Geofísica Internacional (2003), Vol. 42, Num. 4, pp. 613-622

Oil pollution detection using resistivity sounding

Vladimir Shevnin, Omar Delgado-Rodríguez, Aleksandr Mousatov, Edgar Nakamura-Labastida and Abraham Mejía-Aguilar
Instituto Mexicano del Petróleo, México, D. F., México

Received: July 10, 2002; accepted: June 6, 2003

RESUMEN

En este trabajo se expone una tecnología de aplicación del método Sondeo Eléctrico Vertical (SEV) para la caracterización de áreas contaminadas por productos petroleros. Esta tecnología incluye un modelo de contaminación como una zona de baja resistividad, una metodología para los trabajos de campo, procesamiento avanzado de datos, modelación petrofísica e interpretación de los resultados obtenidos. La contaminación por hidrocarburos es un tipo muy común de polución que se encuentra en todas las etapas de la industria petrolera: extracción, transportación, refinación y distribución de los hidrocarburos. Bajo la influencia de la biodegradación, los hidrocarburos contaminantes alteran la resistividad del agua subterránea y de las rocas que los circundan, manifestándose como una zona de baja resistividad. La contaminación del subsuelo por productos petroleros puede ser estudiada mediante el método SEV, siendo posible estimar su posición en planta y profundidad, litología, fuentes de contaminación, dirección de migración de los contaminantes y grado de contaminación. Las mediciones de SEV son realizadas utilizando una variante de Tomografía de Resistividad Eléctrica (TRE) que, con una alta resolución espacial, permite eliminar o disminuir la influencia de las distorsiones causadas por heterogeneidades superficiales (ruido geológico). Para la separación de las zonas contaminadas de las no-contaminadas, se realiza una modelación petrofísica que permite calcular las resistividades teóricas de las rocas a partir de la resistividad del agua subterránea o su salinidad.

PALABRAS CLAVES: Sondeo Eléctrico Vertical, contaminación por hidrocarburos, biodegradación, ruido geológico, modelación petrofísica.

ABSTRACT

Resistivity sounding technology is applied to the characterization of oil polluted areas. It includes the analysis of the model of oil pollution as a low resistivity zone, the field study technique, advanced data processing, petrophysical simulation and data interpretation. Oil pollution is widespread and arises at all stages of the petroleum industry: extraction, transportation, refining and distribution. Under the influence of biodegradation, oil pollution in the ground changes the resistivity of the groundwater and the surrounding rocks, exhibiting as a zone of low resistivity. Resistivity sounding can estimate its position in plan and with depth, lithology, pollution sources, possible migration paths and contamination grade. Resistivity soundings are performed as electrical resistivity tomography (ERT), which has high space resolution and low distortion caused by near-surface inhomogeneities (geological noise). For the separation of contaminated and non-contaminated areas, a petrophysical simulation is used for calculation of rock resistivity based on underground water resistivity or salinity.

KEY WORDS: resistivity sounding, oil pollution, biodegradation, geological noise, petrophysical simulation.

INTRODUCTION

Drilling and chemical analysis of core samples for oil pollution study is rather expensive, and geochemical results are punctual. During the last decade many geophysical methods, especially electrical and electromagnetic methods, were used for the characterization of oil pollution in geological media (Sauck, 1998, 2000; Modin *et al*., 1997). Two models of oil pollution for the application of resistivity method are presented in the literature, namely high resistivity (Olhoeft, 1992; Mazac *et al*., 1990) and low resistivity (Sauck, 1998; Modin *et al*., 1997). Recent oil pollution shows a high-resistivity anomaly, while mature oil pollution produces a low resistivity anomaly (Sauck, 1998). Oil pollution may also be studied with georadar, self-potential, induced polarization (Vanhala, 1997), electromagnetic surveys and vertical resistivity probes (Sauck, 1998).

Since 1993 active studies of oil pollution have been performed in Russia for superficial and underground oil leakages from refineries, and in oil pumping stations with electrical resistivity tomography (ERT) canceling geological noise during data processing (Modin *et al*., 1997). In all cases the pollution zones were mapped as zones of low resistivity. The application of resistivity soundings for oil contamination studies in Mexico is more recent (Shevnin *et al*., 2002; Shevnin and Delgado, 2002). Application of the resistivity method for the geoelectrical characterization of polluted zones was made in different types of geological environment and industrial enterprises such as refineries, oil unloading and pumping areas, and airports. Oil pollution has some specific features, including changes of physical properties and change of location in time by migration.

MODEL OF THE OIL-POLLUTED ZONE

Geophysical study requires a model of the situation and the selection of an optimum technology. After fieldwork, data processing and interpretation is carried out. The stage of formal interpretation (estimation of the parameter values) is followed by geological interpretation.

The resistivity contrast between an oil-polluted area and the surrounding rock depends on the spill age. The low resistivity anomaly in polluted areas appears three to four months after the spill ("mature spill"), but in the case of a fresh spill the presence of a high resistive anomaly is expected. Therefore, the age of spill influences the selection and optimization of the applied technology.

Low resistivity findings in oil-polluted zones appeared rather recently (Sauck and McNeil, 1994; Modin *et al*., 1997; Sauck, 1998, 2000; Atekwana *et al*., 2001; Abdel-Aal *et al*., 2001). According to Sauck, the source of low resistivity is a leachate from an acid environment, created by intense bacterial action on residual hydrocarbons near the base of the vadose zone. This low resistivity zone is produced by high total dissolved solids in the zone where microbial activity is maximal (Sauck, 1998; 2000; Atekwana *et al*., 2001). The leachate is a result of chemical reactions between organic acids, CO_2 and mineral grains and grain coatings.

