A POSSIBILITY OF AN ELECTROMAGNETIC TECHNIQUE TO LOCATE OIL RESERVOIR BOUNDARIES ON BASIS OF ANALOGUE MODELING EXPERIMENTS

L Szarka¹, Z Nagy²

According to the results of analogue modeling experiments, the boundary of circular oil reservoir models (which usually have higher resistivity than the host rock) can be detected by surface electromagnetic measurements. The method needs one surface- and one lowered current electrode placed in an off-centre borehole. From an areal distribution of the individual electromagnetic field components by a simple normalization procedure, information concerning the boundary of the oil reservoir models can be obtained. In the paper the most promising $E_r$ and $H_z$ analogue modeling anomalies are presented in detail.

Keywords: analogue modeling; electromagnetic methods; oil reservoir; reservoir boundary

Introduction

Boundaries of discovered oil reservoirs, usually remain unknown in spite of they are penetrated by several boreholes. Their identification by electromagnetic methods has been an unsolved problem. In this paper possibilities of a special controlled source electromagnetic method, somewhat similar to the VSP are described on basis of analogue modeling experiments: one current electrode is put to the mouth of a borehole penetrating the oil reservoir, and the second current electrode is lowered into the same borehole below the reservoir, and on the surface electric and magnetic components due to the vertical electric dipole are measured. The original idea of this measuring arrangement comes from DC field experiments by Nagy (1970). Assuming simple circular models with higher resistivity than that of the host rock, a close connection was found according to the analogue modeling results between the areal distribution of different electromagnetic components. This technique can be directly applied in the field.

It was also found that a routine-like application of the CSAMT method must not be successful.

¹Geodetic and Geophysical Research Institute of the Hungarian Academy of Sciences, H-9401 Sopron, POB 5, Hungary
²Geophysical Exploration Company, H-1068 Budapest, Gorkij fasor 42, Hungary

Akadémiai Kiadó, Budapest
Description of the modeled problem

In Fig. 1 a typical cross section including a circular oil reservoir model is shown. The oil reservoir model was made of high resistivity plexiglass and the host rock was represented by NaCl-solution. Small copper rings were used as current electrodes. Three different borehole positions (one central and two off-centre ones) and three different buried electrode depths were studied.

![Diagram of the modeled problem](image)

Fig. 1. Cross section of the analogue modeling problem. Nine different current electrode positions (three borehole positions and for each borehole three different B electrode depths) were applied. Distance between measuring sites is 2.5 cm.

The question was how the effect of the reservoir model is reflected in different electromagnetic components in the near and intermediate zones (in the range $0.3 < k \cdot R < 10$, that is in the frequency range 0.125–4 MHz. $k$ is the wavelength in the hostrock and $R$ is the distance between the borehole and the measuring sites).

Anomalies over an oil reservoir model having a certain depth and size are influenced by numerous factors, like: depth of the buried electrode, mutual position of borehole and model, frequency of the electromagnetic field, well-casing, near-surface geological inhomogeneities, etc.

The present results refer to a single model radius/sediment thickness value (this ratio is 1) and the model depth/borehole depth ratio was in the range 0.6–1.0. Two different plexiglass models: a solid and a perforated one were used. The difference between them proved to be insignificant (smaller than 2–3 p.c.) for all components. Effects of well casing and near surface geology were neglected. Nevertheless, the model measurements give general information about exploration possibilities of such structures.

The technical details of the model laboratory are summarized by Márcz et al. (1986).

Theoretical and practical considerations

It is well known that the surface electric field due to a vertical electric dipole submerged in a layered half space has radial and vertical components. In presence
Table I. Radial electric and the tangential magnetic field normalized to those measured in absence of the oil reservoir model as a function of the borehole position and the electrode-depth (Numbers are according to Fig. 1)

a) Maximum values of the normalized electric field $E_r$ along the measuring profile shown in Fig. 1

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<thead>
<tr>
<th>Depth</th>
<th>Borehole position</th>
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<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.4–1.2</td>
</tr>
<tr>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
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</tbody>
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b) Maximum value of the normalized magnetic field $H_t$ along the measuring profile shown in Fig. 1

<table>
<thead>
<tr>
<th>Depth</th>
<th>Borehole position</th>
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<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
</tr>
<tr>
<td>1</td>
<td>1.7</td>
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<tr>
<td>2</td>
<td>3.5</td>
</tr>
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</table>

of lateral inhomogeneities these two components are modified, and at the same time — on condition that the cylindric symmetry is distorted — a tangential field component appears, too.

The magnetic field around this transmitter is due to currents flowing in the earth and currents flowing in the cable section connecting the electrodes. In case of cylindric symmetry neither the cable currents nor the earth currents have vertical and radial magnetic field components on the surface. In addition the tangential magnetic field component on the surface must be zero, too, since the earth- and the cable currents have just opposite and equal tangential magnetic fields (Veitch et al. 1990).

Consequently all magnetic components are in theory due to any deviation from the cylindrical symmetry. Circular oil reservoir models penetrated by central boreholes (like $A_0B_0$ in Fig. 1) cannot be detected by superficial magnetic components.

Geometric inaccuracies because of non-vertical boreholes may appear in all components, but they affect more significantly $E_t$, $H_t$, $H_r$ and $H_z$ than $E_r$ and $E_z$.

