

## The use Time Domain Electromagnetic for delimiting saline water in a Quaternary deposit

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### Summary

The use of geophysical methods can provide important information for mapping the subsurface. In arid and semiarid areas, the detailed knowledge of the geometry of local aquifers can assist to a better management of groundwater. In the Punata alluvial fan (Bolivia), a semiarid region, there is gap in the knowledge of the layering delimitation within the aquifer. During the drilling of boreholes, this gap, causes that fresh water is contaminated with saline water. In order to identify the depth of the possible layers with saline water within the Punata aquifer, the geophysical method Time Domain Electromagnetic is applied. The main objective of this study is to delimitate the depth and thickness of layers with saline content by analyzing and interpreting Time Domain Electromagnetic results, in the Punata alluvial fan. The soundings are performed in a grid of 150 m separation, which provide significant information for proposing 2-D and 3-D models, where it is possible to establish the lateral and vertical extent of the saline layers within the aquifer. With this information, further planning and policies can be proposed for a sustainable and appropriate groundwater exploitation.

### Introduction

In arid and semiarid regions, surface water access is considered to play a crucial role for the development of economic and social activities, but groundwater reserves can be as important as surface water. For a sustainable management of groundwater, however, knowledge of the aquifer geometry and hydrochemical properties is needed.

Different geophysical methods for imaging the subsurface and different environmental applications are available, e.g. Barker (1990), Milson and Eriksen (2011), Rubin and Hubbard (2006) and Sharma (1985). However the selection of the most suitable geophysical method depends of many factors. Benson et al. (2003), describes that the selection of the geophysical method depends on the project objective, extension of the area of interest, physical properties to be measured, geometry of the target, depth of investigation and site specific constraints.

The Time Domain Electromagnetic (TDEM) is a geophysical method, and has been used in many studies with environmental applications, e.g. Danielsen et al. (2003), Goldman et al. (1988), Guérin et al. (2001) and Nabighian and Macnae (1991). This method provides an excellent resolution of conductive materials at large depths, and highlights the contrast between high and low resistivity materials (Christensen and Sørensen 1998). In order to identify the depth of the possible layers with saline water within the Punata aquifer, the TDEM method is applied. The objective of the present study is to delimitate the depth and thickness of layers with saline content by analyzing and interpreting the TDEM results, in the Punata alluvial fan (Bolivia).

### Theory and Method

The general theory behind TDEM is explained in many references such as Bennett and Ross (1978), Fitterman and Stewart (1986) and Danielsen et al. (2003). This method depends on the interaction between magnetic and electric fields. Current is transmitted through a cable that lies on the ground, generally square loop shape. The current is alternatively turned on and off. A static primary field, which is vertical to the surface, is created during the on-time. During the off-time, a electromotive force is induced in

