Analysis of some old unexplained effects in induction logs within anisotropic formations with the electromagnetic triaxial induction tool.

Paulo Roberto de Carvalho* (ICIBE/UFRA), Cícero Roberto Teixeira Régis (CPGf/UFPA, INCT-GP)

Abstract

In this paper, we model coaxial and coplanar vertical logs in one-dimensional (1D) laminated packages and in their equivalent anisotropic beds, neglecting the presence of the borehole and the invasion zones, to simulate geological environments of hydrocarbon reservoirs with resistivity anisotropy.

The objective of this paper is twofold: to perform a quantitative analysis of the anisotropy level of a thinly laminated reservoir as compared to an equivalent anisotropic bed, and, in doing so, to revisit some old and still unexplained effects that appear on the triaxial induction logs. These subtle effects may have only a faint influence on the logs themselves, but their study contribute to our understanding of the electromagnetic phenomena involved in the induction logging.

The results show that the coaxial logs in the laminated formation converge to the equivalent anisotropic bed response much sooner than the coplanar logs. They also show that there is a considerable difference between the anisotropy index obtained by the triaxial induction tool within laminated formations and the anisotropy coefficient of its equivalent anisotropic bed, even for extremely thin laminae thicknesses.

Introduction

From 2000 on, induction tools consist basically of a combination of a coaxial arrangement with two coplanar arrangements of coils, i.e. three sources and three sensors, with axes orthogonal to each other. These tools are commercially referred to as triaxial (Krigshäuser et al., 2000). The responses of the three arrangements of coils are simultaneously registered on multiple channels at multiple frequencies (tens of kHz) and source-sensor spacing. These probes were designed originally to investigate laminated reservoirs, and consequently, an anisotropic behavior.

In this paper the logs are obtained by modeling laminated packages without considering the smoothing effects of the borehole and invasion zones. In this case, some subtle effects on the logs are amplified. These effects are of a geometric or/and electric nature, and some remained unexplained in the well logging literature.

The objective of this paper is twofold: to perform a quantitative analysis of the anisotropy level of a thinly laminated reservoir as compared to an equivalent anisotropic bed, and, in doing so, to revisit some of the old and unexplained effects that appear on the triaxial induction logs. These subtle effects may have only a faint influence on the logs themselves, but their study contribute to our understanding of the electromagnetic phenomena involved in the workings of the induction logging tools.

In the comparative analysis, we find a lamina thickness from which the laminated formation models can be approximated by the response within a homogeneous intrinsically anisotropic bed within a relative difference of one percent (1%).

Theory and Analysis Method

In the models with cylindrical symmetry studied here the six cross-coupled components of the triaxial tools are null. Thus, we have modeled only the coaxial and coplanar vertical logs in one-dimensional (1D) laminated packages and in their equivalent anisotropic beds.

Moran & Kunz (1962) define a “coaxial complex conductivity” to the coaxial coil array (Eq. 1). Analogously, Carvalho & Verma (1999) presented a “coplanar complex conductivity” to the coplanar coil array (Eq. 2).

$$\sigma_R^{cx} + i\sigma_X^{cx} = \sigma + {}^{2i}/_{\omega\mu L^2} - {}^{2}/_{3}\left({}^{L}/_{\delta}\right)\sigma(1+i) + {}^{1}/_{2}\left({}^{L}/_{\delta}\right)^2 \sigma\, i + {}^{2}/_{15}\left({}^{L}/_{\delta}\right)^3 \sigma(1-i) + \cdots, \qquad (1)$$

$$\sigma_R^{cp} + i\sigma_X^{cp} = \sigma - {}^{2i}/_{\omega\mu L^2} - {}^{4}/_{3}\left({}^{L}/_{\delta}\right)\sigma(1+i) + {}^{3}/_{2}\left({}^{L}/_{\delta}\right)^2 \sigma\, i + {}^{8}/_{15}\left({}^{L}/_{\delta}\right)^3 \sigma(1-i) + \cdots , \qquad (2)$$

where a $e^{-i\omega t}$ time factor is used; $i = \sqrt{-1}$; σ is the medium conductivity; $\omega = 2\pi f$ is the angular frequency which f is the linear frequency; μ is the magnetic permeability; L is the transmitter-receiver coil spacing and $\delta = \sqrt{2/\omega\mu\sigma}$ is the skin depth.

