Integrated Mechanical and Electromagnetic Geophysical Imaging of a Complex Aquifer System: The Coastal Plain in Muravera, South-East Sardinia (Italy)

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Abstract. Water management is crucial to lead sustainable development of our societies, and to be effective needs for a detailed characterization of the water resources availability, through the knowledge of their reservoir's main properties in terms of geometries and physical properties. In this way it is mandatory to plan responsible exploitation and use protocols, increasing the system resilience. Usable groundwater scarcity is in fact a major issue to be overcome with smart territorial management. In view of this, the knowledge derived from direct and indirect diagnostic investigations is a key factor to balance the societal pressure over such delicate targets. In the early Twenty-thousands, a geophysical survey using High-Resolution (HR) reflection seismic and time domain electromagnetics (TDEM) was carried out in the south-eastern part of the island of Sardinia, Italy. The main objective of the survey has been to study a very complex coastal aquifer situated in an area where a – still present – huge saltwater intrusion phenomenon had already occurred mainly due to anthropic overexploitation linked to tourism and agriculture. Within this paper, the TDEM results, constrained by seismics, are presented and discussed.

Keywords: TDEM · EM Geophysics · Seismic Reflection · Hydrogeophysics · Sustainable Development · Sea Water Intrusion · Sardinia

1 Introduction

Water scarcity is a major and global issue of contemporary days in large part due to intensive agriculture and industrial use of territories, overpopulation, pollution and Climate Change according to the UN Sustainable Development Goals [1]. Smart territories and communities provide a cultural framework to assess sustainability in natural resources exploitation, protection and renovation thanks to management actions which can be especially effective when taking advantage of the knowledge derived from direct and indirect investigations.

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In the early Twenty-thousands, a geophysical survey using High-Resolution (HR) reflection seismic and time domain electromagnetics (TDEM) was carried out in the south-eastern part of the island of Sardinia, Italy. The main objective of the survey has been to study a very complex coastal aquifer situated in an area where a – still present – huge saltwater intrusion phenomenon had already occurred, and where important interventions (hotels, various buildings for tourism and agriculture and a dam, just closed to the delta of the river Flumendosa) were planned. The effective management of groundwater is of great importance for tourism and agriculture activities, which is probably the main resource for the economic growth of this area. The deep fresh groundwater must be protected from the progressive salination deriving from prolonged periods of drought, uncontrolled over-exploitation of the groundwater resources for drinking water and irrigation purposes, fish breeding works and decrease of the natural recharge of the coastal aquifers as a result of the Flumendosa upstream damming and of the Climate Change. So, it is vital to distinguish the aquifer sub-systems and their saturation with fresh, brackish or salt water and to know the depth and the morphology of the bedrock. This may be achieved by drilling observation wells and by using surface geophysical surveys in integrated diagnostic protocols capable of providing multi-physical underground information to constrain the geologic reconstruction of the aquifer.

Among various geophysical methods, the TDEM and seismic reflection techniques were chosen to be the most suitable for the indicated purposes. The application of TDEM methods has been widely used for describing the depth and thickness of coastal aquifers [2], defining their physical-chemical properties [3], and assessing marine intrusion and pollution levels [4]. In fact, TDEM has better lateral resolution and is more efficient than Vertical Electrical Soundings when the shallow soils are very conductive, but it is usually unable in delineating the resistive geological conditions [5]. The seismic method, vice versa, is very efficient in solving the structural problem, but it is unable to recognize the different aquifers properties. Shtivelman and Goldman [6] have demonstrated the goodness of the application of integrated TDEM and seismic reflection techniques for a similar purpose.

In the past the area has been studied with several hydrogeological and geophysical methods. G. Barbieri et alii have demonstrated, through resistivity and IP soundings repeated in different times, the connection between saltwater encroachment and the opening of various channels [7]. Other authors have studied the very shallow aquifer [8, 9]. In the area no deep wells are present and therefore no direct information about the deep aquifers and bedrock is available. Preliminary parts of the present investigation have been presented at conferences [10, 11] while the seismic investigation has already been published in the journal Geophysics [12].

