On the Value of Electrical Anisotropy in Formation Evaluation

Berthold Kriegshäuser, Baker Hughes do Brasil

This paper was prepared for presentation during the 13th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 26-29, 2013.

Abstract

Delineation of productive low-resistivity reservoirs is a challenge frequently encountered in hydrocarbon exploration. Proper identification and characterization of these reservoirs is essential to recover their reserves. An example of such a reservoir is a finely laminated sand/shale sequence of which the sand contains hydrocarbons, found, for example, in turbidite environments. These thinly laminated sand/shale sequences can pose a challenge in petrophysical evaluation, in case that the thickness of the sand/shale laminae is below the vertical resolution of the wireline data. A multi-component induction tool like the 3DEX^{SM} provides all the data necessary to derive formation resistivity parallel and perpendicular to bedding that allow detection and evaluation of the hydrocarbon bearing sand laminae.

In recent years, further understanding of these multicomponent data allows additional information being derived. Besides enhanced formation evaluation, these data also allow us now to compute structural formation dip and azimuth, and fracture characterization based on an integrated interpretation of multicomponent and conventional induction data.

In this paper, we will examine the underlying concepts of the multicomponent induction logging tool and discuss some typical applications and benefits from the offshore environment. In addition, we will highlight recent advancements in tool measurements and processing techniques allowing determination of structural formation dip and azimuth besides resistivity anisotropy. We will also demonstrate in case histories, how these data can be combined in an integrated interpretation flow to estimate resistive fracture direction and fracture length.

Introduction

The 3DEX^{SM} tool is comprised of three mutually orthogonal transmitter-receiver pairs that measure all nine magnetic field components at multiple frequencies (Kriegshauser et al., 2000, 2001). Similar instruments are available on the market by all major service providers (Rosthal et al., 2003, Hou et al., 2013).

The instrument operates at 10 different frequencies between 20 and 220 kHz. The main objective for this tool is to improve formation evaluation in thinly laminated reservoirs by measuring the horizontal and vertical resistivities, Rh and Rv, i.e., parallel and perpendicular to bedding (Klein, 1996, Mollison et al., 1999, Schoen et al., 1999). Utilizing Rh and Rv jointly in computing hydrocarbon saturations also reduces uncertainties in estimating hydrocarbon reserves (Mollison et al., 2001).

Previous processing software (Rabinovich & Tabarovsky, 2001; Tabarovsky et al., 2001, Kriegshauser et al., 2001) used only the three main in-line components to invert for Rh and Rv. Newly developed processing algorithms utilize all nine magnetic field component to compute both formation resistivities, Rh and Rv, and formation dip and azimuth. We will illustrate these derived dip and azimuth angles in a variety of field cases, highlighting the benefits of these data.

Drilling induced fractures are commonly observed in wells that are drilled overbalanced. These fractures are typically near-vertical and have the same direction as natural or hydraulically-induced fractures that extend parallel to the maximum formation stress direction. With the advent of unconventional resources, fractures have gained additional importance in reservoir characterization (Wu et al., 2013). The appearance of fractures filled with a mixture of oil-based mud and formation fluid changes resistivity distribution around the borehole. This resistivity change affects the multiple components and multiple depths of investigation measurements of the modern induction tools differently depending on fracture orientation, fracture length, and formation resistivities. Analysis of the measured induction data using advanced inversion and modeling techniques allows recovery of the fracture orientation and length as well as horizontal and vertical resistivities of the undisturbed formation.

In the last case study we discuss an application from offshore India where a 12.25” vertical well was drilled overbalanced with a 13.2 ppg synthetic oil base mud. A wide spectrum of logging while drilling (LWD) and wireline logs were acquired including LWD propagation resistivity (MPR), wireline array induction (HDIL), multi-component induction (3DEX), and cross-dipole acoustic measurements (XMAC Elite). The presence of drilling induced fractures in some intervals was immediately apparent based on a large difference between LWD resistivity and array induction resistivity; separation of the shallow and deep array induction resistivity curves; and different responses of Hxx and Hyy multi-component measurements (3DEX). We devised an enhanced data processing scheme to derive accurate information from the formation over the fractured intervals. We applied a joint interpretation of orientation measurements and the differences in 3DEX multi-frequency focused Hxx and Hyy components to reliably provide fracture azimuth. Due to the tool rotation we were able to determine the fracture orientation based on the minimum, maximum and zero crossing points of the Hxx-Hyy curve.

