta and discriminating finer from larger particles. The present study further provides an opportunity to test the validity of two hypotheses recently put forward: (1) that a series of three tsunamis is recorded in the harbor silts, and (2) that an initial lagoon-type harbor was constructed at Ostia Antica, which later evolved into a fluvial harbor. Neither of these hypotheses are supported by the present data.

1. Introduction

When harbor geoarcheology emerged as a discipline at the beginning of the 1990s following the excavations of the ancient harbors of *Caesarea* (Israel) (Reinhardt et al., 1994, 1998; Reinhardt and Raban, 1999) and Marseille (France) (Hesnard, 1994; Morhange, 1994; Morhange et al., 2001, 2003), the analytical and investigative methods used were based on those well known from other domains within the earth sciences, such as micropaleontology (molluscs, ostracods, foraminifera, diatoms, pollen) and sedimentology (texture, granulometry, exoscopy) (Goiran and Morhange, 2003; Marriner and Morhange, 2007; Bravard, 2009; Cubizolle, 2009). Two decades later, while these well-tested methods continue to be used in the field, elemental and isotopic geochemistry has been added successfully to the geoarcheology toolkit, as we show below.

Although geochemistry began to be used in harbor geoarcheology in the mid-2000s to determine human impact based on findings of ancient metal traces (Le Roux et al., 2003, 2005; Véron

* Corresponding author. 7 rue Raulin, 69365, Lyon cedex 7, France.
E-mail address: hugo.delile@mom.fr (H. Delile).

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et al., 2006, 2013, 2018; Marriner and Morhange, 2007; Stanley et al., 2007; Delile et al., 2014b, 2015, 2016b, 2017), it had not so far been used in paleo-environmental studies. It is only very recently that research teams, primarily from Germany, have used elemental geochemistry to improve on paleo-environmental reconstructions in archeological contexts. Important examples of such work carried out on ancient harbors are the studies of Oiniadai (Vött, 2007), Olympia (Vött et al., 2011), Palairos-Pogonia (Vött et al., 2011), Corinth (Hadler et al., 2015a), Kyllini (Hadler al., 2015b), and Alkinoos (Finkler et al., 2018) in Greece; Ephesus (Stock et al., 2013, 2014; 2016; Delile, 2014; Delile et al., 2015) and Elaia (Shumilovskikh et al., 2016) in Turkey; *Portus* and Naples in Italy (Delile et al., 2014a; 2016a); and Magdala (Rossi et al., 2015) in Israel. This recent expansion of geochemistry into geoarcheological research is a direct result of the widespread use of micro-XRF core scanners during the last decade. This technology can rapidly, non-destructively, and automatically scan sediment cores to produce elemental profiles at high resolution, which contribute greatly to the reconstruction of paleo-environments (Croudace and Rothwell, 2015). However, to take full advantage of this technique, it is indispensable to have prior knowledge of the geochemical properties of the sediments in question in order to avoid misinterpretations. One such common mistake consists in using certain elemental ratios capable of tracing the sedimentological (e.g. Zr/Rb and Zr/Ti applied as particle size proxies) or environmental (e.g. Sr/Al, Mg/Ca or Ca/Al, and Si applied as biological production proxies or Mn/Fe, U, and Mo applied as water ventilation proxies) parameters without taking into account the geological, hydrological, and climate contexts of the sites under study, each of which can significantly modify the meaning of these ratios. Initially, the use of geochemistry for reconstructing environmental processes was applied to (i) marine sediments to decipher paleoproductivity, deep water ventilation, and paleo-temperatures, and (ii) lacustrine sediments to track atmospheric pollution, human impact, paleo-climatic changes, aeolian input, paleo-floods, catchment weathering, and source rock compositions (Boyle, 2002; Croudace and Rothwell, 2015).

Here we discuss the types of environmental and anthropogenic processes that are most likely to benefit from the use of high-resolution geochemistry applied to the geoarcheological study of ancient harbors. To that end, we identify the geochemical fingerprints of the main environmental and anthropogenic processes that took place in the ancient harbor basin of Ostia Antica and compare them with:

(i) the “classic” environmental archives documented so far by geochemistry (i.e., lacustrine and marine sediments);
(ii) the “traditional” proxies used in harbor geoarcheology (see above), especially those applied to Ostia Antica's ancient harbor basin, which are well documented from a paleo-environmental perspective (Goiran et al., 2012, 2014; 2017; Hadler et al., 2015a; Sadori et al., 2016; Wunderlich et al., 2018);
(iii) those identified at *Portus* (Delile et al., 2014a for the Trajanic basin and this study for the Claudius basin), Ephesus (Delile et al., 2015), and Naples (Delile et al., 2016a).

