MULTIPROXY PALEOENVIRONMENTAL RECONSTRUCTION: THE PIRAEUS COASTAL PLAIN CASE STUDY

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Abstract

The joint application of benthic foraminifera, pollen and non-pollen palynomorphs (NPPs), molluscs and magnetic susceptibility analyses in Piraeus coastal plain deposits resulted in the detailed study of palaeoenvironmental evolution of the area during almost the last 9000 years and the distinction of five lithostratigraphical-paleoenvironmental units and subunits. Combined results of our analyses features the occurrence of an inner lagoon (unit Aa) followed by an open lagoon (Unit Ab) depositional environment that was transformed to a shallow marine paleoenvironment with lagoonal features (Unit B) after 7800 BP. Since about 4800 BP a closed oligohaline lagoon (Unit C) used for grazing, occurred in the area, while after 2800 BP a marshy oligohaline depositional environment (Unit D) and signs of intensive agricultural activities are evidenced. The very good correlation of benthic foraminiferal, palynological, molluscans and magnetic susceptibility data and resulted indices is indicative of the potential of the applied methodologies as a paleoenvironmental tool box.

Keywords: benthic foraminifera, pollen, NPPs, molluscs, magnetic susceptibility, Holocene.

Περίληψη

Η μελέτη της λεπτομερούς παλαιοπεριβαλλοντικής εξέλιξης για τα τελευταία περίπου 9000 χρόνια βασίστηκε σε ανάλυση των βενθικών τρηματοφόρων, των γυρεόκοκκων και «άλλων» παλυνόμορφων, των μαλακίων και της μαγνητικής επιδεκτικότητας των αποθέσεων της παράκτιας πεδιάδας του Πειραιά. Διακρίθηκαν πέντε λιθοστρωματογραφικές-παλαιοπεριβαλλοντικές ενότητες και υποενότητες, στις οποίες

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καταγράφετε η εξέλιξη της περιοχής από μία αρχικά κλειστή ολιγόαλη λιμνοθάλασσα (UnitAa) αρχικά σε μια ανοικτή (UnitAb) και στη συνέχεια, περίπου 7800 έτη πριν από σήμερα σε ένα ρηχό θαλάσσιο περιβάλλον (Unit B). Περίπου πριν από 4800 έτη πριν από σήμερα στην περιοχή υπήρχε μια ολιγόαλη λιμνοθάλασσα (Unit C), την οποία οι κάτοικοι της περιοχής χρησιμοποιούσαν ως βοσκότοπο, ενώ μετά το 2800 έτη πριν από σήμερα τα στοιχεία μας δημόσιος την έπαρξη ενός ολιγόαλου έλους (Unit D), αλλά και σημαντικές αγροτικές δραστηριότητες στην περιοχή. Η εξαιρετική συσχέτιση των αποτελεσμάτων των επιμέρους μικροεσωμάτων με την αναπόσπαστη επιλογή του πολυαρχικού παλαιοπεριβάλλοντος που χρησιμοποιήθηκαν είναι ενδεικτική των δυνατοτήτων εφαρμογής τους ως μια συνδεδεμένη πολυαρχικονομική πρακτική. 

**Λέξεις κλειδιά:** βενθονικά τρηματοφόρα, γυρεόκοκκοι, άλλα παλυνόμορφα, μαλάκια, μαγνητική επιδεκτικότητα, Ολόκαινο.

1. **Introduction**

The sedimentary sequences deposited between the hill of Piraeus and the plain of Kephissos (Attiki peninsula, Greece), comprise the Piraeus coastal plain (Figure 1). The main factors that feature in the evolution of the Piraeus coastal landscape have been described as the relative sea level rise in the Holocene due to the reaction to glacio-hydro-isostatic changes, the tectonic stability of the area documented by the relative absence of earthquakes during the last few thousand years, the low tidal range (±0.25-0.30m) and the progradation of the deltaic fan of the Kephissos river (Goiran et al., 2011). The palaeoenvironmental interpretation suggested by Goiran et al. (2011), implies that between 6800 and 5400 yr cal. BP, Piraeus was an island in the centre of a shallow marine bay. Until ~3500 yr cal. BP, Piraeus was connected to the mainland after 3000 yr cal. BP and before the sixth century BC.

