

Geoelectrical characterization of a site with hydrocarbon contamination caused by pipeline leakage

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RESUMEN

El método Sondeo Eléctrico Vertical (SEV) es ampliamente utilizado en estudios de impacto ambiental incluyendo el caso de contaminación por hidrocarburos. En este trabajo se presentan los resultados de la caracterización geoelectrica de un sitio contaminado por hidrocarburos relacionado con una fuga en línea de ducto. El estudio geoelectrico fue realizado utilizando el método SEV en la variante de tomografía, realizándose una interpretación 2D de los datos observados. Seis perfiles paralelos de SEV fueron medidos y presentados sus resultados en secciones y mapas. Se determinó un modelo estratificado que incluye acuitardo y acuífero. Aunque el grado de contaminación en este sitio es bajo fue posible localizar dos zonas contaminadas dentro del acuífero. El acuífero y el acuitardo fueron caracterizados con base en su resistividad, contenido de arcilla, porosidad y capacidad de intercambio catiónico. Los valores de resistividad fueron recalculados a valores de parámetros petrofísicos utilizando un algoritmo de inversión que toma en cuenta la salinidad del agua de poro. En zonas no contaminadas los parámetros petrofísicos estimados a partir de datos de resistividad presentan valores cercanos a los reales, mientras que en zonas contaminadas se obtienen valores anómalos. Efectos similares de la influencia contaminación sobre los parámetros petrofísicos fueron encontrados en laboratorio realizando mediciones de resistividad en muestras de arena limpia y contaminada.

PALABRAS CLAVE: Sondeo Eléctrico Vertical, contaminación por hidrocarburos, caracterización geoelectrica, parámetros petrofísicos.

ABSTRACT

Vertical Electrical Sounding (VES) method is used extensively in environmental impact studies including hydrocarbon contamination. In this work, the results of the geoelectrical characterization of a contaminated site caused by pipeline leakage are presented. Geoelectrical study was performed with multi-electrode technology and 2D profile data interpretation. VES results from six parallel profiles were presented in resistivity sections and maps. Layered model of the site was found including aquifer and aquitard layers. Although the contamination grade of the site is low, we found two contaminated zones into sandy aquifer. Aquifer and aquitard were characterized by its resistivity, clay content, porosity and cation exchange capacity values. Recalculation of resistivity data into petrophysical sections and maps was performed by an inversion algorithm taking into account pore water salinity. Petrophysical parameters for uncontaminated areas estimated from resistivity are close to real values; meanwhile, in contaminated zones petrophysical parameters have anomalous values. Similar effects of contamination influence on petrophysical parameters were found in laboratory by resistivity measurements made at clean and contaminated sand samples.

KEY WORDS: Vertical Electrical Sounding, hydrocarbon contamination, geoelectrical characterization, petrophysical parameters.

INTRODUCTION

Vertical Resistivity Sounding (VES) method has proven to be useful for the characterization of oil contaminated soils (Modin *et al.*, 1997; Sauck, 1998, 2000; Shevnin *et al.*, 2003; 2005). During the last two decades the VES method, known from 1912, has been changed greatly by application of new field technology called Resistivity Imaging (RI) or Electrical Resistivity Tomography (ERT) and 2D data interpretation (Loke and Barker, 1996).

Information about changes of physical and chemical soil properties due to oil biodegradation in near-surface conditions was published in Bayley *et al.*, 1973 and then in papers of geophysicists (Modin *et al.*, 1997; Sauck, 1998). Recent hydrocarbon contamination results in high resistivity anomalies, while mature oil contamination produces low resistivity anomalies (Sauck, 1998). Several months after the spill has occurred, oil contamination creates a low resistivity zone (Atekwana *et al.*, 2001; Sauck, 1998; 2000). Shevnin *et al.* (2003) applied ERT technology in a site

contaminated by oil for more than 30 years. In this site the contaminated zones (TPH > 2000 ppm) were correlated with low resistivity anomalies.

The formation process of a hydrocarbon contaminated area is linked to chemical reactions and variations in physical characteristics of the affected medium (Sauck, 1998; 2000; Atekwana *et al.*, 2001). According to Sauck (1998), the low resistivity anomaly is due to an increase of Total Dissolved Solids (TDS) in the acid environment created by the bacterial action in the inferior part of the vadose zone or below groundwater table (GWT). Atekwana *et al.* (2003) have found that contaminated soil resistivity has poor correlation with pore water resistivity. This fact was explained later with the help of Induced Polarization (IP) measurements in laboratory where the changes of soil resistivity resulted in an increase of superficial resistivity rather than in electrolytic resistivity (Abdel Aal *et al.*, 2004).

