

Effectiveness of electromagnetic conductivity mapping for delineating subsurface structures related to the Roman port of Emporiae

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Abstract – In this paper we present the results of a geophysical survey conducted using frequency domain electromagnetics (FDEM). The geophysical survey is part of a wider archaeological research project designed to obtain conclusive evidences about the location the Roman harbour expected to be buried under alluvial sediments in the bay close to the remains from Greek and Roman times.

A total of 3545 stations were recorded with a Geonics EM31 MK2 ground conductivity meter in two dipole configuration modes: horizontal and vertical dipoles. Apparent conductivity measurements were sampled every meter along lines.

The results obtained in this study indicate that shallow electromagnetic induction is a very useful alternative for mapping the buried paleolandscape related to harbours and coastal plains laying over a high resistivity

I. INTRODUCTION

Since the beginning of the archaeological investigations in Empúries, the plain existing between Neapolis and Palaiaopolis, has been considered that was a commercial port of considerable significance in the Antiquity [1]. The plain is currently an agricultural land as consequence of the changes in sea level and sedimentation processes that transformed the coastline. Related to it, there are the remains of a building known as the dike, dated to the 1st century BC [2].

Previous researches about sedimentology and evolution of coastline suggested that alluvial sediments of the Fluvià River and sands transported by the sea concealed the historical port of Emporiae [3].

The current name of Empúries comes from the Greek term Emporion, which means shopping centre or mall, and faithfully described the purpose of the site, because the city was built initially in the delta of the Fluvià River, crossing several trade routes, and with a natural port, which offered adequate protection to commercial ships. The first Greek settlement is dated to the 6th century BC. The location was in the present town of St. Martin Empúries (Palaiaopolis) which at that time was surrounded by water, and later was integrated to the coast by an isthmus thanks to the contributions of the sediments of the Fluvià River. In the 5th century BC the Greeks moved Emporion, from St. Martí Empúries to the south, at an emerged hill in the shoreline (Neapolis). Then, Emporion quickly became one of the most important commercial ports in the Mediterranean (Figure 1).

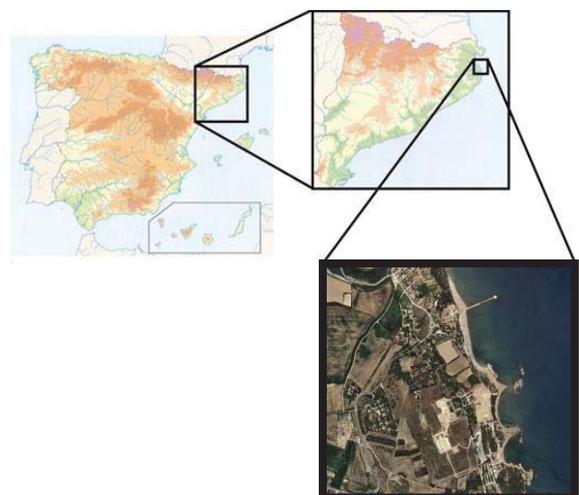


Figure 1. General map of Spain and Catalonia showing the location of the archaeological site of Empúries.

II. HISTORICAL FRAMEWORK

The various nuclei of population that, over time, were found in Empúries (the Gulf of Roses) and its more immediate environment show the importance that this commercial place had during ancient history. During the 7th century BC, the ideal location of the Empordà coast favoured the stable occupation of the various hills in the Empúries area by indigenous communities and the establishing of initial commercial contacts which, soon after, were to culminate in the setting up of the well-known Greek Phocæan emporion on the promontory of Sant Martí d'Empúries, the Palaia Polis.

The particular morphology of the Emporitan topography, with a small natural bay that served as a port between the island/peninsula of Sant Martí to the north, and the much bigger coastal promontory further to the south meant that, a short time later, a new Greek city, which kept the name of Emporion.

