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The combined use of radio-frequency electromagnetics and radiomagnetotellurics methods in non-ideal field conditions for delineating hydrogeological boundaries and for environmental problems

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Abstract Radio frequency geophysical methods are known for being very versatile tools in ground- and groundwater investigation at shallow depths. They are fast and easy to use and allow a high density of information over large surfaces, which makes them very suitable for geological mapping sensu lato (faults, lithological contacts, groundwater-bearing structures, vulnerability maps, and contaminant plumes) and for selecting borehole locations. Significant improvement concerning 2D and 3D modelling of the data has occurred in recent decades. However, field surveys are very seldom performed in "ideal conditions"—the lack of necessary transmitters, in the convenient direction, in order to catch the structures in E- and H-pol for modelling purposes, is not an unusual situation. The present paper shows how the use of RMT and RF-EM is nevertheless of great help and suggests different ways to explore qualitative data in different geological settings.

Keywords Geophysics · Radio-magnetotellurics ·
Radio frequency electromagnetics ·
Groundwater-bearing structures · Groundwater quality

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Introduction

Electromagnetic methods in the radio frequency domain have proven their value in subsurface exploration due to their high-resolution capabilities and easy application. These techniques are non-invasive (Tezkan et al. 2000) capable of delivering a comprehensive image of the near underground (0–50 m).

However, geophysicists are still in search of more adequate interpretation tools (Kaikkonen and Sharma 1998) and geologists/hydrogeologists often complain about the difficulties of using the geophysical models. The main difficulty comes from the fact that models are oversimplifications of reality and often require hardly achievable field conditions, like the existence of simultaneous transmitters parallel or perpendicular to the direction of the geological strike (E- and H-Polarisation) (Reynolds 1997; Tezkan et al. 2000). Geologists are quite often confronted with the fact that they cannot go further with the quantitative analysis of field data and that the only earnest thing to do is to remain in their qualitative exploit.

Nevertheless, qualitative data can be extremely valuable per se if one gets the best information out of it. This can simply be done by georeferencing the data, transforming it to 3D data (profiles and surfaces) and coupling it with available topographical, geological and hydrogeological information, by means of GIS routines (e.g. ArcMap).

This paper shows the outcome of a few experiences in diverse geological settings, different kinds of field conditions and for various purposes:

- Locating water wells in heterogeneous karst aquifers (Moura, Portugal),
- Characterisation of compartmented coastal aquifer system for environmental impact assessment (peninsula of Tróia, Portugal),
- Determining the geometry and structure of a fractured granite medium (Castelejo, Portugal) for future groundwater flow- and transport modelling purposes.

Brief description of methods

Two radio frequency methods were applied: radio frequency—electromagnetics (RF-EM) and radio-magnetotelluric (RMT). These methods and their related instrumentation were developed during the last 20 years by Müller and Dupperex at the University of Neuchâtel, Switzerland (Centre of Hydrogeology of the University of Neuchâtel, CHYN). A complete description of the devices as well as the principles of these methods can be found in the doctoral theses of Turberg (1994), Stiefelhagen (1998) and Bosch (2002). A reminder of some basic principles and related sources of experimental errors is nevertheless provided here to better define a data acquisition in non-ideal field conditions.

Radiofrequency-electromagnetic method (RF-EM)

The RF-EM method uses radio frequencies ranging from 12 up to 300 kHz. The general principles of the data collection are shown in Fig. 1.

The receiver antenna used in this study is automatically oriented towards selected transmitting stations by a motorised pilot device. It captures the horizontal component of the primary field and the vertical components of the resulting magnetic fields, which are in phase or out of phase with the primary field. This magnetic component is considered to be the vertical component of the secondary field (Hs). The relationship between the secondary (Hs) and primary (Hp) magnetic fields is studied as a percentage-expressed Hs/Hp ratio (Fig. 1).

The investigation depth (in metres) is a function of the apparent resistivity of the underground and of the radio frequency (F, in Hertz) used:

$$P = 503\sqrt{\frac{\mathrm{Rho}}{F}}$$

This equipment (Fig. 1) has been designed for fast and extensive mapping of geological contacts by combining a data logger, which registers every 2 s and a global positioning system (Garmin 12 XL). It is particularly targetted at rapidly identifying subsurface heterogeneities, such as faults, karst channels associated with faulting (Turberg and Müller 1992) or paleochannels in unconsolidated material (Carvalho Dill 1993).

The figure also shows the correct orientation of the profile regarding the main investigated structure (in this case a geological fault) and the typical measured signal. The direction of the profiles should be perpendicular to the structure strike and to the direction of propagation of the primary wave, in order to get the best induction geometry (best coupling). These conditions are scarcely achievable, due to the fact that geological contacts, faults, dykes and veins, are seldom-linear structures. Indeed, they are often deformed, folded and faulted. Figure 2 shows the layout of a non-ideal profile, which fails to fulfil the geophysical modelling requirements, due to: (1) irregular boundaries, (2) the lack of clear resistivity contrasts (carboniferous basin with intercalated coal layers in conglomerates, sandstones and breccia), (3) inexistence of radio transmitters parallel to the main direction of structures, (4) non-linear structures with a complicated thrust-fault and (5) the Jeep forced to use a curved “land road”—non-perpendicular to the main structures.

The obtained outphase signal is hardly interpretable. The wrong orientation towards the transmitter damps the signal meaning that several anomalies can appear but their origins are unclear; they can be due to lithological contrasts or attributed to filled fractures, coal layers, etc (Fig. 2).

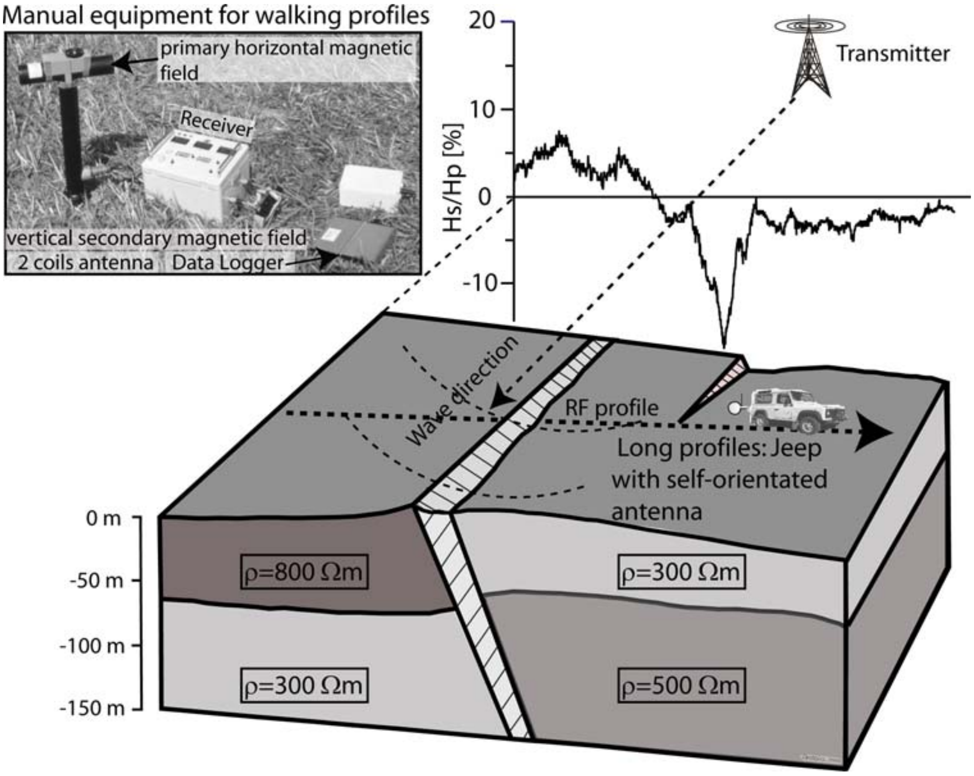
The existence of electric power lines (EPLs) may also cause strong artificial anomalies which can mask the geological ones. Figure 3 shows how the artificial anomaly can cover the natural ones created by caverns and karst channels. According to the intensity of the current and the frequency used, a certain distance should be maintained.

A water pipeline (like the straight structure, N18°W in Fig. 4) also has an effect on the outphase component. The magnitude of the anomaly depends on the layout of the pipeline towards the transmitter. In this particular case the pipeline lies oblique to both transmitters. We can observe that the registered anomaly using the 216 kHz emitter, which is approximately N–S, is of higher magnitude than the one from the 162 kHz (E–W). The profile was performed for the most part, perpendicular to the direction of the 216 kHz emitter.

Radiomagnetotelluric (RMT)

The great advantage of the RMT method is its rapidity in data acquisition. It enables both profiling and sounding (Fig. 5) by using several frequencies (different depth information), from 10 up to 300 kHz. The principle is the same as for the very low frequency with resistivity mode (VLF-R): the electromagnetic waves penetrate into the

Fig. 1 Radiofrequency-electromagnetic method (RF-EM) equipment with manual and Jeep with self-orientated antenna. The *graphic* represents a typical measured signal of a geological fault



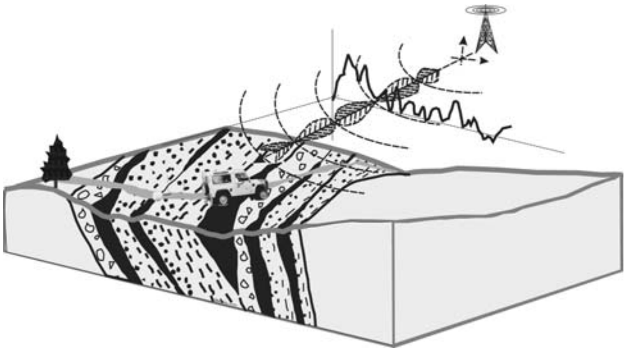


Fig. 2 Measuring constraints referred in the text

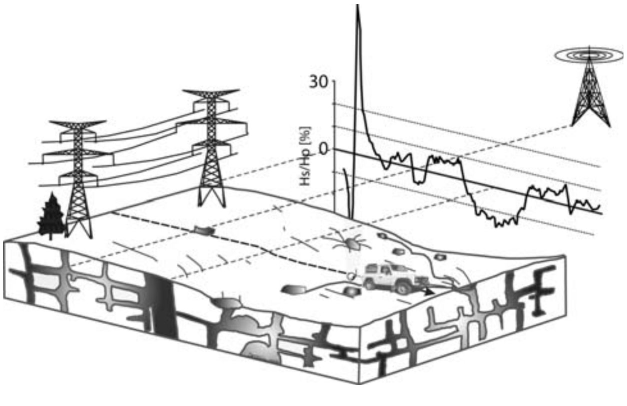


Fig. 3 Artificial effect caused by an electric power line (EPL) compared with natural anomalies in a karst region

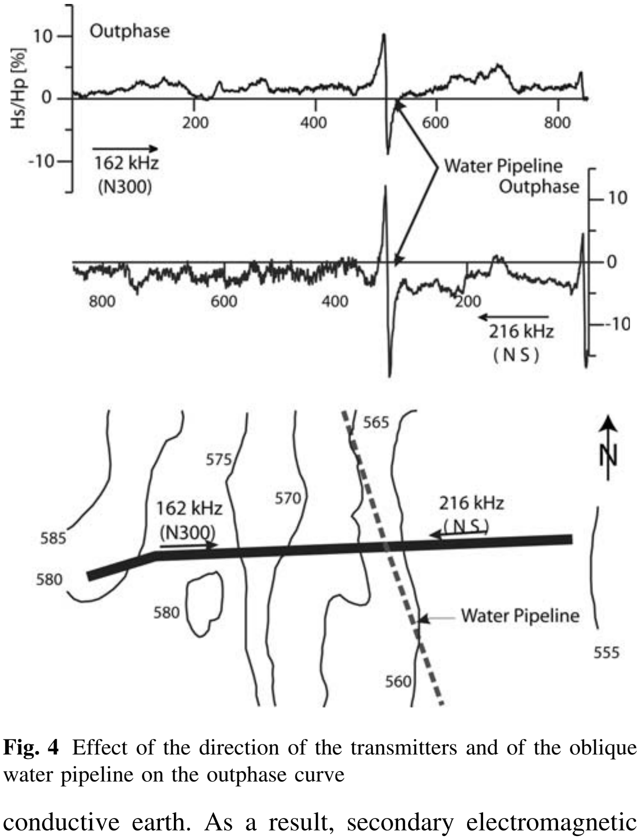


Fig. 4 Effect of the direction of the transmitters and of the oblique water pipeline on the outphase curve

conductive earth. As a result, secondary electromagnetic fields are induced, modifying the total field. The resultant field will differ from the primary field in intensity, phase and direction (Parasnis 1997, Telford et al. 1990).

