STUDY OF PETROLEUM CONTAMINATED SITES IN MEXICO WITH RESISTIVITY AND EM METHODS

Vladimir Shevnin, Mexican Petroleum Institute, Mexico city, D.F.
Omar Delgado Rodriguez, Mexican Petroleum Institute, Mexico city, D.F.
Aleksandr Mousatov, Mexican Petroleum Institute, Mexico city, D.F.
Hector Zegarra Martinez, Mexican Petroleum Institute, Mexico, D.F.
Jesus Ochoa Valdes, Mexican Petroleum Institute, Mexico city, D.F.
Albert Ryjov, Moscow State Geological Prospecting Academy, Russia.

Abstract

Hydrocarbons are among the main factors of geological medium contamination. We differentiate long-term contaminations lasting years or decades of years and short-term contaminations or single accidents. The first produces give more evident geophysical anomalies, whereas anomaly strength of the second depends on the time since the accident occurred. After 6-12 months following the accident this type of contamination gives measurably low resistivity anomalies.

Our experience with contaminated sites characterization in Mexico shows that low resistivity anomalies caused by hydrocarbon contamination is possible to localize with the help of vertical electrical sounding (VES) or with electromagnetic profiling (EMP). Such contamination gives low resistivity anomaly as a result of petroleum biodegradation at shallow depth in the earth. It is more difficult to characterize the second type of contaminated sites because the anomalies are not as intensive. Short-term contamination is more abundant in the oil industry.

Introduction

Study of oil biodegradation with the help of laboratory reactors (Atekwana et al., 2001) and in the field demonstrates that the most evident changes (decreasing) of ground resistivity take place above groundwater level in the lower part of the vadose zone (Abdel-Aal et al., 2001). In field studies, such low resistivity layers were found in the lower part of the vadose zone by W. Sauck (1998, 2000), D. Werkema et al. (2002, 2003) with the help of vertical resistivity probe (VRP).

During last year of investigation our group studied 8 different sites of oil contamination in Mexico. These sites are different in contamination age and scale, depth of groundwater level (GWL), environment and surface conditions and the cause of contamination. Some information about these sites is in Table 1.

Table 1.: List of contaminated sites studied with geoelectrical methods (VES and/or EM profiling)

N	**Name of site**	**Origin of contamination**	**Environment**	**Surface**	**Depth of. GWL, m**	**Cont. age, years**
1	Paredon, Tabasco	Oil borehole	rural	Open	1.5-2	35
2	Campo – 10, Veracruz	Oil wastes utilization plant	rural & industrial	Open	1.5-2	30
3	Reynosa, Tamaulipas	Oil refining factory	rural	Open 60%	10-15	50
4	Km 42, Tabasco	Pipeline accident	rural	Open	3-4	1
5	La Venta, Tabasco	Pipeline accident	rural	Swamp	0	1
6	Altace, Mexico city	Oil products storage	industrial	Concrete 90%	4	15
7	Sanchez Magallanez, Tabasco	Pipeline accident	rural	Swamp	0	1
8	Km 124, Tabasco	Pipeline accident	rural	Open	1-4	1

This field and interpretational experience demonstrated possibilities (and restrictions) of VES and EMP methods and their interrelation with geochemical methods of contamination study. Preliminary study of contamination area with geoelectrical methods before application of geochemical methods has more advantages when groundwater level depth is more than 1 m, when superficial layer is hard enough to obtain soil samples, when the ground is covered with asphalt or concrete layer. In all these cases geoelectrical methods give valuable information for planning and optimizing geochemical probing. And geoelectrical methods can give more detailed maps of contamination zones than geochemical sampling. Depth position of contamination obtained with geoelectrical methods help to avoid perforation into aquifer to diminish risk of petroleum contamination of this layer during sampling process. VES method gives valuable information about aquifer and aquiclude layers, helps to calculate their filtration coefficients on known formulas (Salem, 2001) and to estimate aquifer vulnerability (Kirsch et al., 2003).

Geoelectrical Results and Considerations

VES results visualization.

