**CHARACTERIZATION OF OIL POLLUTION IN MEXICO USING RESISTIVITY SOUNDING METHOD**

***Vladimir Shevnin (vshevnin@imp.mx), Omar Delgado-Rodríguez (odelgado@imp.mx), Aleksandr Mousatov (amousat@imp.mx), Edgar Nakamura-Labastida (enakamu@imp.mx) and Abraham Mejía-Aguilar (fido_abr@yahoo.com)***

***INSTITUTO MEXICANO DEL PETRÓLEO.***
***Eje Central Lázaro Cárdenas 152. San Bartolo Atepehuacan 07730, México, D.F.***
***vshevnin@imp.mx***

**ABSTRACT**

Resistivity sounding (VES) method is frequently used in environmental studies with investigation depth until 20-30 m. During the last years a new faster and more detailed VES modification, named electrical resistivity tomography (ERT), has appeared which deals no with independent soundings, but with sounding profiles with preliminary installations of great number of electrodes.
In urban areas with high level of EM noise AC instrument is more noise resistive in comparison with DC measurements. It is possible to reach more sensitivity for AC instrument and to diminish the current value used in AC measurements.
In this work we present an optimized methodology for the realization of the field-work, as well as for the processing and interpretation of the measurements. In areas with high level of geological noise it is possible, applying the mentioned methodology, to cancel the distortions caused by small superficial objects, increasing the quality and accuracy of the results.
VES is effective method at oil pollution study. Low resistivities in oil-polluted zone, resulted from oil degradation under the influence of oil-transforming bacteria, can be confidently localized by VES in place and depth. Theoretical calculation of rock resistivity and their comparison with values measured in the field is used to resolve the problem of separation between contaminated and non-contaminated areas on resistivity values. Several practical examples for different geological situations are presented in this report.

**INTRODUCTION**

For determination of the presence and concentration of oil pollution the drilling and chemical analysis of core samples are commonly used. This operation is rather expensive and the results frequently are not very accurate.

Many geophysical methods, especially the electrical and electromagnetic methods were focused on the characterization of oil pollution of the geological media during the last decade (Sauck, 1998, 2000). Two principal models of oil pollution for the application of the electrical and electromagnetic methods are presented in the literature; these are high (Olhoeft, 1992) and low resistivity (Sauck, 1998; Modin et al., 1997) models. Now it is evident (Sauck, 1998) that recent oil pollution gives the high resistivity anomalies, while mature oil pollution produces the low resistivity ones. Oil pollution also can be studied with the help of georadar, self-potential, induced polarization (Vanhala, 1997), electromagnetic survey and vertical resistivity probe (Sauck, 1998).

In Russia since 1993 the active studies of oil pollution were performed by geophysical group of Moscow State University (MSU) headed by Shevnin and Modin (Modin et al., 1997). The studies were fulfilled on superficial oil leakages, in places of underground leakages from refineries and on oil pumping stations. In all cases the pollution zones were mapped as zones of low resistivity. VES method was performed on the Total Electrical Sounding technology (variant of resistivity tomography) with canceling geological noise at data processing stage (Modin et al., 1997).

In Mexico the application of the electrical and electromagnetic methods for oil contamination study is more recent (Shevnin, Ryjov et al.; Shevnin and Delgado, 2002). With application of resistivity method the geoelectrical characterization of the polluted medium is possible in different types of geological environment and industrial enterprises as: refinery, oil unload and pumping areas and airports.

The main purpose of this work is in presenting the state of the art of oil pollution study with optimized resistivity sounding technology in Mexico.

## METHODS AND RESULTS

The geophysical study of any area for a solution of some specific geological problem starts from creation a priori model of the situation and selection of an optimum technology. After fieldwork realization a data processing phase occurs, and an interpretation is carried out, which one frequently is iterative, when there is a transfer from a priori information to the first a posteriori model, which one then is considered as new a priori one for the following iteration, etc. The stage of formal interpretation (estimation of the parameters values) is followed by geological interpretation.

