Was the Piraeus peninsula (Greece) a rocky island? Detection of pre-Holocene rocky relief with borehole data and resistivity tomography analysis

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A B S T R A C T

According to historical documents, Piraeus was a rocky island consisting of the steep hill of Munichia, known as modern-day Kastella. It was connected to the mainland by a low-lying stretch of land (“Halipedon”) that would flood with sea water most of the year and was used as a salt field whenever it dried up. Apart from being an area of archaeoological interest, the extended area of “Halipedon” is densely populated, thus being of geotechnical interest and is currently being investigated through borehole and geophysical data analysis. 52 boreholes were lithologically-geomorphologically analyzed and results from 11 resistivity tomography profiles were considered. Lithostratigraphy of the borehole data was classified into three lithostratigraphic units: Cultural deposits, Pleistocene–Holocene deposits, pre-Holocene bedrock (“Marls of Piraeus”). The deeper unit shows a big depression in the southeastern part of the survey area and a circular sinking (channel) in its north part. These depressions were probably covered by the sea at a time when the southern part of the Piraeus peninsula was an island. This is confirmed by stratigraphical and geophysical investigation in the area where resistivity tomography profiles could be performed. The big southeastern depression is covered by the river sediments implying a high sedimentation rate.

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1. Introduction

In prehistoric times, Piraeus was a rocky island, as Strabo confirms (Jones, 1968) that consisted of the steep hill of Munichia, modern-day Kastella, and was connected to the mainland by a low-lying stretch of land that flooded with sea water most of the year and was used as a salt field whenever it dried up (Panagos, 1968; Garland, 1987). Consequently, it was called the Halipedon, meaning the ‘salt field’, and its muddy soil made it a tricky passage. Through the centuries, the area was increasingly silted and flooding ceased. Thus, by early classical times, the land passage was made safe. The rocky island of Piraeus was connected to the mainland during the 5th century BC (Strabo in Jones, 1960, Conwell, 1992). In ancient Greece, Piraeus assumed its importance with its three deep water harbors, the main port of Cantharus and the two smaller ports of Zea and Munichia (Loven et al., 2007) and gradually replaced the older and shallow Phaleron harbour which fell into disuse (Fig. 1). In the late 6th century BC, the area drew greater attention due to its advantages. In 511 BC, the hill of Munichia was fortified by Hippias and four years later, Piraeus became a deme of Attica by Cleisthenes.

Recent geoarchaeological research (Goiran et al., 2011) has suggested that Piraeus was an island, as previously mentioned. This research was based on samples taken by ten boreholes in the northern area of the Piraeus peninsula which were analyzed for microfaunal content and radiocarbon dating. Four maps show the paleogeographical evolution of Piraeus during Holocene.

Today, Piraeus is the main port of Greece (Fig. 2), the neighboring city of Athens and, like the capital, is densely populated, showing clear signs of rapid growth and change.

The detection of the landscape’s evolution provides much information and data for geotechnical and paleogeographical studies that can help optimize urban planning in the further development of the city. It was within the context of this purpose that a borehole data analysis and geophysical study was
conducted with the geophysicists and geomorphologists working in parallel. More specifically, data from 52 boreholes were analyzed for their lithostratigraphy and were correlated with resistivity data taken from 11 Electrical Resistivity Tomography (ERT) profiles (Fig. 3).

2. Geology of the Piraeus and Neo Faliron area

Papanikolaou et al. (2004) have presented a paleographic evolution of the Athens Basin from Upper Miocene to present. The Athens Basin represents a complex neotectonic asymmetric graben bounded by NNE–SSW marginal faults. The presence of sedimentary sequences indicates continental and lacustrine sediments in the west and north and coastal marine sediments in the southeast. An E–W fault zone divided the basin in a northern subsided part and a southern part where lakes existed only during Late Miocene in the central western part, while shallow marine environments dominated in the south and southeast during Late Miocene–Pliocene with the coastline being very close to the present day Acropolis and Philopapou hills. The central eastern area was in a high position with the Alpine bedrocks under erosion and constituted a barrier towards the south. This situation changed before the middle Pleistocene when the Kifissos River was formed in such a way that it cut through the hilly area and connected the northern drainage system with the south, which resulted in the saturation of the remnant lakes of the northern segment.

The existing formations covering the greatest area in the site under survey are Pliocene and Pleistocene deposits, as well as the Holocene river deposits. In a small area, there are deposits of talus material, coastal deposits of sands and silty sands which were outlined in older geological maps (Lepsius, 1893) and are now covered by cultural deposits of the decades that followed.