Method

Magnetic field measurements by multi-component induction tools, like 3DEX, can be described by a 3-by-3 matrix, where the first and second index corresponds to the transmitter and receiver magnetic dipole direction (Figure 1).

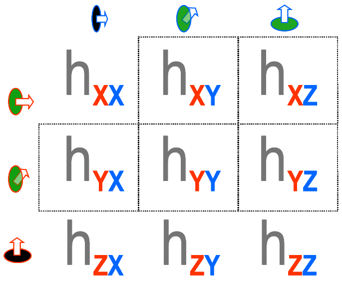


Fig. 1 *Magnetic measurement tensor. The first and second index indicates the orientation of a transmitter and the receiver, respectively.*

The magnetic field tensor, generally, is not symmetric. This means that there may be models and situations when $h_{xy} \neq h_{yx}$, $h_{xz} \neq h_{zx}$, $h_{yz} \neq h_{zy}$ (Figure 2). This demonstrates there is no direct correspondence between the structure of the conductivity tensor and the measurement tensor.

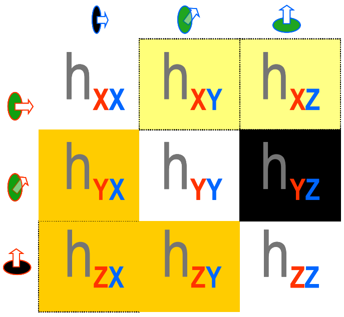


Fig. 2 *Non-symmetric measurement tensor. Generally all 9 components are different.*

We apply a Multi-Frequency Focusing for the 3DEX measurements, MFF, which allows us to eliminate effects of the near borehole zone (Tabarovsky and Rabinovich, 1998; Tabarovsky et al., 2001; Yu et al., 2003).

An additional feature of this multi-frequency focusing technique is that the measurement tensor can now be diagonalized:

$$\hat{\mathrm{H}}_{MFF} = \begin{pmatrix} \tilde{h}_{xx}^{p} & & \\ & \tilde{h}_{yy}^{p} & \\ & & \tilde{h}_{zz}^{p} \end{pmatrix}.$$

3DEX PROCESSING FLOW CHART

A general 3DEX processing flow chart is presented in Figure 3. It consists of two main parts:

- Processing for formation dip and azimuth and two principal components;
- Sequential inversion for Rh and Rv using two principal components.

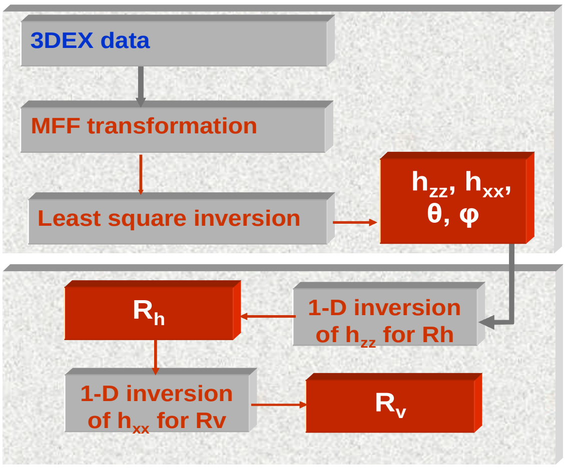


Fig. 3 *3DEX processing flow chart.*

Examples

We will show a variety of field example, where we compare image data-derived formation dip and azimuth with 3DEX-derived formation dip and azimuth.