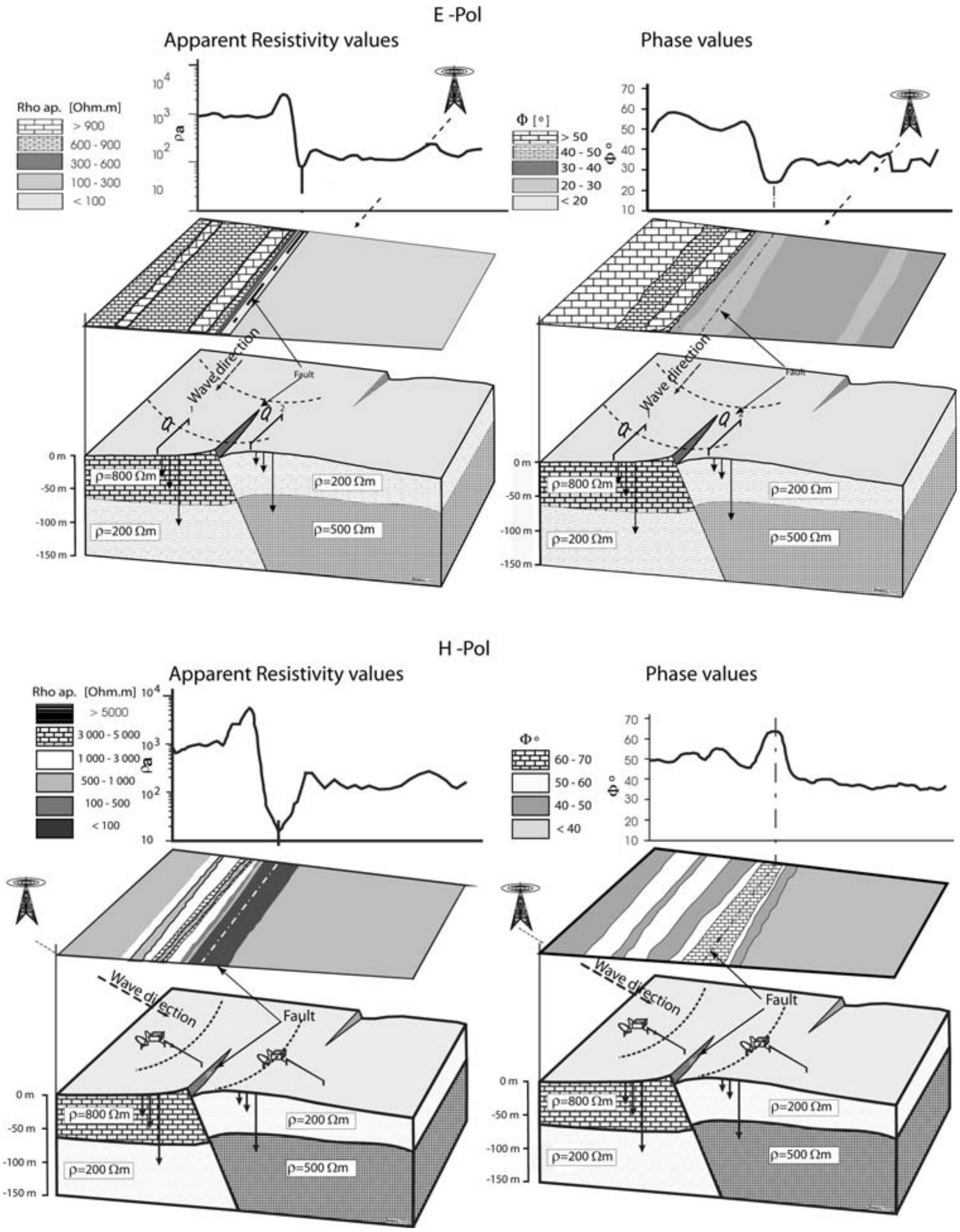


Fig. 5 Graphics and interpolation maps (VLF domain) of the gathered apparent resistivity- and phase-values, in a two layer situation and the effect of a conductive fault in E-pol and H-pol. *Vertical arrows* correspond to expected penetration depth

Both electric and magnetic components of the resultant field are measured by means of two grounded electrodes and a coil. Our RMT instrument is also a prototype developed in Switzerland. The magnetic coil has a diameter of 0.4 m and the distance between the electrodes is 5 m. The data collection is relatively fast and is interpreted quantitatively using well-known magnetotelluric modelling programs (Fischer et al. 1981; Thierrin and Müller 1988; Tezkan et al. 2000) enabling the calculation of actual resistivities and thickness of the strata. Under specific conditions, these calculated resistivities could be used to better determine the permeability distribution when studying subsurface aquifer flow processes (Tullen et al. 2006).

A lot of information can already be obtained with a simple analysis of the raw data; directly exploiting of the apparent resistivity data allows the construction of contour maps, whenever sufficient data is available, indirectly revealing the lithological nature of the ground. It is not only the apparent resistivity but also the phase shift, which supplies valuable information, usually showing the structure of the ground.

To put it briefly:

- If the phase is around 45°, the subsurface is expected to be homogeneous (one layer case).
- If it differs, two situations can occur: phases higher than 45° indicate a two layer situation with a more

resistive overburden over a conductive one – this often occurs in coastal aquifers and is a good indicator for the presence of salt water (Müller and Schotterer 1986). The presence of a conductive overburden laying over a resistive is revealed by values lower than 45°.

The combined use of both parameters is therefore of the highest importance. Plotting both parameters in the same graphic is moreover very elucidative. Usually it is useful to transform the rho data into logarithmic values to better represent their log normal distribution

Anisotropy information can also be gathered by using transmitters of similar frequency and from different directions (Turberg 1994; Bosch 2002). Multidirectional RMT is based on the anisotropy of the electrical properties of the ground. Its principles can be summarised as follows (Fischer et al. 1983, Fischer 1985):

Depending on whether the alignment of a conductive body is perpendicular or parallel to the direction of the transmitter, a measurement will be said to be respectively in H-polarisation or E-polarisation.

- In the presence of a conductive body and when the measurement is made in E-polarisation, both the resistivity and the phase will slightly decrease (Fig. 5), and it is often observed that the drop of resistivity is preceded by a small increase.
- If the measurement is made in H-polarisation, an abrupt drop of the resistivity and an increase of the phase are to be expected. This is why H-polarisation mode is recommended for the location of lateral boundaries between distinct geological formations of diverse resistivities (Tezkan et al. 1996).
- In an isotropic medium all the measurements performed at the same point in different directions will be similar.

If, instead of a conductive body, one has a resistive one, such as quartz dykes in shales, paleochannels filled by washout pebbles, or air field cavities, measurements made perpendicular to the strike direction (H-Polarisation) will have the lowest phase and highest resistivity (Ogilvy 1991).

Significant improvement concerning 2D (Kaikkonen and Sharma 1998) and 3D modelling of data (Newman et al. 2003) has occurred in the last decades. Unfortunately, as previously mentioned, these models have such specific requisites (for instance data acquired in E- und H-polarisation), that “Nature” cannot provide the necessary conditions in most cases. A list of natural and artificial constraints is summarised in Table 1. These conditions can be related to the nature of the ground itself (geological nature), to the topography of the surface (topographic nature), to the signal/noise ratio of the primary electromagnetic signal or to other practical disturbances of artificial nature. They have direct consequences on the interpretability of the collected data and even on the possibility to perform RF-EM and RMT surveys.

A very useful tool for data exploration is the construction of contour density points from the apparent resistivity and phase shift values. Figure 6 illustrates six case studies reflecting the influence of the lithology, the climate and the environment on the measured values. Two fissured aquifers – Gneiss at Cascina/Switzerland (Casc) and Granite – very weathered valley deposits (C weath) and outcrops (C outcr) at Castelejo /Portugal – highlighted the role of the weathering in the obtained apparent resistivity values (ρa). The granites in Portugal are not only older but also very weathered, mainly along a fault valley (C weath). The values measured on the outcrops (C outcr), although still reflecting a higher weathering degree, are much closer to those measured in the gneiss. Two examples of karst aquifers are plotted –Koeshing (Koe) /Germany and Moura/Portugal (Mo). Again the lower resistivity values acquired in Portugal reflect the higher degree of carbonate alteration. Two studied porous media areas are also presented: – Coastal aquifer with salt water interface at Troia/ Portugal (T23 and T16); Fluvio-glacial deposits – Gimel/ Switzerland (Gi). Both cases illustrate the situation of resistive overburden laying over a more conductive layer ($\phi > 45°$). The fluvial-glacial deposits have broader grain size distribution and the presence of pebbles and gravels increases the resistivity values (ρa ranges from 50 to 500 Ohm.m), whereas the sediments are predominantly silty/sandy in Tróia. Tróia distinguishes itself by its very high phase values (> 60°) reflecting the existence of saltwater underneath the upper aquifer. It is interesting to compare the values obtained with both frequencies 16 kHz (T16) and 23.4 kHz (T23). The former attains deeper regions being much more influenced by the saltwater underneath.

Case studies

Finding the best location for the construction of water wells in a karst aquifer system

Electromagnetic surveys were performed at the request of the Municipality of Moura (Alentejo). The aim was to indicate the best place for the drilling of two new public water supply wells in a karst aquifer system, since the old ones were no longer sufficient to face the water demand. Previous attempts to drill in the vicinities of the old wells were unsuccessful (for the locations of the dry wells see also Fig. 10).

The failure is clearly related to the extremely heterogeneous media, as shown in Fig. 7: metamorphic volcanic rocks, cherts, crystalline and dolomitic limestones, schists

Table 1 Natural and artificial constraints

	Methods	Non-ideal conditions	Consequences	Ideal conditions
Geological nature	RMT + RF	Non-linear geological contacts	Limit the quantitative analysis of data/use of models	Linear structures
		Lack of resistivity contrast	Limit of the methods (no detection)	Significant electrical contrasts between geological units
		Very conductive (upper) layers	Reduction of the wave penetration	Very resistive upper layer
	RMT	Very thin horizontal layers (≤ 2 m)	Limit of the methods (lack of resolution)	Reasonable thickness (a few metres)
	RF	Sub-horizontal or horizontal faults, contacts	Limit of the methods (no detection)	Vertical or sub-vertical faults, contacts
Topographic nature	RMT + RF	Thick vegetation; rock outcrops	Discontinuity of the surveying	Wide, large field allowing the performance of the surveys in a regular rectangular net
	RMT	Very steep slopes	False measurements (deformation of the magnetic field)	Flat surface, gentle slopes
	RF	Very steep slopes, or slope ruptures	Continuous profiling is impossible to be performed (Jeep or manual antenna)	Flat surface, gentle slopes
Meteorological effects/disturbances of the Earth magnetic field	RMT and RF	Bad weather, storms, lightning, perturbations of the Earth magnetic field	False interpretation/limit of the method (shifting the wave orientation)	Good weather; increased signal/noise relationship
	RMT	Lacking of moisture in the soil	Limit of the methods (no measurement/ no electrode contact)	soil with enough moisture
Artificial nature	RMT and RF	No transmitters or inexistence of transmitters in the right direction	No signal No quantitative analysis or modelling of data	Existence of enough transmitters allowing the performance in E and H polarisation
		Intermittent transmitters and weak signals	survey interruption /or changing of the transmitter (unequal performance conditions)	Regular, constant transmitters with strong signal
		Electric Power Lines (EPL)	Artificial anomalies mask the geological ones	EPL at an ideal distance (depends on the intensity of the current, the frequency used and the method—RF is more sensible than RMT
		Fences or screens	artificial anomalies ; survey interruption	Wide, large field allowing the performance of the surveys in a regular rectangular net
		Crops; cultivated areas	Survey interruption	Fields with no plantations allowing the performance of the surveys in a regular rectangular net
		Survey is only possible on Roads (curved)	No quantitative analysis or modelling of data	No constraints of the survey

and phyllites, affected by known and “supposed” faults, covered by carbonate overburden, gravels and alluvial deposits. The 1:5000 geological cartography, still unpublished, was carried out by Oliveira,V. in 1985 and worked out by Francés A. in 2001.