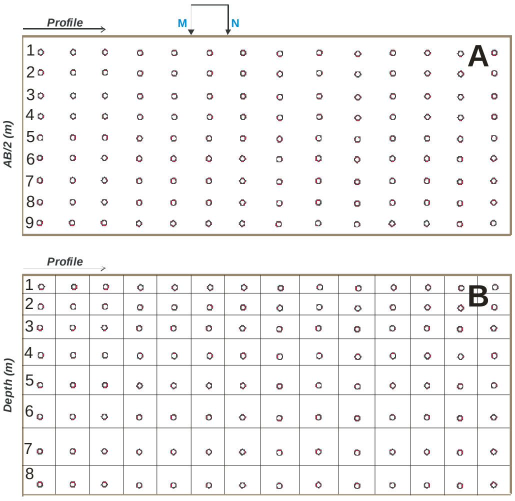

Figure 1.: Matrix of apparent resistivity data obtained with vertical electrical soundings along profile on Electrical Imaging technology (A) and matrix of 2D data interpretation (B).

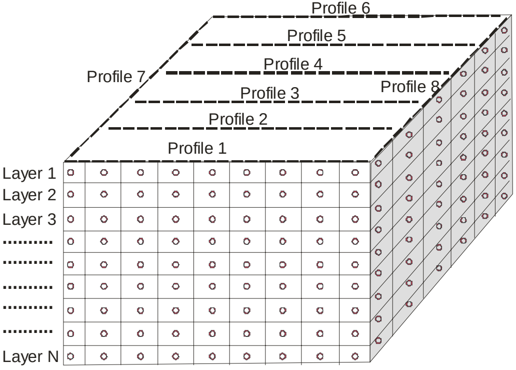

Figure 2.: Presentation of VES survey along profiles as data cube.

Vertical electrical sounding (VES) application on contaminated site has the purpose to characterize contamination with depth and in plan. For that purpose a system of profiles is used. Each site is being crossed by profiles with multi electrodes measuring technology called in some papers as Electrical Resistivity Tomography (ERT) or Electrical Imaging (EI). Such profiles measurements allow two-dimensional interpretation. We used for 2D interpretation software Res2DInv (Loke and Barker, 1995, 1996).

This 2D interpretation has several good features that made the interpretation results suitable for different visualizations. Resulting model has the same layers number for all soundings along all profiles of the site. Thicknesses of all blocks in the same layer are equal. With the help of additional software X2IPI (Bobachev, 2003) it is possible to convert Res2DInv model into IPI format model having the same blocks widths in all layers and reference points exactly below each sounding point (Figure 1). After that with the help of IPI2Win software (Bobachev, 1994), we create files in Surfer format both as sections for each profile and maps for each layer. Due to these possibilities we call VES data collection for each site as data cube (Figure 2). In some cases we construct not only horizontal maps, but maps for any surface inside the cube (dipping or curved). The last feature is useful when we have evident layers dip at the site (Delgado et al., 2004).

What form of VES data visualization is better, sections or maps? Visualization in sections has less interpolation between measuring points. For maps construction we need interpolate between profiles. But maps have less resistivity range than sections (electrical properties change more with depth than in plan) (Figure 3). As a result we can reach more resolution in maps visualization that gives us possibility to localize weaker anomalies. To increase visualization

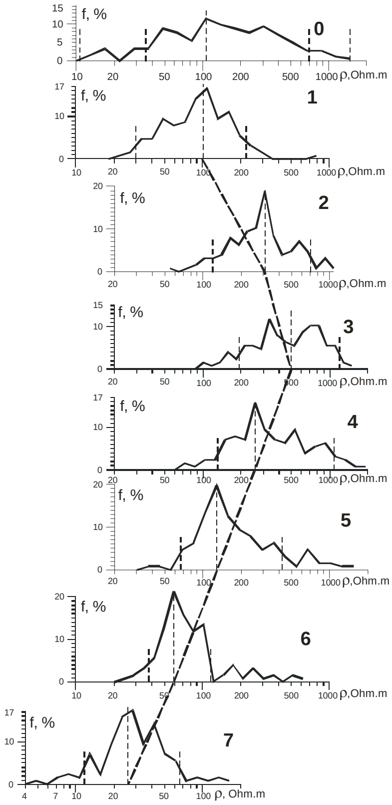

Figure 3.: Histograms for each horizontal layer in data cube for the site Km124 (1-7) and histogram for all resistivity sections (0).

resolution we apply statistical distribution analysis (histograms) to adjust resistivity range (Figure 3) and color scale range. Without special adjustment of resistivity range frequently it is not possible to localize oil contamination anomalies on sections and maps.