We remove the direct coupling term $2i/\omega\mu L^2$ from Eqs (1) and (2), so that the complex conductivities signals come exclusively from the medium. The imaginary component is now called the reactive signal (σ_{XF}^{cx}). Thus, Eqs (1) and (2) then become:

$$\sigma_R^{cx} + i\sigma_{XF}^{cx} = \sigma\left[1 - {}^{2}/_{3}\left({}^{L}/_{\delta}\right)(1+i) + {}^{1}/_{2}\left({}^{L}/_{\delta}\right)^2 i + {}^{2}/_{15}\left({}^{L}/_{\delta}\right)^3 (1-i) + \cdots\right], \qquad (3)$$

$$\sigma_R^{cp} + i\sigma_{XF}^{cp} = \sigma\left[1 - {}^{4}/_{3}\left({}^{L}/_{\delta}\right)(1+i) + {}^{3}/_{2}\left({}^{L}/_{\delta}\right)^2 i + {}^{8}/_{15}\left({}^{L}/_{\delta}\right)^3 (1-i) + \cdots\right]. \qquad (4)$$

These complex conductivities (Eqs. 3 and 4) may also be written in terms of the magnetic fields registered by coaxial and coplanar coil arrays:

$$\sigma_R^{cx} + i\sigma_X^{cx} = \left({}^{2i}/_{\omega\mu L^2}\right) h_z^{cx}\,, \qquad (5)$$

$$\sigma_R^{cp} + i\sigma_X^{cp} = \left({}^{-2i}/_{\omega\mu L^2}\right) h_x^{cp}, \qquad (6)$$

where h_z^{cx} and h_x^{cp} are the secondary magnetic fields, which come exclusively from the medium, i.e., without the transmitter/receiver mutual coupling terms.

In cases of relatively low conductivity ($\sigma < 0.1$ S/m) the first term in each of the series of the Eqs (3) and (4) is enough to estimate the conductivity of the medium, i.e, if ${}^{L}/_{\delta} \approx 0$ then $\sigma \approx \sigma_R^{cx} = \sigma_R^{cp}$. However, in conductivities ranging from 0.1 to 1 S/m it is necessary a first order skin effect correction in the resistive signals σ_R^{cx} and σ_R^{cp} by the factors $[1 - 2L/3\delta]$ and $[1 - 4L/3\delta]$, which are also present in the imaginary components. In conductivities above 1 S/m more terms of the series would be necessary, although there is no longer an exact correspondence between the real and imaginary components. According to Ellis & Singer (2007), in low conductivity environments this correspondence is good enough that, in actual logging, the tools measure the imaginary component to obtain and apply these “boosters” on the resistive signals:

$$\sigma_c^{cx} = \sigma_R^{cx}/(1 - \sigma_{XF}^{cx}), \qquad (7)$$

$$\sigma_c^{cp} = \sigma_R^{cp}/\left(1 - \sigma_{XF}^{cp}\right). \qquad (8)$$

Although all the analysis presented above is for homogeneous isotropic media, in actual induction logging it is common practice to apply Eqs (7) and (8) to fields from more complex media such as anisotropic or inhomogeneous media.

In the comparative analysis that will be performed in this paper, the logs will be simulated in thinly laminated packages and in intrinsically anisotropic beds. The main difference between these two models is in the form of representing the electrical conductivity: in the thinly laminated formations there are two distinct and alternate scalar conductivities, σ_1 and σ_2, whereas in the anisotropic bed the conductivity is a tensor $\tilde{\sigma}$. However, when the anisotropic medium has Transversely Isotropic conductivity with a Vertical axis of symmetry (TIV), the off-diagonal terms are all zeros and $\sigma_{xx} = \sigma_{yy} = \sigma_h$, and $\sigma_{zz} = \sigma_v$ and the degree of anisotropy is given by $\lambda^2 = {}^{\sigma_h}/_{\sigma_v}$.