One is not aware of the difficulties of such a geological setting at first sight. Lithological contacts are often masked out; the soil is frequently ploughed up (agriculture) or simply covered by wild vegetation. The topography is not of great help either: an almost flat surface with a wide shallow stream (Fig. 7), indicating no geological structures at all.

Rectilinear contacts are rare, making the selection of the best transmitter difficult. According to the theory, the latter should be aligned with the strike (E- polarisation) and the profile parallel to the magnetic field.

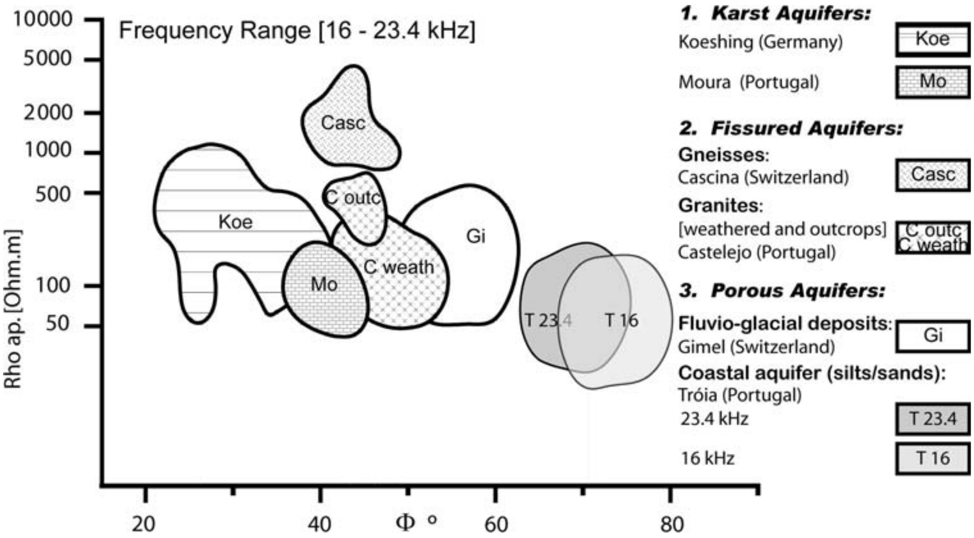


Fig. 6 Density contouring of measured apparent resistivity and phase shift values for different lithologies

Looking at the map (Fig. 7) we notice that lithological contacts and structures, far from being perfectly aligned, look like they are "pieced together". As a consequence it is impossible to ensure the ideal layout for the profiles, although the survey was almost performed in quite good conditions—see Table 2 in the Electronic supplementary material.

Twenty RF-EM profiles were carried out, for a total of 4.5 km in a 12 hectares area. The main directions of the rectangular grid layout were NE–SW, NW–SE (Fig. 7). E-W profiles were performed twice. The distance between profiles was about 40–50 m in average. The aim was to get a good coverage of the area with sufficient density of data for interpolation. The available emitters were the GBR-Royal Navy Rugby Radio Hillmorton (16 kHz ~ N 30 E) and the NAA: US NAVY NCTS Cutler, Maine (24 kHz ~ NW–SE).

The in- and outphase signals were recorded every two seconds at the speed of 1, 5 m/s.

The 2D interpolation of the outphase variation (Fig. 8) can be transformed into a pseudo 3D surface of the outphase values for a better visualisation (Fig. 9).

The existence of an abrupt variation in the outphase signal is clearly evidenced in the 3 D representation of the outphase variation, by means of the "relief" alignment followed by a depression. This suggests the existence of a fault acting as a hydraulic barrier (Fig. 10 "detected fault"). As a result the groundwater would concentrate and preferentially flow, parallel to it, creating the favourable conditions for the development of an important karst channel, explaining the productivity of the old water wells (50 L/s). This fault was confirmed by the drillings which were performed later.

The implantation of the new wells was chosen in accordance with the "karst channel" hypothesis mentioned above. A certain distance from the fault was respected and the "deepest part" of the outphase channel was chosen.

The drillings were successful: two 80 m depth productive wells—55 L/s, intercepting three water bearing layers between 55 and 72 m depth. A third drill performed just over the "fault", was almost dry and it was transformed into a piezometer. It was interesting to observe that the old productive wells were also located in the same deepest part of the "outphase depression" (Fig. 10).

In Conclusion: the use of the RF-EM was decisive for the implantation of the new wells. The method was employed in almost *ideal artificial and topographical conditions*, so that it was possible to achieve a regular rectangular net of observations and consequently a good interpolation of the outphase data. The transformation of the interpolation map into a 3D outphase surface, led to the choice of 2 exploratory sites located at the deepest part of the channel. The public wells turn out to be very productive.

Characterization of a compartmented coastal aquifer system

The peninsula of Tróia is located 30 km south of Lisbon (Portugal) (Fig. 11). It is bordered westward by the Atlantic Ocean, and eastward by the Sado river estuary. It is a slim, 2 km wide and 12 km long, emerging surface build up of Quaternary estuary and dune sands, of variable grain size and irregular thickness. This porous formation is limited below by discontinuous Pliocene clayish layers with very low vertical hydraulic conductivity and which lie over limy Miocene sandstones. As a result, the aquifer system consists of an unconfined upper porous aquifer overlying a multilayered confined to semi-confined porous

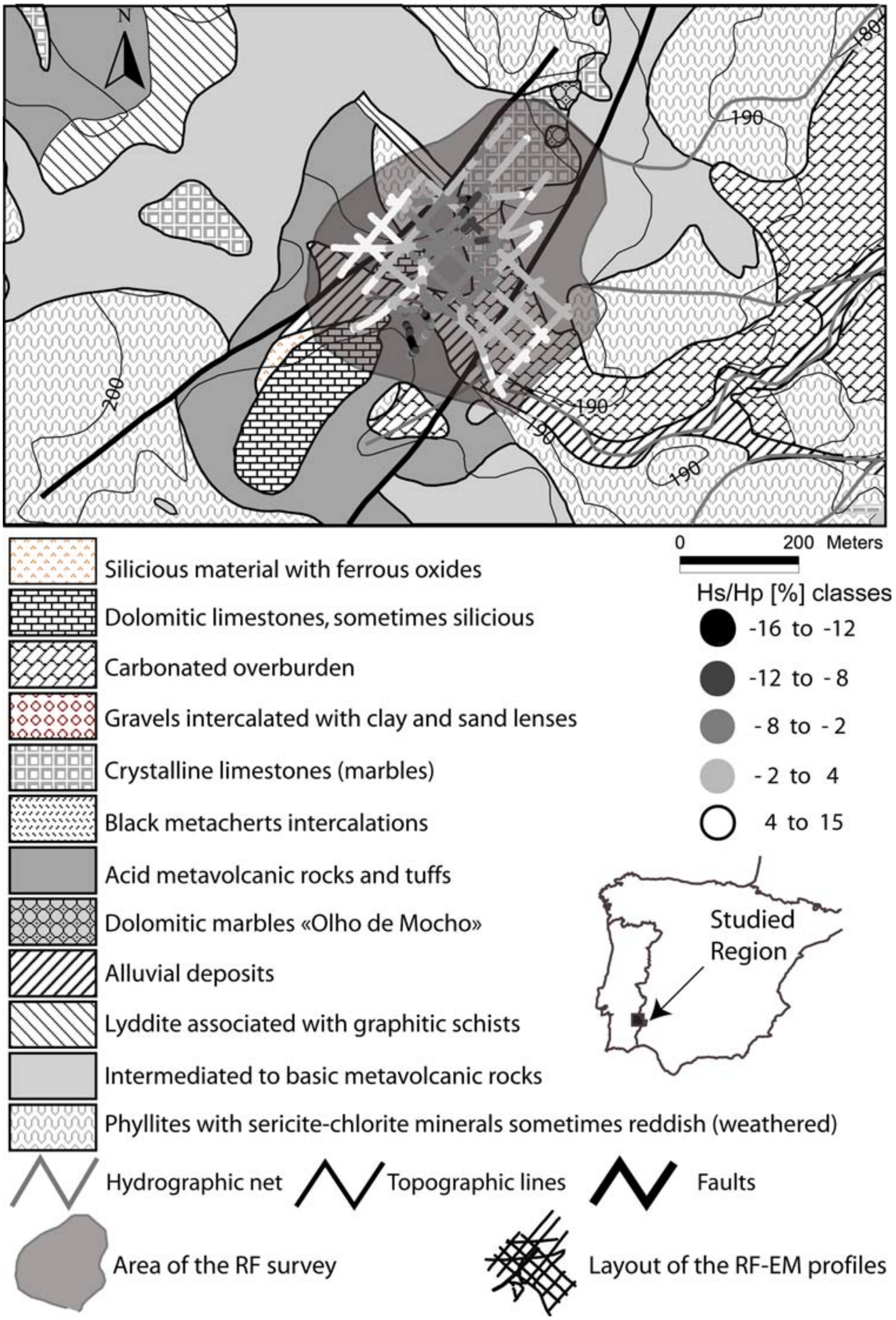


Fig. 7 Radiofrequency-electromagnetic method profiles in a rectangular net. The outphase intervals values reveal a great conformity with the geology

and fissured aquifers (Pliocene and Miocene). Additional information pointed out the presence of saltwater between the upper and the deeper aquifer, as is to be expected in a coastal ("half-island") environment (Carvalho Dill et al. 2001).

Several faults cut this system, (Afonso A A 1989 *in* Prospecção Geoeléctrica na Península de Tróia, *unpublished geophysical report, Physics Department of Lisbon Science Faculty)*, eventually allowing the interface to vary vertically. This configuration leads to complex interrelationships between both aquifers, also due to the compartmentalisation, to tidal effects and to local responses to water extraction.

There is an important tectonic accident (Fig. 11)—a graben approximately N–S and 2 km wide (Cabral 1995.) which is indicated in Fig. 11. This graben is linked to

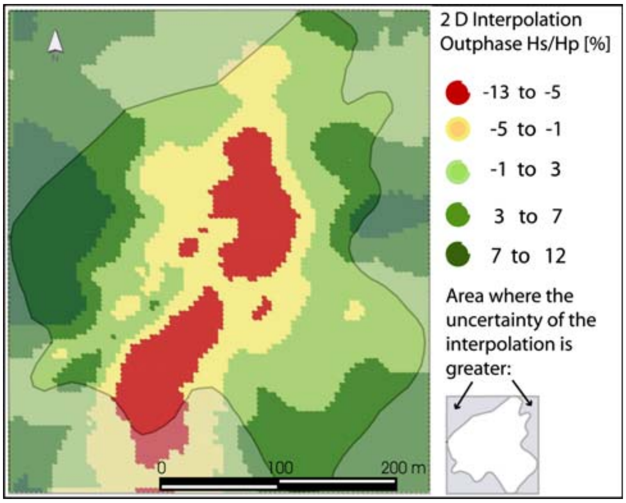


Fig. 8 2D interpolation of the outphase data. *Shadowy bordered areas* correspond to regions where the uncertainty of interpolation is large

diapir salt injections and responsible for the existence of some contaminated wells located along it (Almeida et al. 2000). It is interesting to look at the position of the "graben structure" in regard to the Tróia Peninsula.