### I. Initial model

The type and range of resistivity contrast between oil-polluted zone and surrounding rocks at the moment of the geoelectrical research depends on the time of spill happened. Some studies indicated the prevalence of a conductive anomaly in polluted areas after more than 3 - 4 months of spill (“mature spill”), while in the case of a fresh spill the presence of a resistive anomaly is expected. Thus, this aspect influences significantly in the selection and optimization of the applied technology.

The process of formation of oil pollution zone was described with many details and with variations of physical characteristics and chemical reactions in the articles of Sauck (1998, 2000) and his colleagues (Atekwana et al., Abdel-Aal et al., 2001).

Another aspect to take into account is the groundwater salinity in the area. Field studies of oil pollution are more difficult in the case of high groundwater salinity, when the difference in resistivity between different rocks and polluted and non-polluted areas is minimal (Ryjov and Shevnin, 2002).

Differences in lithology establish a background resistivity range of the studied medium, from very resistive like limestone until very conductive rocks like clay and we need to recognize influence of oil pollution among changes created by lithology.

The location of GWL position is another important factor. In dependence of the salt concentration in the porous water, the resistivity of the saturated rocks varies considerably. Besides, the electrical response of pollutants changes the electrical characteristics of rocks above and below of GWL.

Frequently oil pollution happens in industrial zones and urban areas, where the upper part of geological media has been changed by excavations, trenches, underground pipes and cables. This change can be considered as geological noise, acting like fractured window glass or wavered water surface preventing geophysicists from clear seeing of deeper objects. Small near surface inhomogeneities make high distortions of resistivity data because of their close position to the points of current excitation and field measurements. Distortions from small near-surface inhomogeneities are different when those are placed near current and measuring electrodes.

All that shows, that the geoelectrical characterization of an oil-contaminated area is quite complicated, and requires a correct VES application, as well as an appropriate data processing and interpretation. Our experience in canceling geological noise from many VES data after 1991 shows that the best array for that operation is two-sided pole-dipole array AMN+MNB with current electrode positions along one profile with constant step between electrodes and the same (or proportional) step between sounding points. After correct measurements of resistivity field it is possible to cancel geological noise and increase the accuracy of interpretation (to diminish fitting error and increase correlation between neighboring VES curves) in 4-5 times.

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.
- Control and monitoring of the pollution and remediation processes.

**II. Fieldwork**

In recent years, a new technological modification of VES called Electrical Resistivity Tomography (ERT) has arisen, with small step of measurements along profile for 2D study of inhomogeneous media, at using 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 geological noise we use two-sided pole-dipole AMN+MNB).

Based on the (EM and/or 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 with surface covered for concrete or asphalt;
d) Urban Area without concrete or asphalt.

Each one of these situations has some peculiarities in VES field application. In the case of covered surface there are some problems with grounding electrodes. We can solve this problem by drilling small holes for electrodes grounding.

The geoelectrical study of the oil contamination depends mainly of five aspects related with the geological environment: EM and/or geological noise level, depth of groundwater level, groundwater mineralization, time of spill happened, and physical conditions of the terrain surface.

<u>EM noise</u>: The conventional resistivity instrument uses direct current (DC). AC resistivity instrument is less affected by EM noise than DC. With AC instrument it is possible to reach

sensitivity 1000 times higher than with DC one and perform very selective and EM noise resistive measurements. In noisy environment it is possible to obtain an appropriate signal/noise relationship with AC current smaller that one need for DC measurements. In our case, AC instrument at frequency 4.88 Hz have been developed, with sensitivity 1 μV, guaranteeing reliable measurements in geological environment with high EM noise level with current value in AB line equal to 10 mA.

### III. Processing to cancel the geological noise

The filtration process with Median algorithm for canceling geological noise was described in several publications (Modin et al., 1997; Ritz et al., 1999, Shevnin et al., 2002). This processing is performed for two matrices of $\rho_a$ values (AMN and MNB) and cancels the local distortions resulted from near-surface inhomogeneities placed near the current (C-effect) and potential electrodes (P-effect). On our estimation fitting error at VES curves interpretation after application of Median program decreases 4-5 times. After that it is possible to integrate AMN and MNB resistivity sections in a single AMNB section for Schlumberger array.

