ELSIL (Extra Long Spaced Induction Log)

T. Hagiwara, Terry Research and Development, Houston, TX, U.S.A., terryh@pdq.net

This paper was prepared for presentation at the 8th International Congress of The Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 14-18 September 2003.

Abstract

Response of an induction-logging tool with extra long transmitter-receiver spacing (10-m and 20-m spacing) and at low induction log frequency between 1 kHz and 100 kHz is examined. The tool is proposed to achieve deeper lateral depth of investigation so that it can detect and identify an adjacent bed in horizontal well logging. In addition to coaxial and coplanar antenna settings, tilted coil configurations are also considered. Looking-ahead capability of such tools is also examined.

Introduction

ULSEL (Ultra long spaced electric log) is an electric log with long electrode spacing ranging from 600-ft to 2,000-ft, and is useful to detect a resistive anomaly, such as a nearby salt dome, as far as 300-ft away from the borehole (Ref.1). It can detect salt dome face either sideway (laterally) or ahead of the tool. This deep depth of investigation is a result of ultra-long electrode spacing combined with DC current. However, the ULSEL is not necessarily suitable to detect a conductive anomaly such as shale layer or oil-water contact from inside of the resistive zone.

To detect a conductive anomaly at a distance, an induction-type logging tool is preferred (Ref.2). To achieve deeper depth of investigation than conventional induction tools, the longer transmitter-receiver spacing has to be used. With the longer spacing, the long wave length approxim*ation, kL* << 1, may no longer hold in conductive formation, where k ($k^2=i\omega\mu\sigma$) is the wave number and L the spacing; consequently, the apparent resistivity (or conductivity) may have to be defined differently for such a tool in conductive formations.

Though the deeper depth of investigation is expected from such a tool, how deep can it actually read is not known. This should be investigated. Because of axial symmetry, coaxial induction-type tools have no azimuth sensitivity. Azimuth sensitivity can be attained using tilted coil antennas (Ref.3). Such a tilted coil induction tool (DRT: Directional Resistivity Tool at 2 MHz –500 kHz frequency) has been proposed for LWD resistivity tools (Ref.4-6). The tilted coil induction tool at lower frequency and with extra long spacing must be also examined.

Similarly to ULSEL, there is look-ahead capability in the proposed ELSIL induction tool, if lower frequency of 1 kHz is used.

Though deeper lateral depth of investigation is desired for better well placement to detect a nearby shale layer or oil-water contact, the concept of ELSIL is also applicable for monitoring flood front movement when such tool is placed permanently outside casing (Ref.7).

ELSIL tool

We consider an induction tool that operates at induction log frequencies between 1 kHz and 100 kHz. Unlike conventional induction tools, the transmitter-receiver spacing is extra long in ELSIL in order to attain deeper depth of investigation. In this paper, we consider spacing as long as 10-m and 20-m (30-ft and 60-ft).

In conventional induction tools where both transmitter and receiver antennas are coaxially placed, the voltage output in the receiver loop antenna is given in a homogeneous formation of isotropic conductivity σ by,

$$V \propto -i\frac{2}{L^3}\left(1-ikL\right)e^{ikL}$$

where k is the wave number defined by $k^2=-i\omega\mu\sigma$ and L the transmitter-receiver spacing.

Compared to conventional induction tools with L≈40 in. (1-m) at 20 kHz, where the long wave length approximation (kL << 1) hold, the ELSIL response is subject to more skin effect with longer spacing, say L=10-m and 20-m. This is illustrated in Fig.1 where the in-phase signal (VR) is shown in a homogeneous formation for coaxial tool with L=20m (60-ft) at different frequencies.