Table 2.: List of initial and adjusted histogram ranges (Figure 3)

Sample collection	**Rho min, Ohm.m**	**Rho max, Ohm.m**	**Range max/min**	**Adjusted Rho min, Ohm.m**	**Adjusted Rho max, Ohm.m**	**Adjusted range max/min**
All data	10	1600	**160**	35	700	**20**
Layer 1	20	350	**17**	30	220	**7.3**
Layer 2	65	1000	**15**	120	700	**5.8**
Layer 3	100	1500	**15**	200	1300	**6.5**
Layer 4	60	1600	**27**	140	1100	**7.9**
Layer 5	55	1000	**18**	67	420	**6.3**
Layer 6	38	140	**7**	38	140	**3.7**
Layer 7	6	80	**13**	13	65	**5**
Mean value	of range		**16**			**6**

In case of aged contamination resistivity ratio between uncontaminated and contaminated soil is between 2 and 5. To localize anomaly of contamination we need to use maximum resolution of visual presentation and it is easier to obtain in case of maps. But both forms sections and maps help us to formulate idea of contamination distribution in space.

Contamination Indicator's Horizon

W. Sauck and his colleagues applied for localization of contamination with depth vertical resistivity probing (VRP) method that is a kind

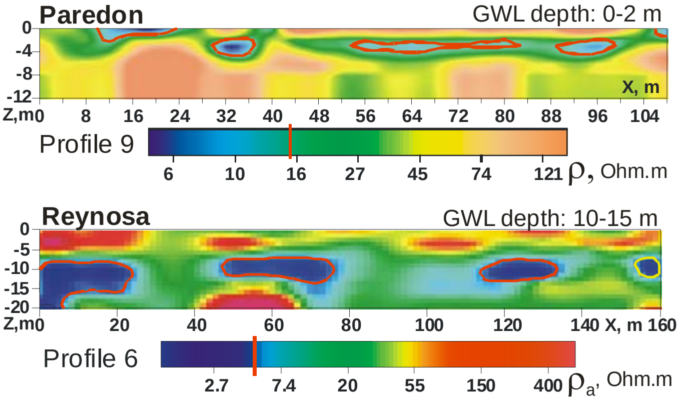

Figure 4.: Appearance of contaminated zones on resistivity sections

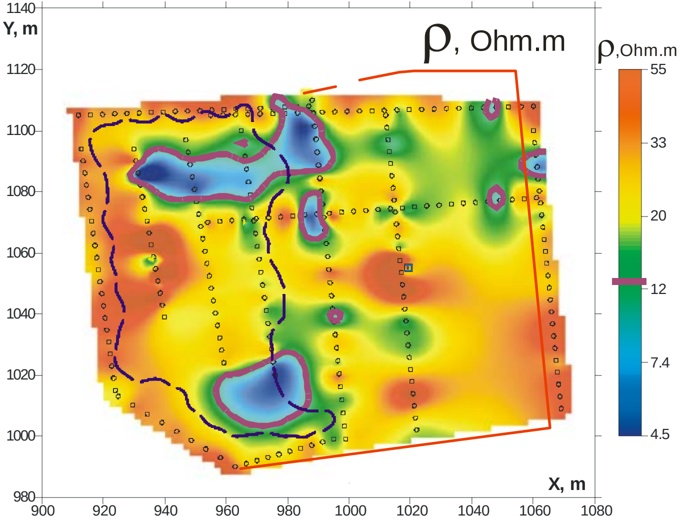

Figure 5.: Resistivity map for contamination indicator's horizon at the site Paredon.

of resistivity log in shallow boreholes (Sauck, 1998; 2000; Werkema et al., 2002). They found that aged contamination appears as low resistivity horizon a bit above ground water level.

