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Measuring Formation Anisotropy Using Multifrequency Processing of Transverse Induction Measurements

L.A.Tabarovsky, Baker Atlas, and M.I.Epov, Russian Academy of Science, and M.B.Rabinovich, Baker Atlas

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Abstract

Multi-frequency processing of transverse induction measurements (3D Explorer - 3DEX™) allows us to reduce the distortion of interpretation by near-borehole effects. Recently, we have developed a multi-frequency processing technique for determining formation anisotropy in vertical and deviated wells. The method, based on a separation of induction and galvanic modes, provides a fast and stable indicator of anisotropy in real time.

We consider a borehole oriented along the Z-axis. Axes X and Y are positioned in a perpendicular plane. The set of measurements under consideration includes XX, YY, and ZZ data. The magnetic field XX is excited by an X-oriented transmitter and measured by an X-oriented receiver. Similar definitions are true for YY and ZZ components.

We start processing by performing a multi-frequency skin-effect correction on the measured XX, YY, and ZZ data. Correction pre-conditions the data for rotation from the tool coordinate system to the formation coordinate system. As a result of the rotation, we calculate responses XX', YY', and ZZ' where axis Z' is orthogonal to the formation boundaries. Axes X' and Y' belong to the boundary planes. The rotation of multi-frequency processed data does not require knowledge of the full tensor of electromagnetic measurements: the rotation can be done only with the principle components XX, YY, and ZZ.

Rotation isolates the induction mode in the ZZ component and removes the dependence on the vertical conductivity. This allows for applying a very fast processing technique to calculate horizontal resistivity of the formation, R_h. The technique utilizes a modified geometric factor with the transmitter and receiver shifted horizontally with respect to each other.

Next, we produce a synthetic response for XX' and YY' components in an isotropic model with formation resistivity, R_h. The calculated synthetic response is used to correct the field data for the horizontal conductivity. If the formation is isotropic, the corrected signal will be equal to zero. A non-zero residual signal indicates the presence of anisotropy.

The methodology is illustrated with several examples.

Introduction

Electrical anisotropy is a macroscopic appearance of a microscopic non-uniformity of space. The "macroscopic" and "microscopic" scales depend on a resolution of the measuring device. The macroscopic dimension is on order of the tool resolution. The microscopic size is determined as being much smaller than the tool resolution. The macroscopic (average) parameters of the formation are obtained by upscaling the individual parameters of very small volumes to the level of the tool resolution. The upscaling may lead to a spatial non-uniformity of macroscopic parameters including directional non-uniformity.

In logging applications, the most common microscopic non-uniformity is represented by thin laminations. A sequence of thin (few millimeters) sand/shale layers behaves as an electrically anisotropic formation, provided the electric field is uniform at the scale of few centimeters (Fig.1). Such a formation represents a transverse (bi-axial) anisotropy.

The transverse anisotropy adds one parameter to each layer. Instead of one resistivity, uniform in all directions, we have to address two, R_h and R_v. Traditional logging methods suffer significant uncertainties in interpretation of anisotropy due to increased equivalence, i.e., variety of models producing similar responses. Some traditional methods are not even sensitive to anisotropy. For example, in vertical wells, induction instruments with vertical coils produce only a horizontal electric field. As a result, the measured magnetic field depends only on horizontal resistivity. On the contrary, a galvanic device, for example LL7, excites currents in both vertical and horizontal directions. Measurements are dependent on vertical and horizontal resistivity but the number of measurements is insufficient for interpretation.

To determine anisotropy, first of all, we need to provide measurements sensitive to both vertical and horizontal resistivity. Secondly, more measurements are needed compared to any method designed for isotropic formations. In this paper, we consider combining traditional array induction measurements with the measurements acquired using transverse induction coils oriented perpendicular to the borehole axis.

Transverse measurements are strongly affected by the borehole and invasion zone. We propose a multi-frequency focusing scheme, MFF, eliminating the dependence of measurements on both borehole and invasion parameters. In MFF processing, we, initially, interpret the measurements that depend only on horizontal resistivity (vertical coils). After that, we determine the vertical resistivity from the transverse measurements.

For deviated wells, we developed a processing scheme based on separation of induction and galvanic modes. We prove that a certain combination of MFF processed data in a deviated well depends only on horizontal resistivity. This allows us to sequentially interpret vertical and horizontal resistivity, similar to a vertical well. This improves the stability of processing. Finally, we consider field examples.

3D Explorer Physics

A schematic configuration of 3D Explorer is shown in Fig. 2. The tool consists of three orthogonal transmitters and three orthogonal receivers. The actual transmitters contain pairs of mutually balanced coils. At every logging depth, 3DEX acquires 5 components of the magnetic field (3 main: H_{xx}, H_{yy}, H_{zz} ; 2 cross-components: H_{xy}, H_{xz}) at multiple frequencies in the range of 20 - 220 kHz (Kriegshauser et al., 2000).