Organic and non-organic acids in polluted zones arise through karstic processes, increasing the porosity in carbonate rocks. Hydrocarbons after biodegradation become heavier than water (Bailey *et al*., 1973). The oil pollution seeps below the groundwater level (Modin *et al.,* 1997). We have found oil-polluted areas in two depths: above groundwater level and in zones of water saturation (at depths of 4 m to 50 m). We find that oil pollution is more easily recognizable in sandy - clayish soils than in pure sand. Oil pollution increases oil-transforming bacteria population, surfactants in water, groundwater salinity up to 5 times, and it lowers groundwater resistivity (Sauck, 1998; 2000; Atekwana *et al*., 2001). In the first stage of contamination, oil products and leachates are concentrated in sandy layers but eventually they are absorbed by clayish soils (Shevnin *et al*., 2002). Surfactants significantly diminish the size of oil particles in water; as a result, the contamination can percolate into clay pores. Our experience indicates that pore water salinity in clays can be 50 times higher than before contamination. Below groundwater level all pores in clays are filled by bound (osmotic and adsorptive) water. The leachate and the oil move into clayish rocks under the influence of gradients in salt content. Diffusive - osmotic water flow and temperature contrast cause heat and water transfer; and electric potential contrast cause electro-osmotic water movement. In principle, all these mechanisms are possible. In clays these types of transfer can dominate headwater filtration (Shevnin *et al*., 2002).

Field studies of oil pollution are more difficult in the case of high groundwater salinity, as the resistivity contrast between soils with and without pollutants is minimal (Ryjov and Shevnin, 2002).

Difference of lithology establishes a background resistivity range of the medium, from highly resistive rocks like limestone, to highly conductive ones like clay. Thus oil pollution also depends on lithology.

The groundwater level position is another important factor. Depending on salt concentration in the water, resistivity of saturated rocks varies considerably. Besides, the pollutants change the electrical characteristics of rocks above and below groundwater level.

Frequently, oil pollution takes place in industrial zones and urban areas, where excavations, trenches, underground pipes and cables affect the upper geological strata. These may be considered as geological noise, like broken glass or a wavy water surface may prevent geophysicists from observing deep objects. Small near-surface inhomogeneities may cause large distortions of resistivity data. The distortions from such inhomogeneities are different when placed near the current and measuring electrodes (Modin *et al*., 1997).

In conclusion, the geoelectrical characterization of an oil-contaminated area is quite complicated. It requires a correct resistivity sounding application, as well as appropriate data processing and interpretation. Our experience suppressing geological noise from resistivity soundings shows that the best array is a two-sided pole-dipole array AMN+MNB with current electrode positions along the profile, constant step between electrodes, and the same (or proportional) step between sounding points. Correct measurement of resistivity may cancel geological noise, increase correlation between neighboring resistivity sounding curves and improve the accuracy of interpretation decreasing the fitting error 4 to 5 times.

A model of oil pollution has the following features: rapid changes of electrical properties in time in comparison with natural geological processes; migration in space together with groundwater flow; migration at depth across the groundwater level; diminishing groundwater resistivity (up to 5 times in sands and up to 50 times in pore space of clays); structural control of contamination by faults, and lithological control. Oil pollution zones are often situated in industrial areas with a high level of geological noise.

FIELDWORK TECHNOLOGY

In recent years, a new technology of resistivity sounding called Electrical Resistivity Tomography (ERT) has been developed, using small steps of measurements along profiles for 2D study of inhomogeneous media, and a great number of electrodes reconnected manually or automatically. In this technological modification different arrays can be used (pole-dipole, dipole-dipole, Wenner, Schlumberger). For effective canceling of geological noise we use a two-sided pole-dipole AMN+MNB array (Figure 1).

All electrodes are placed along the profile. A cable is connected to current electrode A1 nearest to the potential electrode M, while the current electrode C is practically located at infinity. In this way the potential difference between M and N is measured. Then the cable is reconnected to the next current electrodes A2, A3, A4, ..., An. The distance between the current and potential electrodes is used to calculate values of ρ_a for different positions of A. All measurements are referred to the central point between MN electrodes. Finally, the ρ_a curve represents the AMN sounding (Figure 1). The same procedure is repeated for all positions of the current electrode B, yielding MNB sounding. Afterwards, the MN dipole is moved to the next reference point and the process is repeated.

Finally we obtain two ρ_a matrices for AMN and MNB measurements along the profile (Figure 2) considering positions of the reference points O along the x-axis and the AB/2 distances along the y-axis.

A cross-section of ρ_a is obtained for each profile. The set of profiles in the area allows building maps of ρ_a for each value of AB/2 (m). Both forms of visualization constitute useful tools for a qualitative geoelectrical interpretation.

Based on the geological noise level and the physical conditions of the surface, the geological environments can be classified as (a) Rural Area with low geological noise level; (b) Rural Area with high geological noise level; (c) Urban Area covered with concrete or asphalt; or (d) Urban Area without concrete or asphalt pavement.

In the case of covered surface there are problems with electrode grounding. We can solve this problem by drilling holes for the electrodes or using non-contact electrodes.

Depending on the resistivity instrument and field technology we need to take into account the level of electromagnetic noise and low resistivity values, and the presence of geological noise in a contaminated zone. The estimated minimal level of the signal measured with MN dipole is to 10^{-5} V when the value of exciting current is in the range of 10 to 100 mA. For estimating the influence of the induction part of the electromagnetic field, the lowest operating frequencies are preferable. The recommended rejection level of industrial noise (reaching up to 10^{-2} V/m in urban areas) is at least 4 orders of magnitude. For experimental characterization of the polluted zones we designed robust equipment that includes a 4.88 Hz generator with stabilized current (10 to 100 mA) and a measuring instrument with the intrinsic noise of $3*10^{-7}$ V. The attenuation of signals for 60 Hz is 10^{-6} and it is more than 10^{-4} for frequencies below 0.1 Hz (rejection of fluctuations in self potential on the measuring electrodes).