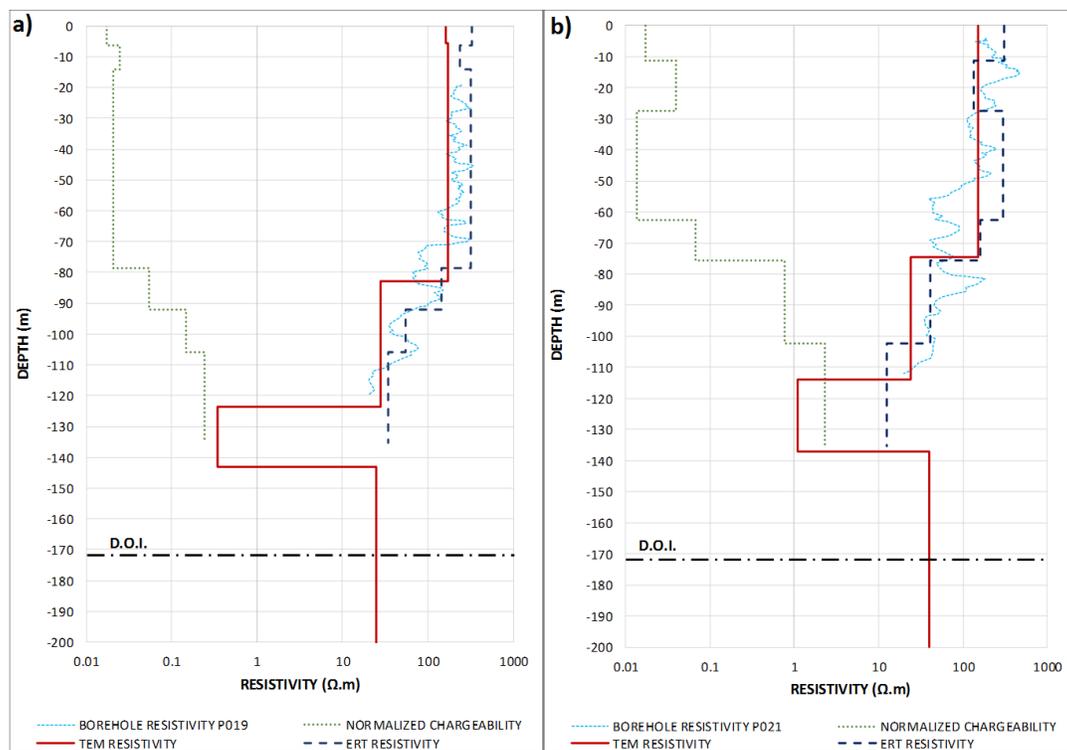
the ground by the decaying primary field. This force, produces eddy currents in conductive bodies, and creates a secondary magnetic field. This secondary field has an amplitude which decreased with time and it is measured by a receiver loop. The reading of the measures is done at several times during the off-time. The shape of the decay curve reflects the resistivity distribution with depth.

The TDEM is sensitive to conductive layers, therefore it is optimal for mapping the thickness and depth of conductive formations, such as clay or saline layers. The depth of penetration in TDEM surveys, depends on the transmitter loop moment. The transmitter moment is a function of the transmitter current, and the transmitter loop radius (if the loop is circular) or the loop length side (if the loop is square). This restriction makes easier to reach large depths of penetration with less effort regarding to the equipment field setup. However TDEM is sensitive to noise, such as power lines, metallic objects and couplings.

In the Punata alluvial fan 130 TDEM soundings were performed and are distributed in two areas. The soundings have a separation of 150 m between each other. A WalkTEM equipment has been used, with a transmitter loop of 50x50 m, and a receiver loop of 10x10 m. Two batteries, each of 12 V were used as source power. The inversion process of the TDEM soundings were performed in the SPIA-TEM version 2.1.3. While the interpolation and creation of 2-D profiles were performed in Workbench version 5.2.2. Both programs are distributed by Aarhus GeoSoftware.

## Results and discussion

All the TDEM sounding curves show a decreasing trend of resistivity with depth (**Figure 1**). Generally, in area 1 the resistivity in the top layers is between 100 to 200  $\Omega.m$ ; while in area 2 the values of resistivity on the top layers are lower, e.g. 20 to 60  $\Omega.m$ . However, in both areas at the bottom of the soundings, the resistivity values are similar and are as low as 0.1  $\Omega.m$ .

