Application of airborne electromagnetics for coastal areas' characterizations and geothermal studies in Croatia and Italy

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BIOGRAPHY

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SUMMARY

Groundwater salinization is a serious problem affecting numerous coastal areas of the world. Airborne electromagnetics is already widely used to feed data-driven decision and management processes with accurate (hydro)geomodels and, by doing so, to mitigate the detrimental effects of saltwater intrusion.

In this perspective, airborne electromagnetic surveys were performed, in 2021, in Croatia, and, in 2023, in Sardinia (Italy). The overall goal of the surveys was to better understand the hydrogeology of the coastal areas leading to a more quantitative assessment of the saltwater intrusion and possible preferential paths.

In an attempt to find alternative energy sources, geothermal potentials are investigated more and more frequently around the world. Indeed, this was one of the objectives of the additional survey flown in Sardinia in the Campidano plain, in the proximity of Sardara.

Here, we present the preliminary, but extremely promising, results of data processing and inversion of those three datasets. We built (pseudo-)3D resistivity models based on 1D forward approximation. And we compare them against other available ancillary measurements and prior knowledge. Not surprisingly, freshwater is generally related to a relatively resistive unit, whereas potential geothermal fluids are associated with conductive features.

Key words: inversion, saltwater intrusion, airborne electromagnetics, frequency-domain, time-domain.

INTRODUCTION

Over the past years, airborne electromagnetics (AEM) has become a key tool in tackling hydrogeological problems (Christiansen et al., 2006; Viezzoli et al., 2010; Ageev et al., 2022; Knight 2022). Specifically, numerous works have been devoted to investigating groundwater salinization problems (Palamara et al., 2010; Ball et al. 2020; Tosi et al., 2022; Billy et al., 2022). Generally, during coastal surveys, it is reasonable to expect quite low resistivity values: in the order of 0.2-0.3 Ω·m for the seawater, and about 0.3-0.8 Ω·m for the seafloor. In our case, the task was to detect and characterize the subsurface coastal structures up to around 100-m depth. The targets were quite challenging because of conductive overburden. In this respect, the areas under investigation were the Neretva Delta in Croatia (Figure 1) and the southeastern of the two areas in Sardinia (Italy) (Figure 2). Both cases are significantly affected by seawater encroachment.

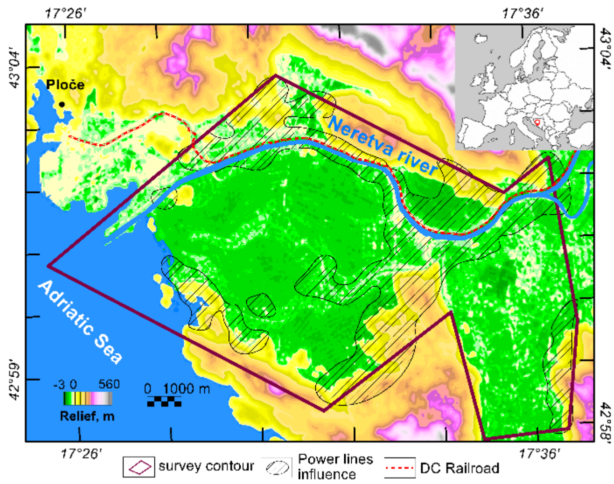

Figure 1. Overview of the survey area in Croatia.

The second area in Sardinia (collectively named Sardara, in Figure 2) is supposed to be rich in faults (evident from the seismics), potentially relevant from a geothermal perspective. Also concerning this kind of target, AEM is gaining popularity (Santilano et al.,

2015) for the potentially high resistivity contrast of the targets.