1.1 Geological Settings

The Flumendosa is the biggest river in Sardinia, originating from the Gennargentu mountains approximately in the middle of the island and flowing into the Mediterranean Sea on the southern part of the Sardinia East coast. The coastal aquifer here extends from the village of S. Vito to the Mediterranean Sea reaching the width of 7 km westward. Several natural channels flow in the area (Foxi Padrionnas, Foxi Bau Obilu and Flumini

Becciu), probably indicating the old mouths of the ancient delta, but appearing without hydraulic connection to the present river (Fig. 1).

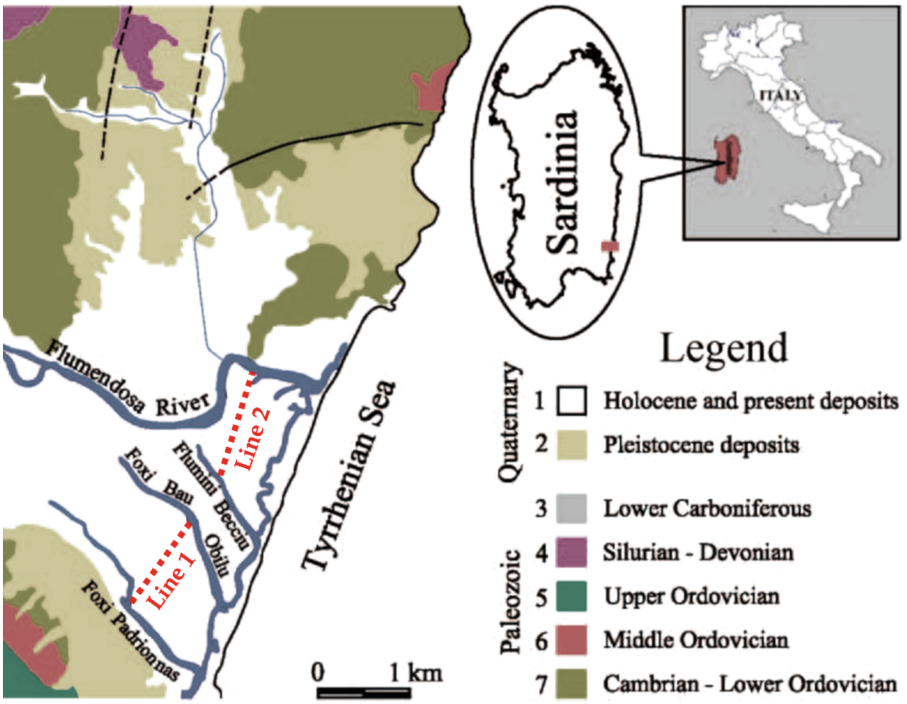

Fig. 1. Simplified geological map of the Muravera plain survey area, showing the location of seismic and geophysical profiles (modified from [12]). Unit 1: Alluvial deposits, including second-order alluvial terraces, colluvial, eolian, and littoral gravels, sands, silts, and clays. Unit 2: Conglomerates and sands forming first-order alluvial terraces connected to the Piedmont alluvial fan. Units 3–6: Metamorphic rocks, mainly metaconglomerates, metasandstones, metasiltstones, metalimestones, and porphyritic metavolcanic rocks, representing the Paleozoic basement. Unit 7: The Arenarie di S. Vito Formation, consisting of irregular sequences of micaceous metasandstones and metaquartzarenites, is the main outcropping unit bordering the Muravera plain. Red dotted lines indicates the geophysical profiles layout: Line 1 indicates the first seismic reflection and the TDEM profile, and Line 2 corresponds to the second seismic reflection and the TEM-FAST profile.

