USING ELECTRICAL TECHNIQUES FOR PLANNING THE REMEDIATION PROCESS IN A HYDROCARBON CONTAMINATED SITE

Omar DELGADO-RODRÍGUEZ[1], Vladimir SHEVNIN[1], Jesús OCHOA-VALDÉS[1] and Albert RYJOV[2]

[1]Instituto Mexicano del Petróleo, Eje Central Lázaro Cárdenas 152, San Bartolo Atepehuacan, 07730, México DF, odelgado@imp.mx
[2]Moscow State Geological Prospecting Academy, Geophysical Faculty, Volgina str. 9, 117485, Moscow, Russia

ABSTRACT

We confirm that electrical methods are effective tools in the characterization of oil contaminated sites, as they help to delineate the geometry of the contamination plume, and their results are useful for planning the remediation process. In this work, the results from the application of the VES method in the characterization of an oil contaminated site are presented. Electrical measurements in groundwater samples and petrophysical modeling helped to define the geoelectrical boundary between contaminated and clean zones. Highly contaminated zones are associated with the presence of free-phase hydrocarbons. By using contamination plume and limestone thickness maps some recovering drill holes were proposed for the remediation of the site by extraction of free-phase hydrocarbons.

RESUMEN

Se confirma la efectividad de los métodos eléctricos en la caracterización de sitios contaminados por hidrocarburos, ayudando a definir la pluma de contaminación, útil para planear los procesos de remediación del sitio. En este trabajo se presentan los resultados de la aplicación del método SEV en la caracterización de un sitio contaminado por hidrocarburos. Las mediciones eléctricas en muestras de agua y la modelación petrofísica ayudaron a definir la frontera geoeléctrica entre zonas contaminadas y no-contaminadas. Las zonas con máxima contaminación están asociadas con la presencia de hidrocarburos en fase libre en el subsuelo. A partir de los mapas de plumas de contaminación y del espesor de las rocas calizas, se proponen varios pozos de recuperación de hidrocarburos en fase libre para la remediación del sitio.

INTRODUCTION

Geophysical methods are frequently used to study subsoil contamination caused by industrial residues of different nature. Particularly, the effectiveness of electrical methods for the characterization of oil contaminated subsoil has been reported by several works (Vanhala *et al.* 1992, Atekwana *et al.* 2000, 2002, Osella *et al.* 2002). The application of vertical electrical sounding (VES) method is based on measurements of voltage variations, at the ground surface, caused by electrical direct current injected to the ground. Apparent resistivity values are determined with the help of some four-electrode array. As a result of interpretation an electrical model is obtained.

Two electrical resistivity models for oil contamination are presented in the literature, namely high resistivity (Osella *et al.* 2002) and low resistivity (Sauck 2000, Cassidy *et al.* 2001). Recent oil pollution shows a high resistivity anomaly, while mature oil pollution produces a low resistivity anomaly (Sauck 2000). Months after spill, a low resistivity anomaly is developed in the contaminated zone, with a strength that depends on the geological characteristics of the subsoil (Sauck 2000, Abdel Aal *et al.* 2004). The formation processes of such low resistivity anomaly are related to chemical reactions and to variations in the physical characteristics of the oil contaminated zone. The low resistivity anomaly is caused by an increase in the total dissolved solids (TDS), due to bacterial degradation of hydrocarbons in the lower part of the vadose zone (Sauck 2000). Sauck (2000) found that aged contamination appears as a low resistivity horizon slightly above groundwater table (GWT). Thus, the low resistivity anomalies are associated to the existence of aged oil contamination. Therefore, 2D VES-based resistivity imaging is a useful tool to define low resistivity anomalies related with oil contamination (Shevnin *et al.* 2003). The electrical boundary between contaminated and clean zones can be determined with groundwater resistivity measurements (GWRM) and petrophysical modeling (PPM) (Shevnin *et al.* 2005).