Rylov (1987) and Rylov and Sudoplatov (1990) developed an algorithm of sand-clay soil resistivity modeling. Based on this approach we began estimating clay content, porosity and Cation Exchange Capacity (CEC) first from resistivity versus pore water salinity measurements in laboratory and then by recalculating of field resistivity data taking into account groundwater salinity (Shevnin *et al.*, 2004). Joint analysis of resistivity and petrophysical cross-sections and maps allowed improving data interpretation at contaminated sites. In uncontaminated zones petrophysical parameters are close to real values, estimated by traditional

geological and chemical methods, but in contaminated zones these parameters have anomalous values. Nevertheless these anomalous or apparent values are useful for localization and characterization of oil contamination. The cause of these anomalous parameters is in increase of superficial conductivity in soil (Abdel Aal *et al.*, 2004).

ERT technology was used to study a site contaminated with crude oil as a result of exploitation of a well drilled 17 years ago (Shevnin *et al.*, 2005). Petrophysical maps were recalculated from resistivity maps and groundwater salinity values, correlating the oil contaminate zones with petrophysical anomalies.

In the present work, VES method (ERT technology) was applied to a contaminated site 9 months after a presumably small volume of gasoline was spilled from a pipeline.

The site

The study was conducted in an area of approximately 9100 m² near Cárdenas City, Tabasco, Mexico. Four pipelines cross the site (Figure 1).

In March 2002, a hydrocarbon spill from a pipeline was occurred. After carrying out an excavation around the spill point to recover a great part of the hydrocarbons, a soil gas survey was performed and then a geoelectrical characterization to assess the soil environmental impact.

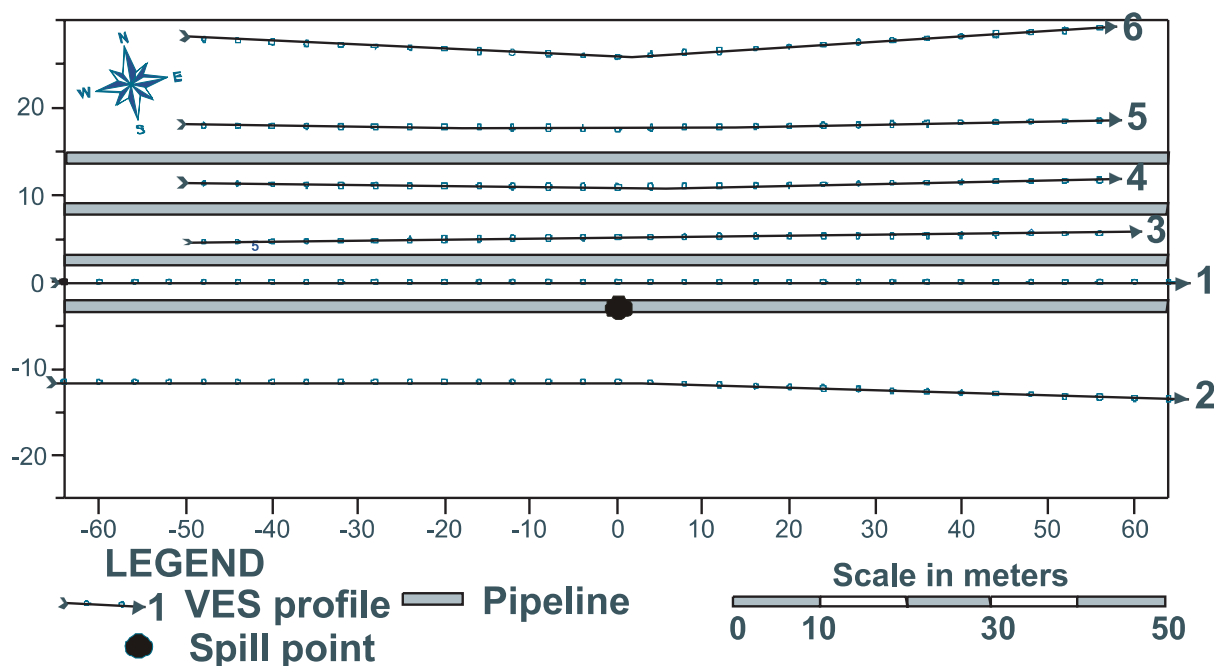


Fig. 1. Scheme of the site.

Soil gas survey

The soil gas survey consists of extracting gas from soil samples to detect volatile organic compounds (VOC – including hydrocarbon) and their concentrations. The results were displayed as maps for a preliminary assessment of the coverage and distribution of the hydrocarbon plume.

In November 2002, VOC measurements were carried out *in situ* using a photo ionization meter. Results were used as a direct indicator of hydrocarbon contamination. Thirty-three sampling points were symmetrically distributed around the spill point (Figure 2).

VOC values higher than 2 ppm indicate the existence of volatile compounds associated with hydrocarbon contamination. Figure 2 shows an anomalous zone with values of more than 20 ppm, indicating migration of contaminants from the spill point 20 meters to East (point CDS-18). A smaller anomaly is detected at point CDS-21, 50 meters from the spill point. In general, these data indicate that the contamination level is low with a small horizontal distribution.