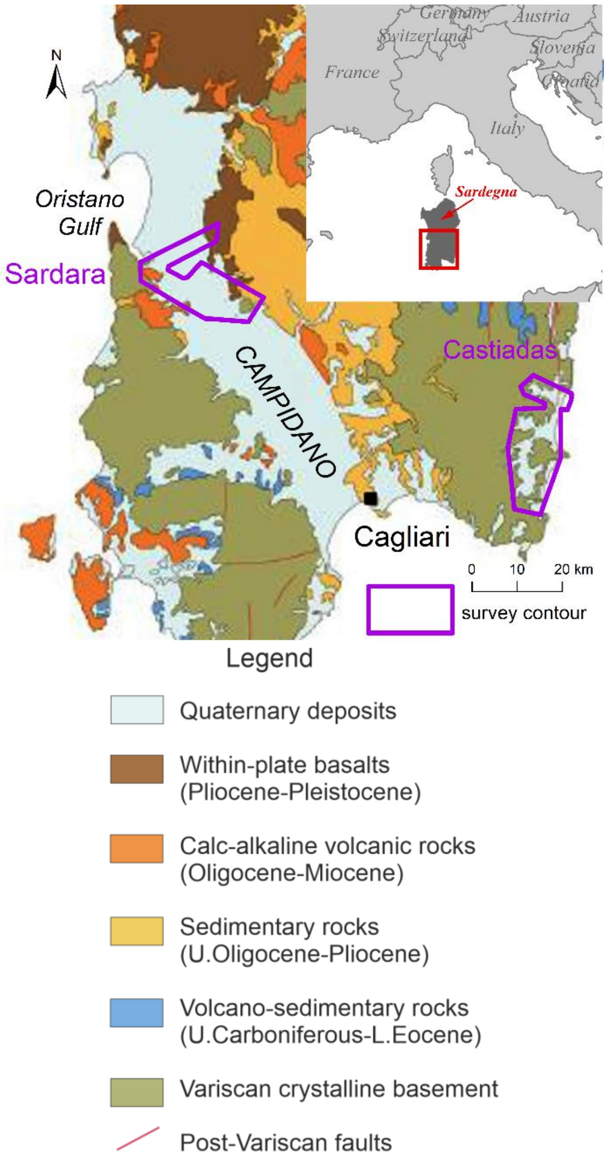

Figure2.Overview of the survey area in Sardinia

In terms of AEM measurements, nongeological issues are due to the presence of industrial noise. The AEM system used to perform the survey is EQUATOR (Figure 3). EQUATOR has been developed by Geotechnologies LLC as a tool providing EM data both in frequency and time domains (Moilanen et al., 2013; Karshakov et al. 2017; Moilanen, 2022). Such a system is by design suited for the targets: high productivity (it can fly at more than 150 km/h), high vertical and lateral resolution (due to the capability to measure on-time and its 77 Hz base frequency) to infer the presence and characteristics of thin/shallow sand and clay lenses, and possibly subvertical features such as faults. Moreover, to cope with the industrial noise, instead of the commonly used spatial filtering (Kang et al. 2022), we managed to effectively remove the industrial noise in the frequency-domain by suppressing uniquely the disturbed frequencies.

Figure 3. The AEM system EQUATOR during the Neretva survey in Croatia.

DATA PROCESSING AND NOISE REMOVAL

Sometimes, industrial noise contaminates specific frequencies, in Europe, close to harmonics of 50 Hz. The most significant interference was found in the channels: 848 Hz (near the 17th harmonic of 50 Hz) and 540 Hz (near the 11th harmonic). In case of considerable amplitude of the industrial noise, also other harmonics can be distorted. Clearly, from a time-domain perspective, noise components with low amplitude can impact merely the (low amplitude) late-time channels, whereas noise components with larger amplitudes might be able to significantly distort also the (stronger) earlier time gates (Figure 4).