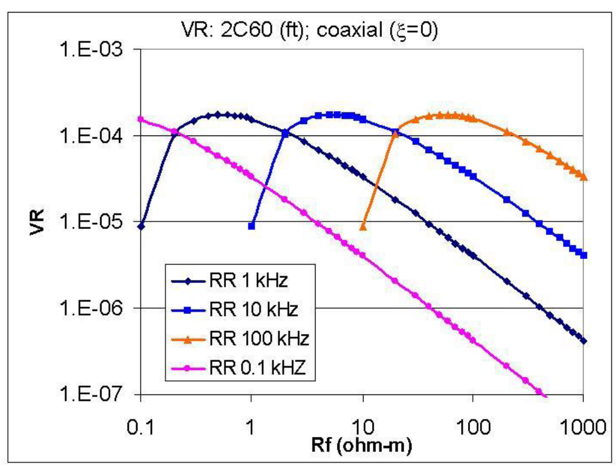

Fig.1 Normalized in-phase response

In addition to coaxially placed transmitters and receivers, the ELSIL tool may be configured to have coplanar transmitters and receivers. It may also have tilted antennas to form DRT (Directional Resistivity Tool) configurations. See Fig.2. In a transversally anisotropic homogeneous formation, the tool response (-r type) is given by,

$$V \propto -\frac{i}{L^3}\left\{\begin{aligned}&2(1-ik_H L)e^{ik_H L}\\&+\sin^2\xi\left[-(1-ik_H L)+(ik_H L)^2\right]e^{ik_H L}\\&+ik_H L\left(e^{ik_H L}-e^{ik_H L\beta}\right)\frac{\sin^2\theta-\sin^2\xi}{\sin^2\theta}\end{aligned}\right\}$$

where $\alpha^2=\frac{\sigma_V}{\sigma_H}$ and $\beta=\sqrt{1+(\alpha^2-1)\sin^2\theta}$. The θ is the borehole dip angle. The third term vanishes in a homogeneous isotropic formation as β=1. The coaxial and coplanar tools are specified by ξ=0° and ξ=90°, respectively.

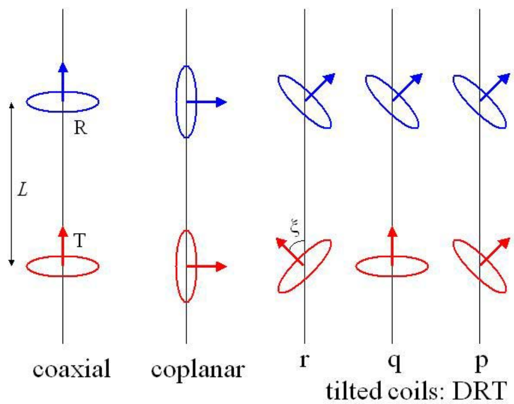

Fig.2 Coil configurations

Apparent resistivity/conductivity from ELSIL

The concept of apparent resistivity is useful in analyzing ELSIL tool responses in actual reservoir evaluation. The apparent resistivity is defined as the resistivity of a homogeneous formation that would generate the same tool response to the measured response. It can be defined from the in-phase response (VR) for a transmitter-receiver spacing at each frequency. It is straight forward to determine the apparent conductivity from the in-phase (VR) response at higher resistivity as the VR response is nearly linearly proportional to the formation conductivity, as shown in Fig.1.

The apparent resistivity/conductivity may be defined differently, especially to correct for the skin effect at higher frequency, with longer transmitter-receiver spacing, and in more conductive formation. For instance, the in-phase (VR) responses from multiple transmitter-receiver spacing may be used at each frequency. Or, both in-phase (VR) and quadrature (VX) responses are used simultaneously from single spacing at each frequency. Or, in-phase responses from multiple frequencies at a spacing may be equally applicable.

The apparent resistivity/conductivity are defined separately for coaxial, coplanar, and for tilted coil configurations. However, it is also useful, in particular in anisotropic formations, to define the apparent resistivity using both coaxial and coplanar responses simultaneously.

Lateral depth of investigation: Proximity detection in horizontal logging

ELSIL is proposed for the deeper depth of investigation. How deep can it actually read? Coaxial induction-type tool has no azimuth sensitivity[3]. To gain the azimuth sensitivity, measurements from coplanar and/or tilted antennas are needed. Such a tilted coil induction tool (DRT: Directional Resistivity Tool) has been proposed for LWD resistivity tools[4,5] (at 2 MHz –500 kHz frequency). Such tilted antennas should also work for ELSIL at lower frequency and with extra long spacing. To investigate the lateral depth of investigation, I examined the ELSIL responses in a horizontal well in a two layer model. The depth *d* is the location of the tool from the bed interface (z=0).