Geoelectrical survey

Using a Fisher TW-6 pipeline locator it was possible to locate four pipelines. Six parallel VES profiles (Figure 1) were made with a minimal distance of 2.5 m from pipelines. VES profiles 1 and 2 are 128 m long and profiles 3 to 6 are 104 m long. The spacing between VES was 4 m.

One hundred seventy-four VES points were distributed in six profiles (Figure 1). A Schlumberger array with 2D Resistivity Imaging technology and with AB/2 spacing from 2 to 20 m was used.

For VES survey we used equipment ERA made in Russia that includes a 4.88 Hz generator with stabilized current (10 to 100 mA) and a measuring instrument with sensitivity of 0.3 μV .

Statistical analysis of apparent resistivity data.

A statistical analysis of the apparent resistivity data was done in order to calculate the statistical distribution of ρ_a for different AB/2 values. Statistical images of ρ_a data were made from the calculation of ρ_a statistical distribution for each AB/2 spacing.

Figure 3 shows results for Hermosillo-Sonora (HMO), Poza Rica-Veracruz (POR) and Paredon 31-Tabasco (PRD) sites. Low resistivity anomalies due to biodegradation processes are framed with thick dashed black line. This low resistivity anomaly is separated statistically from the mean curve for uncontaminated zones (dashed white line, Figure 3). The typical curve reflects the basic geoelectrical model for the studied site. At our site (CRD, Figure 3) no additional low resistivity anomaly was observed, which is evidence of low contamination.

At the PRD site, the contamination level was more than 8000 ppm and a low resistivity anomaly was evident

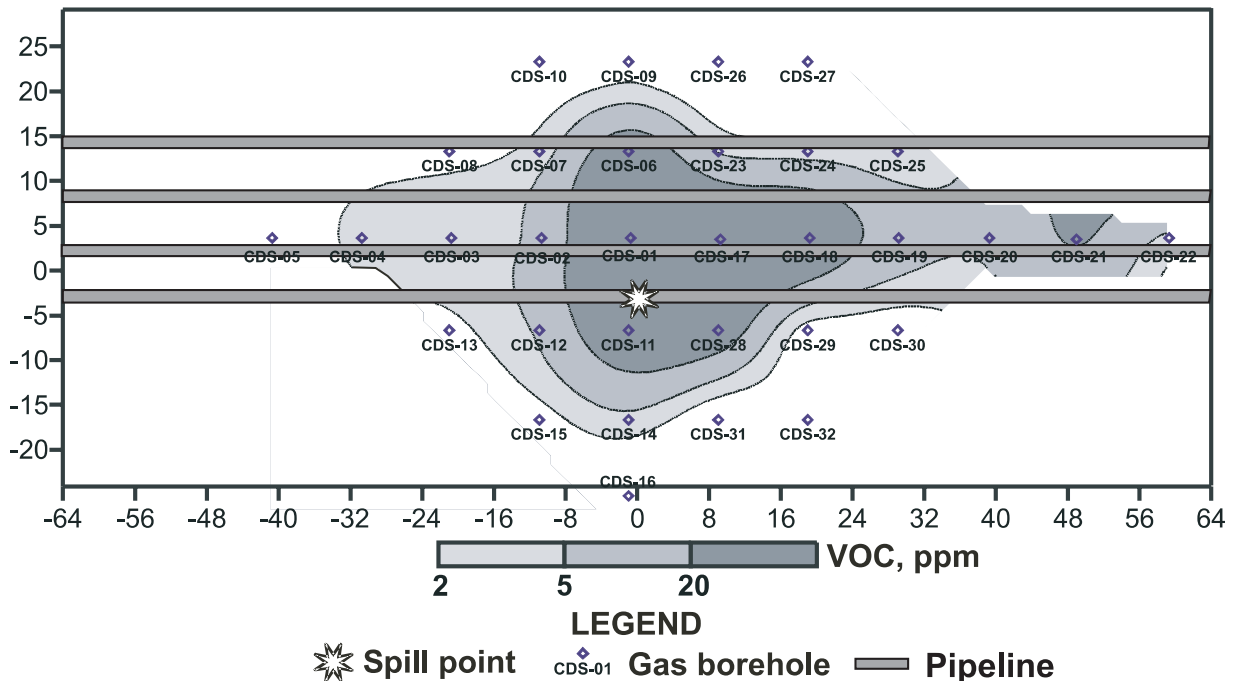


Fig. 2. Soil gas result.