As an indicator of the presence of significant electromagnetic coupling, the 2nd-order variation of un-normalized adjacent Im(Bz(f)) values (at 848 Hz) has been used: when such a variation was larger than a predefined threshold, distortions were expected in all time-domain channels. The hatching area in Figure 1 shows where the noise level is higher than the selected threshold; hence, it is clear that almost half of the entire survey area is potentially heavily affected by anthropic noise and, without the proper data conditioning, the inversion of the measurements would lead to artifacts and possible misinterpretations. A similar workflow has been consistently applied also in the Italian survey areas.

METHOD AND RESULTS

Generally, AEM data are inverted via 1D forward modelling approximations assuming that the subsurface can be reasonably represented locally by a 1D resistivity parameterization (Guillemoteau et al, 2011). In this framework, to enforce spatial coherence to the results and provide (quasi-)3D resistivity reconstruction of the investigated volume, several schemes have been implemented (e.g.: Viezzoli et al., 2009; Bai et al., 2021; Klose et al., 2022; Zaru et al. 2023; Zaru et al. 2024).

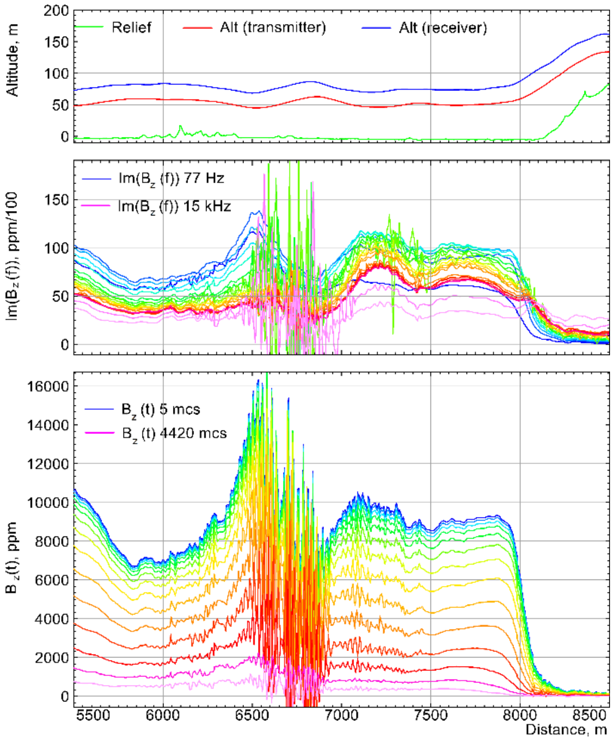

Figure 4. Industrial noise distortion on AEM data in Croatia. Upper chart – the geometry of the system; central chart – imaginary and in-phase components of frequency domain data; bottom chart – time-domain data

An alternative, and extremely efficient, approach to ensure both vertical and lateral spatial consistency of the retrieved resistivity model (while, clearly, fitting the data equally well) is based on the iterated extended Kalman filter (Karshakov, 2020). Indeed, this is the approach used for the inversion of three datasets discussed here. In particular, the used parameterization consisted of 20 layers, and we inverted the observed data uniquely to retrieve the layers' resistivity. The initial model was a homogeneous half-space with resistivity equivalent to apparent resistivity at 77 Hz.

One additional advantage of the approach based on the Kalman filter is that it naturally provides the variances of the estimation error, which can be used for the calculation of the stochastic estimability of each layer (Golovan and Parusnikov, 1998). In this way, each layer can be also characterized in terms of estimation quality and, consequently, the local penetration depth for each measurement location across the survey area can be effectively assessed.

CROATIA

In the case of the Neretva Delta, saltwater intrusion is occurring due to several factors, including climate change and human activities: rising sea levels are causing seawater to encroach in the river and the surrounding aquifers (Lovrinović et al., 2021; Lovrinović et al., 2022). This is exacerbated by the overuse of groundwater for irrigation, which leads to a depletion of freshwater resources and an increase in the amount of saltwater entering the aquifers. In this context, the possible wrong siting of wells might endanger the quality of different aquifers by inadvertently connecting them. In this respect, the ground-based geophysical investigation - in particular, the performed electrical surveys - could not detect the deep conductor.

