# Enhancing the operating range of the multicomponent induction logging tool

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## Abstract

The new multicomponent induction logging tool, 3DEX$^{SM}$ is designed to measure all data necessary to compute horizontal and vertical resistivities of the formation in vertical, deviated or horizontal wells. Horizontal and vertical resistivities are defined as parallel and perpendicular to bedding. The vertical resistivity, in particular, is important in so-called 'low resistivity' pay zones. For example, in thinly laminated sand/shale sequences, where the sand laminae are hydrocarbon bearing, the vertical resistivity is very sensitive to the sand resistivity, while the horizontal resistivity is more sensitive to the shale resistivity. The tool comprises three mutually orthogonal transmitter-receiver configurations measuring the magnetic fields in all three directions. The new coils with their dipole moments perpendicular to the tool axis, however, exhibit strong borehole effects. In this paper, we discuss various data processing techniques to reduce the borehole effect and thus enlarging the operating range of the multicomponent induction logging tool.

## Introduction to 3D Explorer (3DEX)

A few years ago Baker Atlas and Shell Technology Exploration and Production jointly developed and introduced a new induction logging tool that comprises three mutually orthogonal transmitter-receiver configurations (Tabarovsky and Epov, 1979, Beard et al., 1998, Kriegshäuser et al., 2000). The tool configuration is shown in Figure 1. The new transmitters with their dipole moments perpendicular to the tool axis (Tx and Ty) induce currents that flow perpendicular to bedding in vertical wells and horizontal bedding. The corresponding in-line magnetic field responses, Hxx and Hyy, are sensitive to both the horizontal and vertical resistivity of the formation, i.e., Rh and Rv. Because Hzz, the conventional induction tool response, is only sensitive to Rh in vertical wells, we can de-couple Rh and Rv by first computing Rh from Hzz and then computing Rv using Hxx and Hzz (Yu et al., 2000). The cross-components can be used to determine the tool orientation with respect to the principal axis of anisotropy (Gupta et al., 1999) and allow us to discriminate geologic layers between above and below the wellbore in horizontal wells.

In Figure 2 we depict core photos from a typical low-resistivity pay interval (Gomes et al., 2002). The thin sand/shale laminae are below the resolution of the state-of-art wireline tools. Therefore, this formation exhibits electrical anisotropy, with a vertical resistivity (Rv) that is larger than the horizontal resistivity (Rh). Using both resistivities, Rh and Rv, in a petrophysical interpretation greatly improves the accuracy and robustness of the hydrocarbon estimation (e.g., Mollison et al., 1999, and companion paper, Santos et al., 2003).

The new magnetic field responses of the 3DEX, Hxx and Hyy, however, are very complex (Kriegshäuser et al., 2000). The responses exhibit large skin effects and can reverse sign at bed boundaries. The main challenge, however, is the strong borehole effect in the data. Figure 3 sketches the induced current pattern for the conventional transmitter Tz, with a dipole moment parallel to the tool axis and Tx, with the dipole moment perpendicular to the tool axis. The tangential component of the electric field induced by the Tz transmitter is continuous across the borehole-formation interface. This component gives rise to the Hzz component. The normal component of the electric field that is induced by the Tx transmitter is discontinuous across the borehole-formation interface. This leads to a charge build-up at the borehole interface that acts like additional transmitters (Carvalho and Verma, 1998). This can severely distort the magnetic field responses, Hxx and Hyy, that must be considered in data processing.

## The Dual Frequency Transformation

Tabarovsky and Epov (1979) introduced a powerful data transformation technique to significantly reduce the borehole effect in multicomponent induction log data. This transformation uses single frequency data at two different frequencies, $f_1$ and $f_2$, and combines them into a so-called dual frequency pair (Beard et al. 1998):

$$H(f_1, f_2) = H(f_1) - \frac{f_1}{f_2} H(f_2) ,$$

where $H(f_1)$ and $H(f_2)$ are magnetic field single frequency responses, respectively. This transformation reduces significantly the borehole and near-zone effects in the lower frequency data. Figure 4 compares the single frequency data with the dual frequency responses for a cylindrically layered medium. The borehole diameter is 12.25" and the mud resistivity is 0.1 Ohm-m. The horizontal and vertical formation resistivity is modeled at 1 and 2 Ohm-m, respectively. The borehole effect is strong on the new Hxx-components, which can lead to an inaccurate Rv computation. If the borehole fluid is conductive, i.e., a saline mud system is used, and then neglecting the borehole effect will overestimate Rv. In contrast, if the mud system is resistive, such as in oil-based mud systems, then Rv will be underestimated. The dual frequency transformation, however, effectively removes the borehole effect, thus allowing an accurate computation of Rv.