Fig.3 shows the VR response from a coaxial tool with *L*=30-ft (and 60-ft) at 1 kHz. The tool detects a conductive formation (1 ohm-m) further (about 50-ft) from a resistive formation (10 ohm-m), while a resistive formation is identified from a conductive formation at closer distance (about 30-ft).

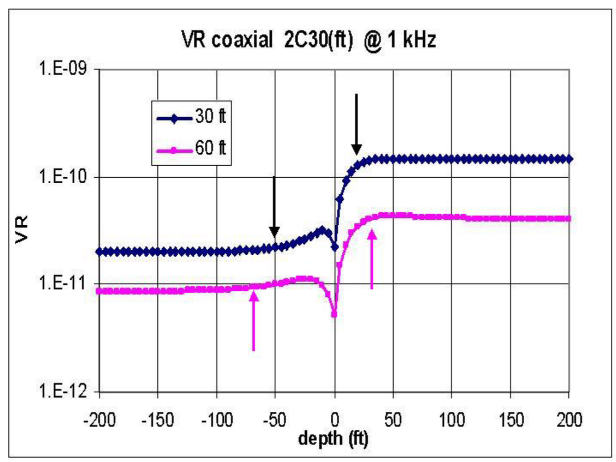

Fig.3 Lateral depth of investigations

For the same spacing *L*, the depth of investigation decreases at higher frequency. At 100 kHz, the VR response changes polarity in a conductive 1 ohm-m formation due to the skin effect.

At the same frequency, the depth of investigation increases for longer spacing. See Fig.3. The longer spacing (*L*=60-ft) causes skin effect at lower frequency (10 kHz) in a conductive 1 ohm-m formation.

For comparison, an example of the VR response from tilted coil ELSIL (DRT-r configuration of Fig.2, with ξ=±45° tilt angle) is shown below. The difference between the response from tools with ξ=+45° and ξ= –45° can be used to determine the azimuth direction to the interface. The difference δV=VR(ξ=45°)–VR(ξ= –45°) is plotted in Fig.4. It is not symmetric with respect to the interface location (depth=0). The lateral depth of investigation is deeper about 50-ft to detect a conductive formation from a resistive formation than to detect a resistive formation 30-ft away from a conductive formation.

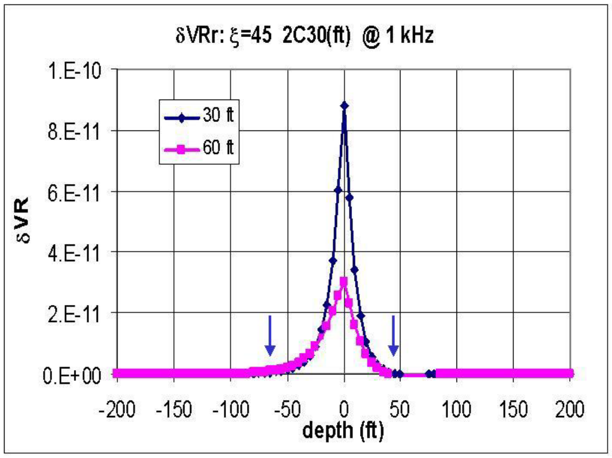

Fig.4 Azimuth sensitivity

Vertical depth of investigation: Look-ahead capability

The ELSIL may be used to detect resistivity anomaly ahead of the tool. To investigate the vertical depth of investigation, I examined the ELSIL responses in a vertical well in a two layer model. The depth *d* is the location of the receiver from the bed interface (z=0). The receiver is placed above the transmitter. The same model is applied also to horizontal logging where the resistivity anomaly lies ahead of the receiver.