In a formation with plane boundaries, particularly, in a thinly laminated formation, the electromagnetic field of an arbitrary source may be described as a combination of two modes: transverse electric, TE, and transverse magnetic, TM. The TE mode has a planar *electric field* parallel to the boundary planes. In the TM mode, the *magnetic field* is planar.

Traditional induction transmitters (oriented normally to the boundaries) excite only the TE mode. The resulting electromagnetic field is sensitive only to horizontal resistivity, R_h (e.g., array induction measurements or the H_{zz} measurement of 3D Explorer).

Transverse transmitters (parallel to the boundaries) excite two modes, TE and TM. Since the electric field contains both components, parallel and perpendicular to the boundaries, the measurements, H_{xx}, H_{yy}, and H_{xy}, depend on both vertical and horizontal resistivity, R_h and R_v. The measurement, H_{xz}, remains dependent only on horizontal resistivity (this conclusion may be derived from the reciprocity principle).

In an anisotropic formation, the currents are not parallel to the electric field. This leads to a concentration of electric charges in the formation volume (Appendix A). In Fig. 3, we evaluate the distribution of volumetric charge in a uniform anisotropic formation. We assume a small anisotropy to understand a departure from the isotropic case. The electric field corresponding to the isotropic case is called “primary field”.

Two remarkable features of the charge distribution must be noticed. First, the distribution has a quadrupole pattern spreading to the peripheral areas. Second, the electrical field of the distributed charge helps to increase the *vertical* currents caused by the primary field and reduces the *horizontal* primary currents. As a result, the currents, initially circular in the isotropic formation, become elliptic in the case of anisotropic medium (Fig. 4).

A significant increase of anisotropy leads to a current leakage in the direction of a magnetic dipole. In the extreme case of a very large anisotropy, current flows in the plane of thin laminations that are perpendicular to the isotropic planar system. The current pattern for a high anisotropy is shown in Fig. 5. It has two centers of circulation, in front of and behind, the dipole. The currents flow in opposite directions. The resulting current system represents a magnetic quadrupole.

Multi-Frequency Focusing (MFF)

The current pattern and the behavior of corresponding magnetic fields measured by 3DEX are very complex, even in a uniform formation. Borehole and invasion can cause additional significant distortions. We have developed a Multi-Frequency Focusing of the 3DEX measurements, MFF, allowing us to eliminate effects of the near borehole zone.

The MFF processing is based on the Taylor expansion of the measured field into a frequency series (Appendix B). The second term of the series does not depend on the borehole and invasion properties. MFF is a mechanism for deriving this term from the multi-frequency measurements. The more conductive the formation, the more frequencies are required to recover the necessary term. In Fig. 6, we show the relative contribution of different terms to the measured field as a function of formation conductivity and frequency. In a resistive formation, two frequencies are sufficient. In this specific case, MFF is known as a dual frequency approach. The dual frequency magnetic field is shown in Fig. 7. It has a very simple geometry and does not depend on the borehole and invasion (center plot). In a more conductive formation, the skin-effect complicates the dual frequency response (right plot). MFF allows us to correct for the skin-effect.

We use MFF to invert 3DEX data for formation parameters. To improve the vertical resolution, we interpret 3DEX together with array induction measurements, HDIL. The first step of inversion consists of interpreting the TE mode of the EM field. In a vertical well, the TM mode is directly measured by 3DEX (H_{zz}) or HDIL. As a result, we obtain the formation horizontal resistivity (Fig. 8, left). The next step includes modeling of H_{xx} and/or H_{yy} measurements in the isotropic model resulting from the first step. Comparing the synthetic response with the measured data, we identify the presence/absence of anisotropy (Fig. 8, center). The last step consists of inverting the difference between two responses for the vertical resistivity (Fig. 8, right). Sequential interpretation of the modes significantly improves the inversion stability.

Inversion in deviated wells

In deviated wells, the TE and TM modes are not separated naturally in measurements. Nevertheless, we can separate the modes using a special processing for 3DEX measurements (Appendix C). The processing results in a linear combination, T, of the MFF processed measurements, H_{xx}, H_{yy}, and H_{zz}. The

T-transformation depends only on the horizontal resistivity of the formation. The T-transformation may be interpreted for horizontal resistivity similar to the vertical well.

In Fig. 9, we show a synthetic example of inversion in deviated wells. The trajectory measurements are taken from a real well (left). Inversion of the induction mode produced horizontal resistivity with a high accuracy (center). In the next step, we invert the combination of measurements, ($H_{xx}+H_{yy}$), for the vertical resistivity. We select this combination for inversion because it does not depend on the rotation angle.