In 1D layered media, in which the presence of the borehole and the invasion zones are neglected, the formulae for the magnetic field components are expressed in terms of improper integrals due to the inverse Hankel transform, which are solved numerically. This is true for the fields generated by vertical (VMD) and horizontal (HMD) Magnetic Dipoles within a laminated formation (Anderson et al., 1986; Carvalho et al., 2010) as well as for the magnetic field components generated by an HMD in an anisotropic bed bordered by two half-spaces (Kaufman & Dashevsky, 2010).

Kaufman & Dashevsky (2010) deduced through current density distribution and Anderson et al. (2008) show through circuit theory (parallel and series resistors) an identical relation between the horizontal and vertical conductivities of the homogeneous anisotropic media and the conductivities of the thinly laminated medium formed by two alternating and distinct laminae (σ_1 and σ_2) when their thicknesses are less than the tool's vertical resolution:

$$\sigma_h = \sigma_1 V_1 + \sigma_2 V_2, \qquad (9)$$

$$\sigma_v = (V_1/\sigma_1 + V_2/\sigma_2)^{-1}, \qquad (10)$$

where V_1 and V_2 are the volume fractions of each material which are obtained by spectroscopy probe.

Kaufman & Dashevsky (2003) show that at the low frequency range, that is $\omega \to 0$ or ${}^{L}/_{\delta} \ll 1$, the quadrature part (imaginary component) of the secondary magnetic fields (without the mutual coupling term) registered by coaxial ($Q\{h_{zz}^{cx}\}$) and coplanar ($Q\{h_{xx}^{cp}\}$) coil arrays are directly proportional to the horizontal (σ_h) and vertical (σ_v) conductivities, respectively. Thus, the ratio between them yields a structural anisotropy index (λ_R^2), which is also obtained by the ratio between the coaxial (σ_R^{cx}) and the coplanar (σ_R^{cp}) resistive signals, since they are obtained by multiplying the respective field components by the same proportionality constant (Eqs. 5 and 6):

$$\lambda_R^2 = {}^{Q\{h_{zz}^{cx}\}}\Big/_{Q\{h_{xx}^{cp}\}} = {}^{\sigma_R^{cx}}\Big/_{\sigma_R^{cp}} \cong {}^{\sigma_h}/_{\sigma_v}. \qquad (11)$$

However, in order to compare the laminated formation responses with the equivalent anisotropic bed, we use yet another structural anisotropy index (λ_c^2), obtained through the ratio of the boosted signals of the coaxial (σ_c^{cx}) and coplanar (σ_c^{cp}) coil arrays, which is closer to the anisotropy coefficient of the equivalent bed $\lambda_c^2 = {}^{\sigma_c^{cx}}\Big/_{\sigma_c^{cp}}$.

Results and Discussions

We use shale resistivity as $\rho_{sh} = 1$ ohm-m and sandstone resistivity as $\rho_{sd} = 5$ ohm-m, following the same values used in Anderson (1986). When the laminae are infinitely thin we apply these values in Eqs (9) and (10) and obtain the horizontal and vertical resistivities $\rho_h = 1.67$ ohm-m and $\rho_v = 3$ ohm-m, for an equivalent anisotropic bed with an anisotropy coefficient $\lambda^2 = \rho_v/\rho_h = 1.8$, which is close to the typical contrast for actual logging situations ($\lambda^2 \cong 2$), according to Anderson (1990).

We will show only the boosted signals (Eqs. 7 and 8), which present all the geometric and electromagnetic effects that will be discussed, and which are, after all, the final product delivered by the resistivity tools in actual logging.

Figure 1 shows the coaxial and coplanar corrected logs within two thick (10L) models: 1) a laminated formation (red lines) and 2) an equivalent anisotropic bed (blue lines). These logs are right in the middle of the models ($z = 0$) with the depth raging from -2L to 2L, i.e., well away from the boundaries to the adjacent infinite half-spaces above and below

In vertical coaxial logs the induced currents flow only parallel to the lamina planes, so that these logs are strongly affected by the conductive laminae (1 ohm-m), and the packages behaves as an isotropic bed with resistivity equal to the bed's horizontal resistivity $\boldsymbol{\rho_h}$ = 1.67 ohm-m. With the progressive reduction of the laminae thicknesses, $\boldsymbol{h = L/n}$ with $\boldsymbol{n}$ ranging from 2 to 10, the coaxial logs for both models are almost indistinguishable for thicknesses less than L/3.