Although micropaleontological (ostracods, foraminifera, pollen) and sedimentological (texture, granulometry) studies have been carried out on the harbor deposits of Ostia Antica, the dynamics and paleo-environmental changes in its water column remain poorly understood. Improving this understanding is all the more important since Ostia Antica had a river harbor located a short distance from the mouth of the Tiber River, which was to subject it to both marine and river influences (Goiran et al., 2012, 2014; 2017; Salomon et al., 2016). As a result, in the present work, we focus in particular on the interaction between fluvial and marine impacts on the harbor water column.

2. Study area

2.1. Archeological and historical background

According to Roman historians, Ostia Antica was founded during the reign of Ancus Marcius in the 7th c. BC. However, the *castrum* (building, or plot of land, used as a fortified military camp) did not appear before the 4th or beginning of the 3rd c. BC (Coarelli, 1988; Martin, 1996; Zevi, 2002; Brandt, 2002). The absence of evidence for the earliest periods has led to hypotheses about the existence of a paleo-Ostia, the location of which remains unknown and would correspond to the city founded by Ancus Marcius (Coarelli, 1988; Martin, 1996; Zevi, 2002; Brandt 2002). Ancient texts reveal that the harbor of Ostia Antica became a commercial and military port during the Punic wars (Livy, 1997, 45, 22) and played a vital role in providing Rome with food supplies (especially olive oil from Spain and grain from the North African provinces) during the 1st c. BC (Le Gall, 1953; Zevi, 2001). Nevertheless, at this time, Puteoli (Pozzuoli) on the Bay of Naples remained the principal maritime port of Rome for trade (Balland, 1965). It was considered to be one of the busiest centers of trade in the Roman Empire, especially for metal ingots, for which a route from the Cartagena/Mazarron and Rio Tinto mines in Spain to Puteoli and Rome was heavily used (Domergue and Rico, 2014; Delile et al., 2016b). The large distance separating the ports of Puteoli and Ostia Antica, as well as a problematic massive siltation of Ostia's harbor basin caused by a succession of floods discharging sediments at the mouth of the Tiber (Strabo, 1924, 5, 3, 5), combined with the need to accommodate an increasing number of merchant and military ships arriving from the Roman provinces, were the main factors that led to the foundation of the new *Portus* harbor complex 3 km north of Ostia Antica in the middle of the 1st c. AD (Keay et al., 2005; Goiran et al., 2014) (Fig. 1A).

2.2. Geography and geology

The Tiber delta constitutes the outlet for the water and sediment discharges of a river 405 km long which drains a watershed surface area of 17,375 km^2, comprising young sediments from the Apennines and modern volcanic deposits in Latium. The annual deposition of sediment in the Tyrrhenian Sea, estimated at 7.2 million tons per year (Iadanza and Napolitani, 2006), has resulted in the construction of a wave-dominated delta 150 km^2 in extent. The Tiber delta can be divided into (i) the eastern inner deltaic plain, related to the paleo-lagoons of Maccarese in the north and Ostia in the south; (ii) the western outer deltaic plain, where the landscape is composed of accreting dunes to which must be added the submerged area; (iii) the deltaic front (mainly composed of sand and silt); and (iv) the prodelta (mainly composed of mud and clay) (Salomon, 2013; Salomon et al., 2017).

The geomorphological evolution of the Tiber delta during the Holocene period is well documented (Bellotti et al., 1994, 1995; 2007; 2011; Giraudi, 2004; Milli et al., 2013; Salomon, 2013; Salomon et al., 2018). During the periods of the Republic and the Empire, the position of the Tiber mouth likely was located close to the Boacciana Tower (Tomassetti, 1897) (Fig. 1B). Additional information about the coastline comes from the immediate surroundings of *Portus* (Arnoldus Huyzendveld, 2005; Giraudi, 2004; Giraudi et al., 2009; Salomon, 2013) and from south of the Tiber delta, on the Laurentine shore (Bicket et al., 2009). However, during the Imperial period, the rapid seaward progression of the coastline recorded by the Tiber delta, which could have been more active at