![Figure 1 - Location map of borehole P4 in Piraeus coastal plain, Attica (Goiran et al., 2011).](http://epublishing.ekt.gr)
level changes and reconstructing detailed paleoclimatic and palaeoenvironmental conditions (e.g., Scott and Medioli, 1980; Carboni et al., 2010; Pavlopoulos et al., 2007, 2010; Triantaphyllou et al., 2010; Koukousioura et al., 2012).

Pollen analysis of coastal sediments considers the pollen input deriving from the vegetation of the entire river catchment, mixed together with the “local” component coming from the littoral vegetation (Bellini et al., 2009; Sadori et al., 2010), therefore the palaeovegetational reconstruction, not only relates to the local environment of the site but also to the entire south-eastern Attica basin (e.g., Kouli, 2012). The location of Piraeus coastal plain close to the City of Athens makes it an excellent opportunity of tracing human shaping of the plant landscape during Prehistory and in the Antiquity.

In environmental magnetism, rock and mineral magnetic techniques are used to investigate the formation, transportation, deposition, and post depositional alterations of magnetic minerals under the influences of a wide range of environmental processes. All iron-bearing minerals are sensitive to a range of environmental processes, which makes magnetic measurements extremely useful for detecting signals associated with environmental processes (Liu et al., 2012). In particular, magnetic susceptibility measurements can be used as a rapid, simple and non-destructive proxy to indicate magnetic changes in the sediments corresponding to different depositional environments (Oldfield and Yu, 1994; Verosub and Roberts, 1995; Ghilardi et al., 2008; Yang et al., 2008; Wang et al., 2009).

The present study aims to provide further interpretations concerning the paleoenvironmental evolution of the area of Piraeus coastal plain since about 9000 BP, with the combined use of micropaleontological studies of benthic foraminiferal assemblages, palynological and molluscan investigations and magnetic susceptibility of the underlying Late Holocene coastal deposits.

2. Material and Methods

Core P4 has been selected among ten rotational boreholes (10 cm in diameter) that were drilled in the Piraeus coastal plain; for core description, samplings and radiocarbon dating framework see Goiran et al. (2011). Core P4 samples (111 in total) were analysed for benthic foraminiferal content. Each sample (10 g dry weight) was treated with H$_2$O$_2$ to remove the organic matter, and subsequently washed through a 125 μm sieve, and dried at 70°C. A subset containing at least 200 benthic foraminifera for each sample was obtained using an Otto microsplitter. The microfauna have been identified under Leica APO S8 stereoscope. A scanning electron microscope analysis (SEM Jeol JSM 6360) has been used for taxonomical purposes. The number of specimens/gram of dry sediment and the relative abundances of benthic foraminiferal assemblages were calculated. Shannon-Wiener diversity index (H’) was calculated using the Past.exe 1.23 software package (Hammer et al., 2001). The use of the ratio between large (L) and small (S) Ammonia tests (A-index), $A = 100 \times L/S + L$, is applied as a measure of size for Ammonia specimens that can support paleosalinity conditions (Koukousioura et al., 2012).

Pollen analysis was performed on 52 samples from core P4, even though only in 28 of them the pollen concentration was sufficient to be included in the present study. All samples were spiked with known quantity of Lycopodium spores, chemically treated with HCl (37%), HF (40%), acetylated and finally sieved over a 10 μm sieve, while residues were mounted in silicon oil. Pollen identifications were based on Beug’s (2004) key and Reille’s (1992-1998) atlas, while for the non-pollen palynomorphs (NPPs) identification van Geel et al. (1989, 2003) were used. Pollen preservation was good while total pollen concentration ranges from 2700 to 32 grains/gram of dry sediment. The samples with concentrations below 150 grains/gram were considerate barren and excluded from this study. Percentage pollen diagram was constructed based on a pollen sum of regional pollen grains, excluding aquatic and hygrophilous pollen and spores. Riverine input has been calculated based on the sum of the erosion indicating NPPs type 207 and Pseudoschizaea.
Molluscan analysis was realized on 113 selected samples, washed into 125 μm sieve and oven dried at 70°C. The residue was elaborated under a Leica APO S8 stereoscope. All molluscs and fragments were identified and counted in a semi-quantitative approach.