The deep drillings (250 m) carried out were quite diverse. They usually obtained good-quality water, currently used to public consumption, but occasionally they revealed the presence of saltwater, probably related to this fault. Ruptures may occur in the tubes at depths where saltwater exists. These corrosion voids and rips can also threaten the water in the surrounding area, because of the daily pumping. In order to prevent the contamination of the deeper aquifer, the well tubes are now being inspected from time to time. Two old wells were closed and are now being replaced.

The use of the electromagnetic methods—RMT and RF-EM—was done in the context of an Environmental Impact Assessment of the Tróia Tourist Resort, which was order to the Guia Marine Laboratory, Lisbon Faculty of Science / IMAR by the Enterprise IMOAREIA/SONAE. The aim was to examine the geometry and structure of the underground, in order to comprehend the functioning of this coastal aquifer and to understand the complex relationships between the upper and the deeper aquifer. According to the Table 2 of constraints, (see Table 2 in the ESM) non-ideal conditions prevailed in this site (Fig. 11) due to natural (topographic nature, soil moisture, presence of salt water,) and artificial restrictions (EPL, inexistence of transmitters at the convenient directions, buried roman ruins).

The RF-EM profiles were performed with the automatic antenna (Jeep) and carried out where it was possible. The EM response was quite remarkable. It clearly indicates a definite compartmentalization, also in terms of RF-EM results. Due to the presence of salt water between the upper and the deeper aquifer, an attenuation of the electromagnetic signal was expected. This was the case with most of the profiles (Fig. 12). The existence of buried roman ruins

Fig. 9 3D surface of the outphase data

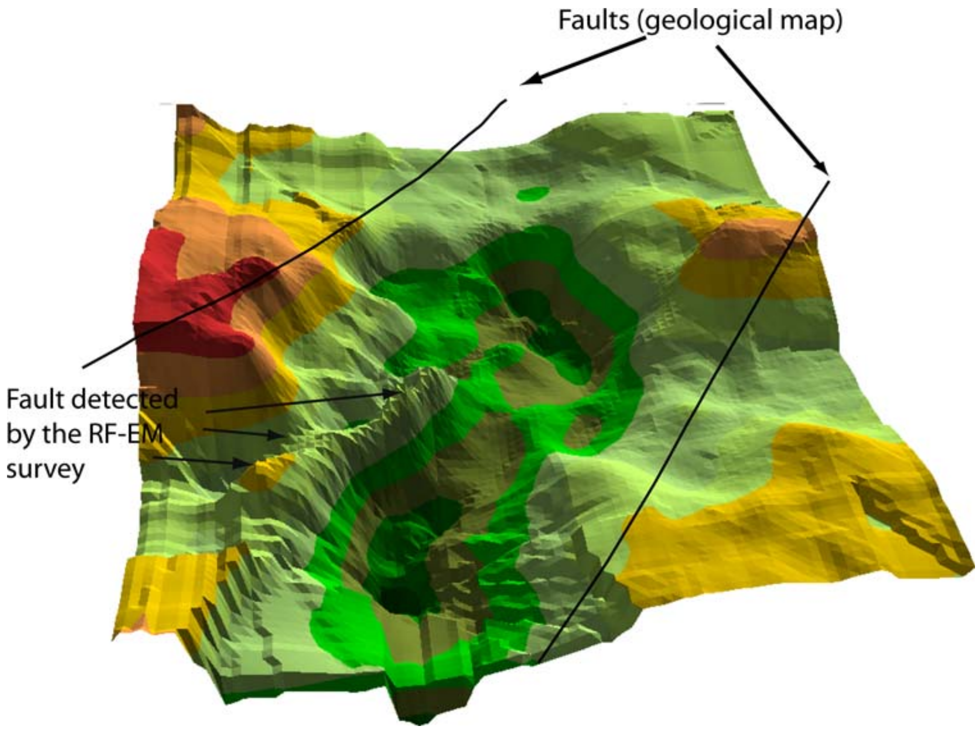


Fig. 10 Chosen places of the new wells, relative to the fault plotted in the 2D and 3D surfaces

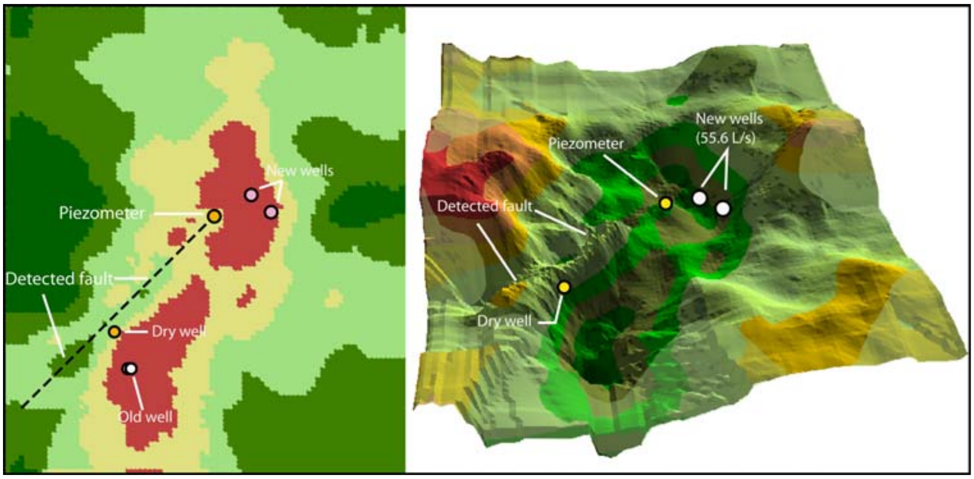
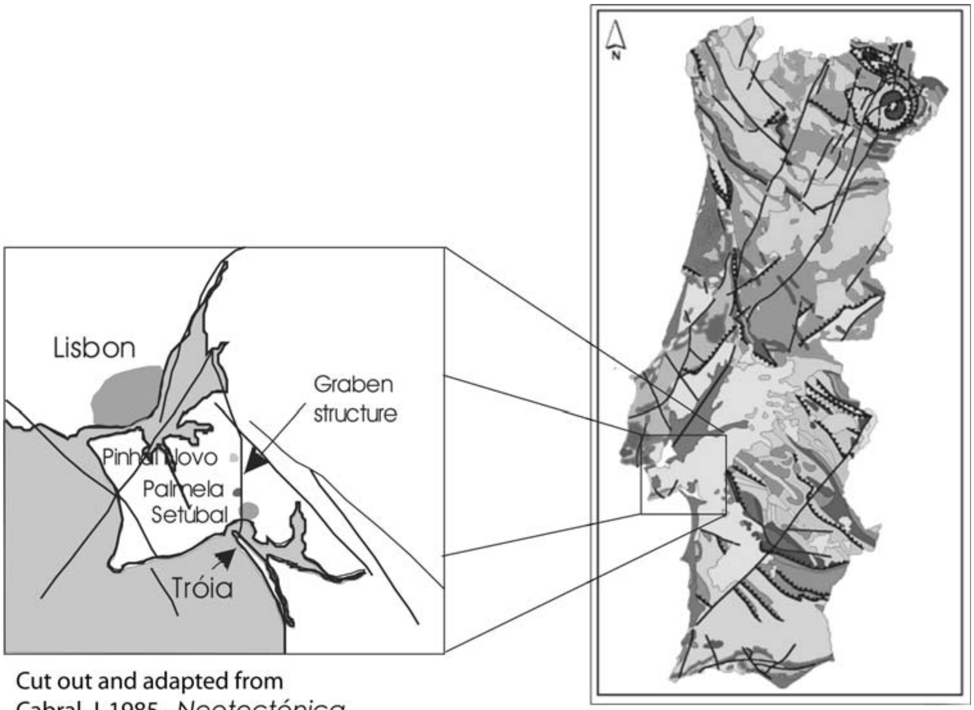


Fig. 11 Geological and geostructural framing of Tróia Peninsula and the position of the "graben structure" with regard to Tróia Peninsula. The Table 3 in ESM, summarizes the main difficulties encountered during the surveys



Cut out and adapted from Cabral, J. 1985 - *Neotectónica em Portugal*

Simplified Geological Map [Geological Surveys of Portugal- INETI/IGM]

with high iron content was also suspected of producing local EM dampings and is thought to be responsible for the values obtained in the RF2 profile. Nevertheless places with strong anomalies—15–20% (shadow zone in Fig. 12, a and b areas in Fig. 13) were detected, corresponding to important tectonic accidents.

It is interesting to observe the relationship between the anomalies and the morphology of the island. The first feature is the connection between the anomalies and the existence of springs inside the dunes, reflected as a depression (Fig. 13, arrow b). This spring is surrounded by "phreatic vegetation" which according to botanists requires a permanent supply of freshwater (Pinto, M. et al, 2001).

The second aspect is the occurrence of the "Caldeira". It represents a discontinuity in the sedimentation, which is thought to be related to the graben structure mentioned above. The anomalies, detected to the north and south (2nd Campaign) of the Caldeira, clearly corroborate this hypothesis (Fig. 14). The existence of this fault system was confirmed later on with the help of a proton magnetometer (Scintrex). The magnetometer revealed the existence of a «step structure" aligned in that direction (Fig. 15).

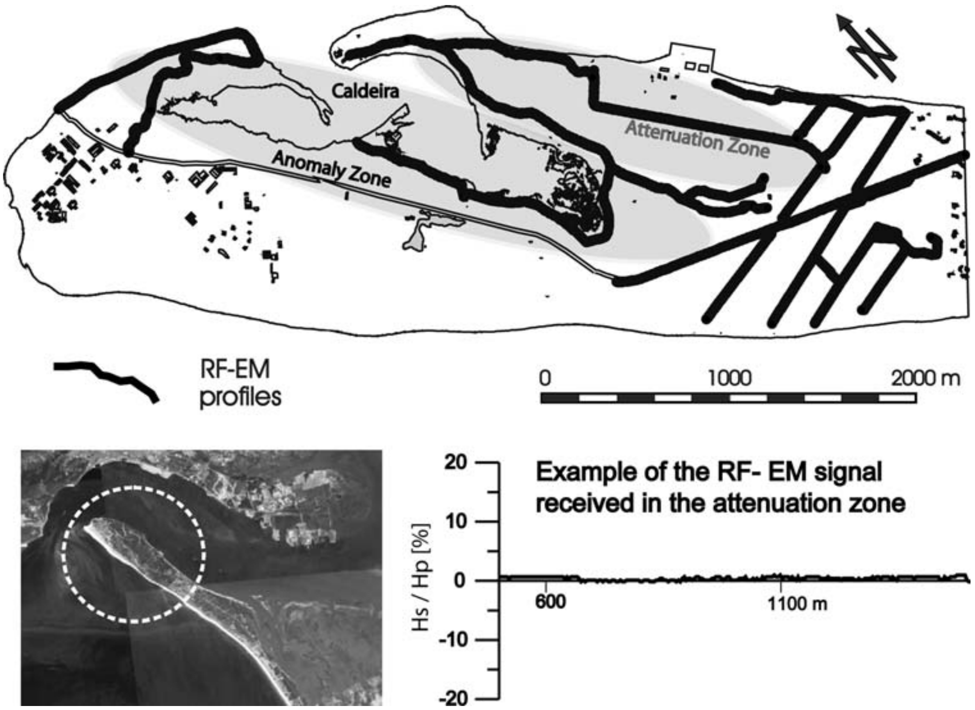


Fig. 12 Location of the RF-EM profiles and the attenuation and anomaly zones. RF-EM response in the RF2 profile due to the buried roman ruins ("Attenuation zone" signalized on the map)