Geoelectrical study of oil contamination depends mainly on five aspects related to the geological environment: EM

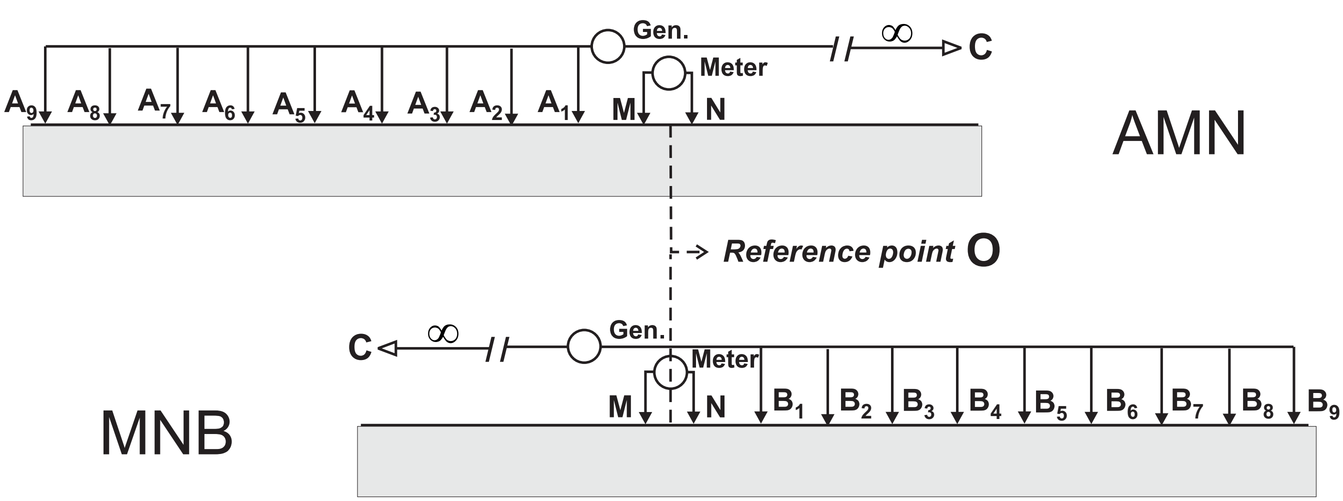

Fig. 1. Scheme of resistivity sounding with AMN+MNB array.

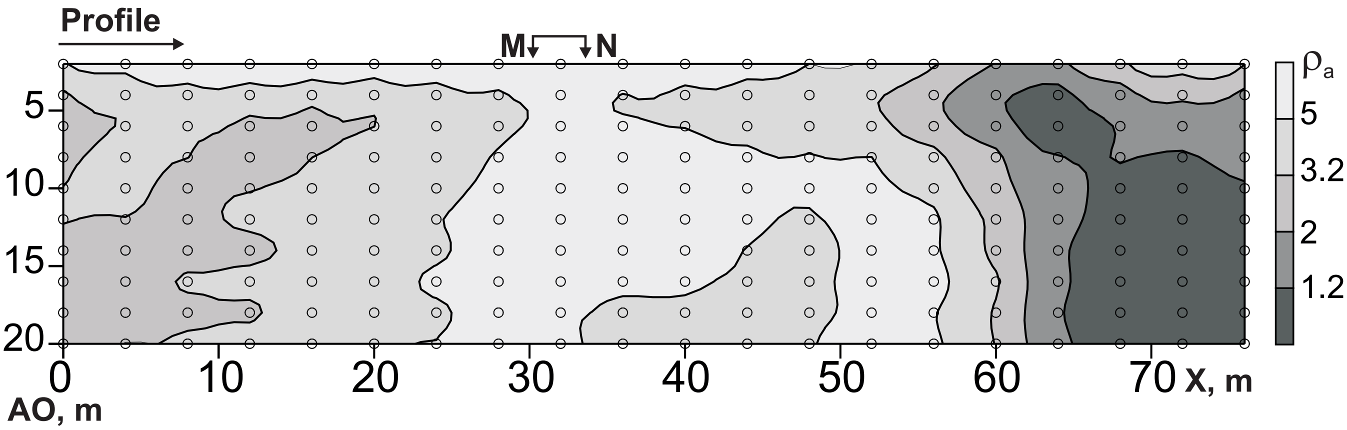

Fig. 2. ρ_a matrix with reference points (on pseudo-cross-section) from VES measurements along profile. (Profile 2, Campo 10).

and/or geological noise level, depth of groundwater level, groundwater mineralization, age of the spill and physical conditions of the ground surface.

PROCESSING TO CONTROL GEOLOGICAL NOISE

The process of geological noise filtering by the Median algorithm has been described before (Modin *et al*., 1997; Ritz *et al*., 1999, Shevnin *et al*., 2002). This operation is based on characteristics of distortions caused by superficial inhomogeneities. The algorithm was checked and adjusted on modeling and field data and has now about ten years of practical application. Processing is performed for two ρ_a matrices (AMN and MNB). It cancels the local distortions resulting from near-surface inhomogeneities placed near the current (C-effect) and potential electrodes (P-effect). After application of Median program, we estimate that fitting errors in interpretation of the resistivity sounding curves should decrease 4-5 times. Afterwards it is possible to integrate AMN and MNB sounding data into AMNB sounding curves for Schlumberger array and AMN and MNB resistivity sections in a single AMNB section.

The field data were obtained in Poza Rica, Veracruz. Figure 3 shows the result of filtering for profile 1 in the Campo-10 area, an urban area without concrete or asphalt pavement. The vertical pseudo- sections for AMN and MNB arrays (Figure 3, A, B) show field data with distortions caused by small superficial objects. After filtering with the Median program, the distortions in AMN and MNB sections are removed (C and D, Figure 3). Now it is possible to obtain an integrated result for AMNB array (E), which afterwards can be interpreted. In Figure 3, E is the central resistive area, which separates two conductive parts of the section. The interval from 70-110 m represents the area with low ρ_a values and can be considered an oil-contaminated zone.

STATISTICAL DATA PROCESSING

The purpose of statistical data analysis is estimating the averaged resistivity sounding curve and dispersion curve (see Figure 4) for some group of apparent resistivity data. Apparent resistivity values fit a lognormal distribution. The average is calculated as a geometrical mean, and the dispersions estimated as a standard factor –STDF (analogous to the standard deviation for a log-normal distribution; see Figure 4). The averaged resistivity sounding curve reflects the basic geoelectrical model for the area, and the dispersion helps to understand the role of geological noise and the changes in data quality after Median filtering. Another useful form of presentation is the statistical distribution of ρ_a in terms of frequency in the ρ_a - AO plane (Figure 5).

Rural areas normally have a low level of geological noise (Shevnin and Delgado, 2002). In this case it is possible to obtain reliable geoelectrical measurements with a Schlumberger array. Otherwise, we recommend an array that allows data processing to cancel geological noise.