A total of 128 samples from core P4 have been used for magnetic susceptibility analysis. All samples were sieved in order to remove all the impurities and packed in cylindrical plastic boxes (2x2x2 cm). The laboratory measurements of the volume-specific magnetic susceptibility (κ, SI units) have been performed using the Bartington MS2B sensor at low frequency (0.465 kHz). Our samples were weighed before the measurements therefore all the results are expressed as mass-specific magnetic susceptibility (χ, 10⁻⁸ m³/kg). Every sample was measured at least 3 times and the average value considered as the final one for the sample. Two air measurements before and after the sample’s measurement have been performed in all samples.

3. Results and Discussion

The results of the present study enable us to analyze in detail the paleoenvironmental units described by Goiran et al. (2011), in the Piraeus coastal plain. Our combined multiproxy analysis resulted to the subdivision of Unit A (lagoonal environment with mesohaline-oligohaline conditions; ~8700-7800 cal BP) of Goiran et al. (2011), into two subunits (Unit Aa and Unit Ab; Figs. 2-4). In particular, in between 17-12 m core depth (Unit Aa), benthic foraminiferal analysis revealed the dominance of *Ammonia tepida* (>50%, sometimes up to almost 100% of the assemblage; Figure 2), together with increased presence of *Haynesina germanica* (reaching occasionally 60%; Figure 2). *A. tepida* is reflecting a wide range of salinity and temperature in near-shore environments; shallow marine, lagoonal and deltaic zones (Jorissen, 1988; Almoghi-Labin et al., 1992; Melis and Violanti, 2006; Frontalini et al., 2009). *H. germanica* is a species tolerant to restricted conditions (Alve and Murray, 1994; Debenay and Guillou, 2002). This assemblage is featuring mesohaline to oligohaline biofacies in modern closed lagoons of the Aegean area (e.g., Koukousioura et al., 2012; Dimiza et al., 2015). Molluscan assemblages consist mainly of *Cerastoderma glaucum* (small sized and juvenile forms), *Abra* spp, and few Hydrobiidae, revealing a typical lagoonal environment (Nicolaidou et al., 1988; Kevrekidis et al., 1996). Similar assemblages feature meso-oligohaline conditions in several Aegean coastal plains (e.g., Triantaphyllou et al., 2003; Evelpidou et al., 2010; Goiran et al., 2011; Syrides, 2008) and define inner lagoon environment (e.g., Carboni et al., 2010; Koukousioura et al., 2012). The interval from 12 to 11 m core depth (Unit Ab) is featured by the high abundance of *A. tepida* (generally higher than 70%), accompanied by the presence of *Elphidium gunteri* and *Aubignyna perlucida* (up to 20%), a typical species of estuarine and shallow marine environments (e.g., Carboni et al., 2010; Evelpidou et al., 2010). Overall similar foraminiferal assemblages have been characterized as open lagoon environments (e.g., Carboni et al., 2010; Koukousioura et al., 2012).

In agreement, mollusc fauna presents similar species with Unit Aa, but considerably richer in abundance, representing a lagoonal environment possibly due to a better communication with the sea. Within Unit A, the occurrence of diverse dinoflagellate cysts and foraminifera linings (Figure 3) is the palynological evidence of the marine influence on the deposits (Kouli et al., 2009). In addition, *Pseudoischitaea* and type 207 are indicators of soil erosion and increased riverine runoff (Figure 3), which together with the high values of magnetic susceptibility (mean ~40 x10⁻⁸ m³/kg) between 12 m depth and the bottom of the core, imply increased fresh water input in the depositional environment, thus supporting the closed lagoon paleoenvironmental conditions (Ghilardi et al., 2008; Liu et al., 2012). The lower values of magnetic susceptibility within Unit Ab (12-9.5 m core depth) in respect to Unit Aa, point to higher marine influence associated with open lagoon paleoenvironmental conditions. Despite the generally low pollen concentrations of the deposits, which resulted in a fragmented record, spectra of P4 denote the occurrence of an open mosaic plant landscape with a big diversity of herb taxa (Figure 3).
Figure 2 - Foraminiferal relative abundances of borehole P4.
Figure 3 - Selected pollen types and NPPs percentage diagram of borehole P4.
Figure 4 - Magnetic susceptibility, benthic foraminiferal indices and palynomorph-based riverine input estimations of borehole P4.
Abies shows a profound short-lived peak that coincides with an increase in Artemisia abundances during Unit Aa in-between 15 and 14 m depth that may be related to a climatic deterioration event during the lower Holocene. Arboreal vegetation (AP), being in general ~30% of the pollen content, with Pinus being the most common tree taxa, followed by deciduous Quercus, exhibits significantly increased abundances during the middle part of Unit A, in-between 14 and 13 m. Throughout Unit A that corresponds to the Prokermatic to Early Neolithic period, there are no clear indications about human impact on vegetation. Nevertheless the increase of Cerealia-type towards the upper part of the Unit may be the signal of first farming communities in the area.