On analyzing the geological status of the area (Fig. 4), it has been found that the geological formations from older to newer are:

- Upper Cretaceous limestones found in the broader mountainous area north of Piraeus Harbor.
- Marls, marly sandstones and limestones, conglomerate, collectively referred to as “Marls of Piraeus”. There are also thin layers of siltstones, clays, silty and clayey sands. The formations and their thickness vary from place to place but the most dominant are marls and marly limestones in alternation with a relatively high percentage of calcium carbonate (more than 50%). The overlying loose sediments usually consist of alternations of clayey or sandy silts, silty sands and sands with shells and organic material. Thin layers of gravel and sand usually exist between marl and loose silty layers which in some places transform into loose conglomerate. From a geological point of view, “Marls of Piraeus” are Neogene sediments of a shallow marine environment, subdivided into two units. The upper unit is the result of continuous sedimentation in a low energy marine environment (Charalambakis, 1952), shown as semi-horizontal layering. The underlying lower unit is in tectonic unconformity with the upper unit and has the same composition and age. Marly sandstones and marls are characterized by differences in the process of sedimentation caused during certain periods by the predominance of more or less

Fig. 1. Map of the south–west part of Attica, Greece, that shows a) the great walls connecting the city walls of Athens and Piraeus in ancient times, b) the three deep water harbors of Piraeus, the main port of Cantharus and the two smaller of Zea and Munichia.
fine grained materials. On the contrary, marls and marly limestones are characterized by differences in weathering and the movement of material transportation with the remnants of chemical dissolution calcium carbonate. From a geotechnical perspective, the Marls of Piraeus are considered to be inhomogeneous, anisotropic bedrock with great solidification and partial cementation.

Holocene deposits. Their stratigraphic relation is in unconformity with the Neogene deposits. The deposits consist of talus material of Pliocene slopes of the Piraeus peninsula, deposits of the Kifisos River (in places), “cultural” deposits (archaeological strata from the classical period, 5th century B.C. onward) and finally, shallow marine and lagoonal deposits (now covered by modern or older embarkments) of sands and silty sands as well as silts or clays of lagoon origin.

3. Lithostratigraphical correlation of borehole data

Data from fifty-two (52) geotechnical boreholes (Fig. 3: defined as “D”) are available from the National Documentation Centre (NDC) Data Base (Marinos, 1999). These boreholes were not regularly scattered throughout the whole area of investigation. On the contrary, the majority were located in groups covering small areas and were made prior to construction projects. The average depth of boreholes was 20 m and most of them meet the pre-Holocene substratum. The formations, Marls of Piraeus and Upper Pleistocene—Holocene deposits are found in various combinations and thicknesses. Two representative boreholes (“D14” and “D22”) with their lithological sequence are shown in Fig. 5 (left part for each borehole). Detail in lithology is shown with a different pattern but each general definition has the same color. If we use only the color
definition, we can see all borehole data (Fig. 6) in 3D mode. A general first conclusion of this 3D presentation is that marls and marly formations have a great degree of thickness and deepen to the east. They are also quite deep in the central part of the survey area.

Since many different layers have been detected, there was a need to draw correlations between them in three different lithostratigraphic units, newer to older, in order to connect them in geomorphological and geophysical terms:

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**Fig. 3.** Map of the survey area (outlined in red) with the roads and topography in the background and the positions of boreholes and Electrical Resistivity Tomography profiles. Some “main” roads are denoted with dashed blue lines which act as reference in the following maps with borehole and resistivity data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Fig. 4.** Geological map of Piraeus. The survey area is outlined in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Unit 1: This unit includes anthropogenic deposits (recent rambles-debris landfills, and archaeological layers). The consistency of this unit includes Holocene coarse material (gravel, cobbles, boulders, sands, silts and clays) according to the composition and stratigraphy of stratigraphic units observed in the boreholes of Goiran et al. (2011). Therefore, the age of these units ranges from 2500 cal. BP till today. This unit consists of loose material (mainly coarse graded) of great porosity (varying from place to place depending on the composition and compaction) and limited geotechnical characteristics. The resistivity range is 30–1000 Ohm-m.

Unit 2: This unit includes lagoon, coastal and fluvioterrential deposits. It occurs at depths from 0.5 m to 19.62 m in places, with interference of fluvial-torrential deposits consisting mainly of silty-sandy sediments rich in marine fossils, bivalves and gastropods (Goiran et al., 2011). The appearance of fossils in these deposits suggest a lagoonal to shallow marine environment. Fluvial deposits with gravel and sands also exist in this unit. Following
observation of the grading, sedimentological composition and color of the different stratigraphic units, it has been found that this unit corresponds to the relevant unit of the boreholes of Goiran et al. (2011), so its age is approximately between 8000 and 2500 cal. BP. From a geotechnical perspective, this unit consists of loose material with great permeability saturated with saline water and has extremely low resistivity (~2.5 Ohm-m).