The origin and evolution of Emporion were always linked to its commercial vocation and its port, as can be seen by the fact that centuries later it also became the Roman gateway to the Iberian Peninsula, initially to solve the war conflict with the Carthaginians and later to contribute to the control and conquest of Hispania. The strategic importance of Empúries at that time is evident from the setting up of a permanent Roman military camp under the shelter of the Greek nucleus, which, once abandoned, was used as a base to create a new Roman city in the early 1st century BC. The settlement was orthogonal in shape and covered a surface area of 22.5 hectares, most of which have yet to be discovered. Towards the change of the era, the Greek and the Roman nuclei merged into a single site that we know as municipium Emporiae (Figure 2).



Figure 2. Location of the different historical sites referred in the text.

III. METHODOLOGY

Field geophysical surveys started in this area in 1996 the framework of a project led by the German Archaeological Institute using a set of different geophysical methods: VES, GPR, seismic refraction and magnetics [4]. Recently our efforts has been concentrated on frequency domain electromagnetic methods (FDEM) that has shown to be very effective for similar archaeological researches [5] and [6].

3.1. FDEM: In this method, time-varying EM resulting fields have in-phase (P_h) and a quadrature (Q_u) component. The in-phase component indirectly reflects the variations of magnetic susceptibility existing in the subsurface, whereas Q_u response is related to the electrical conductivity and can be converted to EC_a , expressed as mS/m, using the formula [7]:

$$EC_a = \frac{2}{\pi \cdot f \cdot s^2 \cdot \mu_0} \left(\frac{H_s}{H_p} \right)_{Q_u}$$

where f , is the frequency (Hz), s is the coil separation (m), μ_0 is the magnetic permeability of free space ($4\pi 10^{-7}$ H/m) and $(H_s/H_p)_{Q_u}$ is the Q_u component of the secondary H_s to primary H_p magnetic field coupling ratio. The formula is an approximation based on the assumption of operating the instrument at low induction number (LIN) conditions. The dimensionless LIN parameter is defined as the ratio of the instrument coil separation divided by the skin depth δ , where the skin-depth in turn is defined as the distance within a half-space wherein a plane wave is attenuated by $1/e$ (aprox. 37%) of the value at the surface [8]. If the induction number is very low, then the quad-phase component of the measurements can be converted into apparent conductivity, expressed in milliSiemens (mS/m) per meter.

The background conductivity noises of the device are 0.1 mS/m for the quad-phase signal and 0.03 ppt for the in-phase signal. The instrumental accuracy is 5% for a measurement of the order of 20 mS/m. Penetration depth depends of the distance between the coils that is 3.7 m along the horizontal axis and the frequency of the emitted signal that is 9800 Hz. In these conditions, the penetration depths corresponds to ~ 3 and 6 meters for the horizontal and vertical dipole configurations respectively. The data acquisition is fast if there are not obstacles during the acquisition as was the case in this survey (Figure 3).

A total of 3545 stations were recorded with a Geonics EM31 MK2 ground conductivity meter in two dipole configuration modes: horizontal and vertical dipoles. Apparent conductivity measurements were sampled every meter along lines (Figure 4). Data was directly stored to a DL600 data-logger. Repeated measurements were recorded at the beginning and end of each profile to perform corrections for intersection errors (miss ties) that could affect the homogeneity of data during gridding.



Figure 3. The research area has very favourable conditions for the application of geophysical methods.

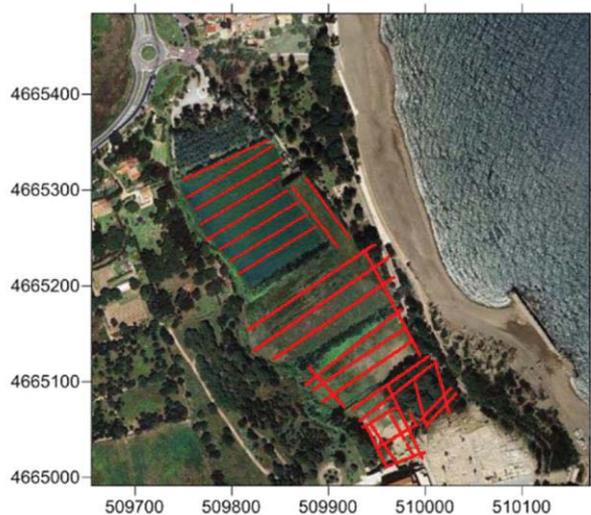


Figure 4. Location of the geophysical profiles (red lines), distributed along the study area.