The aquifer consists of a terraced thick deposits of Quaternary alluvium, overlaying a Palaeozoic granite and schist bedrock. An inactive scree-slope joins the alluvial deposits with the surrounding Palaeozoic schist and granite hills. In the plain both ancient and recent deposits are present. The older terraced alluvial deposits are reddened for oxidation and well cemented, while the recent alluvium, also terraced, are poorly cemented and not yet oxidized. Furthermore, the most coastal area is bordered by palustrine deposits and eolian sands and dunes.

Two aquifers are known to be hosted into the alluvial deposits:

- a shallow phreatic aquifer, highly productive, mostly exploited with wells of a considerable diameter. The bottom limit consists of a few meters deep clay layer;
- a deep multilayer confined aquifer, sandwiched between sands and gravel interbedded with clayey-silty strata of varying thickness and extent.

The groundwater replenishment is due to both rain precipitation and irrigation. More than 2000 wells exist in the coastal plain. The presence of salt water has been monitored since the early ‘70s. At present the sea water encroachment affects half of the coastal plain.

2 Materials and Methods

Two profiles, one parallel to the coast, between the Palaeozoic outcropping and one perpendicular were planned. However, due to the presence of many kinds of tilling, only the parallel one was acquired and it was divided into two lines: about 1000 m of the parallel profile have been exploited (and is presented in the present paper) with both seismic and TDEM measurements along the Line 1 indicated in Fig. 1, while a shorter second inline one had been surveyed with seismics and TEM-FAST for a shallower prospection.

2.1 The Seismic Survey

The seismic data were acquired using single 50-Hz geophones attached to a 48-channel seismograph system with 18-bit recording capability. The sample interval was 0.5 ms and the record length 1 s. Data were recorded using standard common midpoint (CMP) roll-along technique in an end-on configuration with 48 active geophones. Geophone spacing of 5 m and source spacing of 10 m provided 12-fold CMP coverage with a CMP spacing of 2.5 m. Maximum source-receiver offset of 245 m enabled stacking velocities for the relatively deep reflections (e.g., from the bedrock surface) to be determined. Figure 2 shows three shot gathers representative of the entire data set.

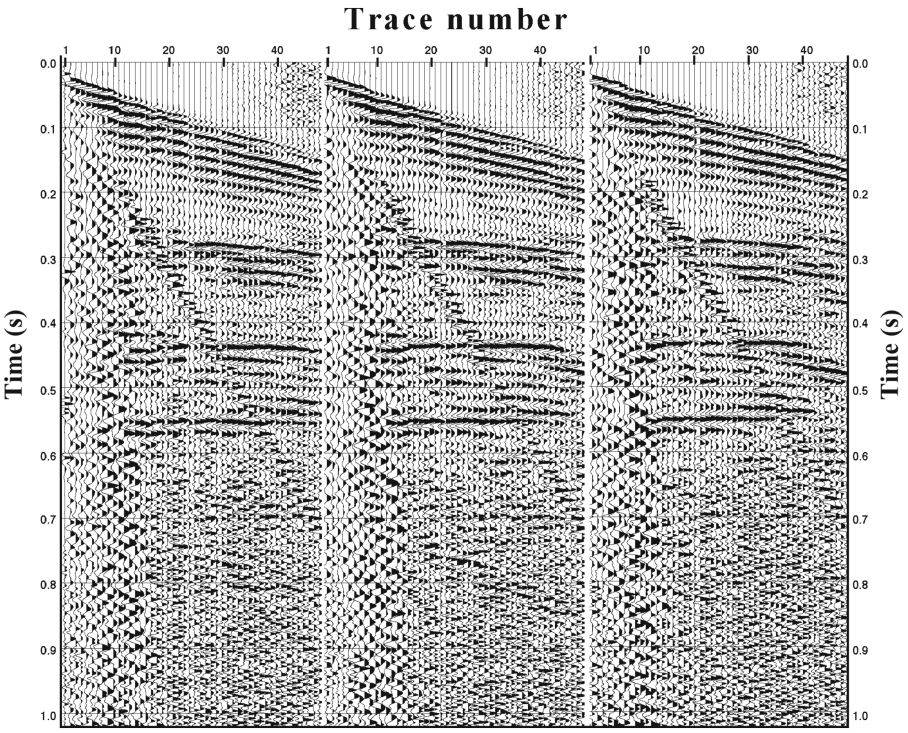

Fig. 2. Three shot gathers representative of the seismic dataset along Line 1, [12].