The disadvantages of the dual frequency transformation are a lower signal-to-noise ratio, and a reduced vertical resolution of the responses. The vertical resolution can be improved by providing the horizontal resistivity from a high-resolution induction device, such as HDIL (Rabinovich and Tabarovsky, 2001).

### Limits of Dual Frequency Transform

The efficacy of the dual frequency transformation depends on various factors, such as borehole size, mud resistivity, and formation horizontal and vertical resistivity. We examined the relative response differences for single and dual frequency data for a cylindrically layered model with the corresponding whole-space responses, i.e., without the borehole. We studied three different cases, representing

1. Anisotropic shale, Rh = 1 Ohm-m, Rv = 2 Ohm-m,
2. Anisotropic reservoir, Rh = 4 Ohm-m, Rv = 10 Ohm-m,
3. Isotropic reservoir, Rh = Rv = 20 Ohm-m.

The three panels in Figure 6 correspond to these three cases. We varied the mud resistivity from 1000 Ohm-m, i.e., oil-based mud, to 0.01 Ohm-m, representing a highly saturated saline mud system. The relative response difference is plotted for the 21 kHz single frequency data and for the lowest dual frequency pair, i.e., 21 and 42 kHz.

The panels show that the single frequency data generally are strongly affected by the borehole fluid, even for resistive mud systems. The borehole effect in single frequency data is small only for resistive formations and for mud resistivities, Rm, greater than 0.05 Ohm-m. The graph also shows that for very conductive mud systems, the dual frequency transformation becomes ineffective. In these cases, a 1-D inversion, i.e., neglecting the borehole in the model, will yield erroneous vertical resistivities. Therefore, a full or an approximate 2-D inversion that incorporates the borehole and near-zone parameters in the inverse process must be used (Kriegshäuser et al., 2001).

### Field example

Figure 6 shows the 3DEX inversion results from a deepwater turbidite reservoir. The 12.25” borehole was drilled with oil-based mud. The left panel depicts Rh and Rv using single frequency data, the right panel shows the formation resistivities using dual frequency data. The objective was to produce a consistent quantification of oil-in-place from saturation calculations in the laminated sand-shale intervals comparable to the results available from external data such as whole core. The zone of interest was between x260ft and x370ft. Over these intervals the Rv derived from dual frequency data is higher than the Rv based on single frequency data. The higher vertical resistivity in both the shales and the laminated sand/shale reservoir is consistent with our theoretical observations.

### Conclusions

The dual frequency transformation of multicomponent induction log data can significantly enhance the operating range of the 3DEX logging tool. Only in a resistive formation can the single frequency data be used to compute the vertical resistivity of the formation without accounting for the borehole effects. In very highly conductive mud systems, we must use 2-D models in the inverse process to accurately compute the horizontal and vertical resistivity of the formation.