Figure 5. Location of a 235 metres long ERT concatenated profile recorded on the northern edge of the study area

3.2. VES: Initially, DC resistivity surveys were performed in the study area by measuring 5 vertical electrical sounding points along a profile crossing the study area. This preliminary survey was conducted to define thickness of clayey Quaternary sediments over the high resistivity basement formed by Cretaceous limestone.

The geophysical equipment used in the field survey consisted of a DataRes digital resistivity meter from Ambrogeo. A Schlumberger array was selected for this survey because of its suitable sensitivity for mapping shallow electrical resistivity variations. The current electrode separations (AB) were ranged logarithmically from 1 m to 60 m. This spread was considered long enough to penetrate the sedimentary cover to a depth of about 15 m.

The electrode coupling with the ground was checked before carrying out the measurement for each of the four electrodes at each measurement. The software IX1D [9] was used to process the VES data sets and obtain the subsurface resistivity model.

The inversion program incorporates a ridge regression routine [10] to achieve a best fit to the observed data. The best fit can be achieved either automatically through the software or manually by adjusting the layer thickness and resistivity values. To overcome the ambiguity problem in the inversion of resistivity curves, the lithologic information of a borehole was used to build the input models of the inversion process. The borehole was drilled close to a VES and some model parameters were fixed during the inversion process according to the available geological data.

3.3. ERT: Five ERT profiles for electrical resistivity imaging were recorded using an IRIS Syscal Pro resistivity meter with 48 electrodes.

All profiles were measured with a Wenner-Schlumberger array and 5 m electrode spacing resulting in a maximum penetration depth of about 20 m. For some profiles several segments were concatenated to obtain longer profiles as for instance the 235 meters long profile showed in the Figure 5. Precise electrode positions were located using a differential GPS.

Apparent resistivity values were first checked for erroneous values that may occur mainly due to bad electrode coupling with the ground that show up as spikes in the apparent resistivity. For all lines, we did then 2D inversion using the commercial program Res2DInv® [11] including the topography. During the inversion process, the root-mean-square value of the difference between experimental data and the updated model response is used as a criterion to assess the convergence [12]. For most lines a root mean square (RMS) data adjustment better than 3% was obtained.

IV. RESULTS

4.1. FDEM: Apparent electrical conductivity maps have been obtained from FDEM values after statistical data processing and gridding using kriging interpolation method. Then, colour contour maps have been superimposed over georeferenced aerial images. Apparent conductivity measurements showed a wide range of values as result of the high resistivity contrast between limestones and clay sediments, varying between 3 and 154 milliSiemens/m. clearly show the subsurface geometry of the basin and the existence of a high gradient between 30 and 40 mS/m conductivity values (Fig 3 and 4). These limits can be interpreted as the natural cliffs of limestones that were geomorphological boundaries of the coastline. Besides other geophysical limits in both horizontal and vertical dipoles configurations that can be associated with either natural or manmade structures related to the Roman port.