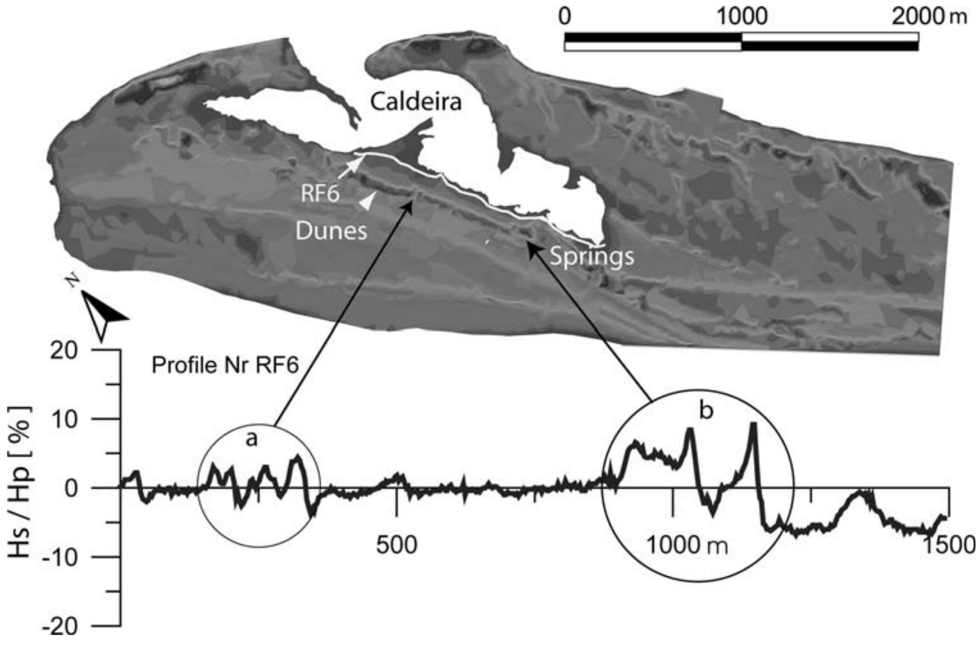


Fig. 13 Topographic map showing the location of RF-EM profile no. 6 and the outphase signal along this profile. The *letter b* indicates the correspondence of the EM anomaly and the spring (inside the dunes)

Through this fault system the groundwater rises up from the confined aquifer, under pressure (artesian), which, in turn, loosens the sediments, creating areas, where deposition occurs with difficulty. The role of groundwater discharges in the creation of estuarine landforms is a subject of great interest and should be more subject to further research in the future.

Due to extreme dryness of the permeable sands, RMT measurements could only be performed at the Golf Camp and football courts (Fig. 17). The cadastral information was checked in order to ensure that there were no metallic tubes in the irrigation system that could affect the signal. The aim was to detect the position of the interface between the freshwater lens and the underlying saltwater edge. Two frequencies of the 20 kHz range were used: 16 and 23.4 kHz.

In such an environment the presence of salt water influences the resistivity and phase values: the apparent resistivity values of the sand are expected to be diminished with simultaneously increased phase values (vide Fig. 6).

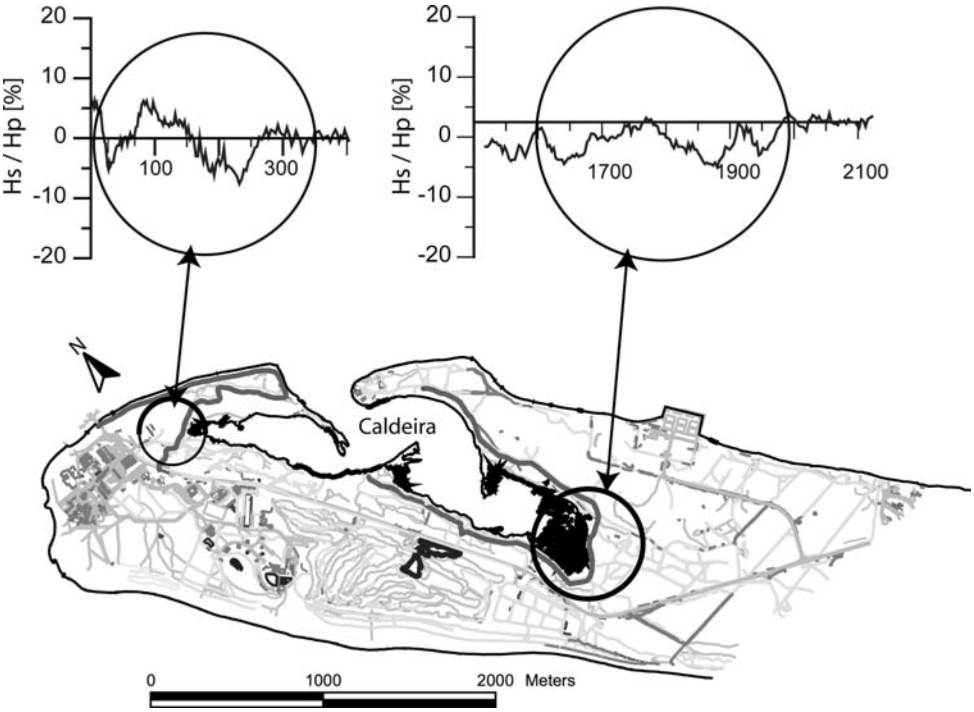


Fig. 14 Electromagnetic anomaly northwards and southwards from the Caldeira

The apparent resistivity and phase values indicated a more resistive layer lying over a more conductive one (salt water). It was thus possible to roughly estimate the position of the interface, which we calculated as varying between 15 to 20 m depth at the Golf area. This calculation was used as an indicative value and with the help of an analytical model (Fetter 1994), the position of the interface in other sections of the island was also estimated (Carvalho Dill et al. 2001). The depths estimated by geophysics were not so far from the ones observed during the drillings performed later on (Figs. 16, 17).

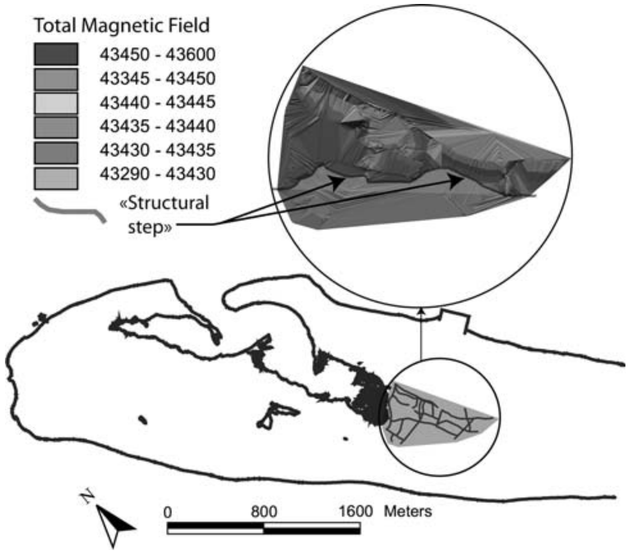


Fig. 15 Sectorial interpolation of the total magnetic field values (nanotesla) measured with the magnetometer southwards of the Caldeira. The "structural step" pointed out above is evident by the *contrasting colours*

Another interesting aspect, which came out by this survey, was to observe that sometimes the apparent resistivity values corresponded typically to sands filled with freshwater (120 to 355 Ohm.m) – These areas are plotted as darkened spots in Fig. 18. This was very curious, since the Golf lies very close to the fault mentioned earlier. A possible explanation would be the same as for the dune springs: freshwater, under pressure in the deep aquifer, is forced towards the surface, locally keeping the salt water away ("fresh water spot areas").

Figure 19 represents the interpolated maps of the apparent resistivity and phase shift values obtained with both frequencies. These maps revealed the same coherent image with clear anomaly areas. The results obtained by 23.4 kHz (lower penetration depth) are logically less affected by the salty water layer underneath: the apparent resistivity values are slightly higher and the phase slightly lower.

The same image can be seen in Fig. 20, where there is a clear shift to the left of the phase and resistivity values. The "fresh water spot areas" (phi values less than 45°) are also noticeable, mainly with the 23.4 kHz.

In short: The use of both electromagnetic methods was very useful in Tróia. The RF-EM method allowed the subsurface detection of a deep fault system, responsible for the existence of freshwater springs in the dunes. This graben system may play an important role in the

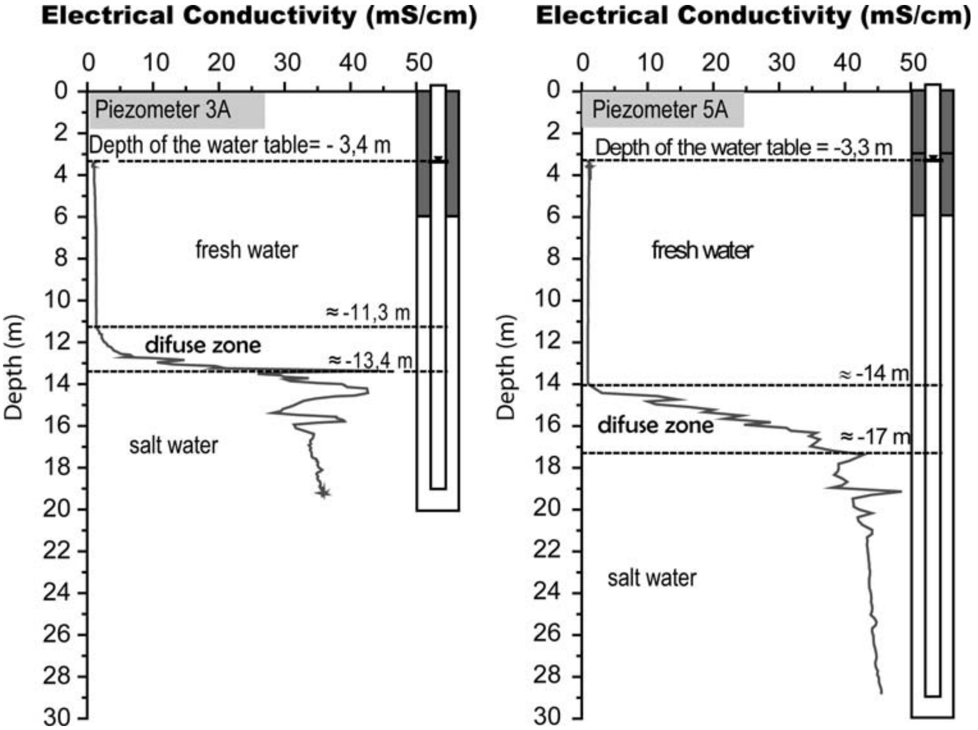


Fig. 16 Position of the interface in two piezometers (A. Carvalho Dill, T. Stigter, in IMAR 2006)

morphology of the peninsula. Unfortunately the use of the RMT method was only possible at the Golf and Football camps. This is due to the fact that sands hardly have enough moisture in order to be measured, especially in dry periods. Nevertheless, it was possible to calculate the depth of the salt/freshwater interface and the survey led to conclude the presence of freshwater flowing out from the deeper aquifer under pressure, which would, in this case, locally keep the salt water away. Furthermore, the information concerning the aquifer, provided by both methods allowed us to choose the best places for the implantation of a monitoring net, consisting of five pairs of double depth (shallow and deep) piezometers. These are now being used to continuously record data concerning conductivity, groundwater level, temperature and cyclical chemical analysis (IMAR 2006).