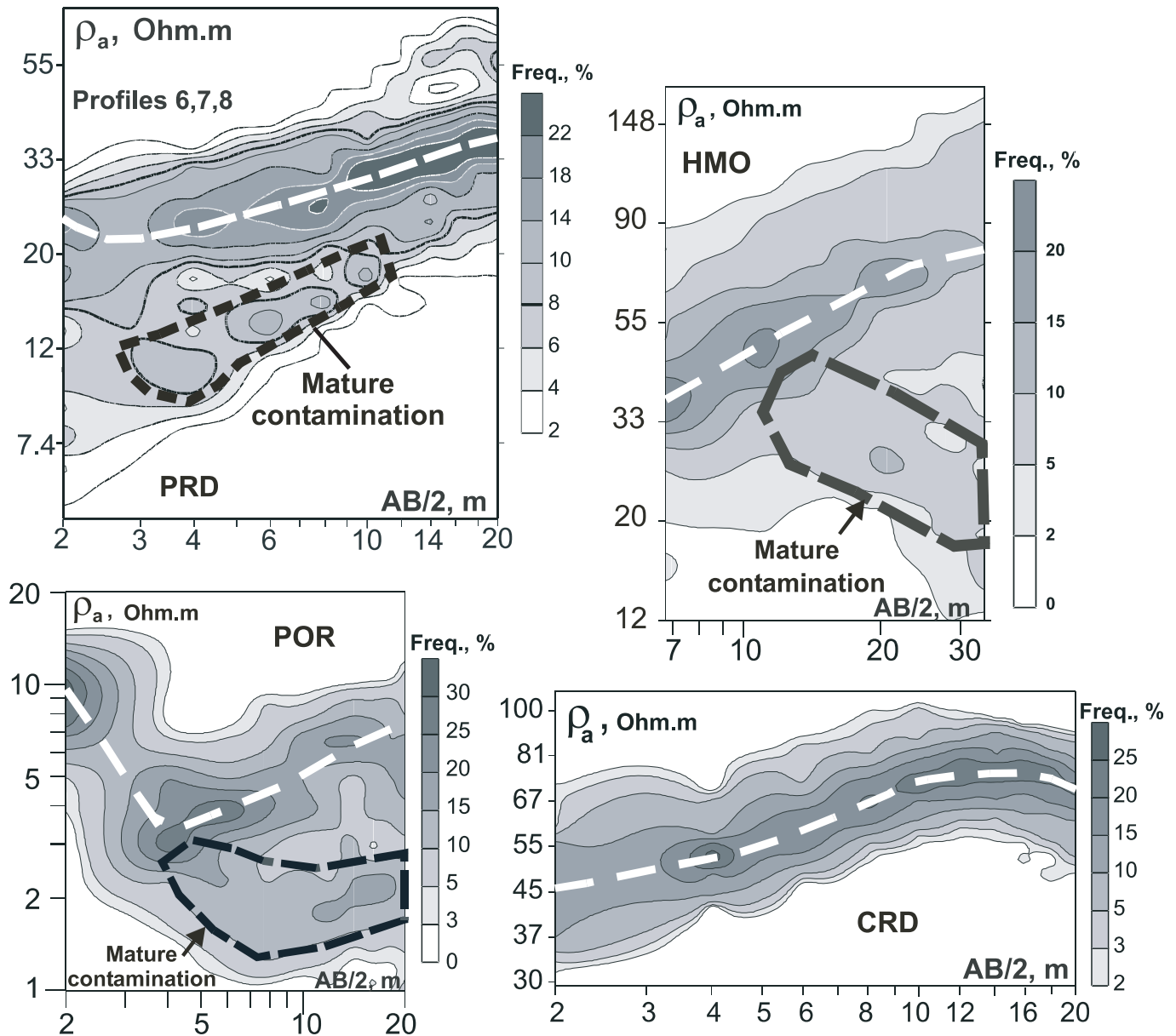


Fig. 3. Statistical analysis of apparent resistivity data.

(Figure 3). In our case the contamination level was below the norm for farmed soil (1000 ppm). Nevertheless, the sensitivity of our procedure allowed mapping a zone with low hydrocarbon concentration.

Apparent resistivity sections

Apparent resistivity section for profile 1 is shown in Figure 4 corresponding to a near-surface geology constituted by horizontal layers. All VES curves have the same K type. Resistive layer is a sandy aquifer, which is visible in Figure 4 at AB/2 spacing of 6 – 18 m. Inside the aquifer, at intervals X of -8 to -34 m, a more conductive zone is visible. Later

we found that it is the contaminated zone. This low resistivity area is associated with the spill from a pipeline next to point 0 m.