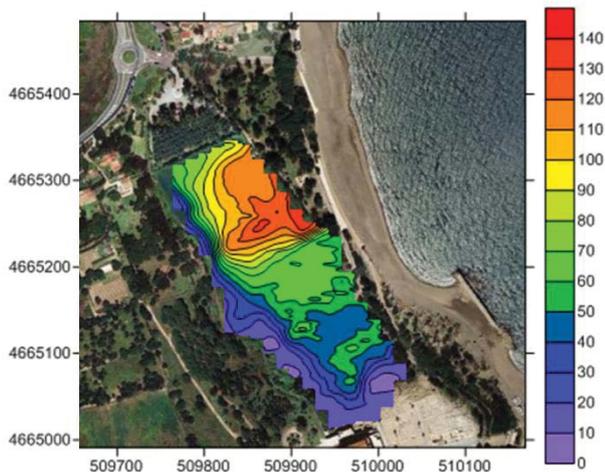


Figure 6. Apparent conductivity maps for horizontal dipoles from the interpolation of all EM-31 measurements.

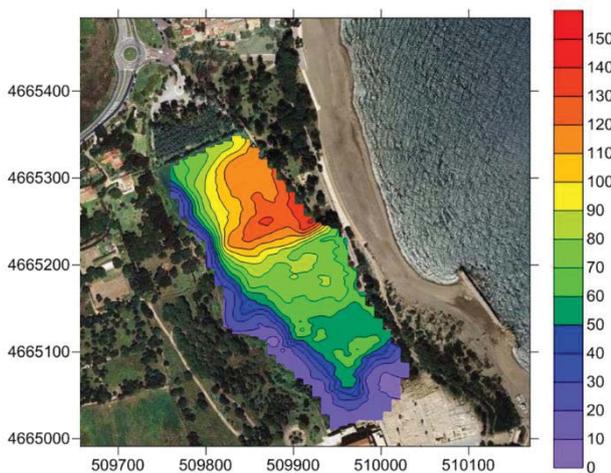


Figure 7. Apparent conductivity maps for vertical dipoles from the interpolation of all EM-31 measurements.

4.2. VES: Inverted Vertical Electrical Sounding data clearly showed three-layer H type models with a thin high resistivity layer at top interpreted as a soil cover, an intermediate clayey layer of low electrical resistivity and thicknesses ranging from 5 to 10 meters and high resistivity basement interpreted as the Cretaceous limestone. In particular, the interpretation of VES-5 constrained by the geological log from the borehole drilled few meters apart (Figure 8).

4.3. ERT: 2D electrical resistivity cross-sections showed the same subsurface structure of three different layers with $\rho_1 > \rho_2 < \rho_3$. The upper layer has an almost constant thickness (1.5 metres) and resistivity (250 Ω .m) but the thickness of intermediate layer of low resistivity changes laterally over a high resistivity basement (Figure 9).

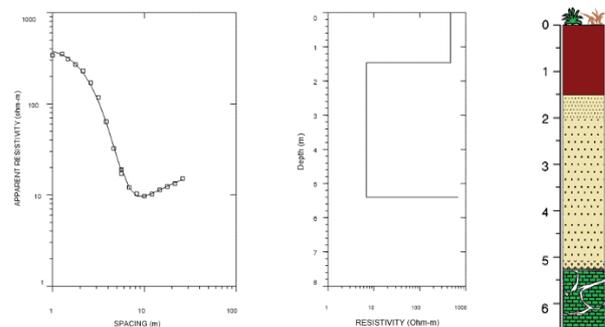


Figure 8. Inversion of the three-layer VES and geological log of the borehole drilled next to this point.

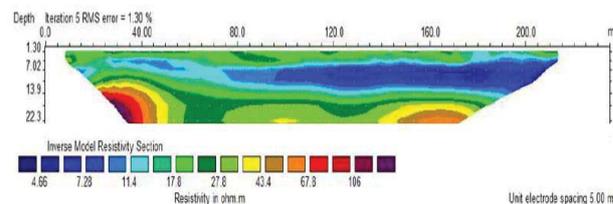


Figure 9. Cross-section of the ERT profile which location is showed in figure 5.