In this work we applied VES, GWRM and PPM methods in order to determine the hydrocarbon contamination plumes caused by the oil industry in a site located in northern México. Based on our results we propose optimal location of several recovery drill holes to extract free-phase hydrocarbons (FPH) during the remediation process.

MATERIALS AND METHODS

Studied site

The studied site is a 320,000 m^2 area where 13 holes were drilled (**Fig. 1**) to obtain the lithological information up to a 10 m depth. According to local topographical characteristics, in the northern and eastern zones, where the height terrain increases, the outcropping of limestone is noticeable and sandy-clayey layers are evident at depth. Sandy-clayey sediments prevail in lowland zones (southwestern zone). Limestone and sandy-clayey sediments are mostly covered by artificial filling (i.e., garden soil).

Direct contamination evidences are not shown in drill holes 8-13, while drill holes 1-7 present free-phase hydrocarbons on the GWT.

According to the information provided by the drill holes (**Fig. 1**), the depth of the GWT varies from 2 to about 8 m.

Groundwater resistivity measurements (GWRM)

Groundwater resistivity was measured in 13 water samples collected from drill holes (**Fig. 1**) us-
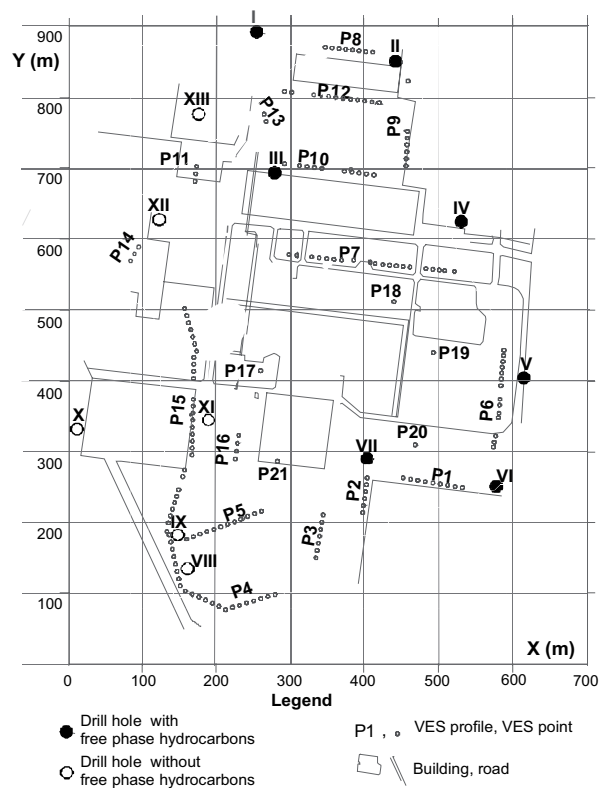
Fig. 1. Scheme of site with location of drill holes and VES profiles

ing a resistivity-meter Hanna model HI98130. High resistivity values are observed in the northern and eastern zones where the presence of limestone is evident, while in the western and southern portions the resistivity value decreases because of the presence of superficial sandy-clayey sediments.

VES survey

A total of 173 soundings were conducted. They are distributed along 16 profiles. Five additional punctual VES were also obtained (**Fig. 1**). They were designed to determine the geoelectrical structure within a maximal depth of 15-30 meters, in order to delineate the horizontal as well as depth extension of the oil-contaminated zones, and also to estimate the contamination grade.
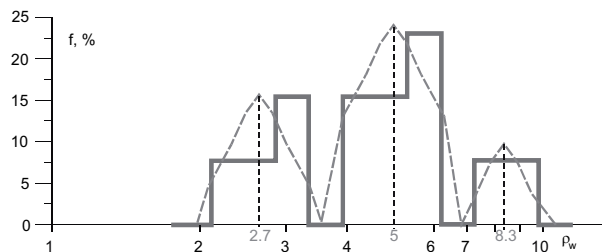
VES survey was carried out using a large number of electrodes (~50) emplaced with a constant interval along each profile (5 m), thus enabling a detailed shallow study. We used the Schlumberger array with AB/2 selected from 5 to 50 m with a step of 5 m. The separation between sounding centers was 10 m.