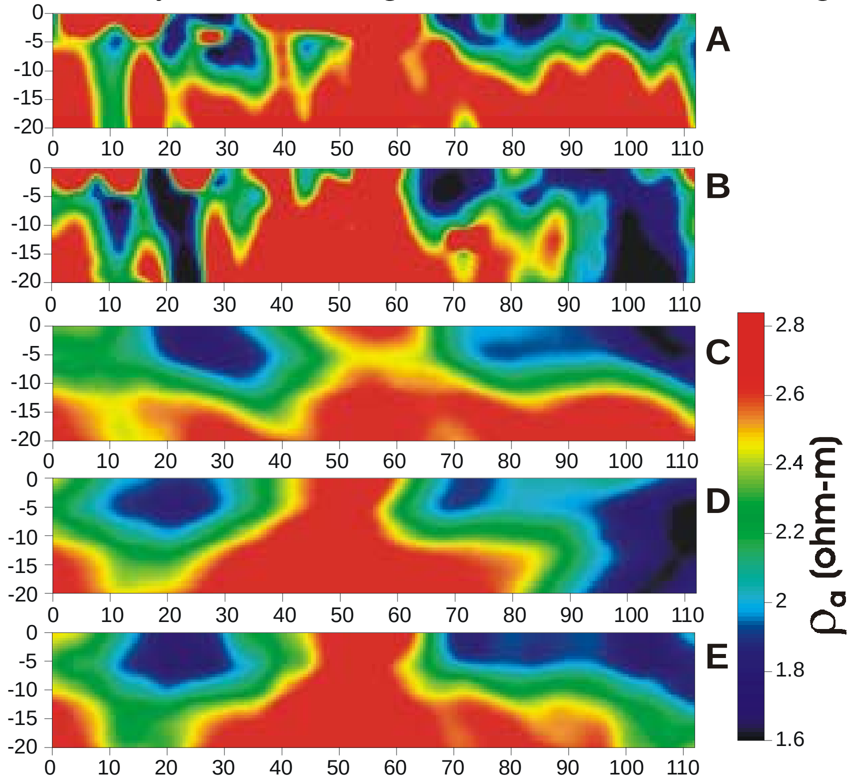


**Figure 1: Filtration process with Median program. (A) and (B): AMN and MNB sections with distortions. (C) and (D): AMN and MNB after MEDIAN. (E): Section AMNB section without distortions.**

Figure 1 shows the result of the filtration process for profile 1, Poza Rica - Campo 10, as example of urban area without concrete or asphalt on the surface. AMN and MNB $\rho_a$ vertical pseudo-cross-sections (A and B, Fig. 1) show field data as with distortions, caused by small superficial objects, preventing to have a clear view of the deeper part of subsurface. After the filtration process with the Median program, the distortions in AMN and MNB sections are canceled (C and D, Fig. 1) and finally it is possible to obtain an integrated result for AMNB array

(E), which can be interpreted qualitatively and quantitatively. On Fig. 1, E a central resistive area is observed that divide two conductive parts of the section. The interval 70-110 m presents the area with low $\rho_a$ values and can be considered as oil-contaminated zone.

## IV. Separation of contaminated and non-contaminated zones

The problem of geological interpretation of VES data at oil-polluted places consists in separation of polluted and non-polluted rocks. For this problem's decision we use theoretical calculation of rocks resistivity based on water mineralization and rocks' lithology. This approach and software were developed by A.Ryjov (Ryjov, Sudoplatov, 1990, Ryjov and Shevnin, 2002). Program "Petrofiz" can calculate different rocks' resistivity on the base of an exact physical – chemical theory. Program works is several steps. 1. Calculation of water resistivity, taking into account types of ions in solution (cations and anions), their mobility and concentration. 2. Calculation of double electric layer conductivity (between water and solid phase), taking into account properties of solution and solid phase (Ionic Exchange Capacity - IOE). IOE is zero for sand, is maximal for clay and also depends on type of clay. 3. Calculation of rock resistivity taking into account rock porosity, pore size, humidity and clay content. Program can calculate resistivity for different positions of clay in pores – as corks in capillary paths and as thin layers at capillary wall.