Understanding the geometry and geological structure of a fissured aquifer. An application in cases where groundwater has been contaminated due to acid mine drainage

The Castelejo Uranium Mine is located on the Rio Mondego Basin, on the left margin of the Ribeiro do Paço, NW from Vila Cortês da Serra. It belongs to the Central Iberian uranitic belt, occurring within coarse, almost porphyritic two-mica granites. The uranium appears mainly as Uranium phosphates—“autunite, torbernite and sabugalite”—secondary minerals derived from the uraninite—and is associated with vein quartz (Fig. 21) (Teixeira et al. 1967; Falcão et al. 2005)

The ore exploitation procedure was open-air from 1979 till 1990. Afterwards, the Mining Company undertook the

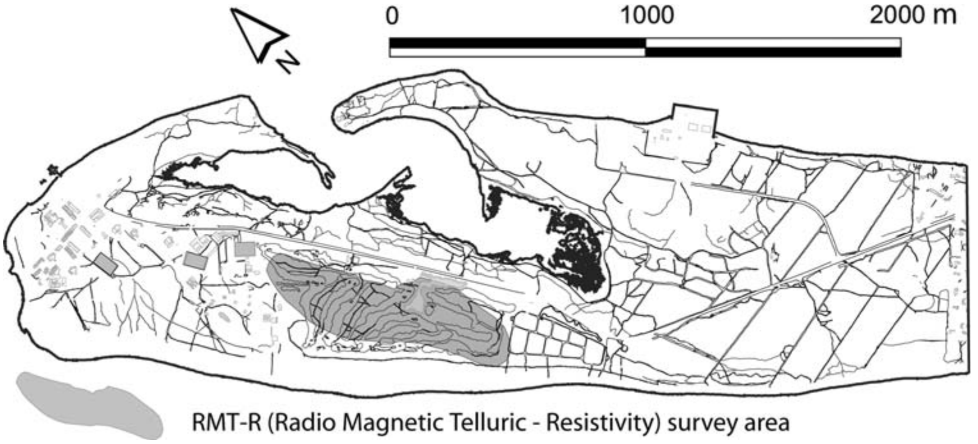


Fig. 17 Location of the radio-magnetotelluric (RMT) surveys: Golf Camp and football courts

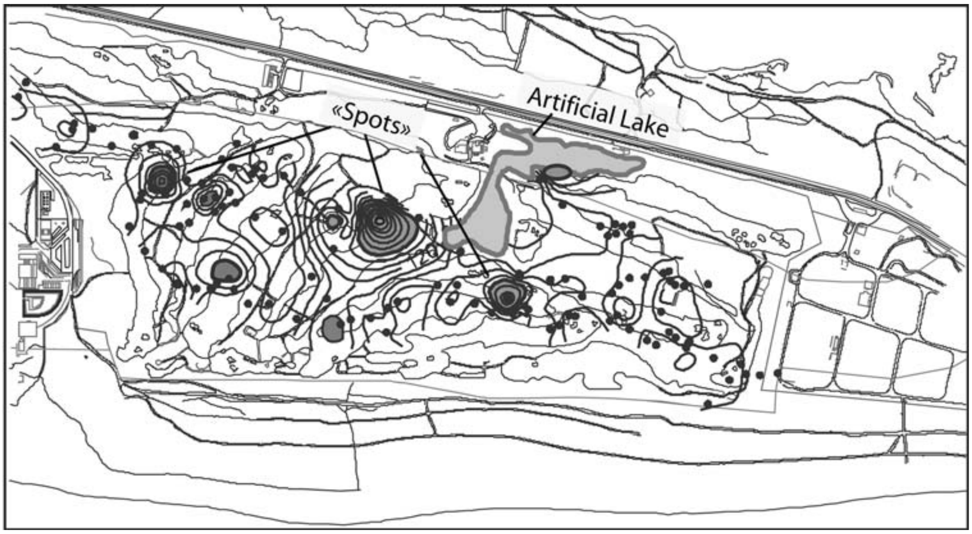


Fig. 18 Radio-magnetotelluric surveys measurements points. Anomalies in resistivity measurements (23.4 kHz) are signalized by *darkened spots*

recovery of the Uranium mill tailing disposals from Castelejo as well as other surrounding mines. This was done by leaching the waste with sulphuric acid (Pinto et al. 2005). The consequence was the production of acid mine drainage.

A preliminary geophysical characterization of this area was performed in order to obtain more information about the aquifer structure and to delimit the contaminated plume.

Several RF-EM profiles (Fig. 21) were carried out around the Mine in order to detect faults and fractures which could act as preferential groundwater flow pathways for the contamination. The results were compared with the analysis of the fractures and joints performed on the aerial photo. Figure 22 shows the outphase response of a profile section performed along the road. The graphic was then placed over the 3D model of topographic map where these fractures are noticeable, in order to relate the fractures with the EM anomalies. The correspondence is quite visible, demonstrating that fractures are clearly detected through the produced anomalies in the outphase curve.

The correspondence with the morphology is remarkable. In order to obtain this visual aspect the outphase values were transformed into 3d shape files and also put together

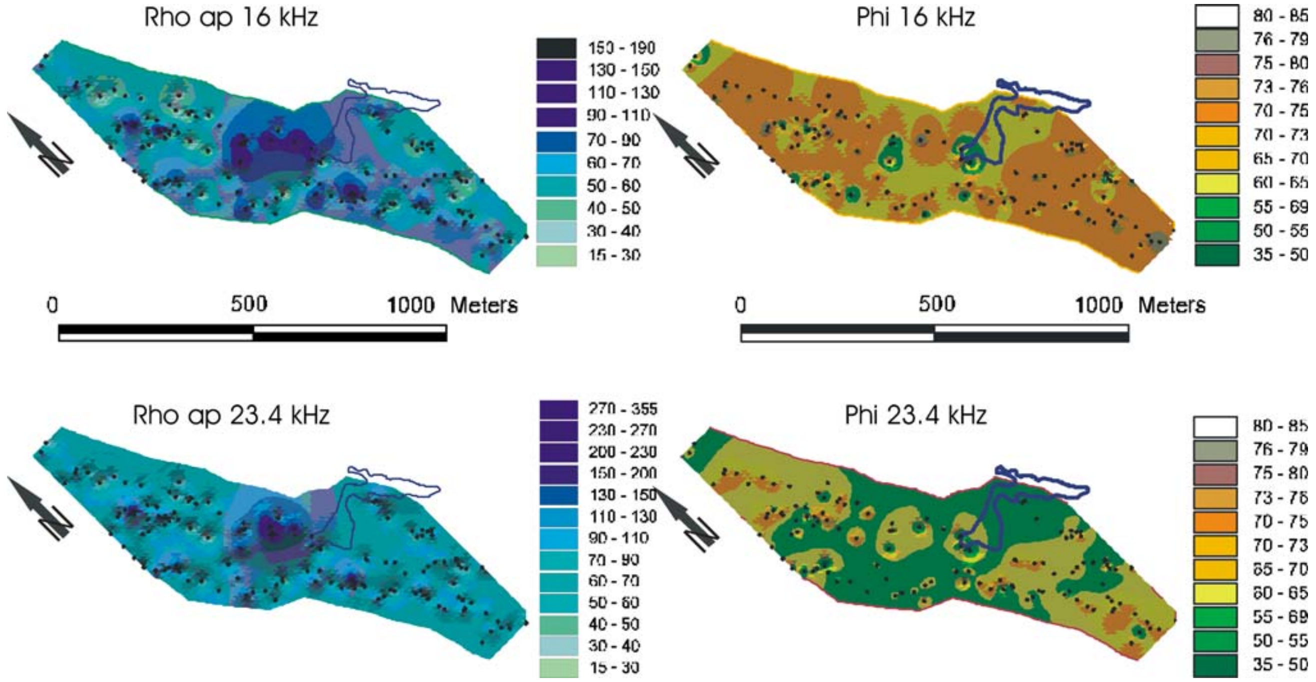


Fig. 19 Interpolation of the resistivity and phase values measured with 16 and 23.4 kHz

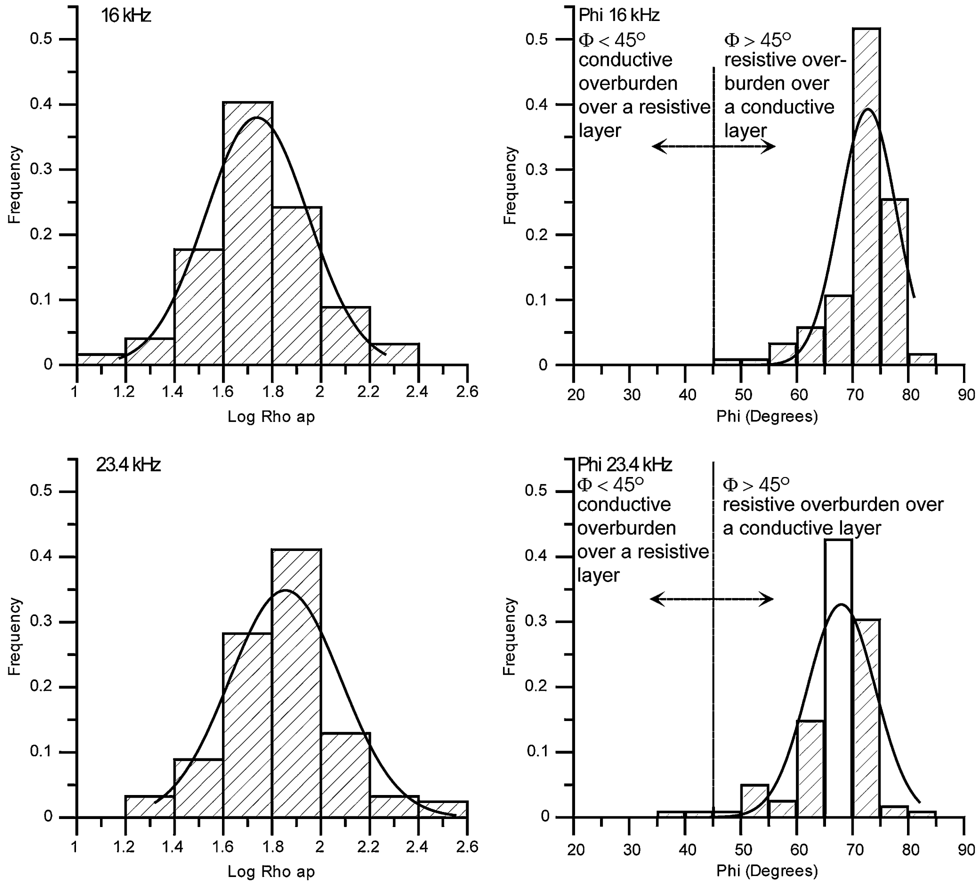


Fig. 20 *Histograms* and frequencies of the resistivity and phase values measured with 16 and 23. 4 kHz

with the 3d model of the terrain. The advantage of this procedure is that we can exaggerate vertically both the surface area and the profile if we want to emphasize the structures (see also Fig. 23). 3D Viewers also give the possibility to rotate the subject matter or even to incline it and turn it upside down. If there are several profiles, this method facilitates the finding of the structures and their directions.

After having identified the main structures with the help of the RF-EM method, a hypothesis about groundwater flow directions was formulated.

Granites are known to have a rectangular net of fractures, so that the flow can take different pathways and in extreme cases be divergent, according to regional groundwater flow net organisation. Nevertheless, the fault detected in A (Fig. 22) suggested that the main groundwater flow could follow the fault valley as the surface streams do. The RMT measurements were concentrated to the northwest of the pit lakes and along the valley. One profile was carried out in the opposite direction, north from Vila Cortês da Serra (Fig. 21). The idea was to detect low resistivity values caused by acid mine drainage.

Three frequencies were used: 183, 77.5 (or 81) and 23.4 kHz. It was possible to detect situations of E- and H-pol, which clearly indicate the existence of geological structures that could act as preferential groundwater pathways (Figs. 22, 23, 24).