### Acknowledgments

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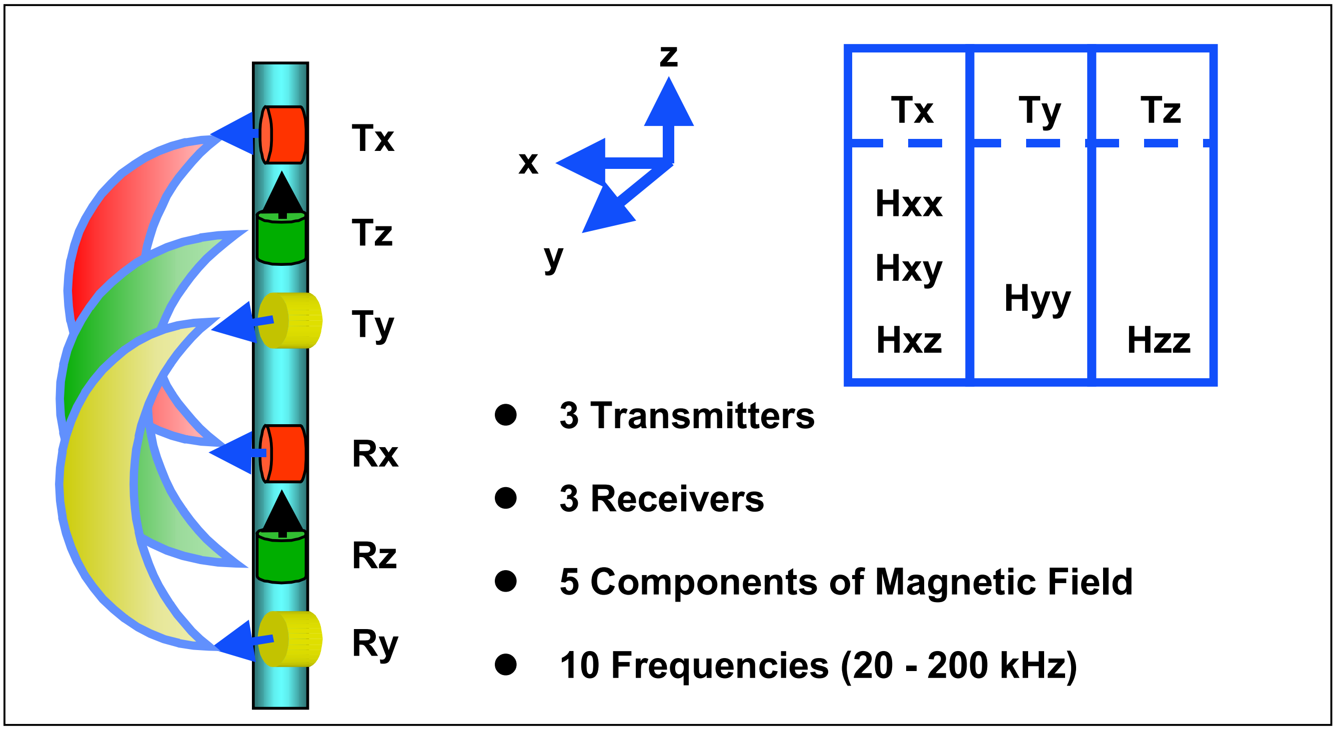

- 3 Transmitters
- 3 Receivers
- 5 Components of Magnetic Field
- 10 Frequencies (20 - 200 kHz)

FIG. 1: 3DEX tool configuration. Three mutually orthogonal transmitter-receiver arrays survey the formation in all three directions.

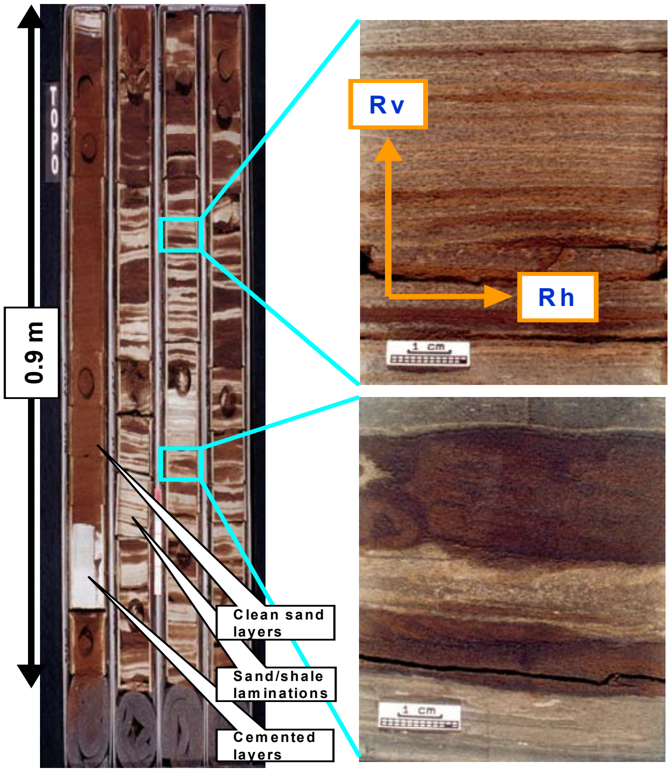

FIG. 2: Typical deepwater turbidite low-resistivity reservoir. The sand/shale laminae are well below the vertical resolution of any wireline device, therefore exhibiting electrical anisotropy.