IV. INTERPRETATION

Usually the interpretation of EMI data for archaeological surveys is based only on mapping and delineation of the borders of anomalies. Nevertheless, in this study we have tried to get as much information as possible by a constrained inversion of EMI data. The characteristics of sedimentary filling and depth of the limestone substrate have been interpreted from the solution of the 1D direct and inversion problem of synthetic models based on the geological log of the boreholes and the models (depths and electrical resistivities) obtained from the inversion of the five vertical electrical soundings (VES) distributed along the basin.

Any inversion process aims to find a plausible model of the subsurface, which adequately fits the observed data within the limits of the data uncertainty. The process consists of two components: forward modeling and inversion. Forward modelling generates the response of a specific synthetic model, whereas inversion automatically changes the model to reduce the misfit between measured and forward-modeled data.

The initial model was a three-layer model with the following electrical conductivity values

4 mS/m for the first layer (soil)

150 mS/m for the second layer (clay)

1 mS/m for the third layer (limestone)

The thickness of the first layer kept fix to 1.5 meters and the thickness of the second layer was considered the free variable.

The response of the model was calculated following the formula [7]:

$$\sigma_a = \sigma_1 [1 - R_V(z_1)] + \sigma_2 [R_V(z_1) - R_V(z_2)] + \sigma_3 [R_V(z_2)]$$

where, σ_a is the bulk apparent conductivity of the layered earth, σ_1 , σ_2 and σ_3 are the electrical conductivities of the top, intermediate and bottom later, z_1 and z_2 the depths to the second and third layer respectively. R_V or R_H are the relative contributions of vertical and horizontal components to the secondary magnetic field or apparent conductivity from all material below a depth z given by:

$$R_V(z) = \int_z^\infty \phi_V(z) dz$$

Then, EMI data have been inverted keeping invariant all the parameters of the model except the thickness of the second layer. For the case of the point where the first borehole was drilled, the apparent resistivity of the model for vertical dipoles was 55.80 mS/m whereas the observed apparent conductivity was 56.2 mS/m.

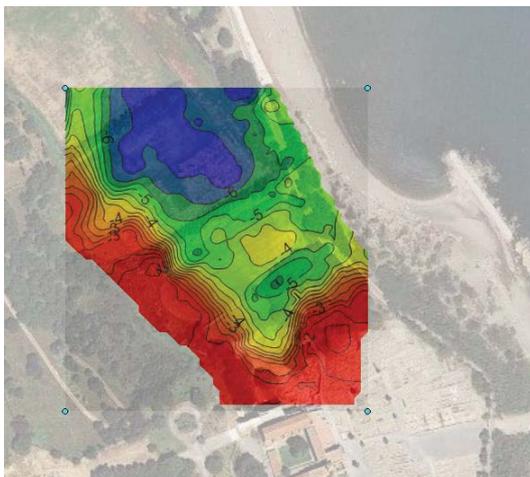


Figure 10. Iso-depth map of the basement derived from the 1D inversion of apparent conductivity values for vertical dipoles.

The same 1D inversion process has been applied to all EMI conductivity values and an iso-depth map of the basement has been generated (Figure 10). The iso-depth map shows the existence of structures that can be assumed as platforms and channels. This interpretation is following the hypothesis advanced by the archaeologists that is reproduced (Figure 11) and with a borehole drilled that found the limestone substrate at 5.20 meters depth. Besides, the radiocarbon dating of plant remains at 4.80 m depth gave an age of 2020 ± 70 years, which is consistent with the historical period of the port.