4. - Quantitative interpretation

Interpreted resistivity section

A two-dimensional interpretation using software RES2DINV (Loke and Barker, 1996) was applied to six geoelectrical profiles. In Figure 5 the interpreted section for profile 1 is presented. Similar results are obtained for all profiles: the first half of each profile is represented by three

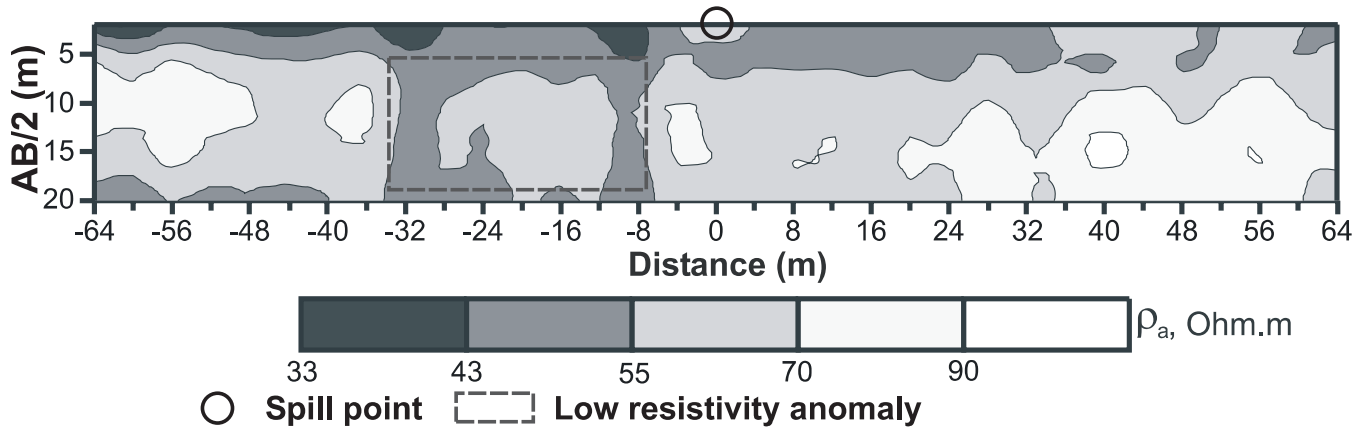


Fig. 4. Apparent resistivity pseudo cross-section for profile 1.

layers (superficial sandy-clay soil, sand and clay basement), while in the second half, a covering (55 ohm.m) more resistive than sandy-clay sediments (30 ohm.m), is added (Figure 5).

A structural section is displayed in Figure 6. Resistive covering (layer 1) correlates with the higher terrain in the eastern portion of site (Figure 6). Mean layer properties are presented in Table 1. Filtration coefficient was estimated from clay content (Shevnin *et al.*, 2005).

Layer 2: aquitard

From six interpreted resistivity sections it was possible to make a resistivity map for layer 2 (aquitard, Figure 7A) to observe the horizontal resistivity variations in the aquitard layer.

In Figure 7A it is possible to distinguish some low resistivity anomalies near the spill point (black circle) and in the northern and western parts of the study area. These

anomalies may indicate an increase of clay content or the presence of contaminants in the aquitard. In addition, the prevalence of high resistivity anomalies is evident in the eastern part of the working site (Figure 7A). Small permeable zones (marked with rhombuses) located around the spill point can be considered as hydrogeological windows that facilitate the infiltration of contaminants to the sandy aquifer.

The modeling algorithm allows recalculating ground resistivity and water salinity into clay content, porosity and CEC (Shevnin *et al.*, 2004).

In Figure 7B the clay content map for the aquitard is shown. The minimal clay content zones correspond to permeable windows. These hydrogeological windows are also observed in the filtration coefficient map (Figure 7C). The filtration coefficient varies by an order of magnitude. Thickness of aquitard layer is 2.5 m and contaminants can cross it during $2.5/0.004 = 625$ days or $2.5/0.03 = 83$ days. As the pipeline was in a trench with a depth of 0.8 m., the aquitard thickness diminishes to 1.7 m and the infiltration time to cross this layer is 426 days or 57 days, respectively.

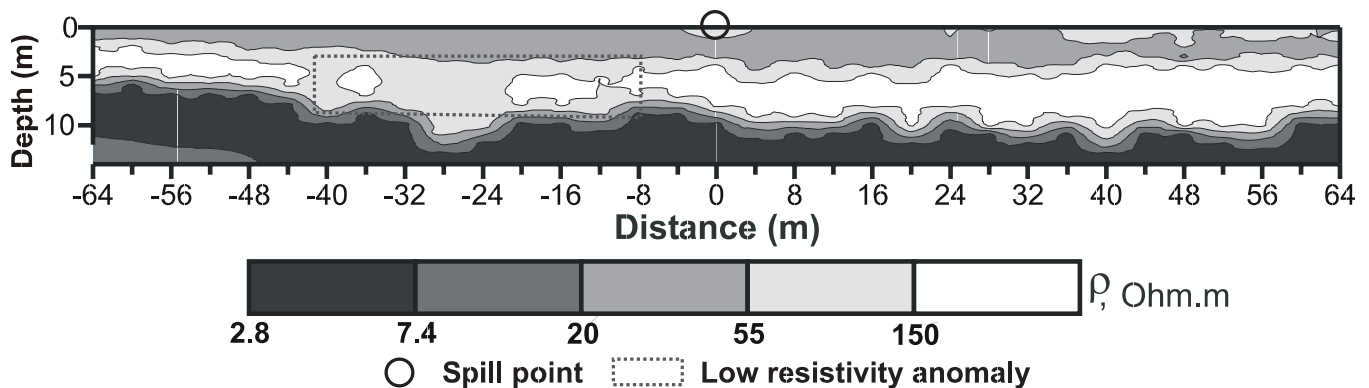


Fig. 5. Interpreted resistivity section for profile 1.