Separation of modes cannot be performed for the HDIL measurements. That is why, in deviated well, we do not use HDIL. As a result, we cannot achieve the high resolution. In the considered example, we use layers at least 2 m thick. We plan to use HDIL in the next iteration of inversion for the purpose of vertical resolution enhancement.

The described inversion techniques for vertical and deviated wells may be performed in real time.

Conclusions

1. The physics of transverse induction measurements is based on a distribution of volumetric charges in anisotropic formation. The quadrupole pattern of the charge distribution in small anisotropy formations causes ellipticity of currents. With anisotropy increase, the planar system of currents becomes fully three-dimensional. In the extreme case of a very large anisotropy, the current system rotates by 90 degrees and becomes planar again in the plane of thin laminations.
2. Multi-Frequency Focusing, MFF, allows us to eliminate the dependence of 3DEX measurements on borehole and invasion parameters. Simultaneously, MFF performs correction of measurements for the skin-effect.
3. In vertical wells, we consider simultaneous inversion of 3DEX and array induction measurements, HDIL. HDIL measurements enhance the vertical resolution. They also allow for a very accurate determination of the formation horizontal resistivity. This is a critical step for the following inversion of 3DEX data for the vertical resistivity.
4. In deviated wells, we use the separation of modes. A special processing has been developed to achieve the separation. Currently, we use only 3DEX data. Eventually, we intend to utilize HDIL data as well for the vertical resolution enhancement.
5. All presented inversion algorithms perform in real time.

Nomenclature

R_h = horizontal resistivity of formation, Ohm-m
R_v = vertical resistivity of formation, Ohm-m
Λ = R_v / R_h – formation anisotropy
h_{snd} = thickness of sand laminae, m
h_{sh} = thickness of shale laminae, m
R_{snd} = resistivity of sand laminae, Ohm-m
R_{sh} = resistivity of shale laminae, Ohm-m
H_{xx} = magnetic field: x-transmitter, x-component, amp/m
H_{yy} = magnetic field: y-transmitter, y-component, amp/m
H_{zz} = magnetic field: z-transmitter, z-component, amp/m
H_{xy} = magnetic field: x-transmitter, y-component, amp/m
H_{xz} = magnetic field: x-transmitter, z-component, amp/m
ρ = volumetric charge density, C/m^3
$\boldsymbol{j}$ = (j_x, j_y, j_z) - vector of the current density, amp/m^2
$\boldsymbol{E}$ = (E_x, E_y, E_z) - vector of electric field, V/m
σ_0 = background conductivity, S/m
$\hat{h}$ = magnetic tensor of auxiliary sources
f = frequency, Hz
ω = $2\pi f$
$s_{k/2}$ = coefficients of the frequency series; k=0,1,2,…
T = linear transformation to separate induction mode
α, β, γ = coefficients of transformation T

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Appendix A—Charge Density in Anisotropic Medium

The charge density, ρ, is determined by the following Maxwell's equation:

$$\rho = \mathrm{div}(\mathbf{E}) \tag{A-1}$$

The divergence of the electric field may be determined from the current conservation law. In the frequency range used by the 3D Explorer, we may neglect the displacement currents:

$$\mathrm{div}(\mathbf{j}) = 0 \tag{A-2}$$

The Ohm's law for a transverse anisotropic formation may be represented in the following form:

$$j_x = E_x / R_h, \quad j_y = E_y / R_h, \quad j_z = E_z / R_v \tag{A-3}$$

Equations (A-1), (A-2), and (A-3) lead to the following expression for the charge density, ρ (Tabarovsky et al., 1979):

$$\rho = \left(1 - \frac{1}{\Lambda}\right)\frac{\partial E_z}{\partial z} \quad \text{(A-4)}$$

Equation (A-4) proves that a volume charge in a conductive formation may appear only if the formation is anisotropic ($\Lambda \neq 1$) and the electric field is non-uniform ($\partial E_z/\partial z \neq 0$).

Appendix B—Multi-Frequency Focusing

Let us assume that formation conductivity is $\sigma(x,y,z)$. Let us consider an auxiliary conductive space with conductivity, $\sigma_0(x,y,z)$, called "background conductivity". The background model includes everything except borehole and invasion. With the electric field, E, known, the magnetic field, H, may be expressed as follows (Tabarovsky et al., 1996, 1998):

$$H(P_0) = H^0(P_0) + \iiint_V (\sigma - \sigma_0)\hat{h}(P_0 \mid P)E(P)\,dP \quad \text{(B-1)}$$

Here, P and P_0 – integration and measure points, respectively; V – borehole and invasion volume; H – the measured magnetic field; H^0 – the background magnetic field; $\hat{h}$ – the matrix of the magnetic field for auxiliary electric dipoles:

$$\hat{h} = \begin{pmatrix} h_x^x & h_y^x & h_z^x \\ h_x^y & h_y^y & h_z^y \\ h_x^z & h_y^z & h_z^z \end{pmatrix} \quad \text{(B-2)}$$

In the matrix, the superscript reflects the orientation of the electric dipole, the subscript shows the measured component of the auxiliary magnetic field.