Vertical electrical sounding in multi electrode configuration and 2D interpretation can also localize this layer. In some cases it is possible to see this layer in resistivity cross-sections (Figure 4) in other cases in maps. We called this horizon as contamination indicator. To characterize oil contamination in plan we build resistivity maps at the level of the contamination indicator's horizon. When we can localize this layer on resistivity sections we reorganize data to make a map of this horizon (Figures 5-6). Such map gives optimal presentation of contamination position in plan.

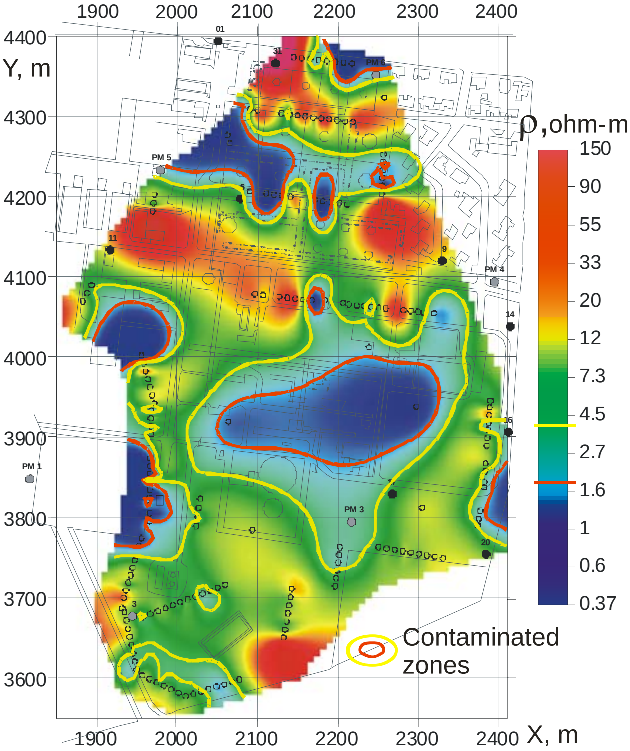

Figure 6.: Resistivity map for contamination indicator's horizon at the site Reynosa.

Recalculation of Soil Resistivity into Petrophysical Parameters

Soil resistivity depends on water content and its salinity, clay content, porosity and some other factors. There are a lot of models describing dependence of soil resistivity from these factors (Archie (1942), Waxman and Smits (1968) and many others). We use petrophysical model developed by A.Ryjov (Ryjov, 1987; Ryjov, Sudoplatov, 1990). If model describes dependence of soil resistivity from some factors we have a chance to find some of these petrophysical factors from soil resistivity data. In laboratory we measure soil resistivity versus water salinity and estimate clay content, porosity and cation exchange capacity (Shevnin et al., 2004). It is possible also to estimate these three parameters for soil resistivity (estimated from VES interpretation) and constant water salinity. Using this approach we can recalculate resistivity cross-sections and maps into petrophysical cross-sections and maps. For uncontaminated soil these parameters (clay content, porosity and cation exchange capacity) are close to true petrophysical parameters, estimated with traditional methods in laboratory. For contaminated soils we receive anomalous