Fig.5 shows the VR response from a coaxial tool with *L*=30-ft (and 60-ft) at 1 kHz. The tool detects a conductive formation (1 ohm-m) from a resistive formation (10 ohm-m) further when the receiver (blue dot) is about 30-ft away from the interface, while a resistive formation is identified from a conductive formation at closer distance when the transmitter is almost at the interface.

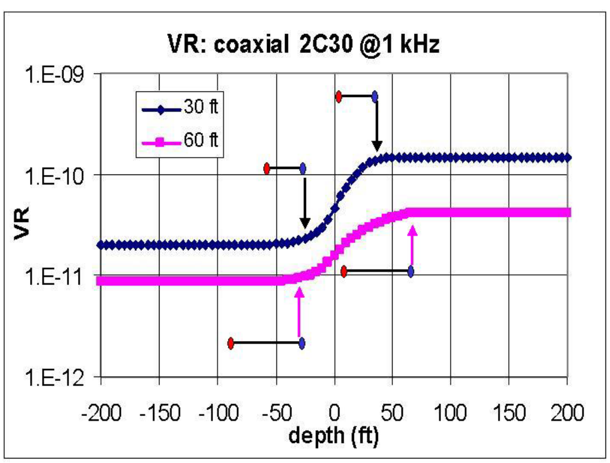

Fig.5 Look-ahead capability

For the same spacing *L*=30-ft, the depth of investigation decreases at higher frequency. At 10 kHz, there appears no significant look-ahead capability with the coaxial tool.

The VR response from tilted coil ELSIL (DRT-r configuration of Fig.3, with ξ=±45° tilt angle) is compared with the coaxial tool (ξ=0°) response. The vertical depth of investigation from tilted coils (DRT-r) is about the same as that from coaxial tool.

However, the slightly deeper depth of investigation can be obtained by using the DRT-p tilted coils of Fig.3, where both transmitter and receiver antennas are tilted and parallel to each other. Fig.6 shows the VR response from such a configuration (with 60-ft spacing and at 1 kHz).

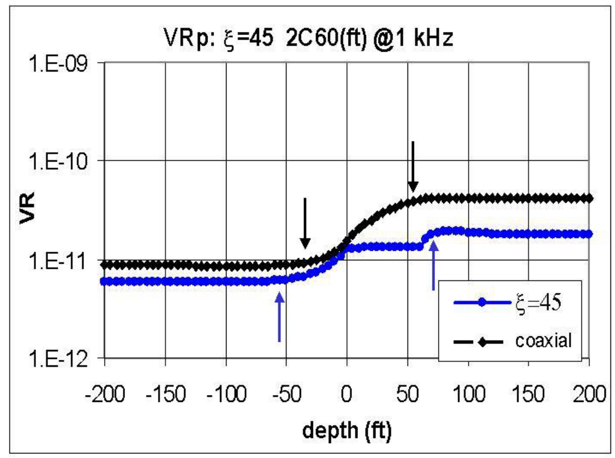

Fig.6 Look-ahead by tilted coils

Vertical resolution

The vertical resolution of ELSIL is dictated by its extra long spacing (*L*=30 – 60-ft) and low frequency (1– 100-kHz). I examined the ELSIL responses in a vertical well in a three layer model. The two shoulder beds are assumed identical with R_s=10 ohm-m and the central bed is more conductive at R_t=1 ohm-m with different bed thickness (Δ=5, 10, 20, 30, 50, and 100-ft). The depth *d* is the location of the receiver from the first bed interface (z=0).