The former refinery in Poza Rica (Poza Rica-2000), an area of oil-waste disposal (Campo-10, Poza Rica-2001) and Paredón-31 (Tabasco-2001) are presented in Figure 4 as examples of an industrial area with the surface covered by concrete or asphalt; an urban area without concrete or asphalt pavement, and a rural area with low geological noise level respectively. Figure 4 shows the dispersion graphs (STDF) as a function of AO for three areas before and after canceling geological noise.

In the first case (Figure 4, A) a significant dispersion is observed both before and after the Median process. After filtering, the dispersion is reduced by half (Shevnin *et al*., 2002).

In the second case (Figure 4, B) there is no concrete on the surface, but the geological noise is rather high. After re-

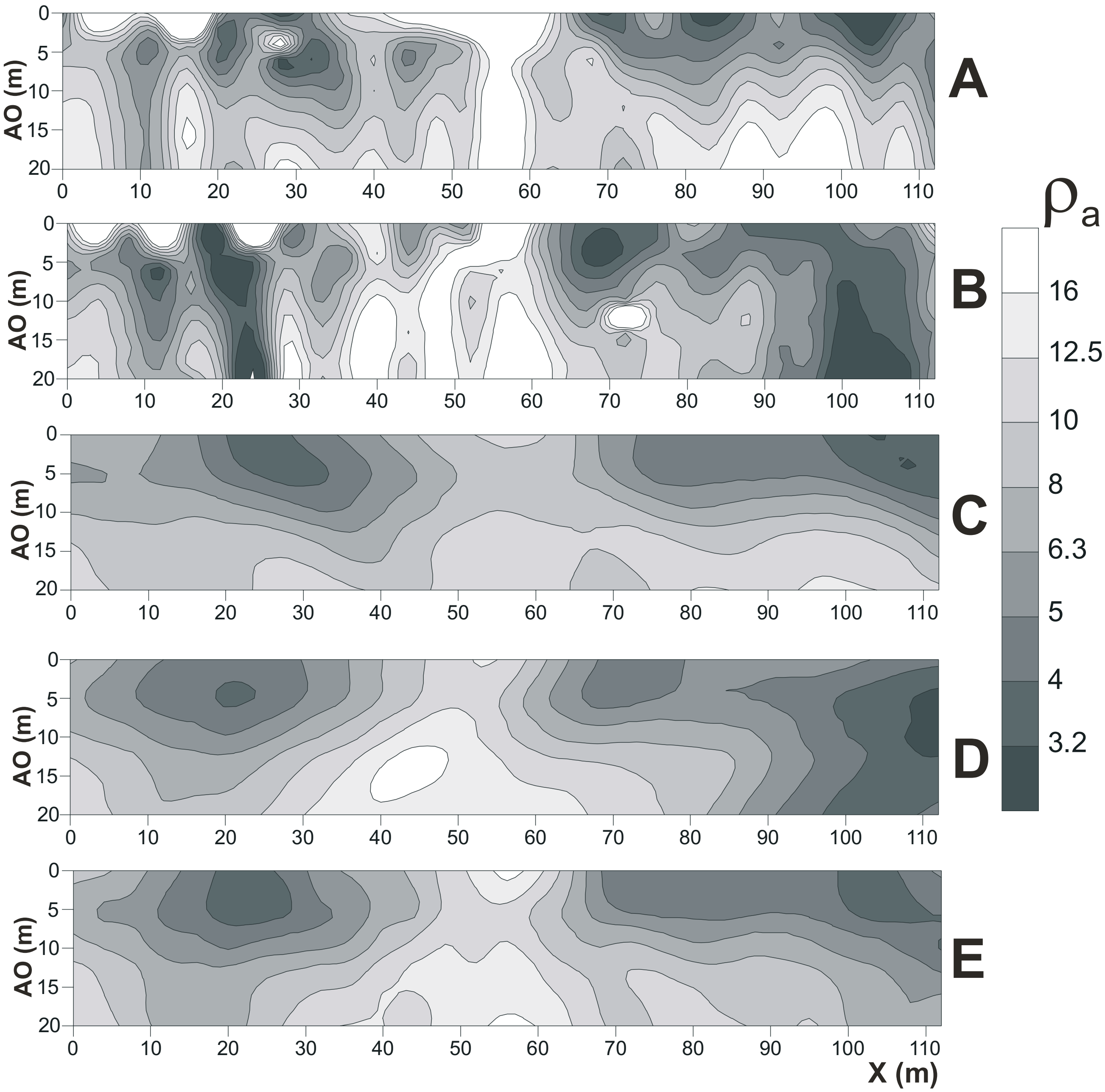

Fig. 3. Filtration process with Median program. (A) and (B): AMN and MNB pseudo- sections with distortions. (C) and (D): AMN and MNB after MEDIAN. (E): AMNB pseudo- section without distortions. Profile 1, Campo 10, Poza Rica.

moving the geological noise the dispersion decreases 1.4-1.7 times. In this case the dispersion was estimated separately for two groups of profiles (profiles 1, 5-8 and 2, 3, 4). For the second group the dispersion is higher because of the oil contamination found at these profiles, which increases the total dispersion.

In the third case (Figure 4, C), the rural area doesn't have concrete or asphalt and geological noise is low. There is no need of a special measuring technology (AMN+MNB). A standard Schlumberger AMNB array was used and there was no geological noise removed. In this case the dispersion is low without filtering.