The measured magnetic field, H, may be expanded into a Taylor series with respect to the frequency, ω:

$$H = \sum_{k=0}^{k=\infty} s_{\frac{k}{2}}\, \omega^{\frac{k}{2}}; \quad s_{\frac{1}{2}} = 0 \quad \text{(B-3)}$$

The term containing $\omega^{3/2}$ does not depend on the properties of the near borehole zone. It is affected only by the conductivity distribution in the background model:

$$s_{\frac{3}{2}} = s^0_{\frac{3}{2}} \quad \text{(B-4)}$$

We use this fact in the multi-frequency focusing. The purpose of the multi-frequency processing is to derive the coefficient, $s_{3/2}$, reflecting properties of the deep formation areas. Rewriting the Taylor series, Equation (B-3), for each measured frequency, we obtain:

$$\begin{pmatrix} H(\omega_1) \\ H(\omega_2) \\ \bullet \\ H(\omega_{m-1}) \\ H(\omega_m) \end{pmatrix} = \begin{pmatrix} \omega_1 & \omega_1^{3/2} & \omega_1^{5/2} & \bullet & \omega_1^{n/2} \\ \omega_2 & \omega_2^{3/2} & \omega_2^{5/2} & \bullet & \omega_2^{n/2} \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \omega_{m-1} & \omega_{m-1}^{3/2} & \omega_{m-1}^{5/2} & \bullet & \omega_{m-1}^{n/2} \\ \omega_m & \omega_m^{3/2} & \omega_m^{5/2} & \bullet & \omega_m^{n/2} \end{pmatrix} \begin{pmatrix} s_1 \\ s_{3/2} \\ s_{5/2} \\ \bullet \\ s_{n/2} \end{pmatrix} \quad \text{(B-5)}$$

Solving the system of Equations (B-5), we obtain the coefficient, $s_{3/2}$.

Appendix C—Separation of Induction Mode

We assume that formation angles (dip, θ_f, and azimuth, φ_f) are known. We select the x-axis of the coordinate system associated with the formation in such a way that the 3DEX tool belongs to the xz plane. It can be proven that the three principle 3DEX measurements, MFF processed, may be expressed in the following form:

$$\begin{pmatrix} MFF(H_{xx}) \\ MFF(H_{yy}) \\ MFF(H_{zz}) \end{pmatrix} = \begin{pmatrix} a_1\, a_2\, a_3\, a_4 \\ b_1\, b_2\, b_3\, b_4 \\ c_1\, c_2\, c_3\, c_4 \end{pmatrix} \begin{pmatrix} MFF(h_{xx}) \\ MFF(h_{yy}) \\ MFF(h_{zz}) \\ MFF(h_{xz}) \end{pmatrix} \quad \text{(C-1)}$$

The matrix coefficients in Equation (C-1) depend on θ_f, φ_f, and three trajectory measurements: deviation, azimuth, and rotation.

The components of the vector on the right hand side of Equation (C-1) represent all non-zero field components generated by three orthogonal induction transmitters in the coordinate system associated with the formation. Only two of them depend on vertical resistivity: h_{xx} and h_{yy}. This allows us to build a linear combination of measurements, H_{xx}, H_{yy}, and H_{zz}, in such a way that the resulting transformation depends only on h_{zz} and h_{xz}, or, in other words, only on horizontal resistivity. Let T be the transformation with coefficients, α, β, and γ:

$$T = \alpha MFF(H_{xx}) + \beta MFF(H_{yy}) + \gamma MFF(H_{zz}) \quad \text{(C-2)}$$

The coefficients, α, β, and γ, must satisfy the following system of equations:

$$\begin{aligned} a_1\alpha + b_1\beta + c_1\gamma &= 0 \\ a_2\alpha + b_2\beta + c_2\gamma &= 0 \\ \alpha^2 + \beta^2 + \gamma^2 &= 1 \end{aligned} \quad \text{(C-3)}$$