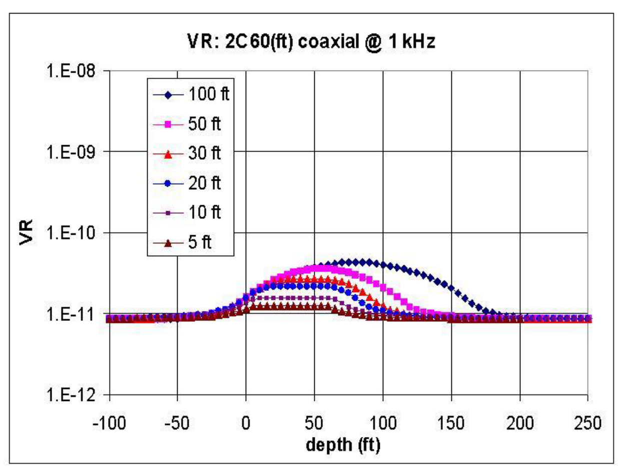

Fig.7 Vertical resolution

Fig.7 shows the VR response from a coaxial tool with *L*=60-ft at 1 kHz. The tool detects a conductive bed (1 ohm-m) even if the bed is as thin as 5-ft. However, it cannot distinguish whether it is 5-ft thick or 10-ft thick by this measurement alone. The bed resistivity is resolved if the bed is 100-ft or thicker.

For the same spacing *L*=60-ft, the vertical resolution improves at higher frequency. At 10 kHz, the bed resistivity is resolved if the bed is 50-ft or thicker.

At the same frequency, the vertical resolution is better for shorter spacing. The 50-ft conductive bed can be resolved with the shorter spacing (*L*=30-ft) at 1 kHz. For comparison, the VR response from tilted coil ELSIL (DRT-r configuration of Fig.3, with $\xi=\pm45^\circ$ tilt angle) is also examined. No significant change is observed in the vertical resolution from the tilted coil configurations.

Conclusion

An extral-long spaced induction logging tool (ELSIL) is proposed to achieve deeper lateral depth of investigation so that it can detect and identify an adjacent bed in horizontal well logging. I examined the response of such an induction-logging tool in 1D multi-layer models for extra long transmitter-receiver spacing (10-m and 20-m spacing) and for frequency between 1 kHz and 100 kHz. In addition to coaxial and coplanar antenna configurations, tilted coil configurations for directional resistivity measurements (the DRT–p, –q, and –r configurations) are also considered.

It was shown that the ELSIL has extended lateral depth of investigation, as deep as 30-ft, from a *L*=30-ft tool at 1 kHz. The effect of frequency and spacing was examined.

The ELSIL with tilted coil antennas can differentiate the direction to the adjacent bed as far as 30-ft away with the same tool (with *L*=30-ft at 1 kHz).

It was also shown that the ELSIL can look-ahead as deep as 30-ft if lower frequency (1 kHz) is used. The effect of frequency and spacing on the vertical depth of investigation was examined. The slightly deeper vertical depth of investigation is achieved if both transmitter and receiver antennas are tilted and parallel to each other (DRT-p configuration).

Because of its extra-long spacing and low frequency, the unprocessed vertical resolution is close to the transmitter-receiver spacing. The effect of frequency and spacing was also discussed.

References

1. Runge, R.J. and Hill, D.G. (1971) “The role of anisotropy in ULSEL”, Paper J, presented at the 12th Annual SPWLA Symposium, May 2-5
2. Moran, J.H. and Kunz, K.S. (1962) “Basic theory of induction logging and application to study of two coil sondess”, Geophysics, v.6
3. Sato, M., et al. (1996) “Apparatus and method for determining parameters of formations surrounding a borehole in a preselected direction”, U.S. Patent 5,508,616, April 16
4. Bittar, M. (2000), “Electromagnetic wave resistivity tool having a tilted antenna for determining the horizontal and vertical resistivities and relative dip angle in anisotropic earth formations”, U.S. Patent 6,163,155, December 19
5. Hagiwara, T., and Song, H. (2001) “Directional resistivity measurements for azimuthal proximity detection of bed boundaries”, U.S. Patent 6,181,138, January 30
6. Hagiwara, T. (2001) “A New LWD Directional Resistivity Tool for Geo-steering”, Contribution to the 7th International Congress of SBGF, Salvador, Brazil, Oct.28-Nov.1
7. Hagiwara, T. (1996) “Use of Induction Log Measurements in Monitoring Flood-Front Movement", presented at the International Symposium on Well Logging Techniques for Oilfield Development under Waterflooding, Beijing, China, September