On the contrary, in Figure 5, the bottom layer, as retrieved from the AEM data inversion, is characterized by a resistivity of 0.5. Ω·m and unknown thickness. Such a low resistivity could be reasonably interpreted as an indication of saltwater presence, and in these cases, particular care should be put in siting the wells. In this respect, drilling should avoid areas in which the saltwater level could be particularly shallow (e.g.: the left side on Figure 5) and/or depths for which the pumping well could intersect unit saturated with saltwater (e.g.: the right part on Figure 5, in which the Drillhole 1 stops at the top of the last resistive unit).

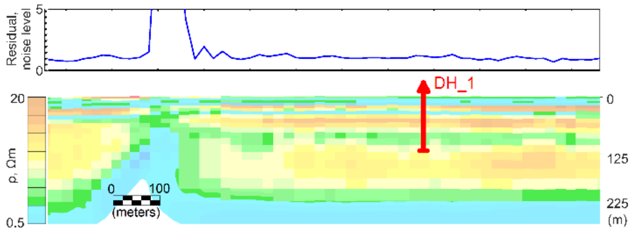

Figure 5. Resistivity section as retrieved by the AEM data (lower chart) with the corresponding data misfit (upper chart) and the location of Drillhole 1 (in red; See Figure 6) for the survey in Croatia.

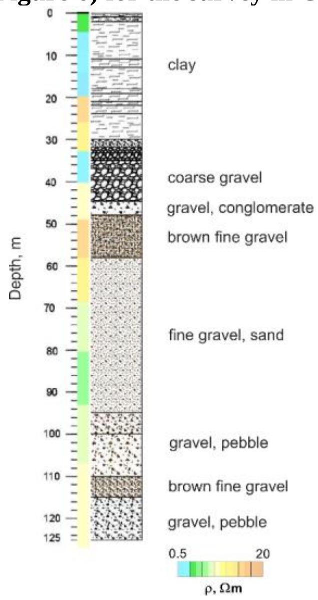

Figure 6. Stratigraphy of Drillhole 1 compared against the corresponding resistivity vertical profile as inferred from the inversion of the AEM data.

In Figure 6, we compare the stratigraphy deduced from Drillhole 1 against the electrical resistivity profile retrieved from the AEM data. Additional boreholes were available or drilled in the area. No freshwater has been found beneath the clay confining unit.

ITALY (SARDINIA) – SARDARA

The second airborne geophysical survey was carried out in the southern part of Sardinia island, within the Campidano graben filled with continental Pliocene-Holocene sediments (Angelone et al., 2005) (Figure 7). These deposits are often watered, and the Sardara thermal water source, known in the work area, comes to the surface in the marginal parts of the graben and is controlled by tectonic disturbances at the contacts of continental sediments with Pliocene-Pleistocene basalts. The survey site is located in the northwestern part of the graben. Ordinary lines were completed at 150, 200, and 250 m spacing. The survey spanned 2700 line-km in total.

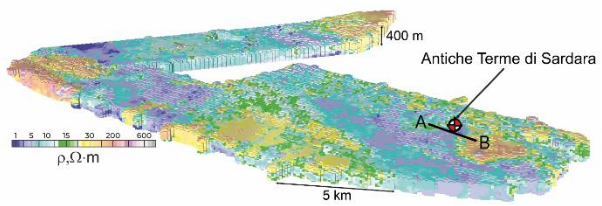

Figure 7. Volumetric geoelectric model of the Sardara survey area in Sardinia, retrieved via 1D-inversion

Figure 8 shows a vertical section of the 3D electrical resistivity model in Figure 7. The entire survey area is characterized by fairly low resistivity, which in this preliminary geological interpretation might be due to the intense watering of, not only continental and marine sediments, but also, possibly, by fractured basalt covers and lavas. The lowest resistivity values (of the order of 1 Ω·m) might correspond to the channel deposits of the main watercourse as it flows into the sea bay.