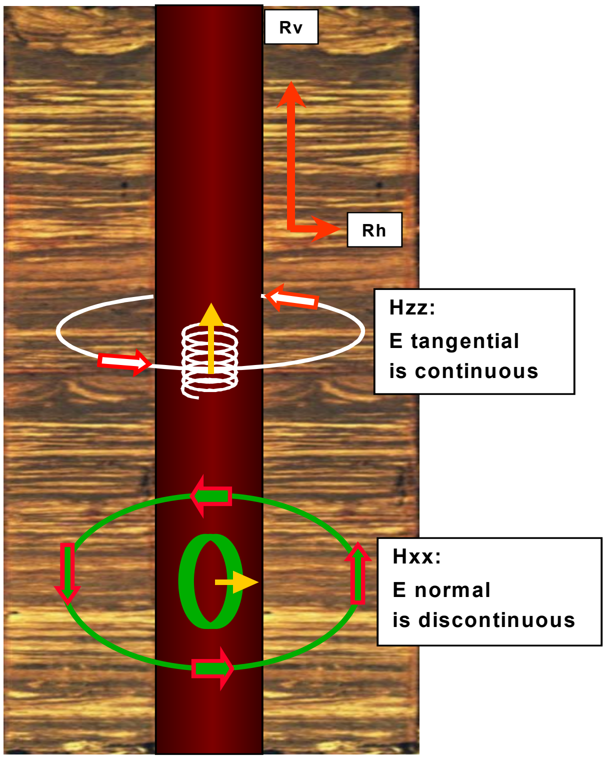

FIG. 3: Electric current pattern of the conventional and new transmitter coil. E normal is discontinuous across the borehole interface; therefore, we have a charge build-up, generating strong borehole effects.