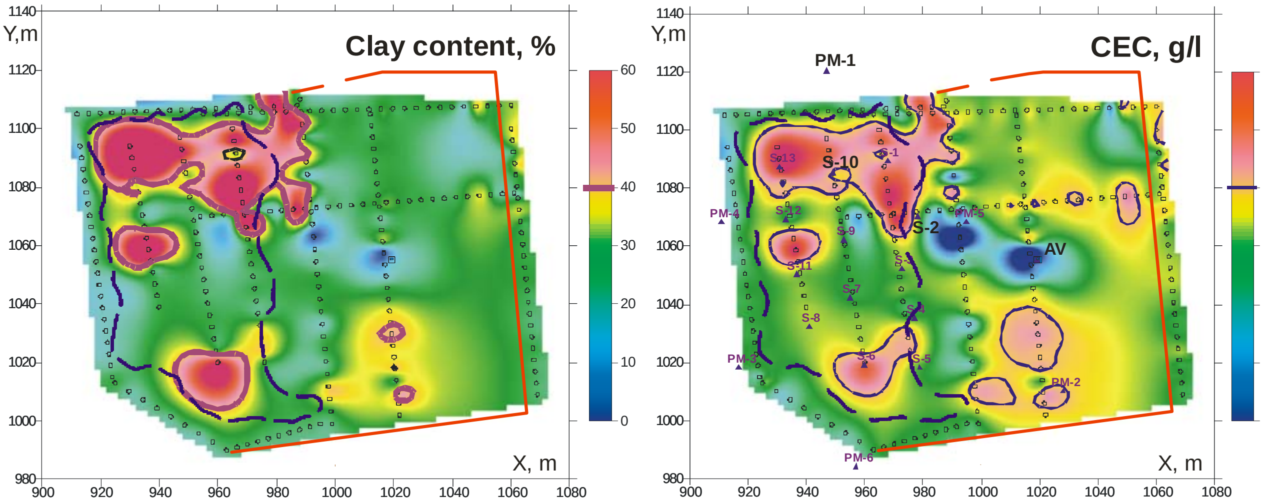

Figure 7.: Maps of clay content and cation exchange capacity for the site Paredon.

parameters, but these parameters help us to localize contamination. Mature contamination gives increased clay content and CEC and anomalous porosity (increased or decreased depending on clay content in soil). This apparent change of petrophysical parameters reflects real increase of superficial conductivity in contaminated zones (Abdel Aal et al., 2004). For example direct measurements of clay content at site Paredon (both geological laboratory determination and geoelectrical sampling ρ(C) curve) shows that maximum clay content is 40%. But at the map of clay content in figure 7 contaminated areas show anomalous clay content between 40 and 60% (boundary line is 40%).

Application of Electromagnetic Profiling Method for Oil Contamination Mapping

Electromagnetic profiling can be also used for oil contamination mapping. We applied EM-31 instrument (Geonics) for this purpose. In some cases we obtained similar information like VES (Figure 4), but 8-10 times more rapidly (Figure 8). EM has higher horizontal resolution, whereas VES has good vertical resolution. In some areas we can use both methods. In other situation (concrete cover with steel bars) EM profiling can't be applied. Sometimes VES method is difficult to apply (for example in swamp areas) and EM profiling is the only possible method of geophysical mapping.

We visualized EM profiling results in the form of apparent resistivity instead of conductivity maps to make these results similar to VES resistivity maps.

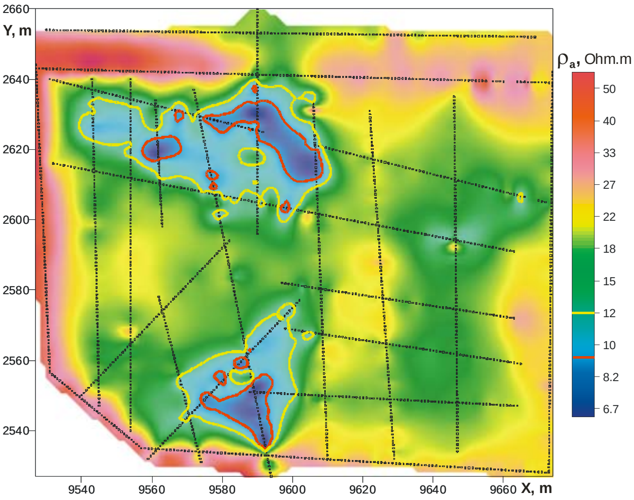

Figure 8.: Apparent resistivity map of the site Paredon obtained on EM mapping with EM31.

Because of these maps (from VES and EMP) similarity we performed recalculation of EMP resistivity maps into petrophysical maps (taking into account groundwater salinity). This operation is not correct because we use apparent resistivity instead of true resistivity, but in some cases we received good results similar to VES method (Figure 9 in comparison with Figure 7). To recalculate EMP resistivity maps into petrophysical maps we need information about water salinity (or water resistivity) that is not a problem in swamp area.