DIFFERENT VISUALIZATIONS FOR GEOELECTRICAL ANALYSIS

Three types of images are used frequently for analysis of a geoelectrical situation, i.e. vertical apparent resistivity cross-sections along profiles, apparent resistivity maps and

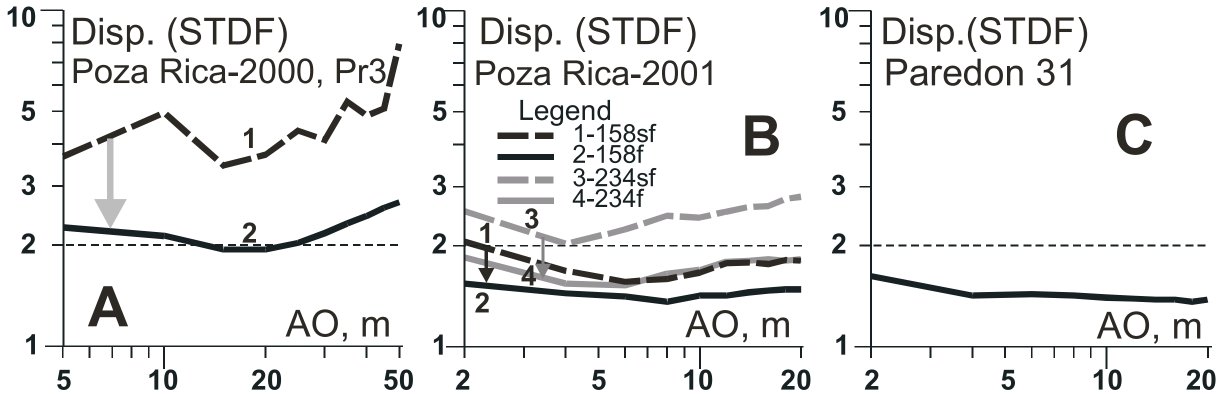

Fig. 4. Dispersion graphs as function of AO distance for three areas.

statistical apparent resistivity distributions in the ρ_a - AB/2 plane. All imaging is performed after removing the geological noise. The statistical image of ρ_a data is based on the calculation of ρ_a statistical distribution for each AO spacing. The case of Campo 10 is shown in Figure 5 separately for two groups of profiles. Both groups present a geoelectrical model formed by three layers. For profiles 1, 5-8 a single characteristic curve has a minimum of 4 Ohm-m for AO = 4 m (second layer). The group of profiles 2-4 (Figure 5B) is represented by two sounding curves. The first is similar to one shown in Figure 5A and the other, with an approximate minimum of 1.5 ohm-m, is typical for soundings in oil-contaminated areas.

The vertical cross-section of apparent resistivity is a traditional presentation for soundings along a profile. Examples are shown in Figures 2 and 3. Also, apparent resistivity maps can be plotted for each AO spacing when ρ_a values are shown as function of the reference point (X, Y) and the spacing AO on a horizontal plane (X, Y). Spacing is related to depth, so a set of maps for different spacings is similar to slices at different depths. When the ρ_a variations with depth are small, such maps may be useful for localization of oil pollution. When layering is significant, maps of true resistivity for the layer in which oil pollution is present are preferable (see example in Figure 8).

IDENTIFICATION OF CONTAMINATED AND NON-CONTAMINATED ZONES

Geological interpretation of oil-polluted areas requires the identification of polluted and non polluted zones. For this purpose we use a simulation of resistivity in non-contaminated formations based on water mineralization and rock lithology. The algorithm and software were developed by Ryjov (Ryjov and Sudoplatov, 1990; Ryjov and Shevnin, 2002). Program "Petrofiz" calculates rock resistivity on the base of physical – chemical theory, taking into account rock

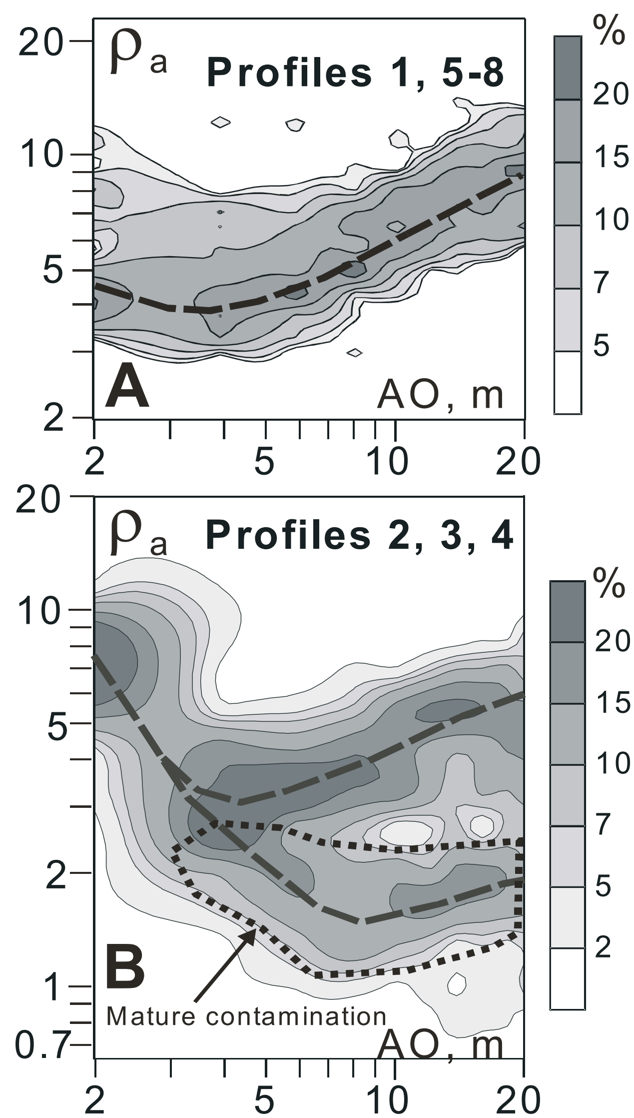

Fig. 5. Results of the statistical visualization of the data obtained at Campo-10, Poza Rica. Highly conductive anomaly (contamination) is marked by dotted line.

porosity, clay content, water salinity and types of salt in water, pore size and some other characteristics.

In Figure 6 the results of theoretical calculations with the program "Petrofiz" are shown. Resistivities of clay, sand and some other rocks are considered as a function of water salinity (NaCl content at 20°C). For high groundwater salinity the rock resistivity is uniformly higher than the water resistivity (line 11 in Figure 6). For lower salinity the resistivity for a clay – sand mixture is below the resistivity of pore water. This case corresponds to the influence of a double electric layer (DEL) in the pores of the clay (Ryjov and Shevnin, 2002).

The upper horizontal dashed line (d) shows a measured groundwater resistivity of 20 Ohm-m for Campo-10. Vertical line (a), which crosses the water line (11) at a resistivity value of 20 Ohm-m (d), indicates a water salinity of 0.3 g/l. For this salinity the resistivity of clay and sand is in the range of 2.3 to 80 Ohm-m. Actually, in the study area some resistivity values below 2.3 Ohm-m were measured. We consider these areas with resistivity below 2.3 Ohm-m as oil-polluted areas, in which the oil has been modified by bacterial biodegradation.