With the reduction of the lamina thicknesses, the coplanar logs show two alternating features within the laminated formation: "smooth" for even values of $\boldsymbol{n}$ (L/2, L/4, L/6, L/8 and L/10) and "angular" for odd values of $\boldsymbol{n}$ (L/3, L/5, L/7 and L/9).

Anderson et al. (1990) also show these two response patterns (smooth and angular) in the coaxial logs within laminated formation crossed by different dip angles, although they do not explain the reason for these apparent strange responses.

In vertical logs, as in the examples in this paper, the coaxial responses are always smooth because there is no discontinuous electric field, and no polarization effects.

In the coplanar smooth logs (even $\boldsymbol{n}$) the transmitter coil is always in a layer with the same conductivity as the receiver coil and the number of interfaces between them is even. Consequently, the interface polarizations between them tend to cancel out, and the polarization effects to disappear. However, in the coplanar angular logs (odd $\boldsymbol{n}$), transmitter and receiver coils are always at different conductivities and the number of interfaces between them is odd. Therefore, the net polarization between them is not null and the horning effects appear in this case as a cusped feature. These polarization effects affect not only the shape (smooth to angular) but also the magnitude of the oscillations of the coplanar logs, so that, for example, going from laminae thicknesses L/6 to L/7 the magnitude increases, even though the laminae in the latter case are thinnest.

Howard and Chew (1992) showed theoretically and Carvalho & Verma (1998) showed experimentally, through test tank measurements, that these horns on the logs are damped if the presence of the borehole and invasion are taken into account.

In some laminae thicknesses such as L/3, L/5, L/6 and L/9, there is a curve reversal with respect to the model for both coaxial and coplanar logs while in others there is a perfect correlation with the model. Anderson (1986) shows similar results in coaxial logs and comments that "reflections from bed boundaries located within the coil spacing make impossible for the electromagnetic waves to contain correct information about the media", which is a true enough statement that does not really explain the phenomenon, which seems to stem from purely geometrical effects of the relative positions of the transmitter and the receiver within the laminae, and which is present in both coil arrays.

To summarize the results for the whole sequence of models, Figure 2 shows the Root Mean Square (RMS) of the relative difference (%) between the laminated formation (red solid lines) and the anisotropic bed (dashed blue lines) responses of the coaxial and coplanar logs showed in Figure 1.

The coaxial logs from the laminated formation converge to the homogeneous anisotropic bed much earlier than the coplanar logs. If we take a relative difference of 1% as an indicator of convergence between both models, Figure 2 shows that this convergence occurs around L/5 in the coaxial logs, whereas in the coplanar logs it comes later, so that in L/9 and L/10 this difference is still 18.22% (odd n) and 1.454% (even n), respectively.

A surprising effect in the coaxial logs and exactly opposite to what happens in the coplanar logs can be clearly seen in Figure 2-a: the magnitude of the oscillation in each of the odd n cases is smaller than that in the following even n case (L/3 and L/4, for example), despite the fact that in the latter case the laminae are less thick. There aren't any polarization charges in these vertical coaxial logs. The only difference between the two cases is that in the even n cases the material volumes (shale and sand) between the transmitter and the receiver coils are always constant and identical ($\boldsymbol{V_{sh} = V_{sd} = 0.5}$), regardless of the laminae thicknesses, whereas in the odd cases they change according to the position of the coils inside the package, oscillating around an average value of 0.5, so that the fields propagate in a medium that is, on average, more or less conductive depending on the sonde position. As the laminae get thinner and thinner, all oscillations tend to disappear and the curves tend to the value of the equivalent horizontal resistivity.