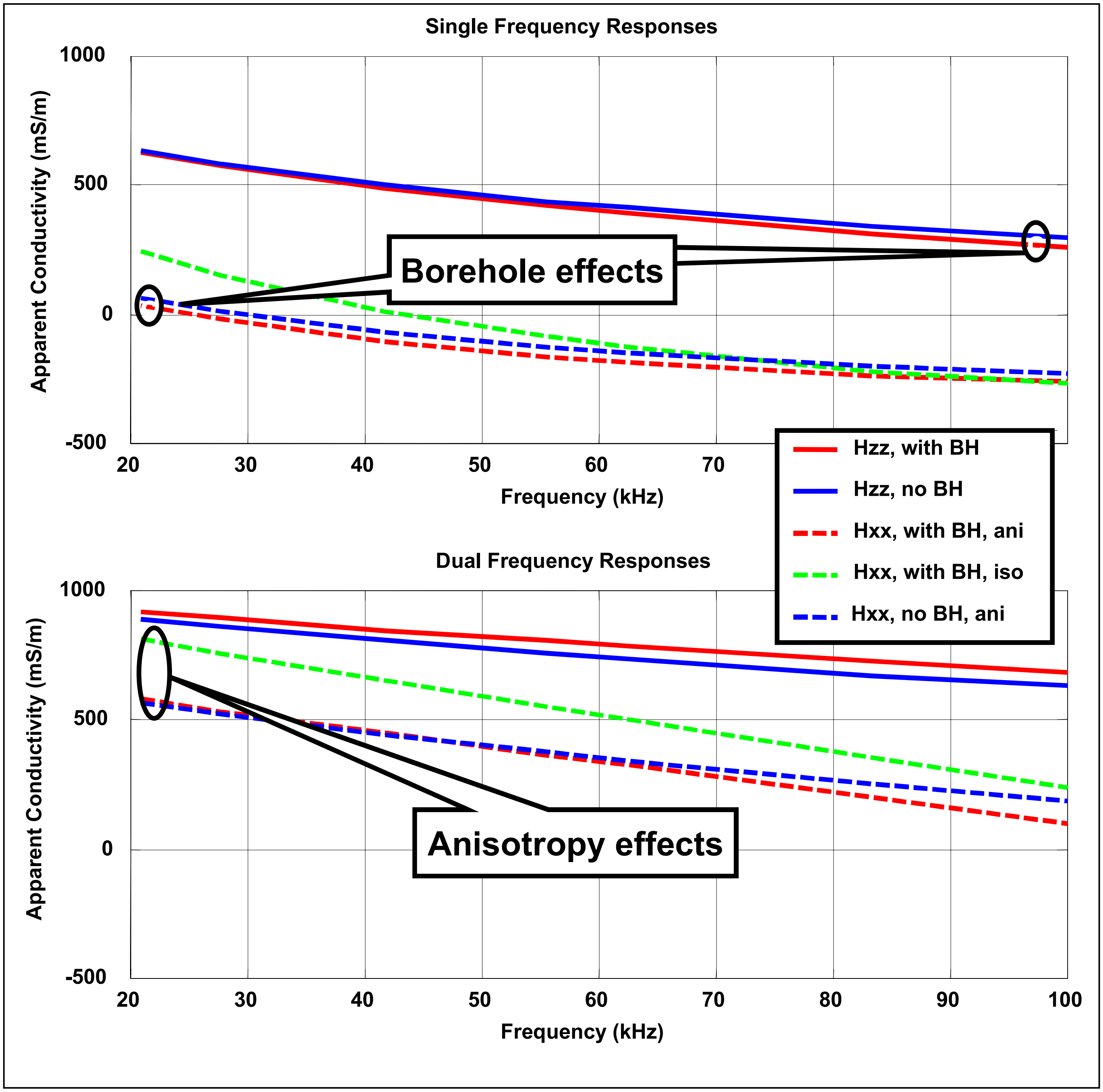

FIG. 4: Borehole effects on Hzz and Hxx or Hyy. The borehole effect can be strong on the single frequency Hxx data, therefore leading to erroneous Rv computations. The Dual Frequency transformed data, however, remove significantly the borehole effect, while maintaining the sensitivity to anisotropy.

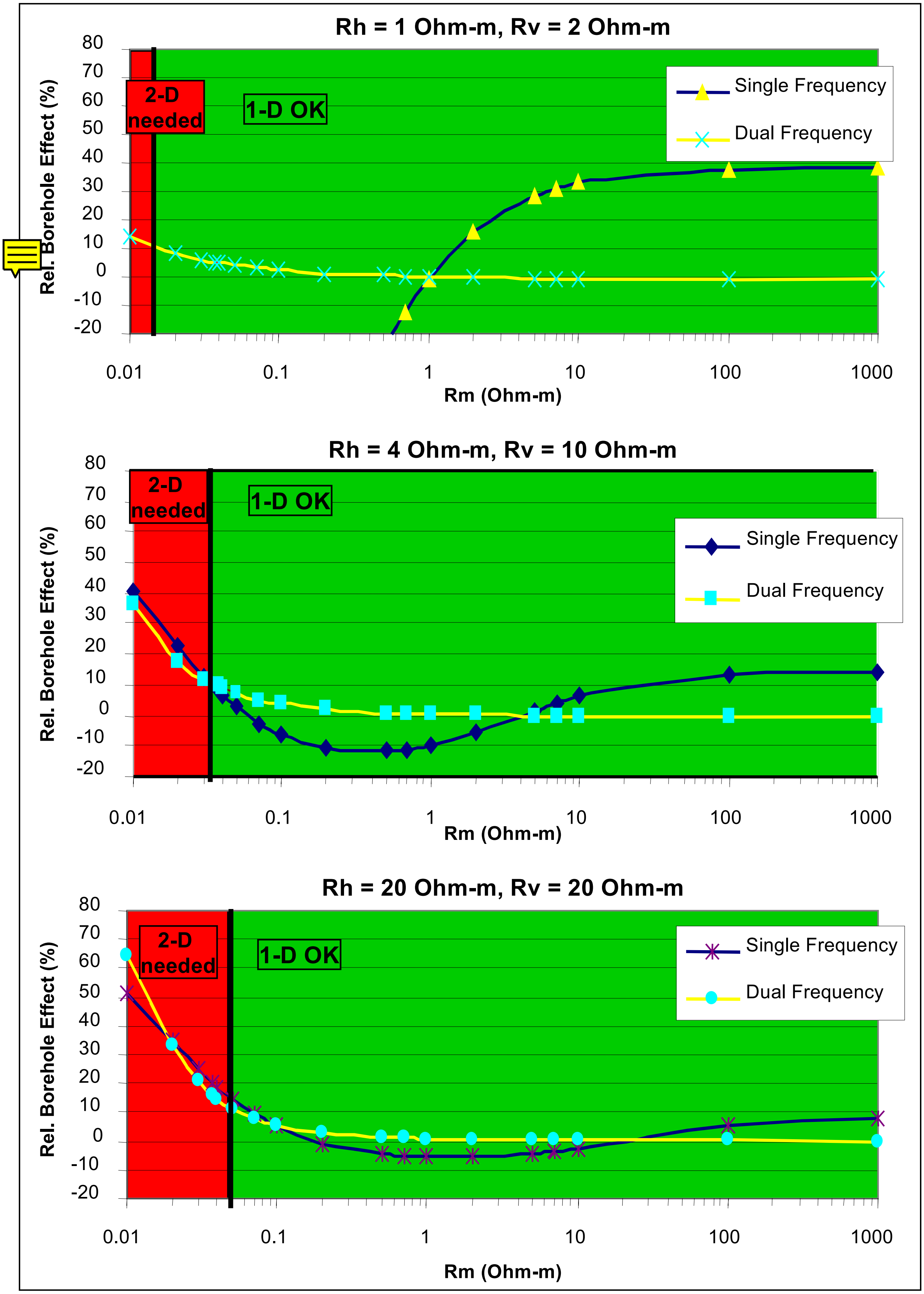

FIG. 5: Three panels examining the operating range of single frequency and dual frequency data in 1-D inversion schemes versus 2-D inversion.