Results in Figure 6 were also used for "lithology" legend, applied for model characterization. In this legend, depending on the resistivity values, different rock names are used. C1 to C3 are different types of clay (heavy, medium, light), L is loam (30% of clay), SL is sandy loam (10% of clay), S is sand, G or Ls are gravel or limestone with porosity below 20%. A1 and A2, with resistivity below 2.3 and 1.5 Ohm-m, are definitely oil-polluted rocks with different grade of pollution. This classification was used for geological interpretation of resistivity maps and resistivity cross-sections (see Figure 7).

According to Atekwana *et al*., (2001), pore fluid resistivity decreases about 5 times as result of biodegradation,

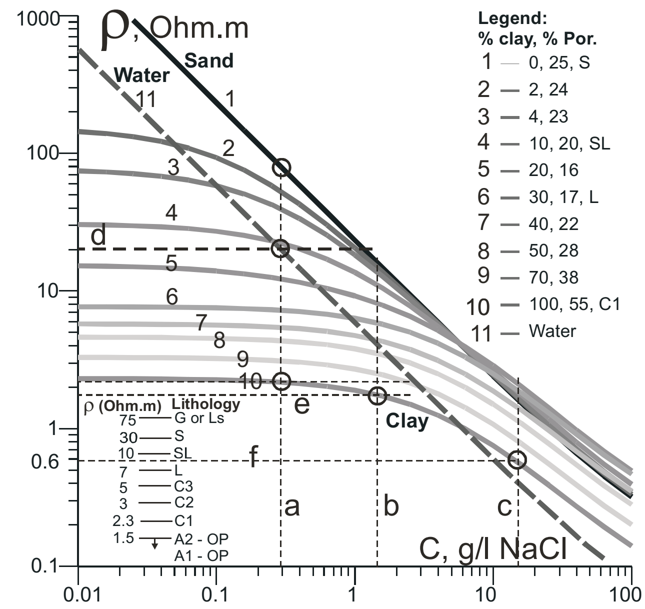

Fig. 6. Theoretical dependence of rocks resistivity on water salinity.

thus reducing rock resistivity. The vertical line (b) for water salinity C=1.5 g/l shows that the clay resistivity decreases to 1.5 Ohm-m (line e). In our studies we estimated resistivity values of about 0.8 - 1 Ohm-m.

DEL in clay can concentrate 50 times more ions than in sand (Shevnin *et al*., 2002). The vertical line (c) for water mineralization of 15 g/l reflects this situation. For this salinity clay should have a resistivity of 0.6 Ohm-m (line f).

When sand is contaminated with oil, its resistivity diminishes from 80 to 20 Ohm-m and thus it falls in the interval between sandy loam and loam. Such an effect can be due to contamination or to clay content in sand, and the interpretation is ambiguous. When clay layers are found at the depth

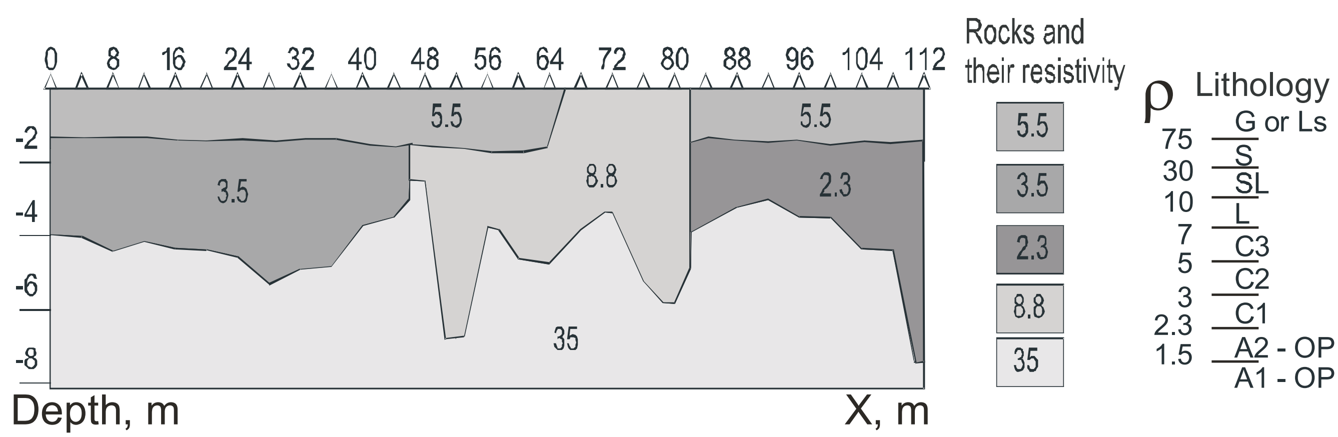

Fig. 7. Geoelectrical model of the profile 1, Campo-10, Poza Rica.

interval of contamination, the oil pollution concentrates in the clay. Salinity of fluid in pores of clay can rise up to 50 times and oil particles move together with the fluid into pores of clay; clay resistivity reaches 0.6 Ohm-m. For normal conditions clay resistivity cannot fall below 2.3 Ohm-m. In the case of contamination it can be 1.5 or 0.6 Ohm-m; thus there are clear limits to classify non-contaminated and contaminated rocks. The main limit is at 2.3 Ohm-m with an additional limit at 1.5 Ohm-m. Discrimination of contaminated and non-contaminated rocks is now possible.

CHARACTERIZATION OF THE CONTAMINATED ZONE

The geoelectrical characterization of oil pollution of geological media includes mapping of contaminated zones in plan and at depth, estimation of the degree of pollution, determining the sources of pollution and the direction of pollutants migration, and control and monitoring of the pollution and remediation processes.

With the IPI2Win program (Electrical prospecting..., 1994) 1D interpretation is carried out for every profile. After removing geological noise the layered model of the medium and 1D interpretation are more reasonable. Figure 7 shows a geoelectrical model for profile 1, Campo 10. A contaminated zone in the second layer is shown at the interval 82-112 m, at 1.5 m depth. After interpretation of all profiles, the polluted zone may be located in the study area.