In the following analogue modeling results will be discussed. Two different techniques were used:

— at first, electromagnetic field components in presence and in absence of oil reservoir models were compared along a characteristic profile (in the case of $E_r$ and $E_z$ it was a normalization to the reservoir-free primary field; in the case of other components not having primary field, it was a simple normalization just to the analogue modeling noise);

— then the areal distribution of the electromagnetic field components were studied in details.

Effect of borehole positions and electrode depths

The effect of electrode depths and borehole positions is summarized in Table I for the $E_r$ and $H_t$ components. (Both components were normalized to their reservoir-free values.) If electrode B was below the model (electrode depths 1 and 2), both the magnetic and electric field values significantly increased compared to the corresponding reservoir-free values. The eccentricity also has a favourable signal-enhancing effect for both components. Therefore in the followings results are shown for off-centre boreholes and for the deepest B$_2$ electrode-position.

Radial electric field
in case of off-center borehole

Fig. 2. Normalized (reservoir/reservoir-free) $E_r$ profiles over the model boundary at different frequencies

In Fig. 2 normalized $E_r$ profiles at six different frequencies are shown for current electrodes A$_2$-B$_2$. At lower and lower frequencies the maxima appear somewhat farther and farther away from the model boundary. (The corresponding $H_t$ profiles have similar maxima over the DC maximum site of that of the electric component, but they do not have any frequency dependence.) From the two similar maxima in $E_r$ and $H_t$ it follows that the conventional impedance $E_r/H_t$ is less sensitive to the model boundary than the electric and magnetic components separately.

Since the reservoir-free values in field conditions are not known, the normalization shown in Fig. 2 cannot be carried out in the practice. The problem is how to find a convenient normalizing function instead of the reservoir-free electromagnetic profiles.

Fig. 3. Plane view of the modeled problem, showing 16 measuring profiles and the measuring sites over a circular oil reservoir model penetrated by an off-centre borehole

The proposed method

In Fig. 3, 16 measuring profiles having radial directions around the borehole were selected. Each profile had equidistant measuring sites in the vicinity of the expected boundary.

In Fig. 4a and in Fig. 5a, resp. measured $E_r$ and $H_z$ profiles are shown along the 1–8 profiles. The difference between them is not significant. In Figs 4b and 5b profiles 1–8 after normalization by the mean curve of the 16 measured ones are shown: in the normalized $E_r$ profiles the maximum sites depend on the horizontal position of the boundary along the actual profile; in the corresponding $H_z$ profiles the boundary is connected by a sharp minimum zone. In Figs 4c and 5c normalized $E_r$ and $H_z$ maps are shown. The effect of the boundary in $E_r$ is not everywhere expressed: far from the borehole it is more emphasized than in its close vicinity. At the same time (see Fig. 5c) the oil reservoir model is unambiguously surrounded by a $H_z$ minimum zone.

It must not be forgotten that this normalizing procedure does not work in the case of a central borehole. Fortunately in the practice the probability of a perfect cylindrical symmetry is near to zero.

Fig. 4. $E_T$ anomalies over a circular oil reservoir model at a characteristic intermediate-zone ($f = 1$ MHz). a) Measured $E_T$ profiles along profiles 1–8 (in relative units); b) Normalized $E_T$ profiles along profiles 1–8 (see the maxima closely connected to the model boundary); c) Normalized $E_T$ map over the measuring area, showing local maximum zones far from the borehole
Fig. 5. $H_z$ anomalies over a circular oil reservoir model at a characteristic intermediate zone frequency ($f = 1$ MHz). a) Measured $H_z$ profiles along profiles 1–8 (in relative units); b) Normalized $H_z$ profiles along profiles 1–8 (see the sharp minima closely connected to the model boundary); c) Normalized $H_z$ map over the measuring area, showing a sharp minimum zone surrounding the model.

In spite of the apparently better resolution of $H_z, E_r$ proved to be much more reliable from technical points of view, because the $H_z$ anomaly is much more sensitive to geometry inaccuracies which might even destroy the $H_z$ anomaly image. Anyway, borehole-geometry based corrections are strongly proposed to be carried out for all components.

Behaviour of other components (both amplitude and phase) was also studied. The phase curves along different profiles had a systematic variation (up to 10 degrees), but an appropriate normalizing procedure for the phase was not found.

Finally it must be remarked that in the case of using the mean curve for the normalization, the frequency dependence of the normalized profiles practically disappeared (even for $E_r$) in contrast with that shown in Fig. 2. It means that in such a situation the quasi-stationary current deflection is the dominant effect.

Conclusions

The boundary of oil reservoir models having higher resistivity than the host rock can be detected by a simple surface electromagnetic technique. The proposed method needs a reservoir-penetrating off-centre borehole. (Boreholes in the centre of a circular structure are to be avoided.) Having one current electrode on the surface, and the second one in the borehole below the reservoir, the current deflection due to the reservoir results in typical electromagnetic field distortions on the surface.

From individual electromagnetic field components measured along different profiles radiating from the borehole, a mean curve for each component can be derived. Normalizing the individual measuring profiles to the mean curve, boundary-dependent anomalies can be determined. The $E_r$ component has lower resolution, but it is less sensible to borehole inaccuracies than the other components.

References

Márcz Gy, Pongrácz J, Szarka L 1986: *Scientific Instrumentation*, 1, 119–133.