We used an ERA resistivity meter, with a sensitivity of 1 μV, with a current of 10-50 mA at 4.88 Hz. Our instrumentation guarantees reliable measurements in geological environments with high electromagnetic noise.

RESULTS

Statistical analysis of GWRM

Figure 2 shows a histogram of groundwater resistivity values. Three groups can be observed: the first one, with a mean resistivity value of 8.3 Ohm.m, represents the groundwater resistivity in zones with a limestone layer; the second group, with a mean value of 5 Ohm.m, represents the groundwater resistivity in sandy-clayey sediments, and the third group, with a mean value of 2.7 Ohm.m, represents, as will be seen, the groundwater resistivity in contaminated zones.

Statistical analysis of VES data

We estimate average apparent resistivity curves ρ_a vs AB/2 based on the statistical distribution of the whole set of measured data. **Figure 3** shows the presence of two types of mean VES curves. The first mean curve (1), type K, characterizes areas with a shallow limestone layer, while the second mean curve (2) type Q or H is associated to areas where the limestone layer is absent. In the present case, the application of VES method to locate the oil contamination lead to a great challenge: considering the shallow GWT (FPH are located above GWT), in the zones with outcropping of limestone is very difficult to distinguish the weak low resistivity anomaly caused by oil contamination, and those due to the high resistivity contrast between limestone and sandy-clayey rocks. Because of this difficulty, a suitable inversion process of the apparent resistivity values is needed. A petrophysical modeling is also required to define the geoelectrical boundary between clean and contaminated soil.
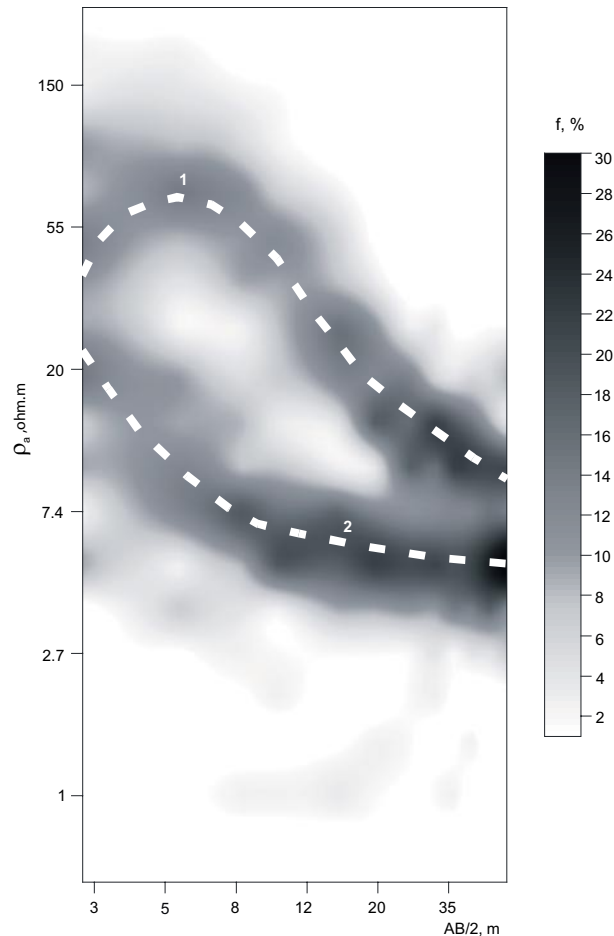
Fig. 3. Statistical distribution of VES data. 1. Mean VES curve for measurements on limestone rock. 2. Mean VES curve for measurements on sandy-clayey sediments


Fig. 2. Groundwater resistivity histogram

Petrophysical modeling (PPM)

The conductivity from soils composed by a mixture of sand and clay is calculated following a model developed by Ryjov and Sudoplatov (1990). They proposed a conductivity model for sandy-clayey unconsolidated soil, taking into account the geometrical microstructure of the components as well as electrochemical processes occurring in the soil for a wide range of the water salinity and clay content. The soil conductivity model is treated as a heterogeneous porous medium composed by sand grains and clay particles, for a wide range of the water salinity and clay content. This petrophysical model enables one the theoretical calculation of soil resistivity based on geological information about water and soil in the survey area. Soil resistivity depends on groundwater resistivity (as in Archie's formula (Archie, 1942)); thus groundwater resistivity measurements are important for resistivity surveys.