Identification of the contaminated zones enables us to estimate the pollution sources and direction of pollutant migration in the study area. A map of the second layer resistivity (oil contaminated layer) is shown in Figure 8. There are two zones of minimal resistivity (highly contaminated zones) in the east and northwest of the area, separated by a more resistive zone with north-south orientation. The general direction of groundwater flow in this area is N-S, as well as the contaminant migration.

We assume that the pollution sources can be found in the zones with minimal resistivity in Figure 8 (highly contaminated zones). These zones are a storage tank near to point 160 m of profile 4 and the northwest end of study area (near the crossing of profiles 2 and 3). The contamination source in last zone appear to be situated approximately at 70 m outside of Campo 10 (some oil tanks).

The results of the study are presented in Figure 9, where the pollution sources and zones with different grade of contamination are indicated.

CONCLUSIONS

The methodology proposed for oil pollution detection by resistivity sounding includes special tomography sounding technology, data processing for removal of geological noise, data visualization in the form of cross-sections, apparent resistivity maps and statistical images for general

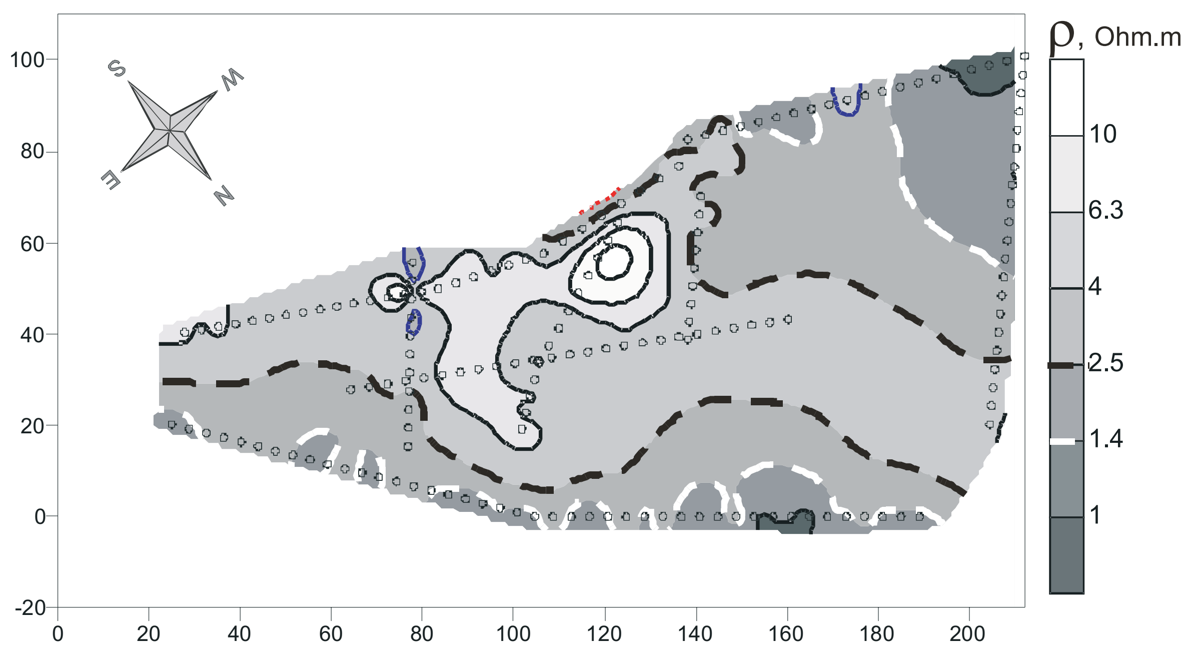

Fig. 8. Map of the second layer resistivity (r2). Dashed lines mark different levels of r2 and pollution.