Table 1

Properties of the layers for the cross-section in Figure 6

Layer	Rho	Clay	Porosity	CEC	Kf (m/d)
Covering (Layer 1)	54	14	19	8	0.02
Aquitard (Layer 2)	30	23	14.6	14	0.005 - 0.01
Aquifer (Layer 3)	280	2	24.5	1.2	1 - 2.65
Basement (Layer 4)	10	59	32	34	0.0006

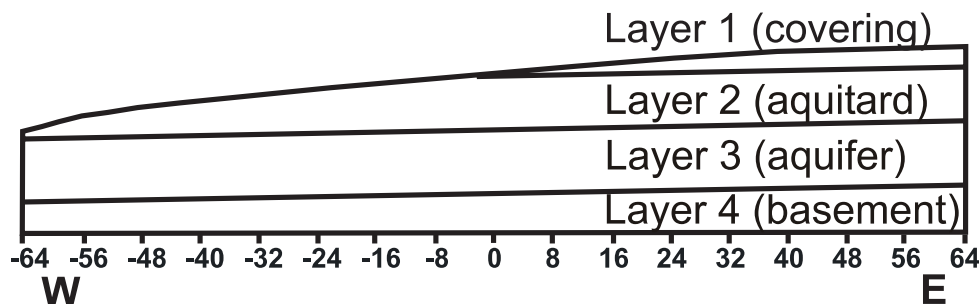


Fig. 6. Structural section for the study area.

It is quite probable that during 10 months the contaminants infiltrated the aquifer through hydrogeological windows.

Layer 3: aquifer

A similar analysis was made for the sandy aquifer. In Figure 8A the resistivity map is shown. Two main anomalous zones are observed: one zone goes from the spill point ($X = 0$ m, $Y = -2$ m) until $X = -40$ m, the other zone is located to east with coordinate $X = 40 - 50$ m and $y = 8 - 15$ m. The origin of the second anomaly is not clear. It may be due to migration and accumulation of contaminants from the spill point or from a second spill from another pipeline belonging to the site.

Clay content (Figure 8B), porosity (Figure 8C) and CEC (Figure 8D) maps match the resistivity map (Figure 8A). In our experience, in uncontaminated zones the petrophysical parameters have true values. In contaminated zones they have anomalous values. For example, from the geological information, clay content in the aquifer is 2%, but the clay content map (Figure 8B) shows values up to 6% in anomalous zones. These values do not reflect actual changes in clay content, but in geoelectrical properties due to contamination.

Petrophysical analysis of contaminated and uncontaminated sand samples from reactor.

Figure 9 shows two experimental curves of $\rho(C)$ with petrophysical modeling results which correspond to

uncontaminated (white circles) and contaminated (gray circles) sands. For all sand samples we measured resistivity versus pore water salinity in the laboratory and we determined their petrophysical parameters. The petrophysical results obtained for clean sand were: Clay content: 0 %, Porosity: 32 % and CEC: 0 g/l.

Now, a sand sample was placed in a reactor (Figure 9) with nutrients, bacteria and petroleum. After several months of biodegradation the contaminated sand sample gave the following parameter: Clay content: 10 %, Porosity: 26 % and CEC: 3 g/l. Amplitude changes of each parameter is similar to that found in sandy aquifer (Clay content 2 to 6%, Porosity 34 to 32% and CEC 1.5 to 3.5 g/l), suggesting that the anomalous values of clay, porosity and CEC in Figure 8 correspond to hydrocarbon contamination. This finding is for locating contaminated zones.

CONCLUSIONS

The VES method is effective for geoelectrical characterization of contaminated zones, allowing future geochemical study with an optimized well location and drilling depths.

The contamination of the study area is low. Only two zones have noticeable anomalies: the first one is associated with spill point and the second is located in the eastern portion of the study area.