Figure 23 illustrates the effect of a minor fault, oriented towards the transmitter (E-pol effect). The profile was vertically exaggerated four times in order to emphasize the morphology. Figure 24 serves as an example of an H-pol situation, where the structure (fault valley) is oriented perpendicular to the RMT transmitter. The RMT results show the resultant decrease of the apparent resistivity values and the increase of the phase values.

The Resistivity values were not in accordance to what is expected in unaltered granites as shown in Fig. 25. (See also Fig. 6 in order to compare the density contour graphic of Castelejo Cascina-gneisses (Switzerland). On the contrary: the highest values, which were obtained in the outcrop areas were 1300 (1st channel) to 1450 Ohm.m (3rd channel). The weathering of the granites is certainly high in Castelejo.

The values obtained around the fault valley suggest that this valley is filled with unconsolidated eroded material, as shown in Fig. 25.

The upper graphic of Fig. 25 represents the measured values obtained along the valley. Except for one point, all the others have resistivities under 250 Ohm.m, which indicates that for modelling purposes, we have to consider

Fig. 21 Geological settings and location of the geophysical survey (RF-EM and RMT) carried out in Castelejo. Table 4 (ESM) indicates natural and artificial constraints for the EM surveys

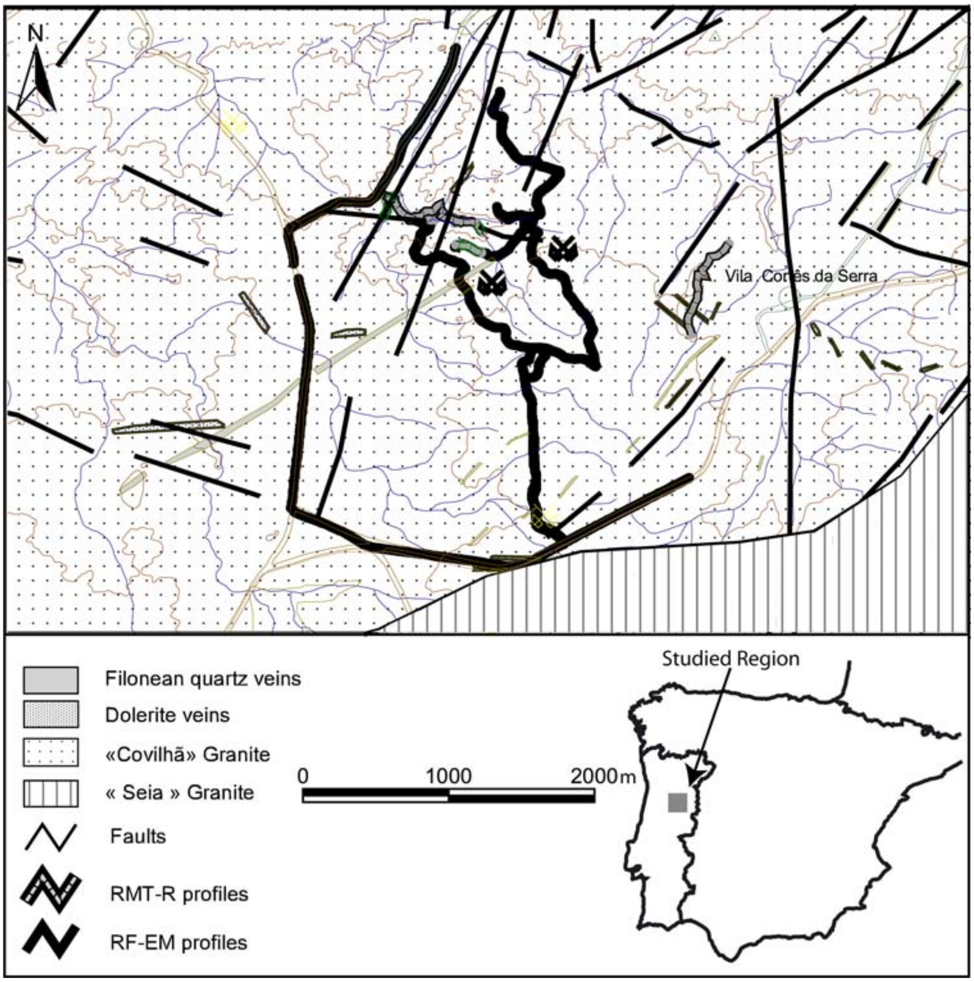
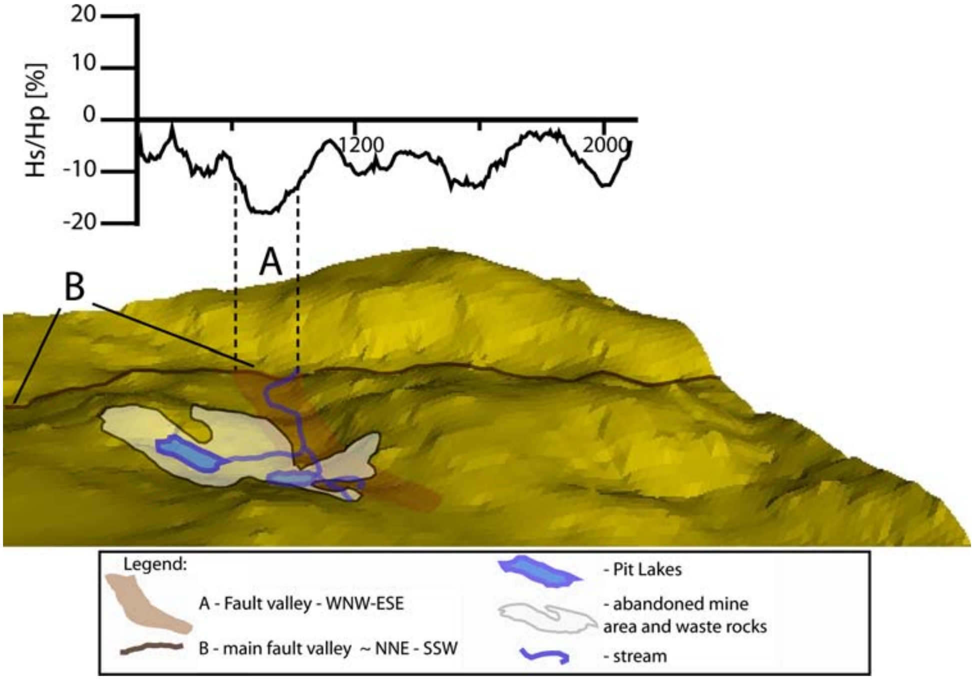


Fig. 22 3-D modelling of the topography and the position of the valley fault identified by the RF-EM method (*A*) and which can act as a preferential flow for transport contamination



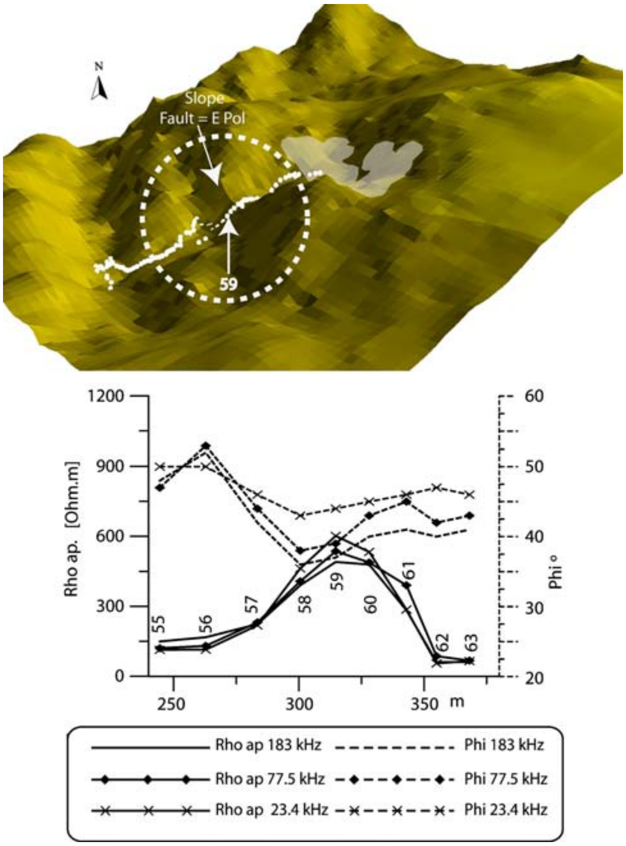


Fig. 23 Effect of a minor Fault oriented towards the RMT transmitter (E-pol situation) on the RMT. The measurement points are located (*white dots*). The surface is vertically exaggerated

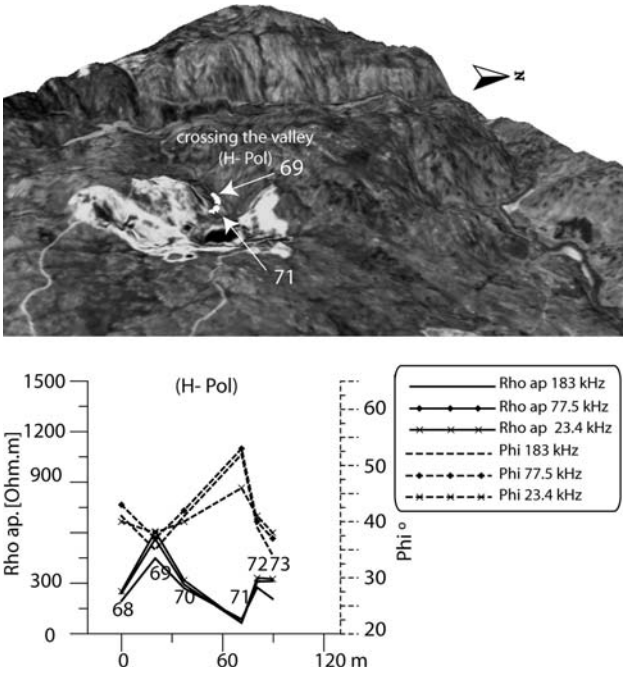


Fig. 24 Effect of a structure oriented perpendicular to the RMT transmitter (H-pol)

a local flow and a transport in porous media instead of via a fissured media. The phase values of the 77.5 and 23.4 kHz indicate the presence of a more conductive layer at greater depths (phi values > 45°) which is not a common situation in granites, although in some places it could corroborate some of the borehole observations: in fact a structural zone, where the granite is highly fractured and weathered, was identified between 50 and 70 m depth in some places. The graphic below corresponds to the geophysical model obtained by 1-D interpolation of the data. The calculated resistivity values are indicated. The limit of the upper layer is specified by the dashed line. The deepest penetration depth of the EM Wave is the lower dot-dashed-dashed line. The decrease of the resistivity, mentioned above, is visible again.

The existence of acid mine drainage at lower depths cannot be ruled out for the moment. In fact, the existence of acid mine drainage would result in a lowering of the resistivity values. This is particular visible in the histograms of the 23.4 kHz values (Fig. 26): there is a shift to the left observed in the apparent resistivity values and a predominance of phase values greater than 45°. In order to prove the possible existence of acid mine drainage, it would be necessary to know the electrical conductivity of groundwater and to perform chemical analysis. Unfortunately no such data is available.

Figure 27 shows five sectorial geophysical logs aiming to be representative for certain areas. Since many factors can influence the individual measurements, like for example E- und H-pol or the presence of metric lateral heterogeneities in the subsurface, a mean apparent resistivity value was calculated for a given set of measurements (and according to the proportionality between the electric tension and the square root of the apparent resistivity) by summing the squared average of the inphase tension and of the out-of-phase tension, according to the following formula:

$$\rho_{\text{average}} = \left(\frac{\Sigma\sqrt{\rho}\cos\phi}{N}\right)^2 + \left(\frac{\Sigma\sqrt{\rho}\sin\phi}{N}\right)^2$$

N is the number of measures, ρ the apparent resistivity and ϕ the phase. Anomalous isolated points or those clearly affected by polarization (E- and H-pol), like for instance point 32 (Fig. 25), or points 58 to 61 (Fig. 23), were not considered, so that the results would no be influenced. After having obtained a sectorial mean value for each frequency, a 1D inversion model was used and the resistivity and thickness of the upper layer was estimated. The logs were constructed in Grapher. The sectors were represented with different symbols.