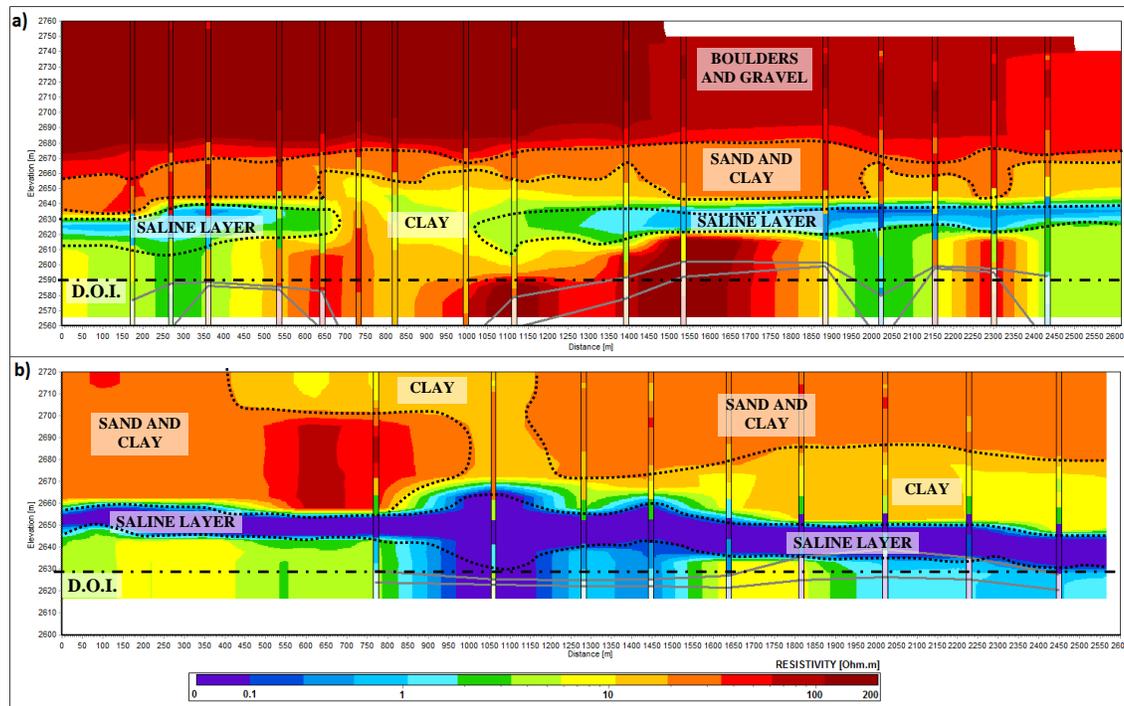


**Figure 1** Comparison of resistivity values from borehole logging, ERT and TDEM. The normalized chargeability is also included. a) and b) are for the borehole P019 and P021, respectively.

These low values in resistivity might be associated to high concentration of salts, e.g.  $Na^+$  and  $Cl^-$ . A total of 45 water samples were taken within the Punata alluvial fan aquifer and surroundings. The results indicated that the increase in the concentration of  $Na^+$  and  $Cl^-$  rises the EC (or decreases the resistivity) of the water samples. The report of UNDP-GEOBOL (1978) found water conductivity values of 9.7 mS/m

(~103 Ω.m) between 0 to 100 m depth, 600 mS/m (~2 Ω.m) at 150 m depth and 3000 mS/m (~0.3 Ω.m) at 250 m depth, which indicates an increase of salinization with depth. The increase in salt content with depth will led to a decrease in the bulk resistivity of the soil. The climate during the lower Pliocene was mainly hot and dry, and paleolakes in the regions were evaporated. During this evaporation period, it was deposited clay with high content in salts.

**Figure 1** shows the resistivity values from three different methods: TDEM, Electrical Resistivity Tomography (ERT), and borehole resistivity at two different locations. Also, it is displayed the curve of the normalized chargeability. In all the cases the resistivity values decrease with depth. However, ERT results seems to be less sensitive to high conductive layer, but TDEM soundings highlight these layers. This is proved in **Figure 1.a** and **b**, where at depths between 120 to 140 m, TDEM curves have values of resistivity close to one Ω.m, while ERT values are close to 10 Ω.m.