The local aquifer (sandy layer) is protected from contamination by a superficial clay layer. However, where

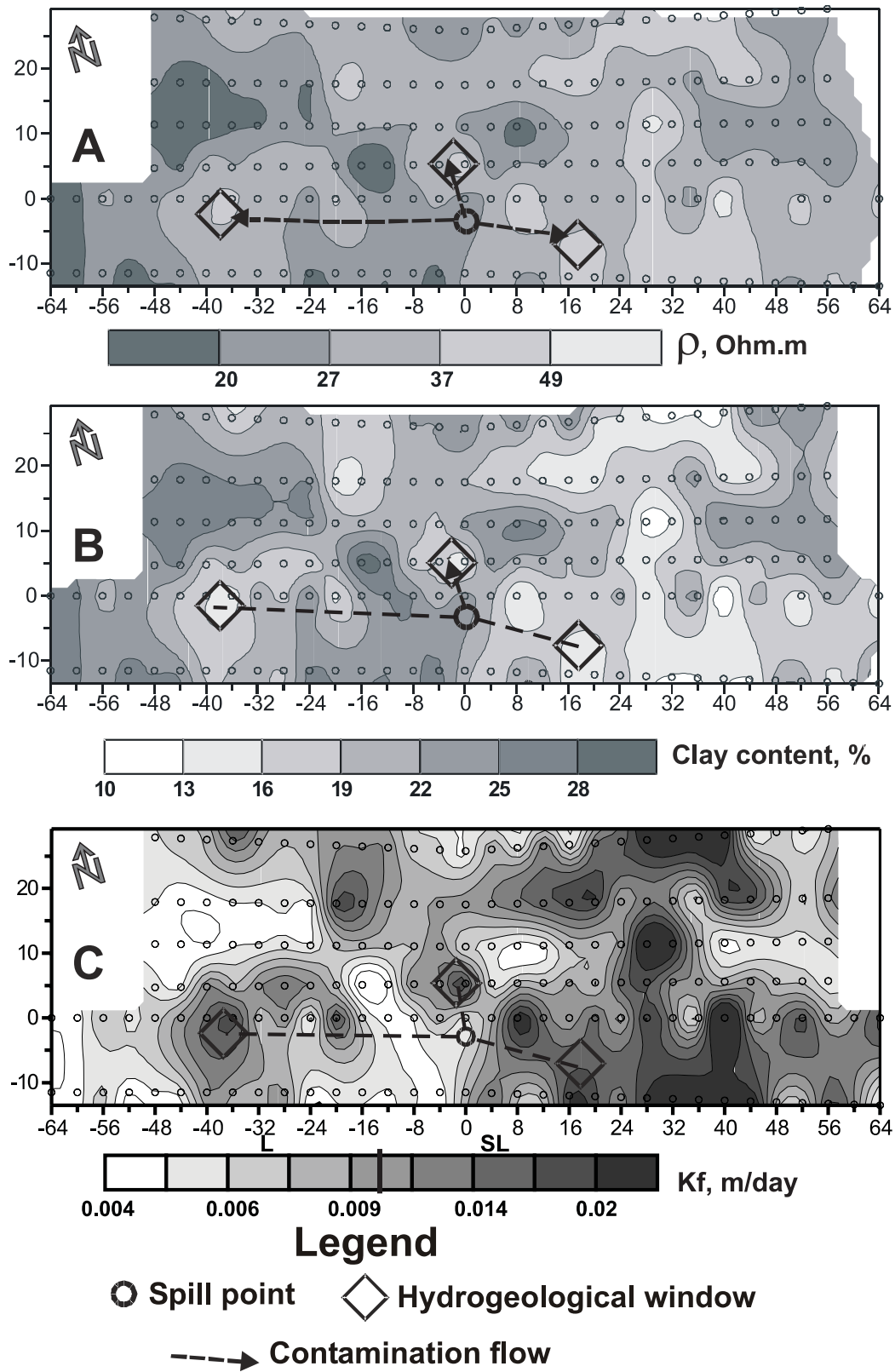


Fig. 7. (A) Resistivity, (B) clay content and (C) filtration coefficient maps for aquitard.

the clay content decreases or trenches related with pipelines are present, the vulnerability is increased facilitating the

infiltration of contaminants into the aquifer, as in the interval $X = -36$ to -8 m of profile 1.