Example 1:

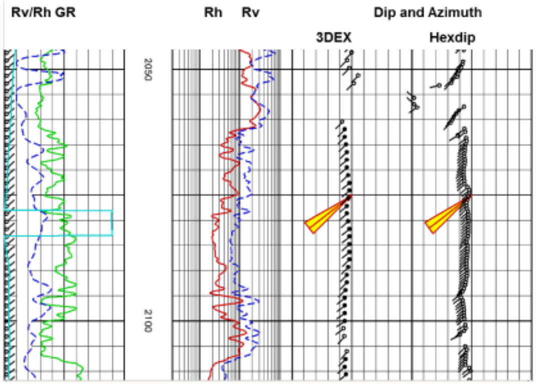


Fig. 4: *Excellent match between 3DEX and Hexdip derived dip and azimuth data.*

Example 2:

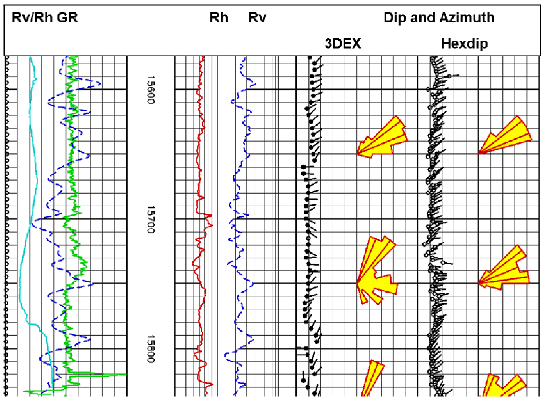


Fig. 5: *Consistent low-angle dips from 3DEX and Hexdip.*

Example 3:

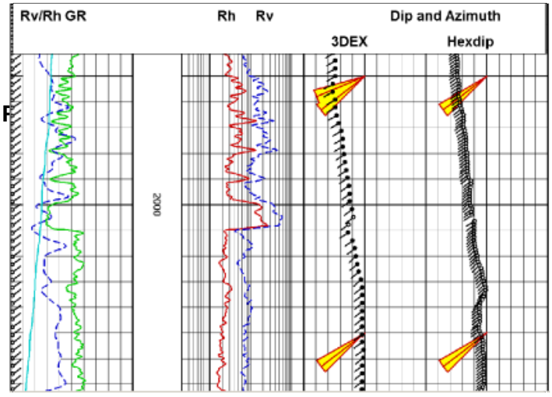


Fig. 6: *Gradually changing dip angles from 3DEX and Hexdip.*

Example 4:

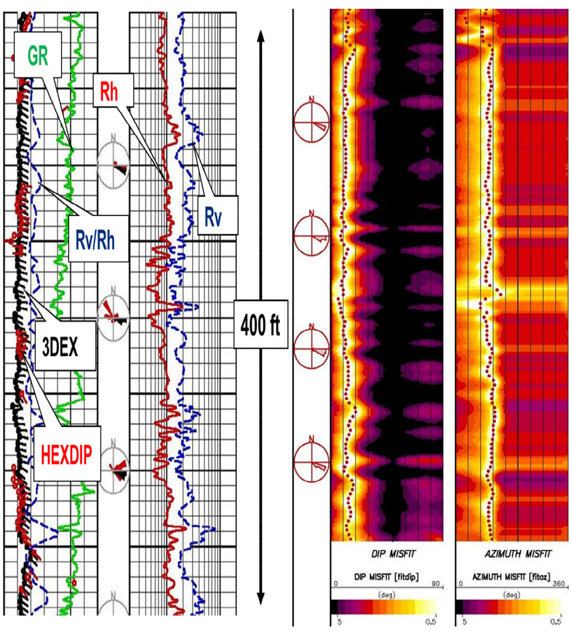


Fig. 7: *Gulf of Mexico example.*

Fracture Characterization

Drilling induced fractures are typically near-vertical and have the same direction as natural or hydraulically-induced fractures that extend parallel to the maximum formation stress direction. These fractures, when filled with a mixture of oil-based mud and formation fluid, change the resistivity distribution around the borehole and will affect conventional and multi-component magnetic field data differently. We can utilize these effects and derive fracture azimuth as well as fracture length into the formation. The figure 8 below illustrates the effect of resistive fractures on the multicomponent induction data, while data acquisition and tool rotation.