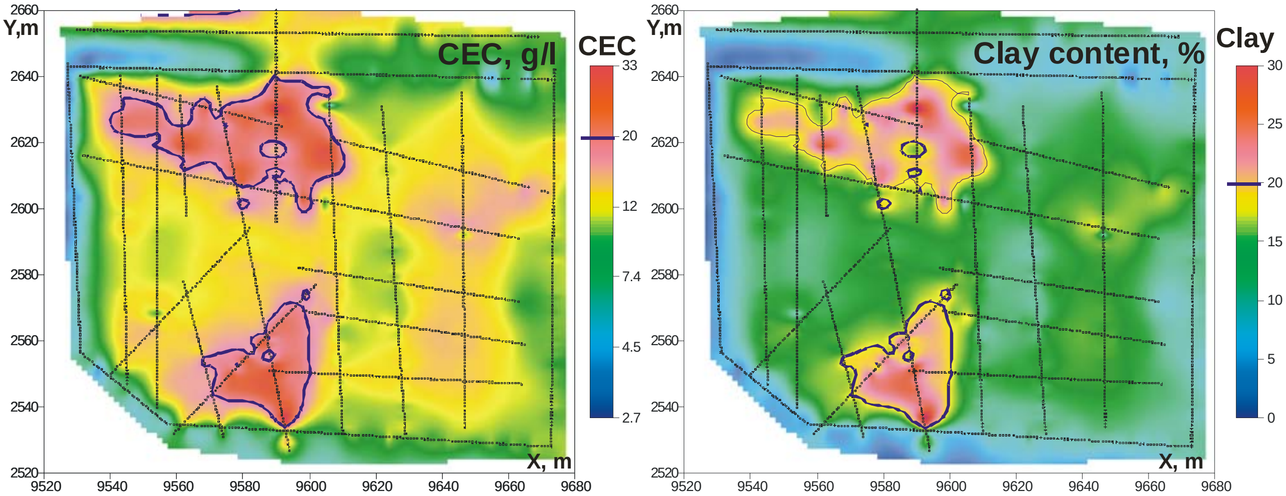

Figure 9.: Maps of clay content and cation exchange capacity for site Paredon estimated for apparent resistivity map (Figure 7).

Example of Contamination Study at the Site Km 124.

Oil contamination at this site occurred one year before our study as a result of pipeline leakage. Area of accident is situated at 25 meters from small artificial lake used for fish-breeding. This area has a lot of rains that sometimes changes water level in the lake at 2.5 meters. As a result groundwater level also changes and oil contamination is smearing in soil at 2-3 meters depth interval. This situation is demonstrated at figure 10 as a series of maps for the depth 1, 2, 3 and 4 meters approximately. In this case we use soil porosity like contamination indicator, but other parameters (soil resistivity, clay content and cation exchange capacity) show similar anomalies resulted in oil contamination.

At figure 11 there are histograms for 4 parameters: resistivity, clay content, porosity and cation exchange capacity. Grey intervals show anomalous values of each parameter resulted in contamination. In our opinion clay content and porosity in figure11 have more resolution between uncontaminated and contaminated zones. That is why we used porosity to demonstrate contamination in figure 10.

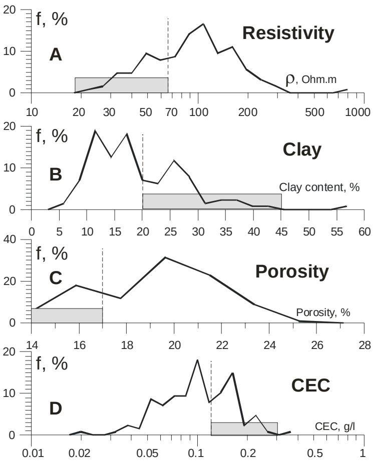

Figure 11.: Histograms for resistivity, clay content, porosity and CEC (Km 124). Gray blocks - anomalous values of each parameter.