Figure 3 shows again the RMS of the relative difference (%) between the laminated formation and the anisotropic bed only for the coplanar logs. The laminae thicknesses is now reducing from L/2 to L/1001 to represent oil reservoirs in sand-shale-silt sequences in which the laminae thicknesses are in the millimeter range, well below the minimum vertical resolution available from resistivity tools (Anderson et al., 2008). The percentage differences of the even n (dashed line) and odd n (solid line) cases decay exponentially with the reduction of the laminae thicknesses and they reach the reference value of 1% around L/12 (1.014%) and L/165 (1.007%), respectively. The even case curve reaches 0.1134% at L/40 whereas the odd case curve reaches 0.1659% only at L/1001.

Figure 4 shows how the structural anisotropy of the thinly laminated reservoirs changes with the sand-shale resistivities. In laminated reservoir environments, the sand resistivity may vary from 2.5 to 25 ohm-m, due mainly to the sandstone compaction and oil saturation (Anderson et al., 1986; Anderson et al., 1990). The points A and B show that a relatively small variation in the shale resistivity causes a large change in the anisotropy index, i.e., when the shale resistivity varies from 1 (solid line) to 2 ohm-m (dashed line) for a 20 ohm-m sand resistivity the anisotropy index reduces from 12 to 4, approximately.

According to Anderson et al. (2008), in actual induction logging this structural anisotropic index yields useful information, so much so that when it is higher than five (horizontal black dash-dot line), it alerts the log analyst to look for a potential pay laminated reservoir. However, one must be careful in this interpretation, because it is possible that a laminated pay reservoir generates a value of the structural anisotropy index below the reference line ($\boldsymbol{\lambda_c^2} <$ 5) if the main reason for the resistivity anisotropy is the oil concentration in the sandstone laminae, as illustrated by point B in Figure 4.

Conclusions

Based on the comparative study between the responses from a laminated reservoir and its equivalent anisotropic bed, for a coil spacing L, we conclude that:

Coplanar logs are more sensitive to detect and delineate thinly laminated reservoirs because of the electric charge accumulation on the laminae interfaces. As the laminae thicknesses (L/n) are reduced the coplanar logs show two alternating features within the laminated formation: “smooth” for even values of n and “angular” for odd values of n. In the even n case the number of interfaces between transmitter-receiver coils is even, consequently, the polarization effects tend to cancel out and disappear. However, in the odd n cases the number of interfaces between the transmitter-receiver coils is odd, consequently the net polarization between them is not null and the polarization effects appear as a cusped feature. Because of these polarizations, the oscillation magnitude in any odd n case is always greater than in the preceding even case (n-1), despite the fact that the laminae in the former are thinnest.

The coaxial logs in the laminated formation converge to the equivalent anisotropic bed response much sooner than the coplanar logs, i.e., the convergence to within 1% occurs around L/5 in the coaxial logs whereas in the even n and odd n cases in the coplanar logs they occur around L/12 and L/165, respectively.

A surprising effect occurs in the coaxial logs where the magnitude of the log oscillation in each of the odd n cases is smaller than that in the following even n case, despite the fact that in the latter the laminae are less thick. There aren’t any polarization charges in these vertical coaxial logs and the only difference between the two cases is that for even n the sand-shale volumes between the transmitter and the receiver coils are always constant and identical ($\boldsymbol{V_{sh} = V_{sd} = 0.5}$) whereas in the odd cases these volumes change according to the position of the coils inside the package, with an average of 0.5.

In some laminae thicknesses there is a curve reversal with respect to the model for both coaxial and coplanar logs while in others there is a perfect correlation. These curve reversals seem to stem from purely geometrical effects of the relative positions of the transmitter and the receiver within the laminae, which are present in both coil arrays.

There is a considerable difference between the structural anisotropy index and the anisotropy coefficient, even for extremely thin laminae thicknesses. This difference is chiefly due to the relatively high frequency used in induction logging (tens of kHz) which is far from the ideal approach condition that is a frequency close to zero.

It is possible that a laminated pay reservoir generates a value of the structural anisotropy index below the reference value (five) if the main reason for the resistivity anisotropy is the oil concentration in the sandstone laminae.