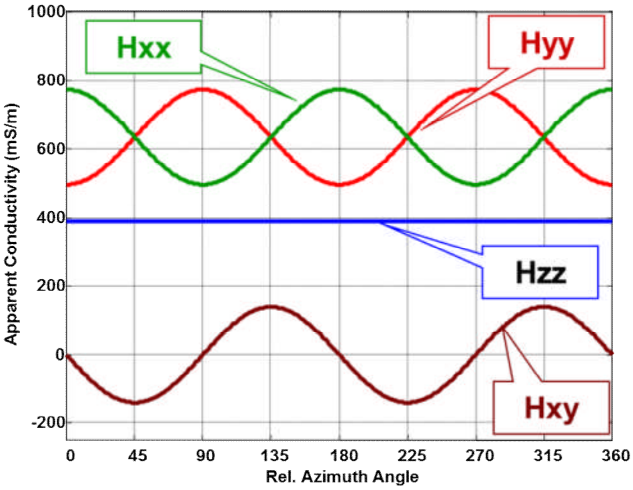


Fig. 8: *Vertical resistive fracture effects on 3DEX data, synthetic example.*

While Hzz remains unchanged during tool rotation, the magnetic field data Hxx, Hyy and Hxy will depend on the orientation of the sensors with respect to the fracture azimuth. Thus, we can these data are sensitive to fracture azimuth.

The figure below depicts a case study, where conventional induction data from HDIL and 3DEX data show the effect of resistive drilling-induced fractures.

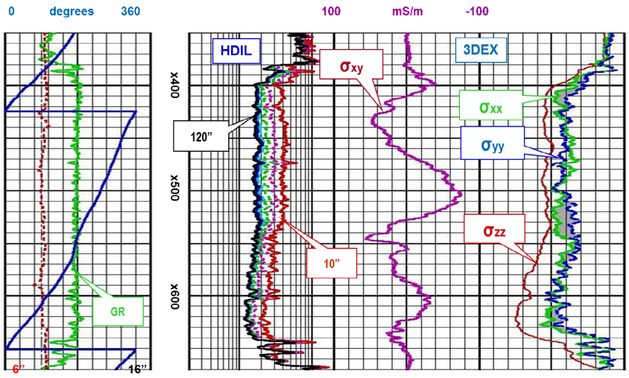
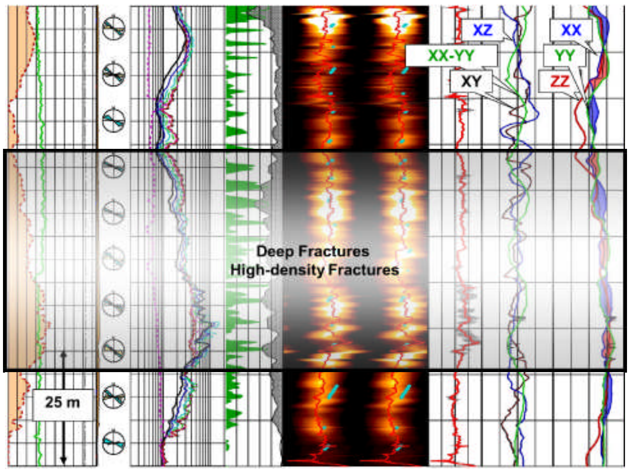


Fig. 9: *Vertical resistive fracture effects on 3DEX data, field data.*

Utilizing statistical analysis, we can derive fracture azimuth from 3DEX data and compare against cross-dipole acoustic data ad depicted in Fig. 10 below. This comparison allows providing an estimate of fracture length and intensity, since acoustic have a shallow depth of investigation, while 3DEX data have deep depth-reading sensitivity.



Conclusions

- 3DEX data yield both horizontal and vertical resistivities, Rh, Rv, structural dip and azimuth angles.
- Identify & Quantify Laminated/Low Resistivity Pay.
- Differentiate productive from unproductive low resistivity zones.
- Reduce interpretation uncertainty and risk.
- Fractures affect many borehole measurements, including conventional and multi-component resistivity data, like HDIL and 3DEX.
- Fracture orientation can be estimated from multi-component induction data and acoustic data.
- Multicomponent induction and cross-dipole acoustic logs complement each other when interpreting drilling-induced fractures.