2.2 The TDEM Survey

The TDEM surveys were carried out along the seismic profile using two different equipment in order to provide a better vertical resolution for the different purposes and very high accuracy in interpretation. The coincident loop configuration was selected using different sizes and multiturn loop in order to increase the penetration depth [13]. In the deep soundings, performed by the Zonge system, a three-turn transmitter loop and two-turn receiver loop, 100 m long, were chosen. In the shallower soundings, an AEMR TEM-48 system, powered by built-in batteries and 12.5 m, 25 m, 50 m and 100 m loop sizes were used. Fifteen TDEM soundings have been carried out in the investigated area, using ZONGE 3 kW Transmitter and GDP32 - six channels - Receiver. Twenty-four frequencies can be selected in binary intervals between 0.0007 Hz and 8 kHz. The experimental data have been collected using a square wave with null phase at five different frequencies, namely 16, 4, 2, 1 and 0.5 Hz. (in six different windows from 0.030ms to 387ms). The transmitting current intensity has been set to 11 A.

Late-time apparent resistivities, after integration and normalization, have been used to interpret by means of mono-dimensional models (Fig. 3). The interpretation has been carried out using ZondTEM1D v.6.1, which is an interactive, graphically oriented, forward and inverse modeling program for interpreting TEM data in terms of a layered

earth (1-D) model. The 26 TEM-FAST soundings were interpreted by the 1-D TEM-RES processing and interpretation package.

The TDEM soundings were inverted using one-dimensional initial models with the minimum possible number of layers. The inversions were constrained by incorporating a priori information from the boundaries identified in the seismic section. This approach not only reduced the misfit error from approximately 8% to slightly more than 4% but also improved the lateral continuity of the 2-D geoelectrical sections, allowing for a more geologically plausible interpretation.

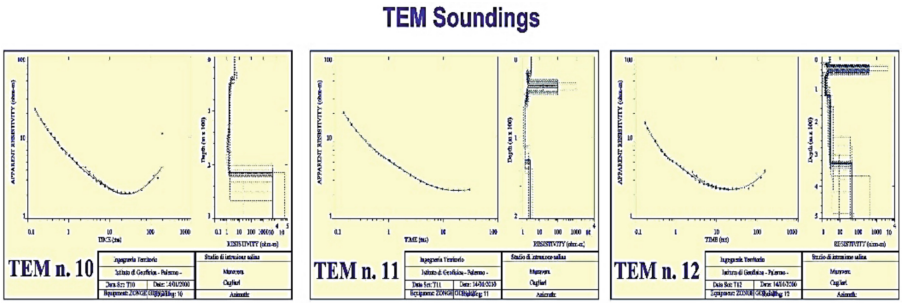

Fig. 3. Three examples of TDEM soundings, showing measured and calculated apparent resistivity curves along with the inverted resistivity model.

3 Results

Seismic data results, already published, are here summarized to allow a holistic portrait of the whole integrated approach. No velocity information from boreholes was available within the area investigated. Therefore, time-to-depth conversion was made based on interval velocities derived from the seismic data. These velocities range from 1700–1900 m/s in the uppermost part of the section to 3400–3600 m/s in the deepest part. The depth section showed several reflectors which reach a maximum depth of about 700 m in the central part. Two strong reflectors dominate the deepest part of the section. The continuity of these events is interrupted in many locations along the entire section. These discontinuities were interpreted as deep faults with vertical displacements up to 100 m. The interpreted units B and C, in Fig. 4, are only supposed on the basis of the geometrical features of the reflectors and on the basis of the seismic-derived interval velocities. Whereas the upper part of the section is dominated by smooth, horizontal reflectors, which are almost undisturbed down to 400 m, even if local amplitude changes of reflectors are present. All reflectors, above about 400 m, were interpreted as boundaries in quaternary alluvium deposits (unit A in Fig. 4). Despite the high quality of the section, seismic data do not allow stratigraphic distinction within the quaternary deposits.