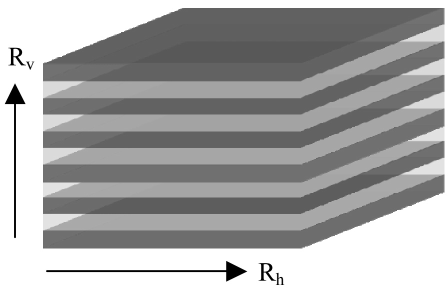

Fig. 1—Thinly laminated formation is electrically anisotropic. If the electric field is horizontal, layers form a parallel connection. With respect to the vertical electric field, layers are connected in series. Resulting horizontal and vertical resistivity have the following expression:

$$R_h = \frac{h_{snd} + h_{sh}}{\frac{h_{snd}}{R_{snd}} + \frac{h_{sh}}{R_{sh}}}; \quad R_v = \frac{R_{snd}\, h_{snd} + R_{sh}\, h_{sh}}{h_{snd} + h_{sh}}$$

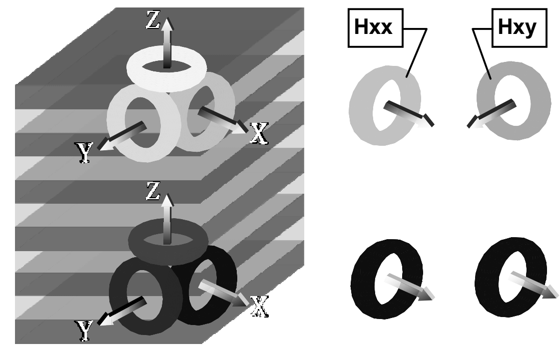

Fig. 2—Schematically, the 3DEX tool contains three orthogonal transmitters (dark shading) and three orthogonal receivers (light shading). Five measurements (H_{xx}, H_{yy}, H_{zz}, H_{xy}, and H_{xz}) are performed at ten frequencies (20 to 200 kHz).

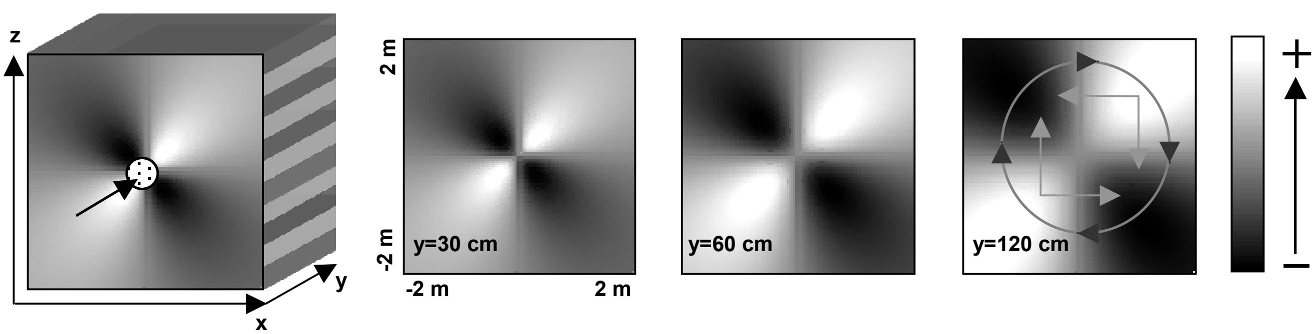

Fig. 3—A magnetic dipole is oriented along the y-axis and situated in the plane y=0 (left). The formation is slightly anisotropic. We show the charge density in three planes perpendicular to the dipole direction (y=30, 60, and 120 cm). Dark and light areas represent negative and positive charge density, respectively. The charge distribution has a quadrupole pattern. It spreads in the peripheral areas. The primary electric field of the magnetic dipole is circular. An electric field produced by the charge quadrupole helps to push currents in the more resistive vertical direction and reduces currents in the less resistive horizontal direction. The resulting current tubes have an elliptic shape (Fig. 4).