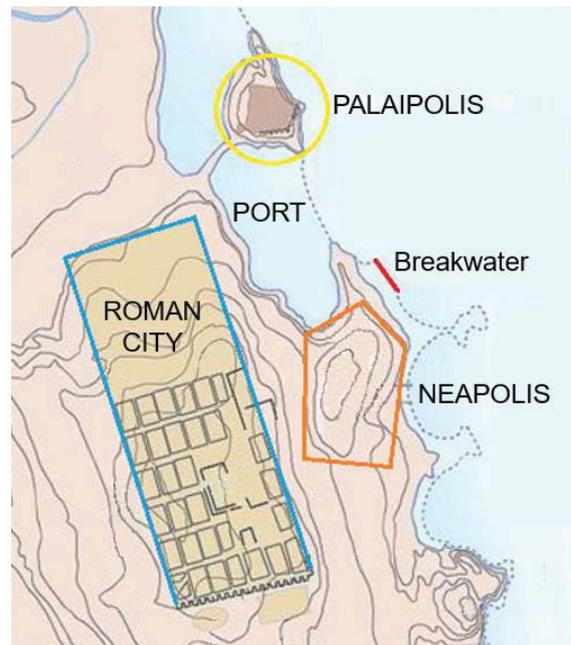


Figure 11. Interpretation of the landscape based on the previous archaeological hypothesis and the geophysical results presented in this paper.

V. CONCLUSIONS

The results obtained in this preliminary study indicate that shallow electromagnetic induction is a very useful alternative for mapping the buried paleo-landscape related to harbors and coastal plains laying over a high resistivity basement. In our case, the existence of a low electrical conductivity top layer underlayed by a highly conductive soil, resolution of subsurface parameters is much better than in the opposite case of a highly conductive layer underlain by a moderately conductive layer.

Particularly, the geophysical images and resulting interpretation from data obtained in this study confirmed the existence of a well-defined basin between the Greek archaeological sites named Palaipolis and Neapolis. The basin could have been used in Antiquity as a natural port as has been suggested by the Archaeologist from long ago without conclusive evidence. Nevertheless, further archaeological diggings and geophysical surveys should be conducted.

REFERENCES

- [1] X.Aquilué, P.Castanyer, M.Santos, J.Tremoleda, "Empúries". Guies del Museu d'Arqueologia de Catalunya, Tarragona. 1999.
- [2] R.Marcet, E.Sanmartí, "Empúries". Diputació de Barcelona, 1989.
- [3] M.A.Marqués, R.Julià, "Coastal problems in Alt Empordà, Catalonia". In: Coastal problems in Mediterranean Sea. Ed. P. Fabri and E.Bird, 1983 pp. 83-94. Bolonia.
- [4] M.Blech, D.Marzoli, F.Burjachs, R.Buxó, A.Casas, S.Giralt, F.Rambaud, "Interdisziplinäre prospek-tionen im Ampurdán: vorbericht der kampagne september 1996". Madrider Mitteilungen, 1998, vol. 39, pp. 99-120.
- [5] M.R.Bates, C.R.Bates, "Multidisciplinary approaches to the geoarchaeological evaluation of deeply stratified sedimentary sequences: examples from Pleistocene and Holocene deposits in Southern England, UK". Journal of Archaeological Sciences, 2000, vol. 27, pp. 845-858.
- [6] A.Tabbagh, "Applications and advantages of the Slingram electromagnetic method for archaeological prospecting. Geophysics, 1986. vol. 51, pp. 576-584.
- [7] J.D.McNeill, "Electromagnetic terrain conductivity measurement at low induction numbers". Technical Note TN-6. Geonics Ltd., Mississauga, ON, Canada. 1980, pp. 1-15.
- [8] B.R.Spies, "Effective depth of exploration in electromagnetic sounding methods". Geophysics 1989, vol. 54, pp. 872-888.
- [9] J.R. Inman, "Resistivity inversion with ridge regression" Geophysics, 1975, vol. 40, pp. 798-817.
- [10] Interpex, Ltd, "IX1D v2 Instruction Manual". Interpex Limited, USA, 2008, pp. 1-67.
- [11] Geotomo Software, "RES2DINV ver. 3.59. Rapid 2-D Resistivity & IP inversion using the least-squares method for Windows XP/Vista/7", Malaysia, 2010, pp. 1-157.
- [12] M.H.Loke, R.D.Barker, "Rapid least-squares inversion of apparent resistivity pseudosections using quasi-Newton method". Geophysical Prospecting, 1996, vol. 48, pp. 181-152.