Once groundwater and soil resistivity are known from GWRM and VES methods, respectively, the petrophysical model helps to estimate soil lithology, clay content and porosity for clean soil. In particular, the PPM, allows one to define the geoelectrical boundary between clean and contaminated soil (Shevnin *et al*. 2006).

In our case, the PPM using GWRM and VES data, enable us to determine the geoelectrical boundary between contaminated and clean zones. Accordingly, calculated resistivity curves versus pore water salinity ($\rho(C)$) for different types of rocks (with varying clay content and porosity) are shown in **figure 4**. Water curve (dashed black line) gives us the relation between water resistivity and water salinity, while the three doted lines represent the mean groundwater resistivity values for areas featured by a superficial limestone layer (8.3 ohm.m), sandy-clayey sediments (5 ohm.m) and for contaminated zone (2.7 ohm.m), respectively. Polygons labeled Ld, Ls, Sd and Ss represent estimations of soil resistivity from VES data interpretation. Ld and Ls denote soil resistivity values obtained for clean limestone rocks (Ld- above GWT and Ls-below GWT); Sd and Ss represent soil resistivity values obtained in clean sandy-clayey sediments (idem, Sd above GWT and Ss below GWT).

Two geoelectrical boundaries are defined in **figure 4** (vertical dashed gray lines). According to textural analysis of the soil samples collected from wells, maximal clay content is 50 % (ρ= 4.2 Ohm.m). Resistivity values lower to 4.2 Ohm.m correspond to contaminated soil (polygon C), while resistivity values lower than 1.7 Ohm.m (resistivity values less than clean pure clay) correspond to maximal
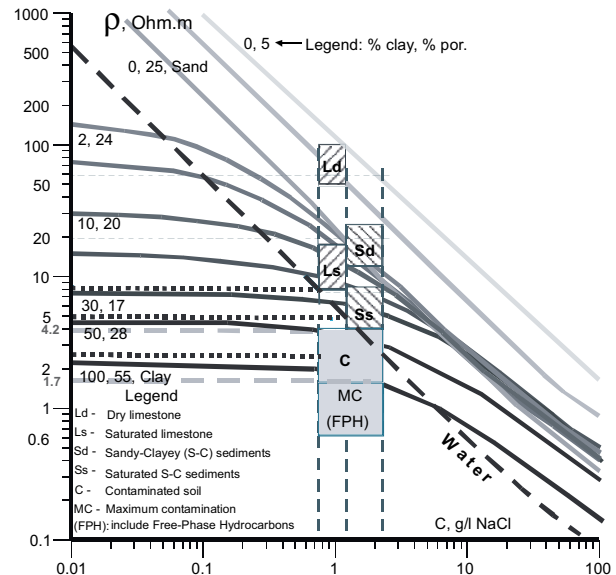
Fig. 4. Petrophysical modeling (after Ryjov and Sudoplatov, 1990)

contamination zone (polygon MC) suggesting, for our studied place, the presence of FPH.

Interpretation of VES data

What kind of VES data visualization are better, sections or maps? Visualization in sections has less interpolation between measuring points. For maps construction we need to interpolate between profiles, but maps have less resistivity variation range than sections (electrical properties change more with depth than in plane). As a result we can reach more resolution in maps giving us the possibility to locate weaker anomalies. Although, to locate the contamination plume we need to use maps with maximum resolution, both forms (map and section) are useful to locate the contaminants in the subsoil.

In this work, the apparent resistivity data from VES profiles are interpreted in terms of a two dimensional(2D) ground resistivity model.