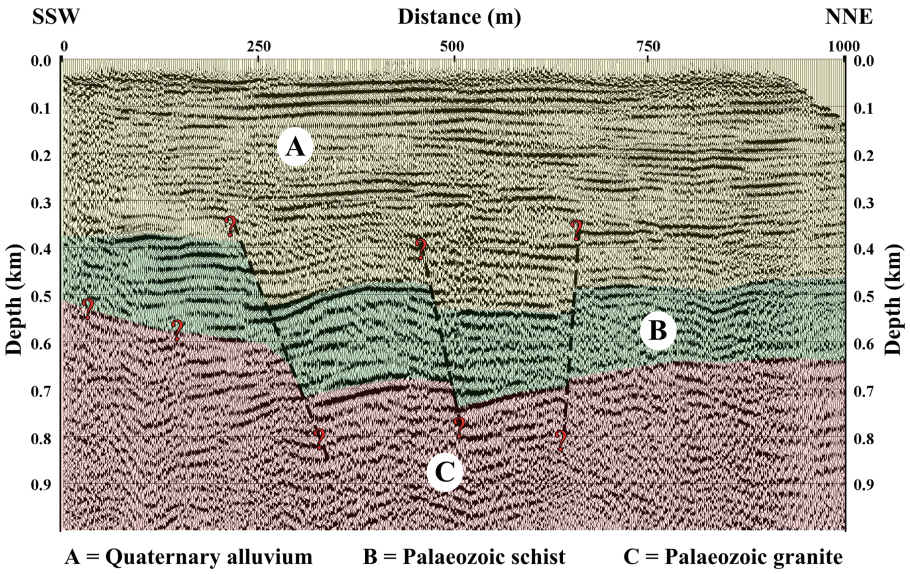

Fig. 4. Preliminary interpretation of the geological structures from the seismic reflection section along Line 1, [12].

The TDEM and the TEM FAST soundings (Fig. 3), have been used to reconstruct 2D section reported in the Figs. 5 and 6 respectively. They show very conductive layers (0.5–10 Ω × m) in the shallower part of the section, obviously due to the presence of salt, brackish or fresh water in alluvium or eolian sand deposits. In the central part of the section, lateral resistivity changes are easily visible. High resistivity layers dominate the section below 250 m.

Also in this resistive layer, lateral variations of resistivity can be seen, probably in correspondence of either faults or changes of the Palaeozoic rocks. The TDEM soundings clearly show the connection between the channels and the encroachment areas and distinguish different aquifers.

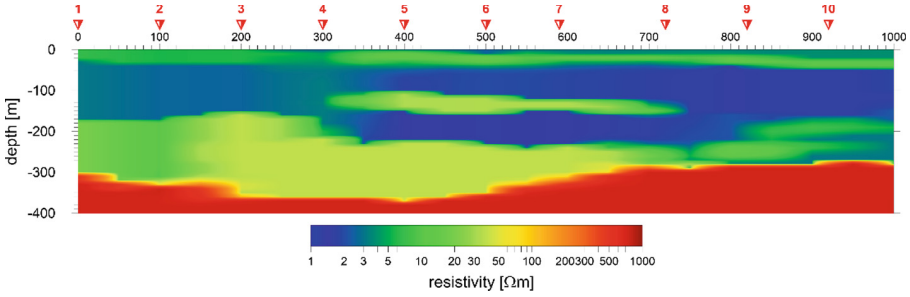

Fig. 5. Electrical resistivity section obtained from the 2D interpolation of inverted TDEM models. Red triangles indicate the locations of the TDEM soundings, black numbers the progressive coordinate in meters along the profile.