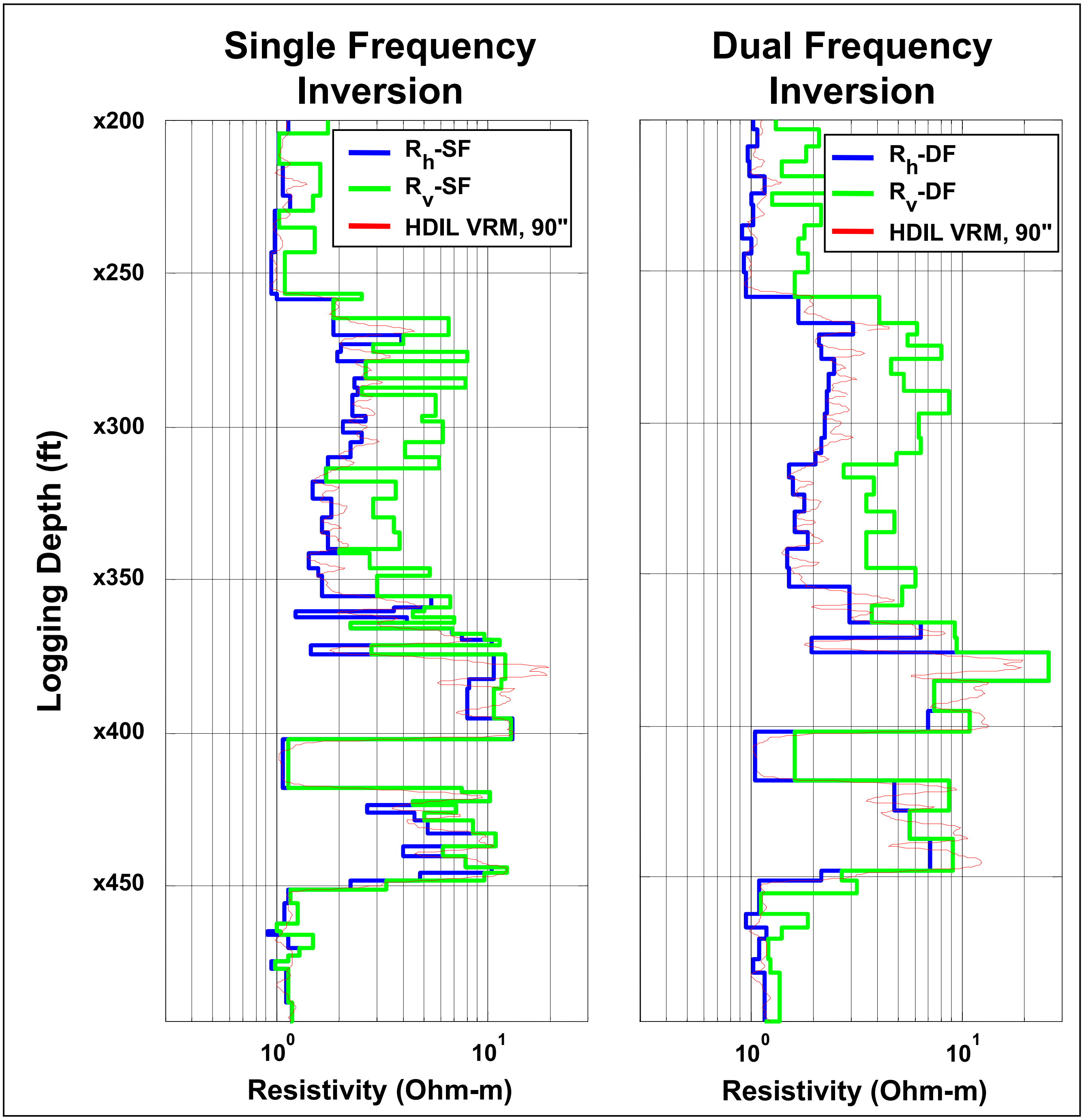

FIG. 6: Field example comparing single frequency data inversion results with corresponding dual frequency data inversion. The enhanced vertical resistivity derived from dual frequency data is consistent with the theoretical findings from this study.