Two-dimensional (2D) inversion of VES data was made for each profile by using Res2DInv software (Loke and Barker 1996a, b). the resulting model has the same layers number for all soundings along each one of the profiles. The ground is divided in a number of cells, where each cell could take a different constant resistivity value. Thicknesses of 2D cells in the same layer are equal (**Fig. 5**). The equations relating the model resistivity distribution with the apparent resistivity measured at the surface by the SEV, are then solved to find a model capable of explain the observed data. This is done by using an optimization
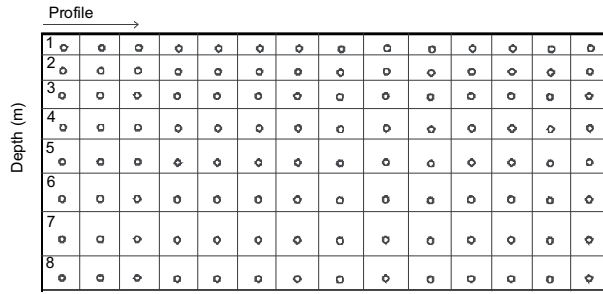
Fig. 5. Resulting model from 2D inversion of VES data made for each profile

process called "inversion".

For each profile a ground resistivity cross-section was obtained. In these cross-sections, the "target layer" was delineated (**Fig. 6**) using the geoelectrical boundary defined from PPM. The target layer is the zone where we claim that contaminants (including free-phase hydrocarbons) are accumulated. Our interpreted resistivity section for profile 6 (**Fig. 1**) is shown in **figure 6A**. Three low resistivity anomalies seem to be related to highly contamination zones. **Figure 6A** shows one of these anomalies nearby drill hole V (30 m toward east), where the occurrence of FPH has been confirmed.

In **figure 6B** the interpreted section from profile 15 is shown. Profile 15 crosses a contaminated sandy-clayey sediments zone marked by a low resistivity anomaly. Nevertheless, the drill hole XI, located near the contaminated zone, does not present FPH. This can be explained in two ways: drill hole XI was made on a small clean portion of soil that divides

the "target layer" in two zones (**Fig. 6B**) or, the low permeability of the sandy-clayey sediments prevents the flow of FPH into drill hole XI. This can be clarified by making some drill holes on low resistivity anomalies located in sandy-clayey sediments in order to evaluate the feasibility of extracting FPH from sandy-clayey sediments.

Using all the resistivity cross-sections it was possible to elaborate a resistivity map showing the horizontal distribution of the target layer, thus delimiting the contamination plumes. Such a ground resistivity map is shown in **figure 7A,** where five maximal contamination zones are observed.

Based on VES data interpretation, we estimate in 8 m the thickness of the limestone layer in the southwestern portion of the area (**Fig. 7B**). Most of drill holes with FPH (**Fig. 1**) are located in limestone zones (**Fig 7B**). Fractured limestone has higher hydraulic conductivity than sandy-clayey sediments, thus, when contaminants are in the limestone layer, the efficiency to extract free-phase hydrocarbon increases.