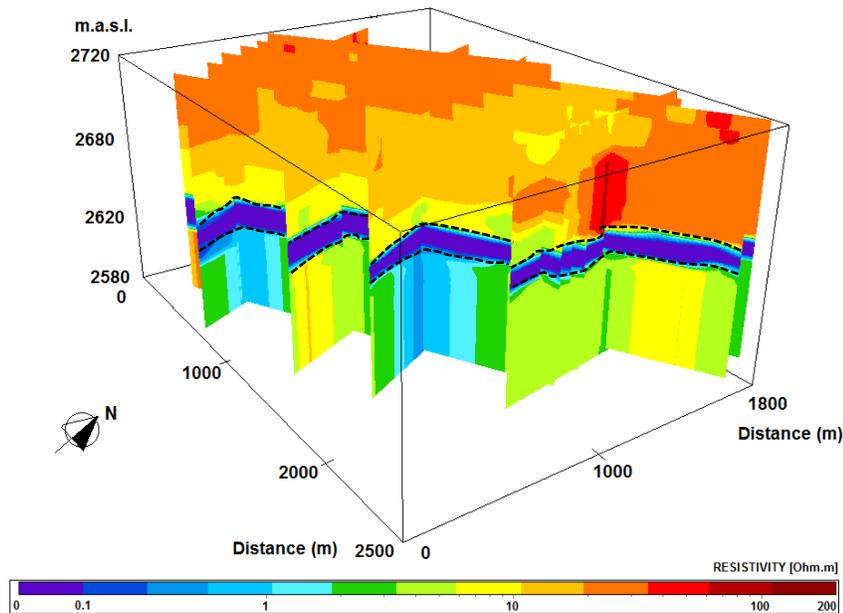


**Figure 2** Resistivity profiles derived from TDEM soundings. a) Profile P1-2 located in area 1. b) Profile P2-4 in area 2. Both geoelectrical sections display a saline layer with resistivity values lower than 1 Ω.m.

The depth of penetration in both, ERT and TDEM are different. While the first depends on the separation of electrodes, the second depends on the transmitter loop moment which makes easier the equipment setup than in ERT. However, TDEM surveys are more sensitive to noise. **Figure 1.a** and **b**, shows that the effective depth of penetration in TDEM is around 170 m. In the TDEM soundings the maximum depth of penetration is determinate by the high clay content and presence of salts. Since the induced electric current will not penetrate beyond this layer, therefore the underlying layers in the Punata alluvial fan are not resolved with TDEM method. The depths of penetration in area 1, are between 150 to 200 m, while in area 2 is around 80 to 100 m. This difference is because the layer with high content in area 2 is shallower.

After all the final models are determinate with the SPIA-TEM program, these are exported into Workbench. The later allow the user to interpolate the 1-D soundings into 2-D profiles. The inversion option of Kriging with exponential variogram was used for all the profiles. **Figure 2**, shows two profiles obtained from the 1-D soundings, and in both cases different geological units can be interpreted. For instance, the profile P1-2 (**Figure 2.a**) is located in area 1. This area is closer to the apex of the fan, where the material is coarser in the top layers, and decrease in size with depth. Close to 140 m depth, there is layer with lower resistivity, which may be related to high salinity content. In **Figure 2.b** the profile P2-4 is shown, and here it is more evident the layer with high salinity content at depths around 70 m. The resistivity of these layer can be as low as 0.1 Ω.m.

**Figure 3** show a 3-D visualization of the soil resistivity in area 2. The TDEM method enhance the location and extension of the saline layer, which is marked between the dashed lines. The depth of this layer 60 m below ground surface. The thickness varies from 10 to 20 m, and the resistivity is close to 0.1  $\Omega$ .m.



**Figure 3** A 3D visualization of the resistivity distribution in area 2.

## Conclusions

This research proved the value of the application of geophysics in hydrogeological investigations of quaternary deposits. The TDEM method demonstrated to be a useful technique for mapping layer with high salinity content. The depth of penetration and resolution can be superior to Electrical Resistivity Methods, but it is high sensitive to environmental noise. The delimitation of this saline layer, will contribute to enhance the local groundwater management and exploitation.

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