Figure 12 demonstrate physical parameters distribution with depth estimated from mean VES data for each layer of 2D interpretational model. Upper part of section until 5 m consist of pure sand. After 5 m it is sandy loam with clay content about 10%. Filtration coefficient was calculated using the formula published in the paper (Salem, 2001): $K_f = 0.6653 \cdot F^{2.09}$, (m/day), where $F=\rho_{soil}/\rho_{water}$. In the paper (Custodio, Llamas, 1983) filtration

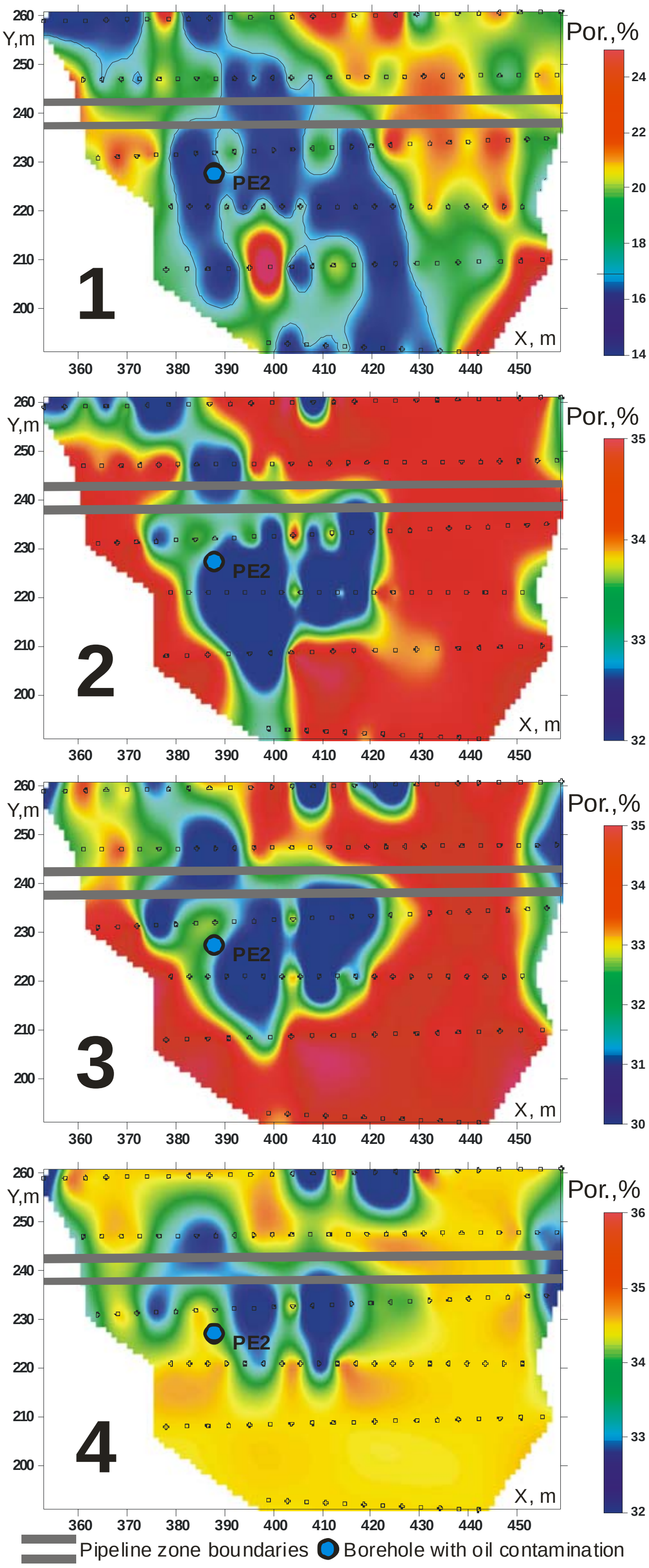

Figure 10.: Maps of porosity for 4 layers calculated from resistivity maps for the site Km 124.

coefficient for soil like in site Km 124 is in interval 1.7 - 8.6 m/day that is in good agreement with our determination (1.2 - 16 m/day) based on soil and water resistivity.