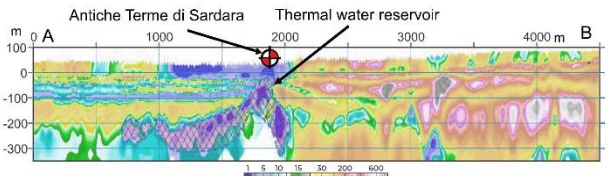

Figure 8. Geoelectric section crossing the Sardara hot point

Interestingly, the zones of minimum resistivity (1-5 Ω·m) do not coincide with the modern talvegs. Perhaps these zones are represented by the maximum thickness of watered loose sediments connected by paleochannels of ancient watercourses. The maximum resistivity of the area (20-200 Ω·m) might indicate lava flows (probably heavily watered) in the west and alkaline basalts in the east, where they come to the surface or are covered by thin sediments.

The thermal reservoir might be located at a depth of about 200 m. If this is the case, it should have a vertical thickness of 50-100 m and a horizontal dimension, along the section, of about 2 000 m. Likely, at greater depths, there might be other thermal fluid reservoirs. These reservoirs should be connected to the surface by tectonic faults. In the subsequent phases of the project, the airborne data results will be thoughtfully compared with the available seismic lines and the other additional geological and geochemical information available (including those from the nearby Sardara hot point, located at the boundary of sedimentary deposits with metavolcanics of Ordovician age).

ITALY (SARDINIA) - CASTIADAS

The third considered EQUATOR survey was performed in the late summer of 2023 and one of its main goals is to determine the area affected by the salt water into coastal terrigenous sediments (Figure 9, 10, 11) and reconstruct the coastal (hydrogeology). Over most of the area, granites and granodiorites belonging to the plutonic complex of Permian-Carboniferous age are present. They are overlain by sequences of young continental sediments of Pleistocene age (Cocco, 2014). They contain highly permeable loose sediments, through which seawater can infiltrate beyond the coastline, with embedded impermeable clay layers. The most conductive features might result from seawater intrusion but also from preexisting salty layers. Granites and young terrigenous sediments are characterized by a weakly differentiated, quiet magnetic field. The granitoids of the work site are characterized by relatively high resistivities from 300 to 2 000 Ω·m. Young loose sediments have very low resistivities from 0.1 to 1-2 Ω·m, the resistivity of sediments potentially containing fresh water is significantly higher, in the range of 30-150 Ω·m.

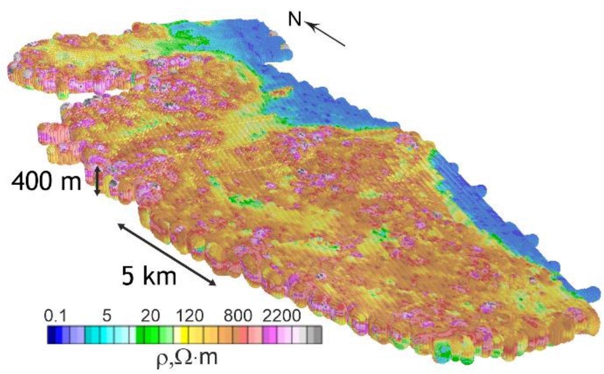

Figure 9. Volumetric geoelectric inversion result of the south-east survey area in Sardinia (Castiadas)