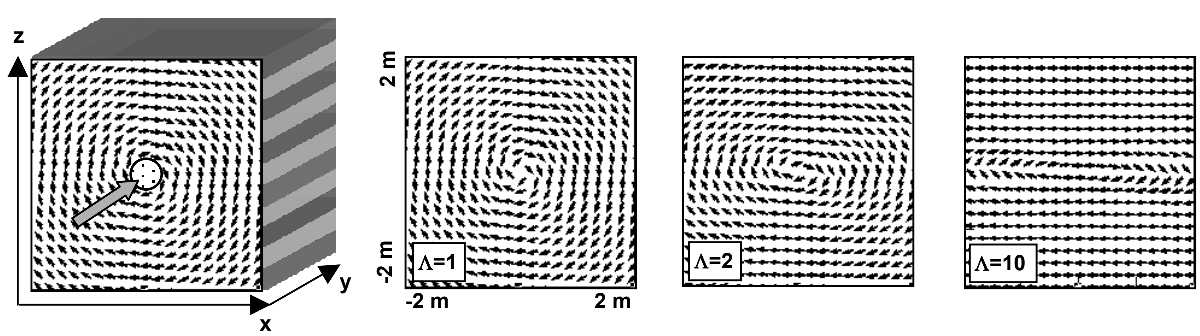

Fig. 4— A magnetic dipole is oriented along the y-axis and situated in the plane y=0 (left). We consider the distribution of electric current in the plane perpendicular to the dipole direction. The plane is close to the dipole (y=1 cm). Three values of anisotropy, Λ, are presented. If the formation is isotropic, Λ=1, the currents flow in the plane, xz, and have a circular shape. The anisotropy increase leads to ellipticity of current lines. In the limit of a very large anisotropy, we observe only horizontal current flow. In this extreme case, the current lines belong to the plane, xy. We see only a projection of the real current system onto the plane, xz. This leads us to an important conclusion: With the anisotropy increase, the current system evolves from the vertical plane, xz, to the horizontal plane, xy. This transformation is caused by the volume charges distributed as shown in Fig. 3

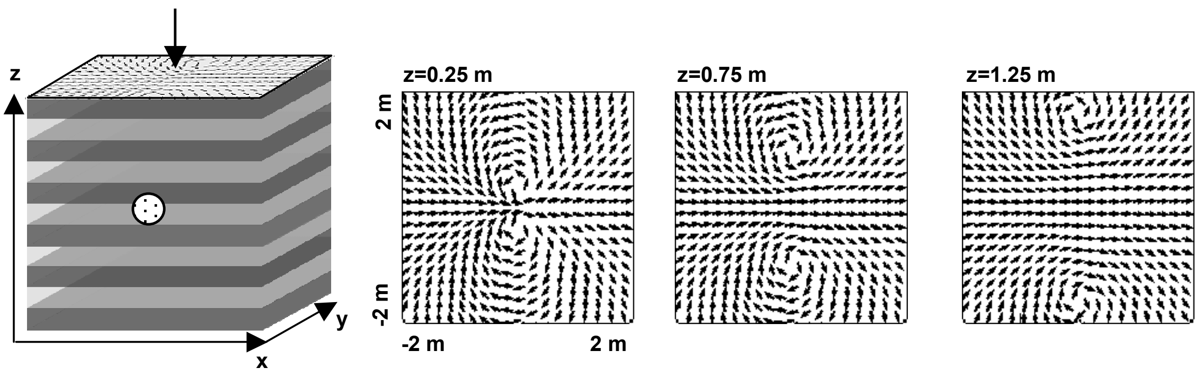

Fig. 5— A magnetic dipole is oriented along the y-axis and situated in the plane y=0 (left). We consider the distribution of electric currents in the extreme case of a very large anisotropy. Currents are flowing in the horizontal plane, xy. The current flow has a quadrupole pattern: two "eyes" with opposite circulation directions. The separation of two circulation centers becomes larger in the peripheral areas.