In Figure 2 the results of theoretical calculations on A. Ryjov program - "Petrofiz" are shown. Clay, sand and some other rocks' resistivities are considered as function of water salinity (for NaCl at 20°C). The upper horizontal dash line (d) shows measured groundwater resistivity (11 Ohm.m in this case). It is interesting to note, that at high groundwater salinity the rock resistivity graphs are situated higher than water resistivity graph (11 at Fig. 2) and practically in parallel to it. At smaller water salinity the resistivity graphs for clay – sand mixture are situated below resistivity of pore water. This case corresponds to the influence of double electric layer (DEL) in pores of clay. A vertical line (a), which crosses water line (d) at resistivity value 20 Ohm.m, shows the water salinity value 0.3 g/l. For this salinity the resistivity of clay and sand is in the range 2.3 - 80 Ohm.m. Practically in the study area some resistivity values below 2 Ohm.m were measured. We consider these areas (with resistivity below 2 Ohm.m) as oil polluted areas, in which the oil has been changed by bacterial biodegradation. Results of theoretical calculation were also used for preparing lithological legend (Fig. 2), applied for models characterization. In this legend depending on resistivity values the different rock names are used. C1 - C3 – are different clays (heavy, medium, light), L – loam (30% of clay), SL – sandy loam (10% of clay), S – sand, G or Ls – gravel or limestone with porosity below 20%. Two positions in the legend - A1 and A2 (with resistivity below 2.3 and 1.5 Ohm.m) are considered as definitely oil polluted rocks. This legend was used for geological interpretation of VES cross-

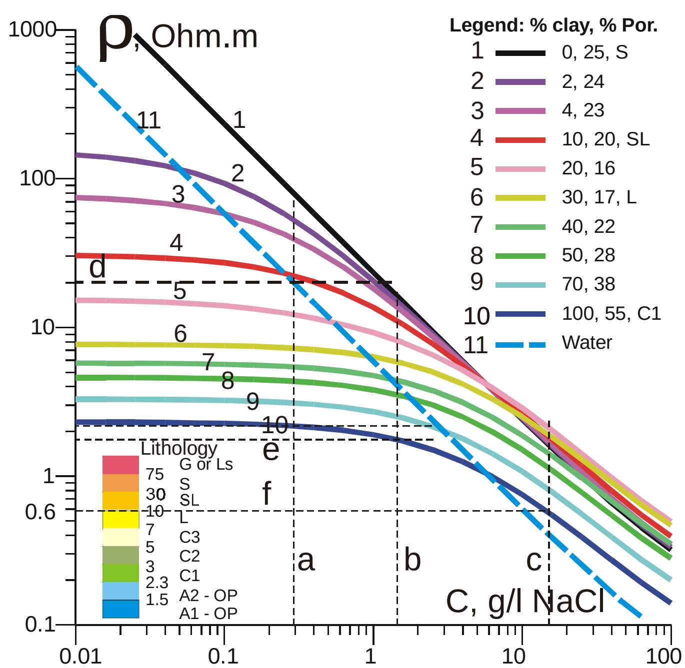


**Figure 2: Theoretical dependence of different rock's resistivity from porous water salinity.**

sections (see Fig. 3).

According to Atekwana et al., (2001) a groundwater resistivity (as a result of biodegradation) decreases about 5 times, that causes decreasing rock resistivity. A vertical line (b) for water salinity C=1.5 g/l shows that in this case the clay resistivity decreases up to 1.5 Ohm.m (line e). Practically we estimated resistivity values about 0.8 - 1 Ohm.m.

According to the properties of the double electric layer in clay, it can concentrate 50 times more ions, then in the same situation in sand. The third vertical line (c) for water mineralization 15 g/l reflects this situation. Clay at such mineralization should have resistivity 0.6 Ohm.m (line f).

## V. Estimation of position and depth of the contaminated zone, direction of groundwater migration, sources of contamination and contamination degree.