Acknowledgments

The author wishes to thank Baker Hughes for permission to publish this work. I acknowledge all important contributions of my co-workers and ex-colleagues: Liming Yu, Michael Rabinovich, Bill Corley, Rahid Gupta, Lev Tabarovsky, Gregory Itskovich, Dan Georgi, Jürgen Schön, Otto Fanini, and Rick Mollison.

Stephen Dymmock was instrumental in many fruitful discussions on dip and azimuth analysis.

References

Hou, J, Sanmartin, L., Wu, D., Torres, D., and Celepcikay, T., 2013, A new multi-frequency triaxial array induction tool for enhancing evaluation of anisotropic formations and its field testing: SPWLA 54th Annual Logging Symposium Transactions, paper CCC.

Klein, J., 1996. Saturation effects on electrical anisotropy, The Log Analyst, Jan-Feb, pp. 47-49.

Kriegshauser, B., Fanini, O., Forgang, S., Itskovich, G., Rabinovich, M., Tabarovsky, L., Yu, L., Epov, M. and van der Horst, M 2000. A new multi-component induction logging tool to resolve anisotropic formation, SPWLA 41st Annual Logging Symposium Transactions, Paper D.

Kriegshauser, B., Fanini, O., Yu, L., van der Horst, J., and van Popta, J., 2001, Improved shaly sand interpretation in highly deviated and horizontal wells using multicomponent induction log data: SPWLA 42nd Annual Logging Symposium Transactions, Paper S.

Mollison, R., Schoen, J., Fanini, O., Kriegshauser, B., Meyer, W., and Gupta, P., 1999. A model for hydrocarbon saturation determination from an orthogonal tensor relationship in thinly laminated anisotropic reservoirs, SPWLA 40th Annual Logging Symposium, Paper OO.

Mollison, R., Fanini, O., Kriegshauser, B., Yu, L., Ugueto, U., and van Popta, J., 2001. Impact of multi-component induction technology on a deepwater field turbidite sand hydrocarbon saturation evaluation: SPWLA 42nd Annual Logging Symposium, Paper T.

Rabinovich, M., and Tabarovsky, L., 2001. Enhanced anisotropy from joint processing of multi-component and multi-arrays induction tools: Transactions of the SPWLA 42nd Annual Logging Symposium, paper HH.

Rosthal, R., Barber, T., Bonner, S., Chen, K.-C., Davydycheva, S., Hazen, G., Homan, D., Kibbe, C., Minerbo, G., Schlein, R., Villegas, L., Wang, H., and Zhou, F., 2003, Field test results of an experimental fully-triaxial induction tool: Transactions of the SPWLA 44th Annual Logging Symposium, paper GG

Schoen, J., Mollison, R., and Georgi, D., 1999. Macroscopic electrical anisotropy of laminated reservoirs: a tensor resistivity saturation model, SPE Annual Technical Conference, SPE 56509.

Tabarovsky, L., and Rabinovich, M., 1998. Real-time 2-D inversion of induction logging data: Journal of Applied Geophysics **38** (1998) 251-275.

Tabarovsky, L., Epov, M., and Rabinovich, M., 2001. Measuring formation anisotropy using multi-frequency processing of transverse induction measurements, SPE 71706.

Tabarovsky, L., and Rabinovich, M., 2001. Determination of formation anisotropy using multi-frequency processing of induction measurements with transverse induction coils, US Patent US 6,574,562 B2.

Wu, P., Barber, T., Li Wang, G., Johnson, C., Heliot, D., Hayden, R., Kumar, A., Xu, W., Wang, H., Clinch, S., and Schmidt, C., 2013, Fracture Characterization using triaxial induction tools: SPWLA 54th Annual Logging Symposium Transactions, paper CC.

Yu, L., Rabinovich, M., Tabarovsky, L., and Wang, T., 2003. The reduction of near zone effects on the multi-component induction logging tool, SPE 84097.