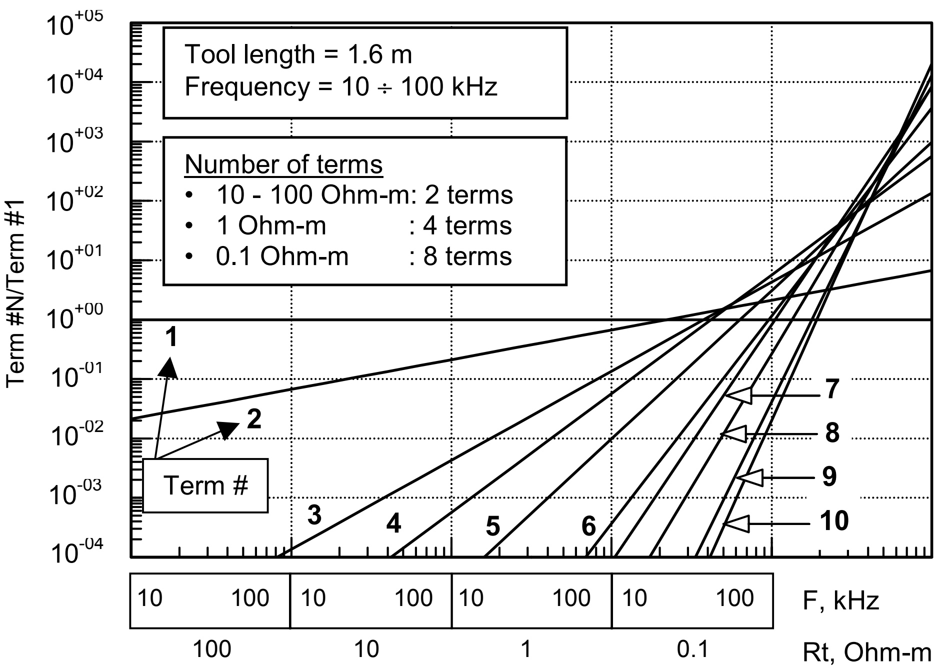

Fig. 6—Term values in the frequency series for a uniform formation. All terms are normalized to the first one. The term number is shown as the curve index. We consider a two-coil array with a horizontal transmitter and a horizontal receiver spaced at 1.6 m. Vertical strips reflect different formation resistivities, from 0.1 Ohm-m to 100 Ohm-m. In each strip, the frequency changes from 10 kHz to 100 kHz. In a resistive formation (1 – 100 Ohm-m), the expansion terms rapidly decay. In a conductive formation (resistivity < 0.1 Ohm-m), all ten considered terms equally contribute to the magnetic field.

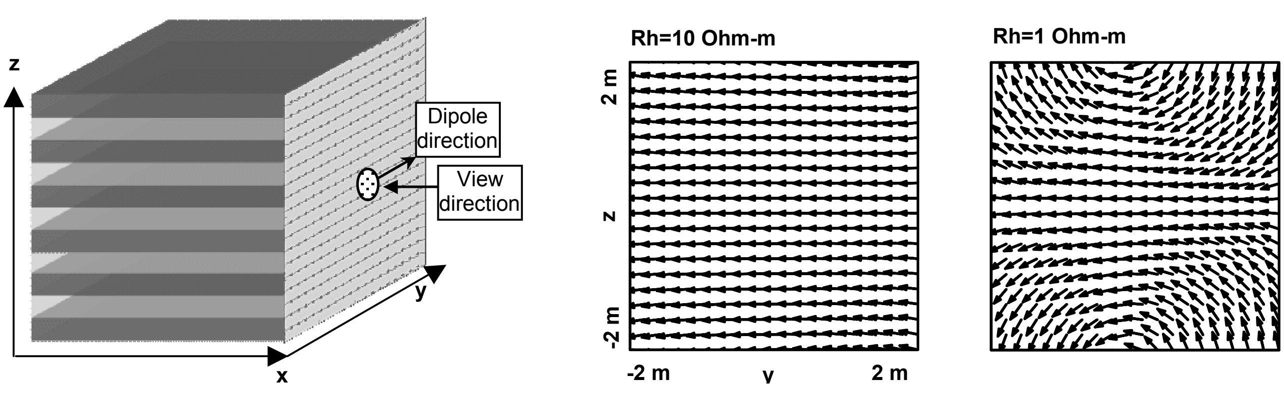

Fig. 7— A magnetic dipole is oriented along the y-axis and situated in the plane y=0 (left). In the plane x=1 cm, we consider the dual frequency magnetic field resulting from combining frequencies of 50 and 100 kHz. In the case of a relatively high horizontal resistivity, R_h=10 Ohm-m, the dual frequency magnetic field is uniform and parallel to the y-axis. For lower resistivity, R_h=1 Ohm-m, the skin-effect produces a disturbance in the uniform pattern. The multi-frequency technique allows us to correct for the skin-effect.