Location of recovering drill holes to extract free-phase hydrocarbons

Following the results discussed above, several boreholes were proposed for free-phase hydrocarbon extraction in order to facilitate the remediation of the site. Four such proposed boreholes were drilled in zones where maximal contamination is associated with the presence of limestone (black circles, **Fig. 8**). In all drill holes, FPH thicknesses range between
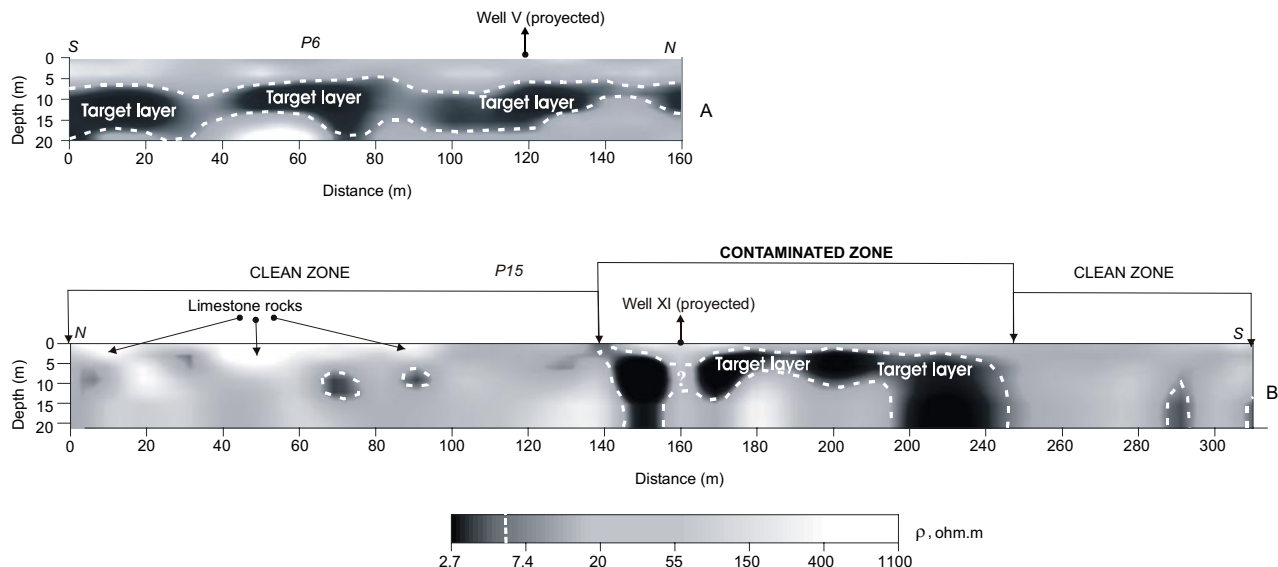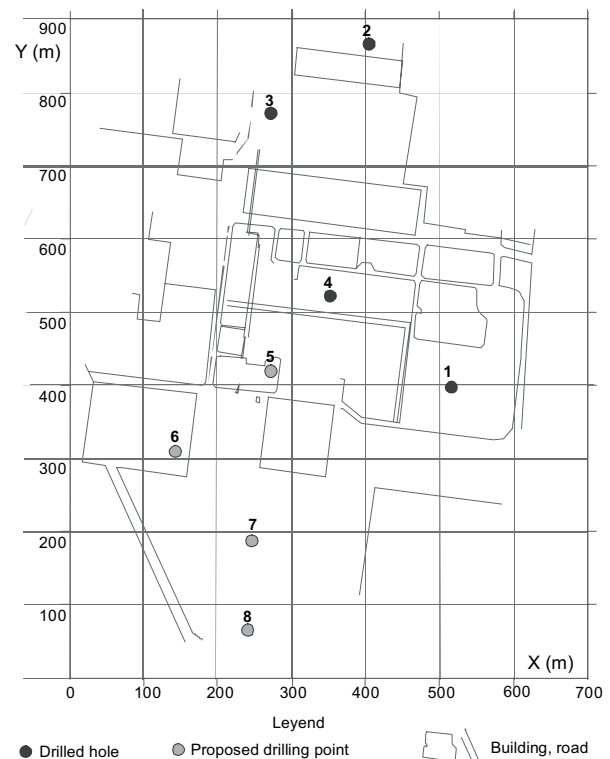