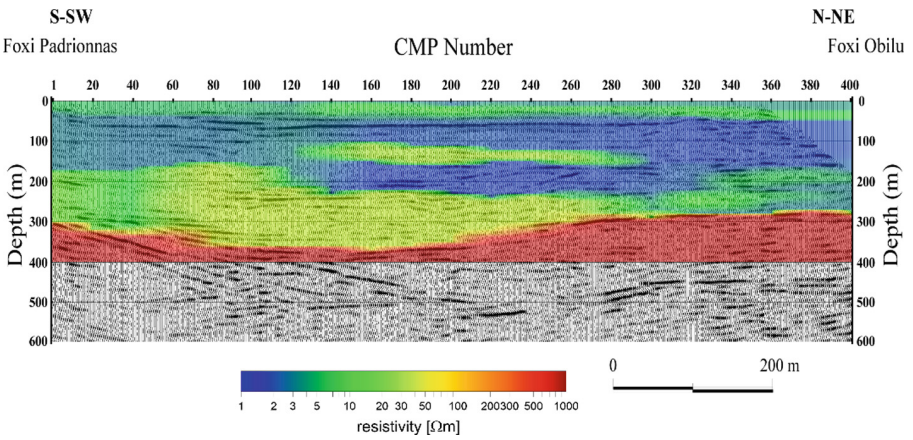

Fig. 6. Overlay of the TDEM section onto the reflection seismic section.

4 Discussion

The integration of seismic and TDEM data provides a comprehensive subsurface characterization of the Muravera plain. The seismic profiles reveal well-defined stratigraphic boundaries and lateral variations in subsurface layers, consistent with previously reported geological interpretations. The presence of discontinuities and velocity contrasts suggests a complex depositional history, with alluvial and colluvial deposits overlaying the Paleozoic basement.

The TDEM data, when overlaid onto the seismic section, confirm the interpreted lithological variations and provide additional constraints on the distribution of conductive layers. The resistivity profiles highlight zones of increased conductivity that correlate with alluvial sediments, while more resistive units correspond to consolidated formations, such as conglomerates and metamorphic rocks. The integration of seismic and TDEM data improves confidence in identifying aquifer-bearing units, as the low-resistivity zones align with potential groundwater-bearing formations. Figure 6 shows some important correspondences: faults, contacts and layering are in many cases exactly positioned. The attribution of low resistivity values to seismic "strata" allows the definition of the geometry and the quality of the aquifers.

A significant aspect of the study is the use of seismic constraints to refine the inversion of TDEM data. The initial unconstrained TDEM inversion exhibited higher misfit errors and lower lateral continuity. However, by incorporating boundaries identified from seismic sections, the inversion process achieved a better fit, reducing misfit error from approximately 8% to slightly above 4%. This methodological improvement enhances the resolution and reliability of the geophysical interpretation.

5 Conclusions

The combined analysis of seismic and TDEM data demonstrates the effectiveness of multi-method geophysical approaches in resolving subsurface heterogeneities in the Muravera plain. Seismic data delineate stratigraphic units with high precision, while TDEM resistivity sections provide complementary information on lithological and hydrogeological properties. The joint interpretation allows for a more robust assessment of potential aquifers and subsurface structures.

By constraining TDEM inversion with seismic boundaries, the study significantly improves the accuracy and lateral continuity of geoelectric sections, leading to a more geologically plausible interpretation. The geophysical survey carried out in the Muravera plain provided valuable information on the aquifers present in the area. In particular, the superimposition of the final TEM sections onto the seismic section—both obtained through independent data processing and interpretation—allows for the transformation of geological information, primarily derived from seismic results, into hydrogeological insights.

These findings emphasize the importance of integrating multiple geophysical methods for groundwater exploration and subsurface characterization in complex geological settings. Future work should consider expanding the survey area and incorporating additional geophysical techniques, such as electromagnetic and gravimetric surveys, to further enhance subsurface models.

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