Unit 3: The pre-Holocene substratum that consists of Neogene deposits (marl, marly limestones, conglomerates) and meta-morphic rock formations (schists and marbles). These are geotechnically considered to be the basement of any foundation and have low permeability. Resistivity can take values from 2.5 Ohm-m to 30 Ohm-m with the lower values being the result of secondary porosity and the presence of discontinuities.

The lithology data of the 52 boreholes were analyzed with the above classification of lithostratigraphic units. Fig. 5 shows this transformation of lithology (left part for each borehole) to lithostratigraphy (right part for each borehole) for two representative boreholes: “D14” and “D22”. This new lithostratigraphic approach is shown in 3D mode for all boreholes in Fig. 7 provided we consider the Units as stratigraphic layers in Fig. 8. The same conclusions are drawn as with the lithology presentation (Fig. 6) but now, both the deepening of pre-Holocene relief (Unit 3) on the east and more importantly, its channel in the center of the survey area are much clearer, which proves that a pre-Holocene depression exists in the north of the Piraeus peninsula. Fig. 8 also clearly shows where the sea coast was in respect of its current position. The relief of the top of Unit 2 also follows the above behavior to a lesser extent showing the long duration of the phenomenon presented in the introduction of alternative flooding and sedimentation of the area between mainland and the “island”.

4. ERT profiles in the urban area of Piraeus

The difference of the previously established lithostratigraphic units in resistivity values led to the use of Electrical Resistivity Tomography (ERT) with its fine detail in underground models. The Schlumberger electrode array (n > 2) was preferred for its greater sensitivity in the detection of horizontal layering, lesser sensitivity to lateral inhomogeneities, good signal-to-noise ratio and good penetration in conductive environments. Most available places in the urban area of Piraeus for ERT profiles have been exploited and the eleven (11) profiles provide a good coverage of the area under investigation, as shown in the map of Fig. 3. The electrode distance is 2–4 m and the length of the profile is 80–160 m.

Cultural deposits near the surface consist mainly of coarse material with very high resistivity on the top. Going to deeper horizons there is a sudden change with very low resistivities due to the presence of saline water and again a sudden change to higher resistivities as the impermeable marls are reached. These sudden changes create problems in the interpretation procedure and a robust approach has been followed. The inhomogeneous coarse surface material created problems with the poor electrode conductance. Therefore, error measurements have been excluded.

The results of interpretation (RES2DINV software, Loke and Barker, 1996) with a 15%–30% RMS error (high RMS for the previous reasons) gave resistivity models of the sub-surface (Fig. 9) with saline water infiltration playing an important role in distinguishing the layers. Borehole data show good agreement with resistivity models.

Firstly, a 3D presentation of all 2D models of resistivity tomography profiles (Fig. 10a) and secondly of horizontal slices of resistivity distribution at various altitudes (Fig. 10b) shows the sedimentation and saline water infiltration.

There is a highly resistive layer near the surface in the western part of the area (altitude 0.0 m in Fig. 10) associated with cultural deposits (coarse material), while when going deeper and further to the east, there is a layer of fine-grained material with lower resistivity. In deeper horizons, this layer has saline water which has infiltrated the area mainly from the southeast. In the deepest slice (altitude −12.5 m in Fig. 10), there is a highly resistive layer to the west associated with the bedrock (conglomerate — “Marls of Piraeus”), while this does not exist to the east.

Most importantly, as the resistivity tomography profiles are positioned in the area where the previous borehole analysis has shown that there was sea in the distant past, it is confirmed that there are sediments of various composition and permeability to saline water with the bedrock being deeper than an altitude of −10 m and not existing to the southeast of the detected levels.