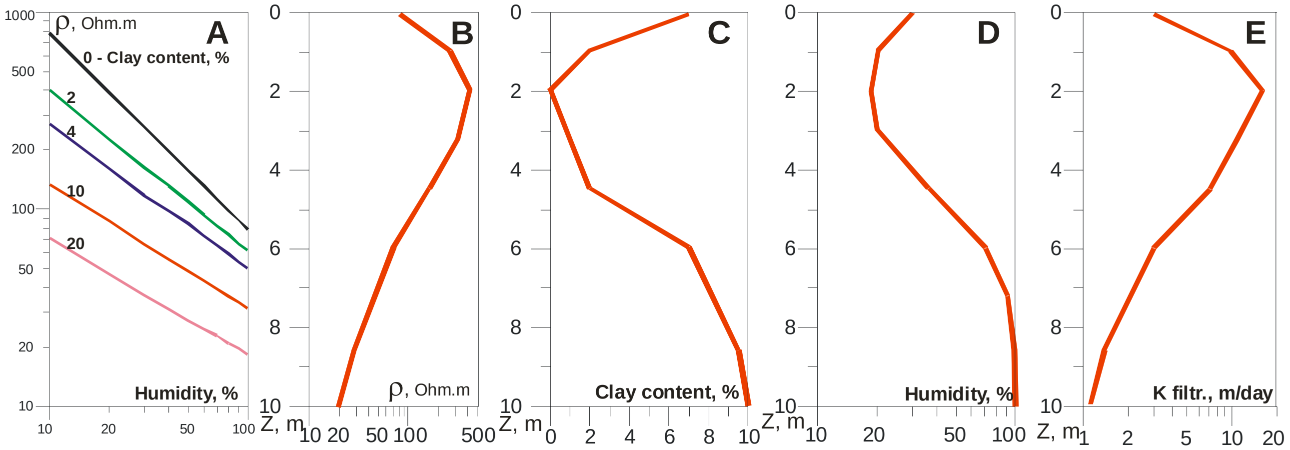

Figure 12.: Distribution of resistivity (B), clay content (C), soil humidity (D) and filtration coefficient (E) with depth. A - Theoretical dependence of soil resistivity from clay content and humidity.

Conclusions

1. Vertical resistivity cross-sections normally have greater resistivity range than maps (electrical properties change more with depth than in plan) that makes their visualization with the purpose of contamination localization more difficult. In most cases we can't reach needed resolution without adjustment of resistivity intervals and color scale range with the help of histograms. Higher visual resolution obtained in maps gives us possibility to localize weaker anomalies.

2. Vertical electrical sounding in multi electrode configuration and 2D interpretation can localize contamination indicator's horizon at the aged contaminated sites when groundwater level (GWL) is at a depth from 1 to 15 m. This horizon is located close and slightly above GWL. For better characterization of oil contamination in plan we recommend preparing resistivity maps for the level of the contamination indicator's horizon.

3. For soil resistivity recalculation into petrophysical parameters we need to know groundwater salinity (determined from water resistivity). Using this approach we can recalculate resistivity cross-sections and maps into petrophysical cross-sections and maps. For uncontaminated soil estimated petrophysical parameters (clay content, porosity and cation exchange capacity) are close to true petrophysical parameters, found with traditional methods in laboratory. For contaminated soils we receive anomalous parameters, but these parameters help us to localize contamination. The true cause of apparent change of petrophysical parameters in contaminated zones resulted in increase of superficial conductivity as was found by Abdel Aal et al. (2004). Joint usage of resistivity and petrophysical parameters helps receiving more detailed characterization of uncontaminated and contaminated soils.

4. EMP method faster acquires data and has more horizontal resolution in comparison with VES. Each method has its own advantages and disadvantages at contamination study. In some cases we can recalculate apparent resistivity values of EMP method into petrophysical parameters taking into account groundwater salinity.

5. Field study of contaminated sites includes VES or EMP methods and water resistivity measurements. Sometimes we make soil resistivity study versus water salinity in the laboratory to estimate soil characteristics: clay content, porosity and cation exchange capacity with maximum accuracy.

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