A process of interpretation, using IPI2Win program (developed by Bobachev, MSU) is carried out for each sounding and every profile. Figure 3 shows the geoelectrical model for profile 1, Campo-10. A contaminated zone (in the second layer) is presented at the interval 82-112 m, at 1.5 m depth. The polluted layer increases its thickness toward the end of profile (from 2 to 6 m). After interpretation of each profile, polluted layer can be mapped, localizing the polluted zone in the study area.

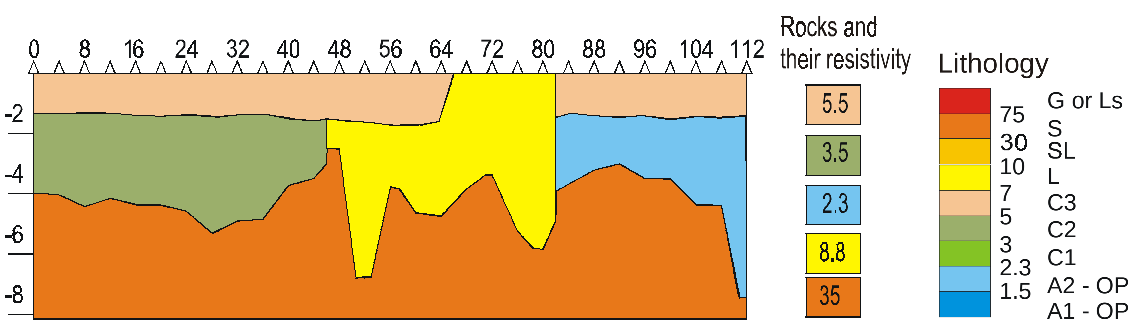


**Figure 3: Geoelectrical model of the profile 1, Campo-10, Poza Rica.**

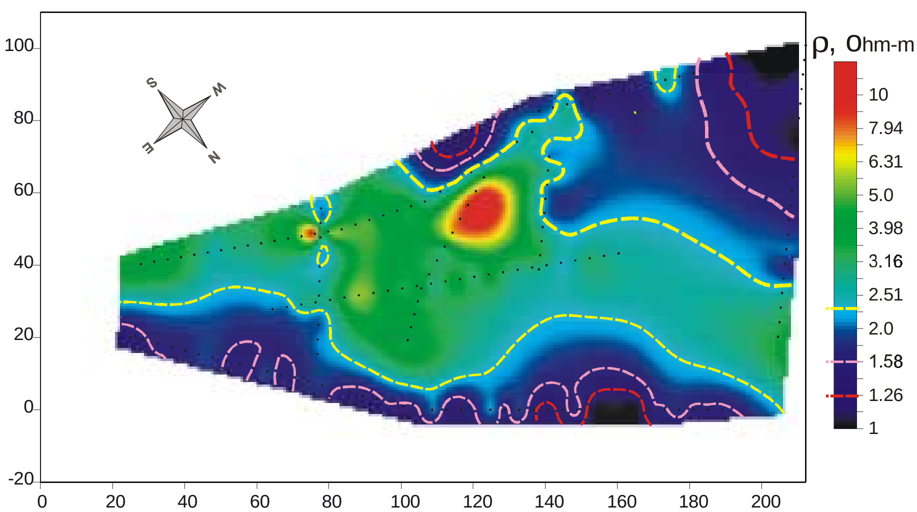


**Figure 4: Map of the second layer resistivity. Dashed lines mark different levels of resistivity and pollution.**

Now, it is possible to analyze oil-contaminated zones in the study area, to locate the pollution sources and direction of pollutants migration.

The map of the second layer resistivity (oil-contaminated layer) is shown in Figure 4. We proposed two zones of minimal resistivity (maximum pollution zones) toward the East and West sides of study area, separated by the more resistive zone with N- S trend. This could imply the existence of a resistive structure controlling the behavior of local groundwater flow. The general direction of the groundwater flow in this area is N-S, as well as the contaminants migration.