Fig. 7. Lithostratigraphy with the suggested units of all boreholes is presented in 3D mode. Blue lines present the position of the “main” roads of the survey area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 8. The relief of the top for each lithostratigraphic unit (Top: Unit 1, Middle: Unit 2, Bottom: Unit 3) is presented in 3D mode. The purple dashed lines represent the position of the “main” roads of the survey area. The current coast line is also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
5. Discussion

The combined use of borehole data analysis and geophysical investigation for the detection of stratigraphy has recently been a well established methodology. Vouvalidis et al. (2010) whose multidisciplinary research involved a detailed geomorphological survey combined with stratigraphical, paleontological and geophysical studies in an area near the village of Agia Paraskevi in Central Greece, 5 km east of Lamia City, revealed a shallow marine palaeoenvironment, gradually shifting to a coastal — lagoonal one and finally changing to a freshwater marshy environment. Geomorphological mapping and 3D geophysical characterization in County Dublin (Bull Island and Killiney Beach) enabled a depiction of the main stratigraphic and hydrostratigraphic units of two study areas (Gibson et al., 2012), one encompassing coastal sedimentary processes and the other undergoing erosional processes. ERT data enabled the depth to bedrock in both areas to be estimated and the delineation of the spatial distribution of soft sediments in Killiney, as well as the hydrostratigraphic units in Bull Island. These data provide extra information for future remedial actions related with sea level change potentially taken on urban areas.

This well established methodology was followed in the Piraeus and Neo Faliron area, an urban — coastal area that involves added difficulties both in borehole analysis as well as in geophysical investigation.

It has been established that, although the analyzed borehole data were acquired by different operators, their lithological units were such that correlation with the lithostratigraphic units was relatively easy. The lithology itself, as shown in Fig. 6, can generally be defined as having the same color, thus indicating a striking resemblance to the suggested lithostratigraphy of Fig. 7. For example, marls and marly formations have a great degree of thickness and deepen to the east and they are also quite deep in the central part of the survey area. The new lithostratigraphic approach shown in Fig. 7 leads to the same conclusions.

Although the boreholes were not regularly scattered in the survey area, they give a reasonable picture of the overall stratigraphy as shown in Figs. 6 and 7 there is not an unreasonable change in the data.

The position of the boreholes whose data were analyzed in detail by Goiran et al. (2011) enables a reasonable correlation to be made with the borehole data analyzed here, thus allowing the age of the lithostratigraphic units to be obtained.

The Schlumberger array proved effective in city conditions with great care having been taken in choosing areas that create the lowest noise in the ERT measurements. It is for this reason that few ERT profiles cover such a large area. The urban noise and the surface cultural deposits created relatively high RMS errors. The ERT models appear reasonable and in good agreement with nearby borehole data.

As was the case with the boreholes, the ERT profiles were not regularly scattered in this heavily populated urban survey area, but they too reasonably presented the general stratigraphy of the area.

A key factor in the lithostratigraphic and geophysical analysis and their interconnection is the distribution of sediments with regard to granular composition, compaction and permeability which have been detected by the geophysical investigation in the area of interest and by the boreholes locally.

The deepening of pre-Holocene relief (Unit 3) on the east and its channel in the center of the survey area proves that a pre-Holocene depression exists in the north of the Piraeus peninsula. The circular
Fig. 10. A 3D presentation (a) of all 2D models of resistivity tomography profiles and (b) of horizontal slices of resistivity distribution at various altitudes. The blue lines represent the position of the “main” roads of the survey area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 11. The relief of the top for lithostratigraphic unit “3” (the pre-Holocene bedrock) with the horizontal resistivity distribution for −5 m altitude laid on the relief. Shadowed relief shows the two depressions.
slight sinking, previously referred to as a channel, has been confirmed by geophysical investigation in the area. The horizontal resistivity distribution of ~5 m altitude agrees with the top relief of the deeper unit (Fig. 11). There is a great agreement although there is not such a dense coverage of ERT profiles since the area is heavily populated, full of buildings and narrow roads.

6. Conclusions

The analysis of borehole data with their lithostratigraphic classification in three units shows that for the deeper unit (the pre-Holocene bedrock), there is a big depression in the southeastern part of the survey area and a circular slight sinking (channel) in its northern part (Fig. 11). These depressions were probably covered by the sea at a time when the southern part of the Piraeus peninsula was an island with the circular sinking representing “Halipedon” and the southeastern depression the deep sea.

The depressions of the bedrock are not deep in the upper surface of the second unit (Holocene deposits) because there had been intense river deposition in the southeastern part. Nevertheless, slight depressions in the same area in the upper surface of the second unit still exist showing the long duration of the phenomenon presented in the introduction of alternate flooding and sedimentation of the area between mainland and the “island”.

The great thickness of the second unit (Holocene deposits) in the southeastern part of the survey area shows intense river deposition having taken place.

The results for the bedrock relief and the distribution of the deposits above give information on landscape evolution and geoarchaeology for the area of Piraeus and Neo Faliro in Greece. They also offer valuable information on geotechnical issues in this fast-developing region.

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