Benthic foraminiferal assemblages of Unit B (9.5-6.5 m core depth) consist mainly of marine foraminiferal species (e.g., Rosalina bradyi, Bolivina dilatata, Elphidium complanatum; Figure 2), increased foraminiferal diversity and high values of A-index (Figure 4). In addition, miliolids (Quinqueloculina bertheletiana, Q. seminula) featuring the infralittoral and upper circalittoral zones (e.g., Sgarrella and Monchamont Zei, 1993), consist an important fraction of the assemblage together with specimens of planktonic foraminiferal species (Figure 2). However, the presence of euryhaline species such as H. depressula, A. tepida suggests a shallow marine palaeoenvironment which also exhibits lagoonal features. Mollusc fauna, represented mainly of Cerithiidae, Bittium sp., Alvania Rissoa spp. and Tricola sp. indicates a shallow marine environment (Syrides, 2008), but the intense presence of C. glaucum suggests lagoonal features, confirming the foraminiferal findings. In this period Piraeus was an island in the center of a wide shallow marine bay (Goiran et al., 2011). Magnetic susceptibility values within Unit B are low; especially in the layer from 5.5 to 8.5 m the lower values of the core (~1 x10^{-8} m^3/kg) are observed, indicating the presence of marine deposits, in accordance with the foraminiferal proxies.

The microfaunal content of Unit C (6.5-4 m core depth) reveals the relative increase of A. tepida and H. depressula, along with Q. seminula (Figure 2), while molluscan fauna consists of C. glaucum, Abra spp. and numerous Hydrobiidae, suggesting closed lagoon paleoenvironmental conditions, which are supported by the relatively increased magnetic susceptibility values (Figure 4). According to Goiran et al., (2011), a wide lagoon became established in this period that was separated from the sea by beach barriers. This oligohaline closed lagoon, featured in pollen diagrams by expansion of the Chenopodiaceae halophytes (Figure 3), was used for grazing, as indicated by the coprophilous fungal remains of Sordaria and parasites. Asteraceae, Poaceae and Chenopodiaceae are the most common non arboreal taxa, with the latter being the dominant feature of Unit C. The human presence is inevitably detected since Unit C (Early Bronze Age) by the increase of cultivars like Cerealia-type and Olea.

Within Unit D (the upper 4 m of the core P4; younger than 2800 yr cal BP, Goiran et al., 2011), the microfauna is characterized by the slight presence of Ammonia and Haynesina and molluscs are totally absent, indicating a marshy oligohaline palaeoenvironment. Magnetic susceptibility shows the higher values of the whole core reaching the maximum of 100 x10^{-8} m^3/kg, thus implying the intense impact of fresh water input (Ghilardi et al., 2008). This is also supported by the maximum values of the palynomorph based riverine input estimation (Figure 4). Furthermore the occurrence of numerous fresh water algae of Pediasstrum and Mougeotia (Figure 3) is indicative of the fresh water depositional environment within Unit D. Both cultivation and pastoral activities appear intensified during Unit D (Geometric- Classical times). Especially Olea seems to have become a significant cultivar in the area during the Antiquity.

4. Conclusions

Our multiproxy interpretation of Piraeus coastal plain paleoenvironmental evolution during the last 8700 cal BP, suggests a very good correlation of benthic foraminiferal results with the palynological and mollusc analysis and magnetic susceptibility data. Thus, the combination of all three methods and resulted indices has the potential to get established as a very promising paleoenvironmental tool box.
5. Acknowledgments

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