Fig. 6. Interpreted resistivity section for profiles 6 (A) and 15 (B). Target layer is defined by dashed white line
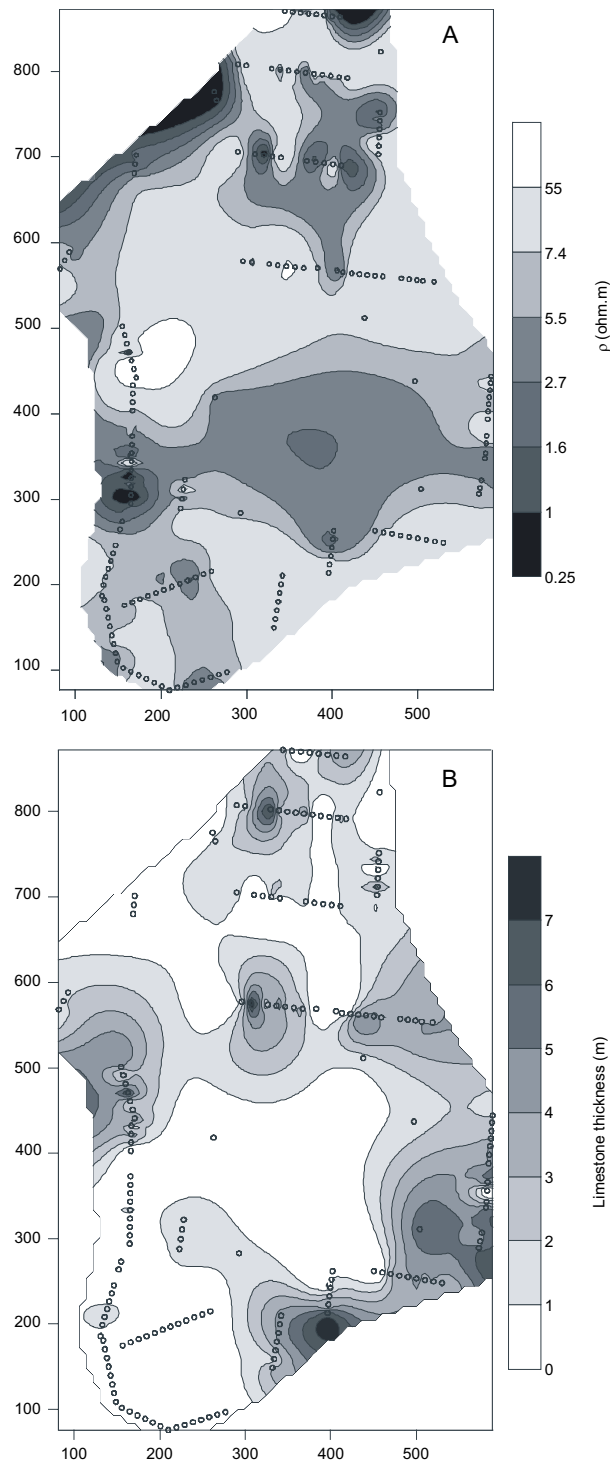
Fig. 7. (A) Resistivity map for target layer. (B) Limestone thickness map

Fig. 8. Location of drilled and proposed recovering wells

in order to verify the feasibility to extract free-phase hydrocarbon from sandy-clayey sediments. At the present time these additional boreholes have not yet been drilled.

TABLE I. DRILL HOLES ON LIMESTONE ROCK

Drilled hole	Limestone thickness (m)	GWT depth (m)	Free Phase Hydrocarbon thickness (m)
1	2	7.7	0.5
2	3	5.3	1.2
3	4	6.0	1.6
4	4	8.1	4.8

CONCLUSIONS

We find five low resistivity anomalies associated with highly contaminated zones and with the possible presence of FPH.

In most of the resistivity cross-sections, the layer with the highest volume of contaminants was located above GWT.

Based on our results, four recovering drill holes were drilled to extract free-phase hydrocarbon at

0.5 to 4.8 m (**Table I**). These drill holes are being currently used for the extraction of FPH. We proposed another four drilling points (gray circles in **Fig. 8**), located in high-contamination associated anomalies,

points where high-contamination anomalies occur in fractured limestone rock. Another four boreholes were proposed in order to evaluate the possibility to extract FPH from sandy-clayey sediments.

This case study illustrates that VES method is an effective tool for characterization of contaminated zones and for planning remediation strategies, as it provides helpful information for the location of recovering drill holes.

ACKNOWLEDGMENTS

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