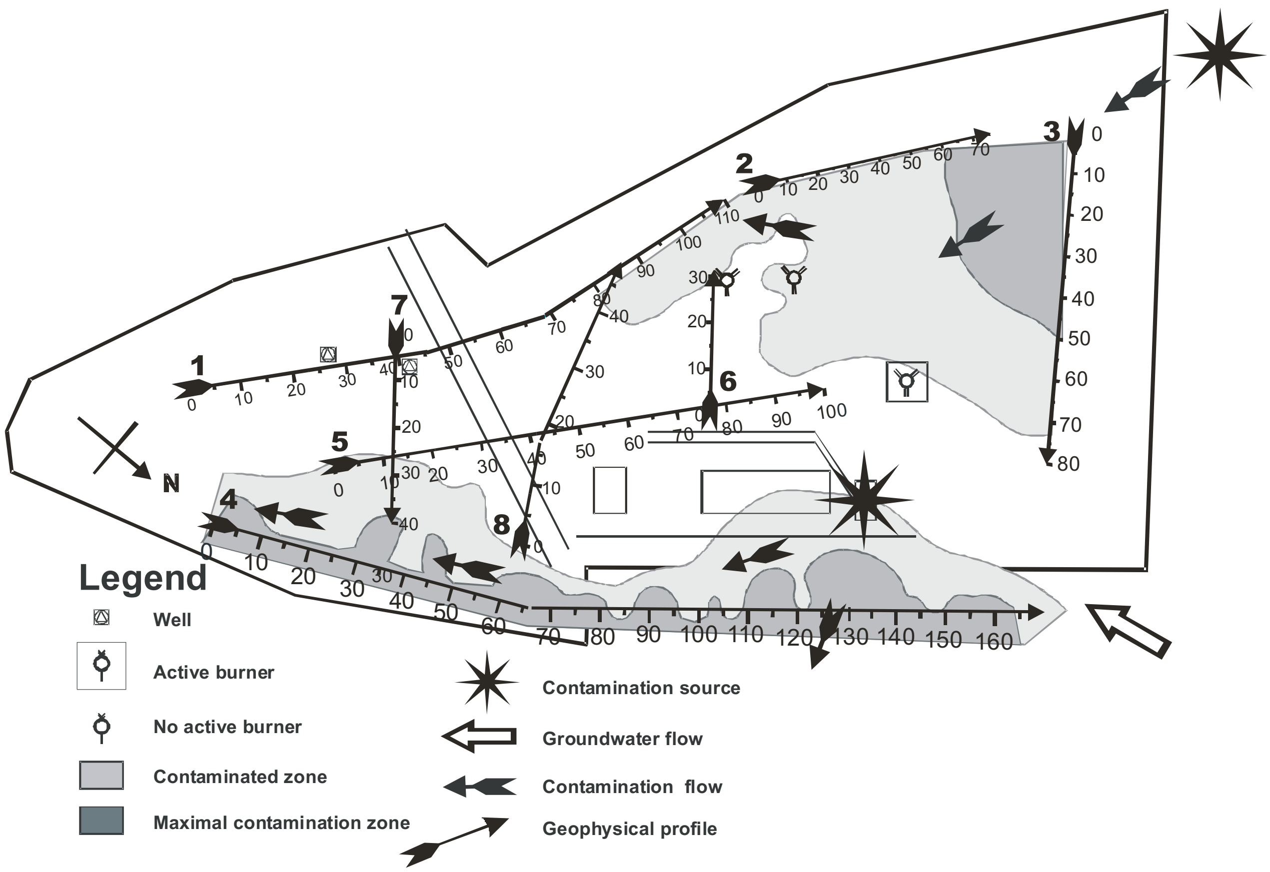

Fig. 9. Sketch of study area Campo 10 including obtained results.

analysis of situation, petrophysical simulation of rocks resistivity for identification of the contaminated and non-contaminated areas, and quantitative interpretation of resistivity sounding data including lithological estimation.

In the area of Campo-10 the zones of low resistivity were found and mapped. Their position is related to the location of pollution sources and groundwater flow. An oil storage tank was identified as one pollution source. The existence of a second source in the northwest direction beyond the study area is likely.

Repetition of the characterization process with time intervals on the order of one year may help to monitor an eventual remediation process.

ACKNOWLEDGMENTS

The authors consider a most pleasant debt to express gratitude to The Mexican Petroleum Institute, where this study was made. We acknowledge the valuable help of Luis Fernández Linares and Héctor Zegarra-Martínez in the field-work at Campo-10. We sincerely thank Dr. A.Ryjov, A. Bobachev and E.Pervago whose software we used in this study. We wish to express our gratefulness to Dr. Cinna Lomnitz for the revisions and corrections carried out to the manuscript.

BIBLIOGRAPHY

ABDEL-AAL, G. Z., D. D. WERKEMA, W. A. SAUCK JR. and E. ATEKWANA, 2001. Geophysical investigation of vadose zone conductivity anomalies at a former refinery site, Kalamazoo, MI. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1–9

ATEKWANA, E., D. P. CASSIDY, C. MAGNUSON, A. L. ENDRES, D. D. WERKEMA, JR. and W. A. SAUCK, 2001. Changes in geoelectrical properties accompanying microbial degradation of LNAPL. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1–10.

BAILEY, N. J. L., H. R. KROUSE, C. R. EVANS and M. A. ROGERS, 1973. Alteration of Crude Oil by Waters and Bacteria - Evidence from Geochemical and Isotope Studies. *Am. Assoc. Petrol. Geol. Bull., 57,* 1276 – 1290.

ELECTRICAL PROSPECTING..., 1994. Electrical prospecting with resistivity method. Moscow, MSU edition, 160 pp. (In Russian).

KELLER, G. and F. FRISCHKNECHT, 1966. Electrical Methods in Geophysical Prospecting.

MODIN, I. N., V. A. SHEVNIN *et al*., 1997. Investigations of oil pollution with electrical prospecting methods. *In:* Proceedings of the 3rd EEGS-ES Meeting. Aarhus, Denmark, 8-11 September 1997, 267-270.

NASH, M. S., E. ATEKWANA and W. A. SAUCK, 1997. Geophysical investigation of anomalous conductivity at a hydrocarbon contamination site. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 675-683

OLHOEFT, G. R., 1992. Geophysical detection of hydrocarbon and organic chemical contamination. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 587-595.

RITZ, M., H. ROBAIN, E. PERVAGO, Y. ALBOUY, CH. CAMERLYNCK, M. DESCLOITRES and A. MARIKO, 1999. A. Improvement to resistivity pseudosection modeling by removal of near-surface inhomogeneity effects: application to a soil system in south Cameroon". *Geophys. Prospect., 47,* 85–101.

RYJOV, A. A. and A. D. SUDOPLATOV, 1990. The calculation of specific electrical conductivity for sandy-clayed rocks and the usage of functional cross-plots for the decision of hydro-geological problems. *In:* book "Scientific and technical achievements and advanced experience in the field of geology and mineral deposits research. Moscow, pp. 27-41. (In Russian).

RYJOV, A. and V. SHEVNIN, 2002. Theoretical calculation of rocks electrical resistivity and some examples of algorithm's application. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems.

SAUCK, W. A. and J. MCNEIL, 1994. Some problems associated with GPR detection of hydrocarbon plumes; Fifth International Conference on Ground Penetrating Radar (GPR'94).

SAUCK, W. A., 1998. A conceptual model for the geoelectrical response of LNAPL plumes in granular sediments. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 805-817.

SAUCK, W. A., 2000: A model for the resistivity structure of LNAPL plumes and their environs in sandy sediments. *J. App. Geophys., 44,* 151–165.

SHEVNIN, V., A. RYJOV, E. NAKAMURA, A. SÁNCHEZ, V. KOROLEV and A. MOUSATOV, 2002. Study of oil pollution in Mexico with resistivity sounding. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems.

SHEVNIN, V. and O. DELGADO, 2002. Application of resistivity sounding method for oil pollution study in urban and rural areas. *In:* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems.

VANHALA, H., 1997. Laboratory and field studies of environmental and exploration applications of the spectral induced-polarization (SIP) method. Academic dissertation, for the degree of Doctor of Technology. Helsinki University of Technology, 104 pp.

Vladimir Shevnin, Omar Delgado-Rodríguez, Aleksandr Mousatov, Edgar Nakamura Labastida and Abraham Mejía-Aguilar
Instituto Mexicano del Petróleo
Eje Central Lázaro Cárdenas 152,
Col. San Bartolo Atepehuacan,
Del. Gustavo A. Madero
07730 México, D. F., México
Email: vshevnin@imp.mx