Profile 1 (☆) was performed on the outcrop area, over the waste rock pile near the uranium mine exploration. In this area, less weathered granite blocs are immersed in a

Fig. 25 Apparent resistivity and phase profiles as measured along the valley (*upper graphic*) and geophysical model obtained by 1D inversion (*graphic* below)

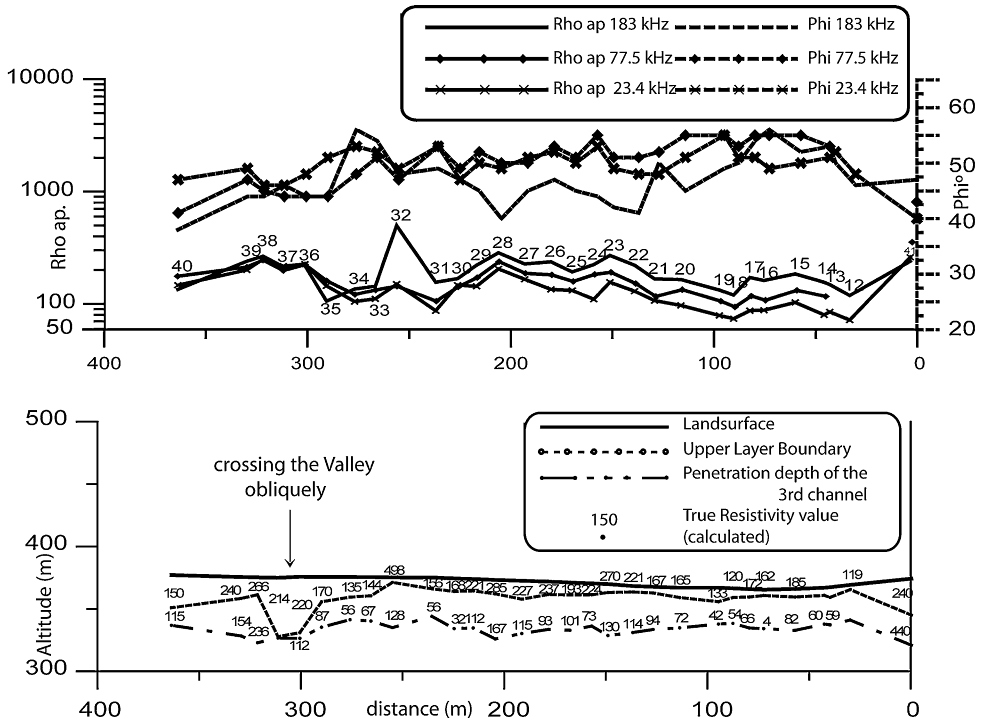
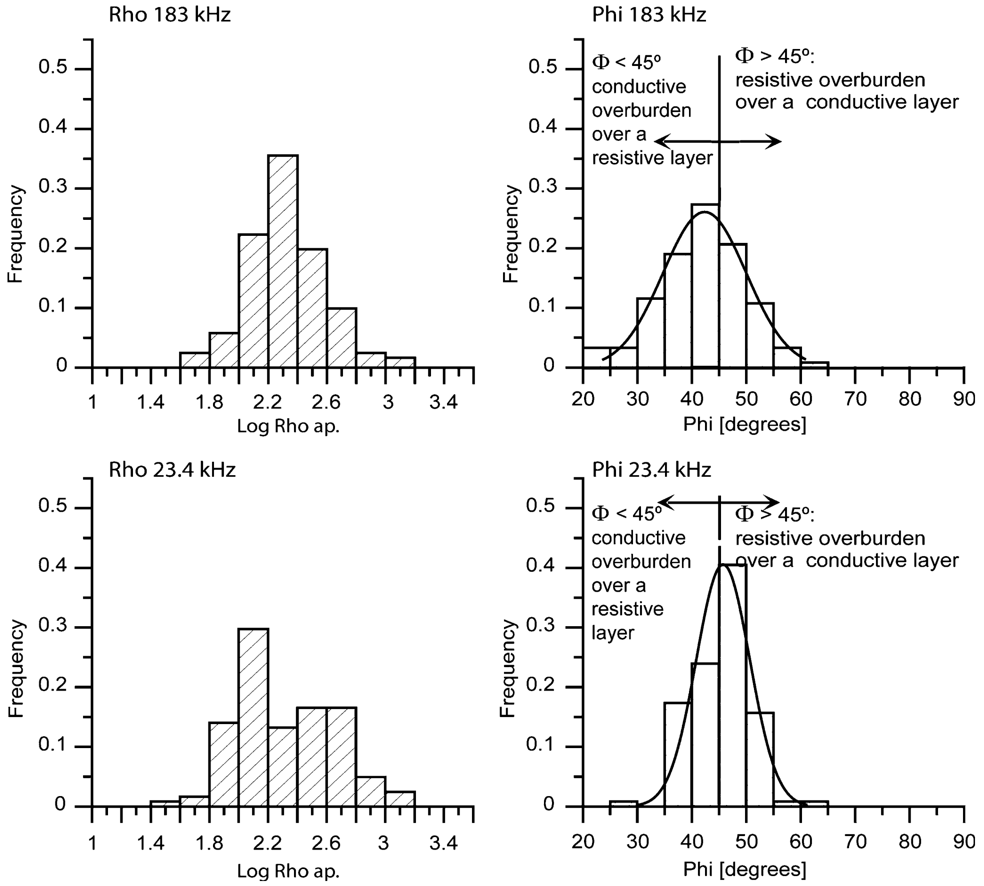


Fig. 26 *Histograms* of the RMT measurements



more altered matrix. The geophysical log indicates an enlarged upper layer with relative-higher-resistivity values, underlaid by less resistivity material.

Profiles 2–4 were performed on the fault valley (WNW–ESE) mentioned above. It is quite interesting to observe that the geophysical logs indicate the increase of an upper

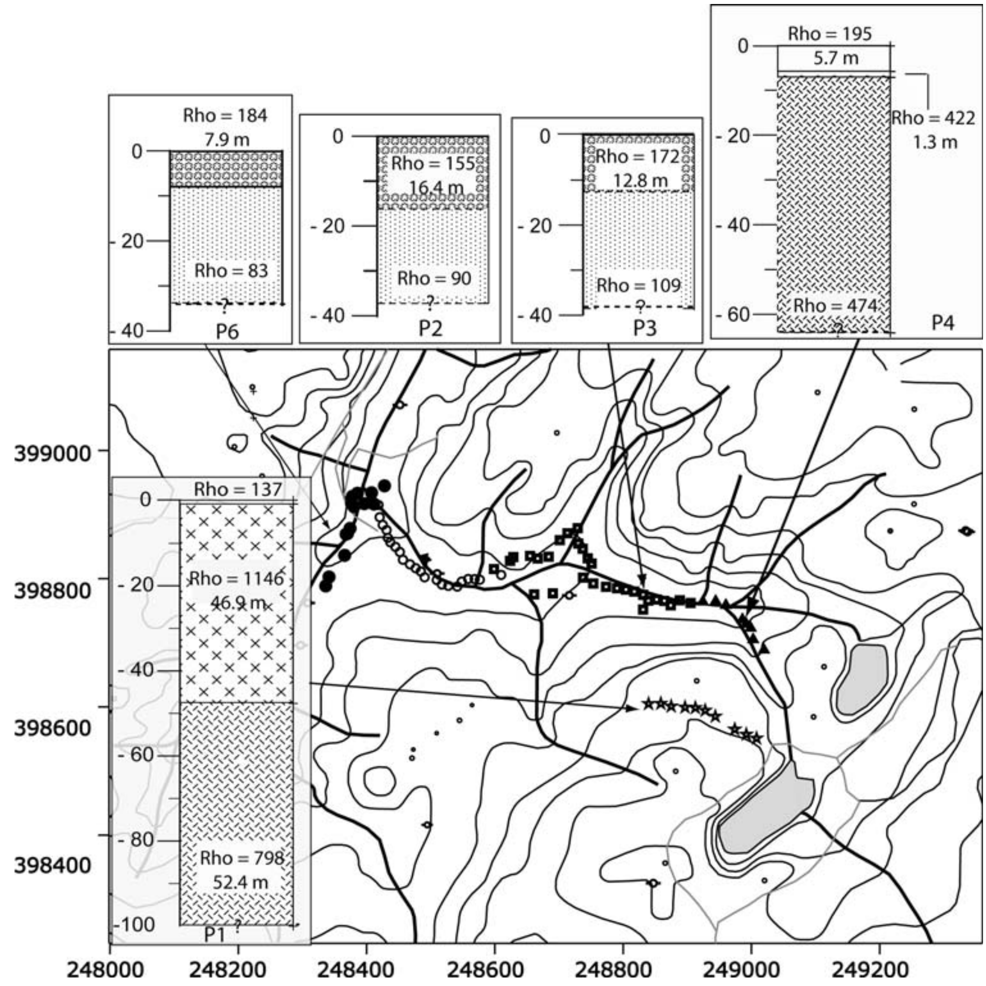


Fig. 27 "Sectorial Resistivity Logs" illustrating the increase of the upper layer thickness associated with the decrease in grain size downstream

layer, accompanied by a decrease in resistivity downstream—profiles 4 (▲), 3 (□) and 2 (○), which is an expected depositional aspect if one considers a decrease in grain size downstream. The thickness of the upper layer diminishes again in the main valley (NNE–SSW). This is certainly due to the increased stream water discharge (higher transport energy) observed there—profile 6 (●).

The geophysical conclusions at the Uranium mine indicate that the transport of contamination is expected to be concentrated along this fault valley, whose geometry can be deduced after the RMT survey. Furthermore the RMT survey concluded that for contaminant transport modelling purposes along the valley, the use of a porous model is more appropriate. These statements need to be confirmed with future drillings.

Conclusions

Electromagnetic methods are known for being very useful tools in ground- and groundwater investigation at shallow depths. Quantitative exploitation of the data is frequently unfeasible, due to unreachable experimental conditions required by present models. Three case studies are presented showing the way in which qualitative data can be explored in different geological settings in order to extract most information:

1. The performance of RF-EM profiles, laid out in a dense rectangular net, indicated the best place for the drilling of two new public water supply wells in a karst aquifer system;
2. The use of both electromagnetic methods for the characterization of a coastal aquifer system led to the conclusion that they can be successfully applied in such environments. Due to the presence of salt water, the outphase signal (RF-EM) will be attenuated or the resistivity values lowered and the phase increased (RMT), but every time there is an important geological anomaly, like a fault through which freshwater flows preferentially, the contrast in resistivities becomes obvious and the geological anomaly quite evident.
3. Both methods were very valuable in the assessment of the geometry and structure of fractured granites and

the understanding of their role in contaminant transport (Castelejo). Although conditioned by the presence of EPLs and the irregular topography (granitic outcrops, tors and boulders) the RF-EM profiles pointed out the existence of faults and fractures through which the transport of contaminants is taking place. Furthermore RMT results suggested that the transport model to be used, should considered a porous media.

The experience gathered with the use of both methods shows that there is a considerable gain if they are used together, since they are complementary. Yet each of them has its own specificities RF reveals its usefulness in regional geological characterization, providing a rapid overview of the existing structures, major accidents and lateral contacts of different formations. RMT is more recommended for more detailed information about the nature of the subsoil, allowing vertical soundings to be carried out. Information about the anisotropy of the ground is also possible, if multidirectional measurements are executed.

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