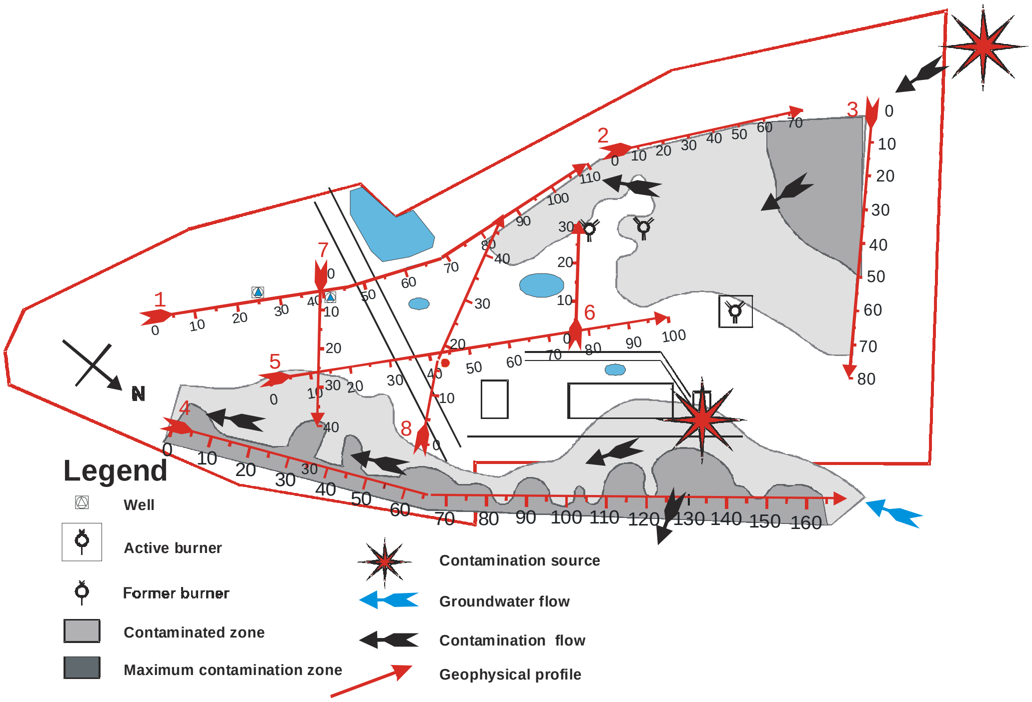


**Figure 5: Sketch of study area including obtained results**

We can.suppose, that the pollution sources could be defined starting from the minimum resistivity zones in the Figure 4 (maximum contamination zones). These zones are:

- Unload tank (point 160 m of profile 4) and,
- West end of study area (end of profile 2 and beginning of profile 3). We think that the source of pollution in this zone is situated approximately at 70 m outside of the Campo 10 (there are oil tanks here).

The obtained results are incorporated to sketch of study area (Fig. 5), where the pollution sources and zones with different grade of contamination are located.

## CONCLUSIONS

1. - The resistivity method was applied for the geoelectrical characterization of oil-contaminated area and the presence of oil contamination was marked by conductive zones.

2. - Application of AC resistivity instrument allows obtaining reliable data in case of high EM noise level.

3. – In case of high level of geological noise, reliable results are obtained applying filtering process, canceling the distortions caused by small superficial objects.

4. - With petrophysical modeling and statistical processing of VES curves, it is possible to separate the contaminated and no-contaminated areas in the study area.

5. – Geoelectrical modeling results joint to the hydrogeological information allow to estimate the position, sources and migration direction of the pollutants, as well as grade of contamination.

6. – In Campo-10 it was possible establishing zones with different grade of contamination, related with location of pollution sources and groundwater flow. Oil unload tank was identified like one pollution source, besides the existence of a second source toward the West end, outside of the study area was proposed.

**ACKNOWLEDGMENTS**

We acknowledge the valuable help of Luis Fernandez-Linares and Hector Zegarra-Martínez in the fieldwork at Campo-10.

**REFERENCES**

Abdel-Aal, G. Z., D. D. Jr. Werkema, W. A. Sauck, 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. Jr. Werkema, 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.

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. 267-270.

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. Improvement to resistivity pseudosection modeling by removal of near-surface inhomogeneity effects: application to a soil system in south Cameroon". Geophysical Prospecting, 47, 85 – 101.

Ryjov A.A., 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, 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., 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, pp. 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. Sanchez, V. Korolev, 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.