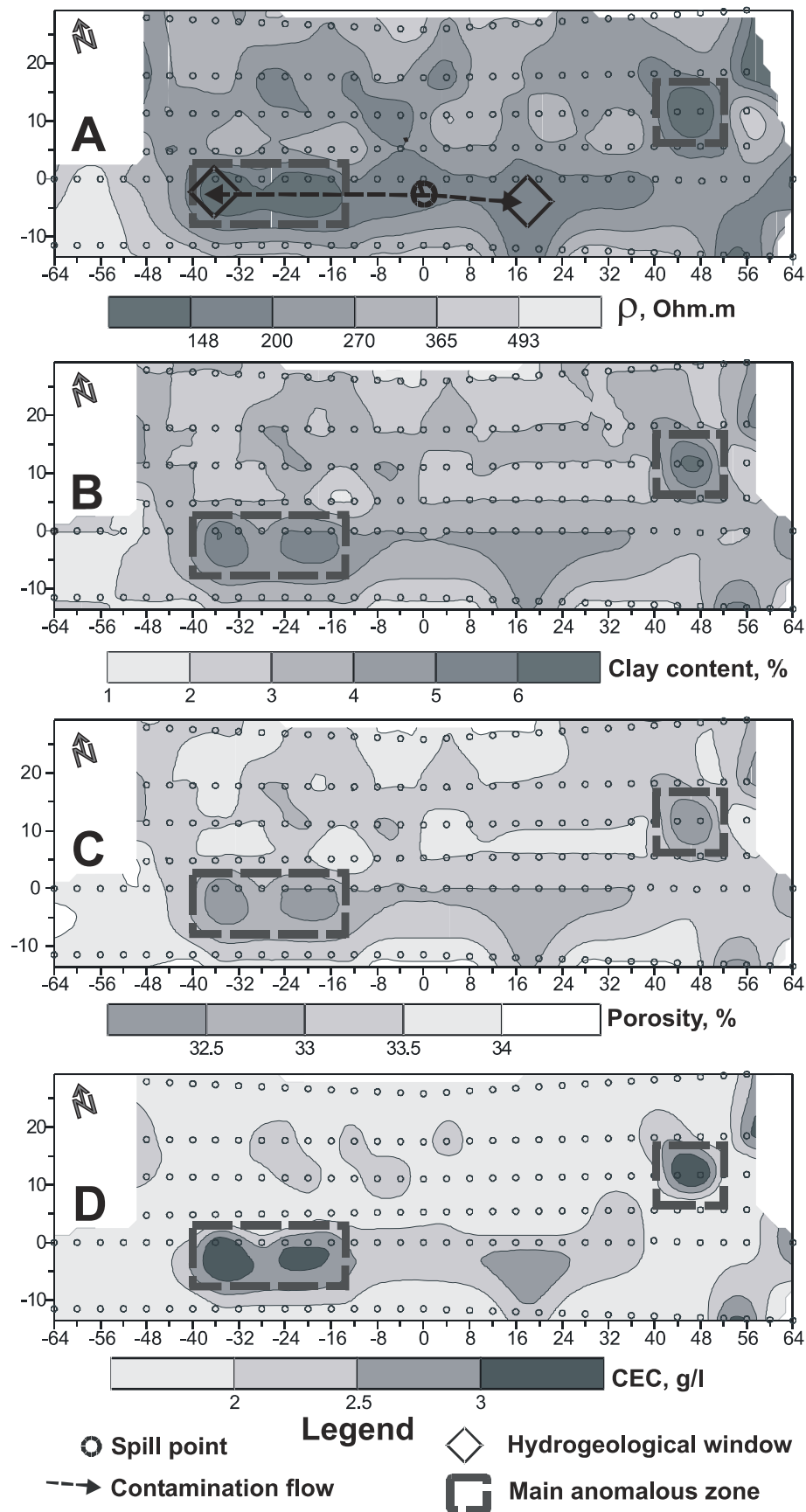


Fig. 8. Comparative (A) resistivity, (B) clay content, (C) porosity and (D) CEC maps for sandy aquifer.

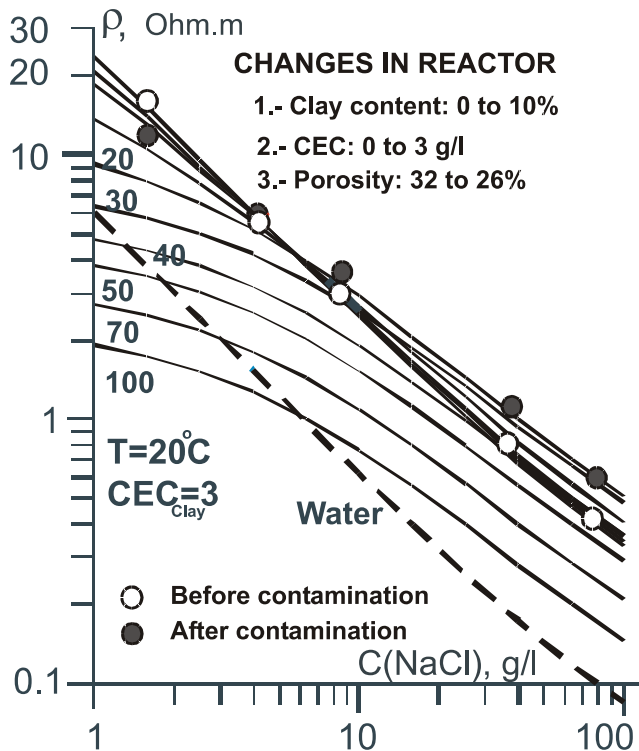


Fig. 9. Calculation of petrophysical parameters for sand extracted from reactor tank (before and after contamination).

Changes of soil properties in the sandy aquifer and in the reactor were very similar.

Recalculation of petrophysical parameters from VES resistivity and groundwater salinity helps characterizing uncontaminated and contaminated zones.

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