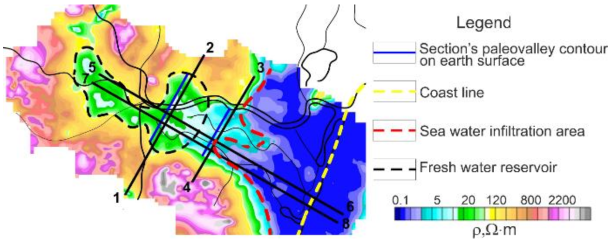

Figure 10. Details of the northern portion of the Castiadas' survey result

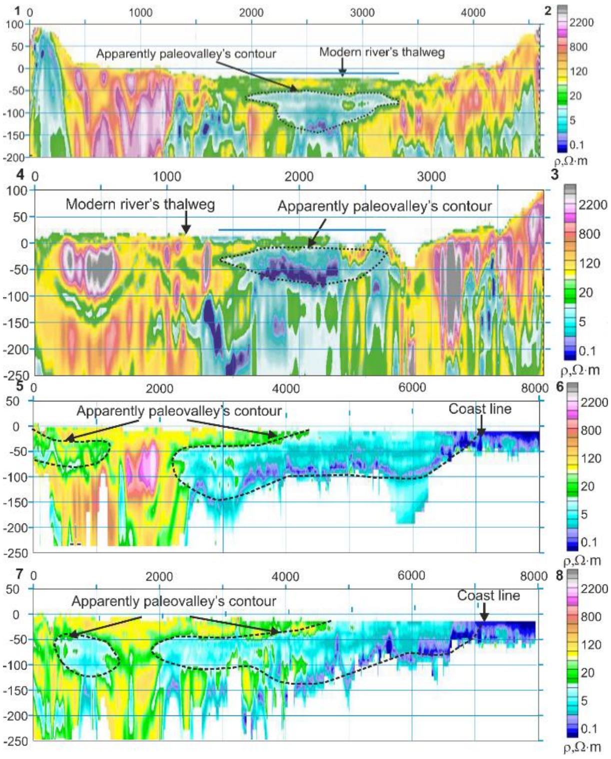

Figure 11. Geoelectric sections with preliminary geological interpretations

CONCLUSIONS

Groundwater resources need to be investigated and characterized to allow their most effective protection and management. This is particularly true in case of coastal aquifers endangered by climate changes, subsidence, sea level rising, or, more often, overexploitation concurrently causing saltwater intrusion.

Similar arguments are valid also in the case of other natural resources. For example, geothermal ones: also in this case, their proper localization and quantification is crucial to plan any effective management and possible exploitation.

In our specific case, we make use of the large coverage and dense sampling typical of AEM data to retrieve (quasi-)3D reconstructions of the subsurface resistivity distribution and, in turn, of the complex geology of three areas in the Mediterranean basin. Specifically: the Neretva delta in Croatia, and the areas in Sardinia close to Sardara (in the Campidano plain) and Castiadas on the east coast of that Italian island.

In particular, the characteristics of the AEM system EQUATOR allowed us to meet the requirements of high spatial resolution and to naturally perform an industrial noise removal in the frequency domain (preserving almost all the collected soundings). Despite the conductive environment, the investigation depth could generally be greater than 200 m.

The AEM results should still go through a comprehensive integration with other sources of information and be thoughtfully interpreted. However, already at this preliminary stage, they look extremely promising.

ACKNOWLEDGMENTS

The AEM surveys were funded by: 1) the Interreg Italy–Croatia Cross Border Collaboration (CBC) Programme 2014–2020 (Priority Axes: Safety and Resilience) through the European Regional Development Fund as a part of the projects "Monitoring sea-water intrusion in coastal aquifers and testing pilot projects for its mitigation" (MoST) (AID: 10047742) and "Saltwater intrusion and climate change: monitoring, countermeasures and informed governance" (SeCure, AID: 10419304); 2) the GEO-CUBE project funded by the Fondazione di Sardegna (CUP F72F20000250007), and 3) the PNRR MUR Project "Multi Risk sciEnce for resilienT commUnities undeR a changiNg climate (RETURN)" (grant no. PE00000005 CUP HUB B63D22000670006).

We are also thankful to Andrea Viezzoli, Pietro Teatini, Veljko Srzić and Francesco Dauti for their company and always useful discussions.

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