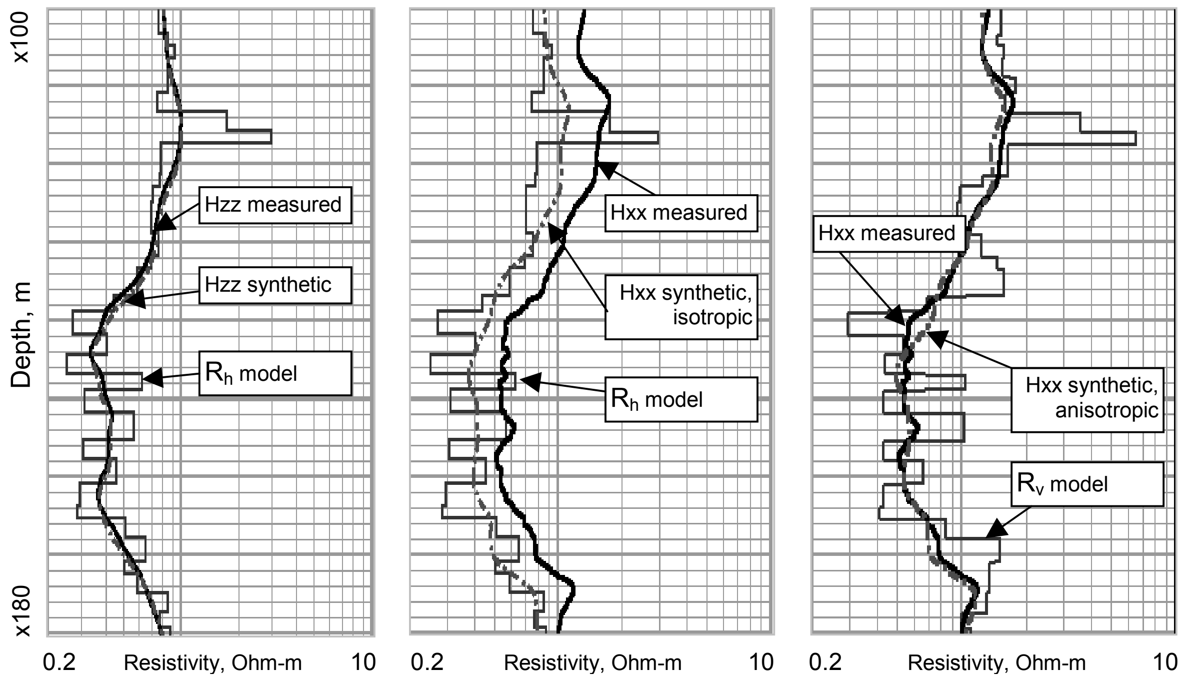

Fig. 8—MFF processing of 3DEX and HDIL data from the Gulf of Mexico. The high resolution R_h model obtained from HDIL data satisfies 3DEX H_{zz} measurements (left). The difference between the H_{xx} response in the HDIL model and real H_{xx} measurements is attributed to anisotropy (center). Inversion for the vertical resistivity allows us to fit H_{xx} measurements as well.

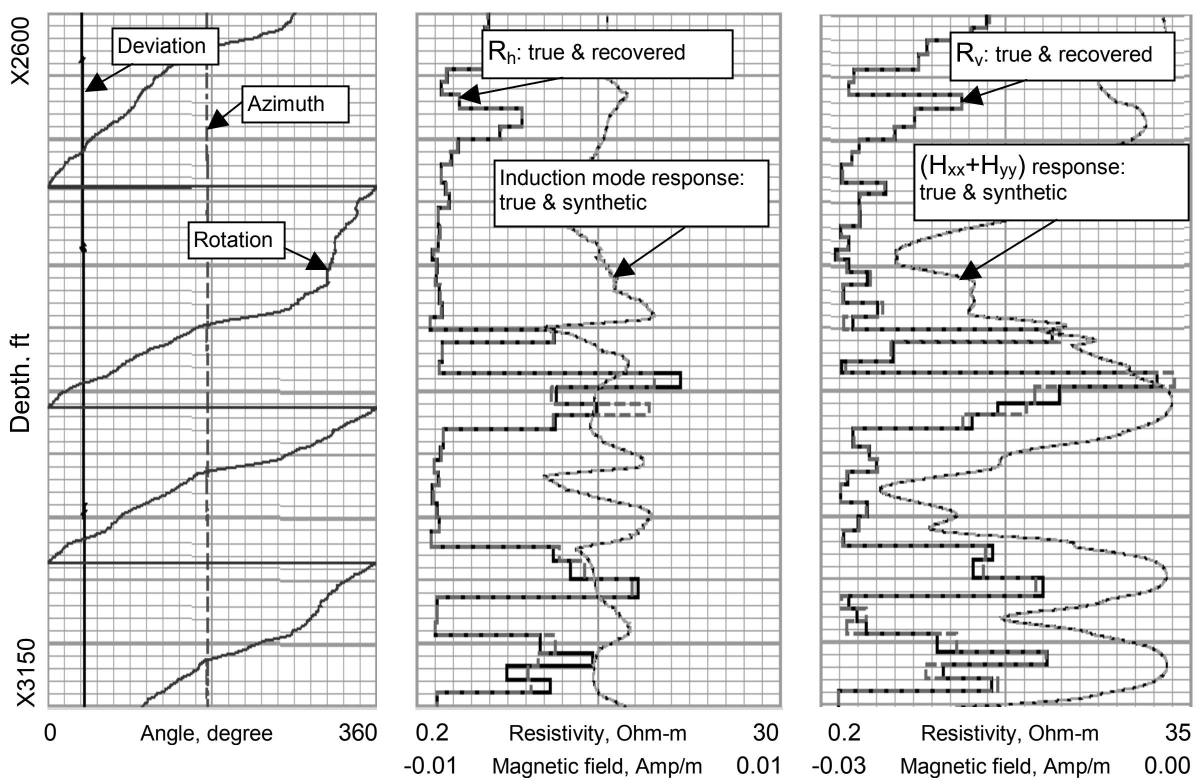

Fig. 9—MFF processing of 3DEX data in a deviated well (synthetic example). The well trajectory measurements are taken from a real well (left). The separation of modes allows us to recover the horizontal resistivity from the induction mode with a high accuracy (center). In the next step, we invert (Hxx+Hyy) for the vertical resistivity (right). Notice that the model contains layers at least 2 m thick.