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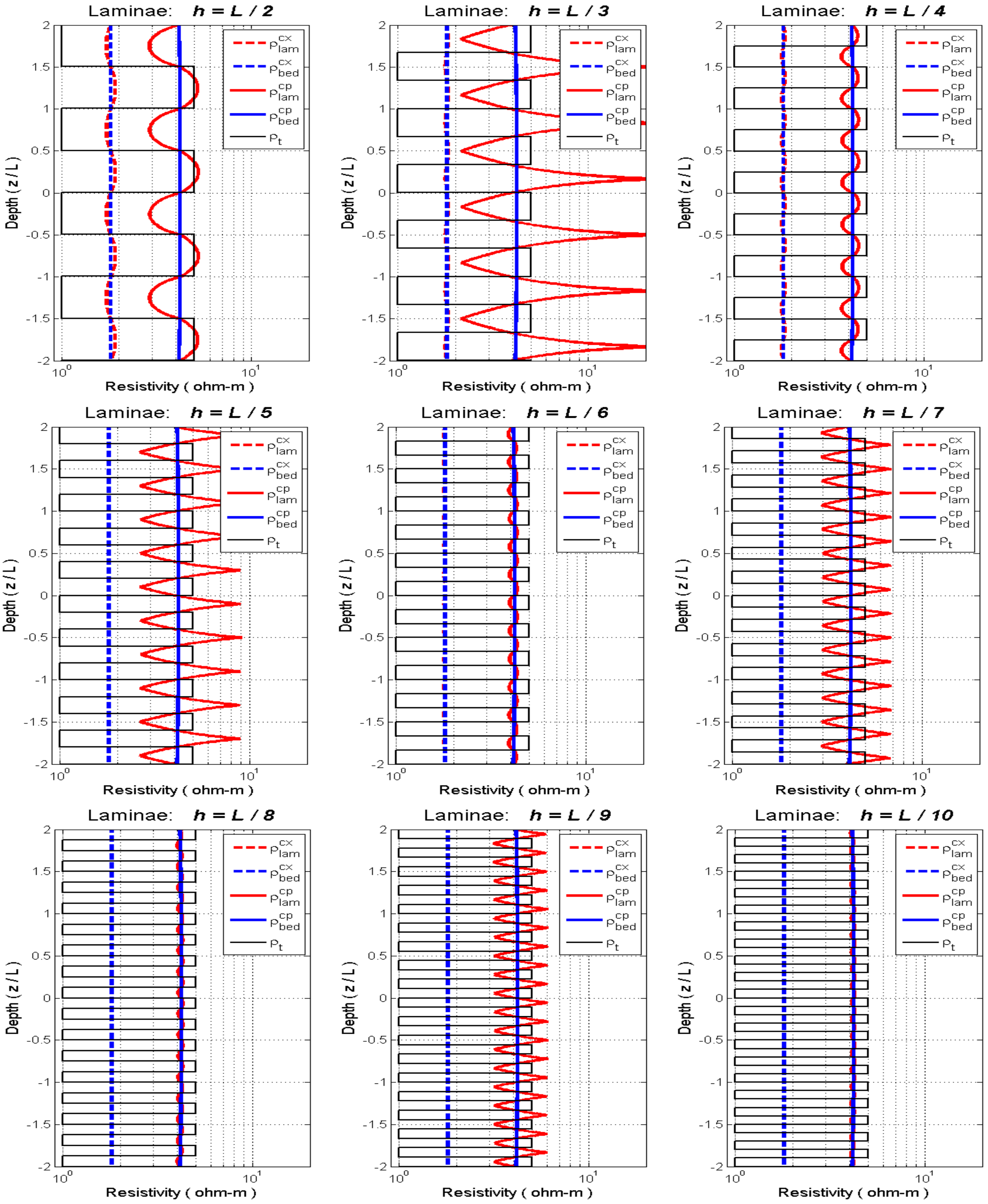

Figure 1 – Evolution of the coaxial and coplanar corrected logs (ρ_c^{cx} and ρ_c^{cp}) within a laminated formation (oscillating red lines) in relation to its equivalent anisotropic bed (straight cyan lines).

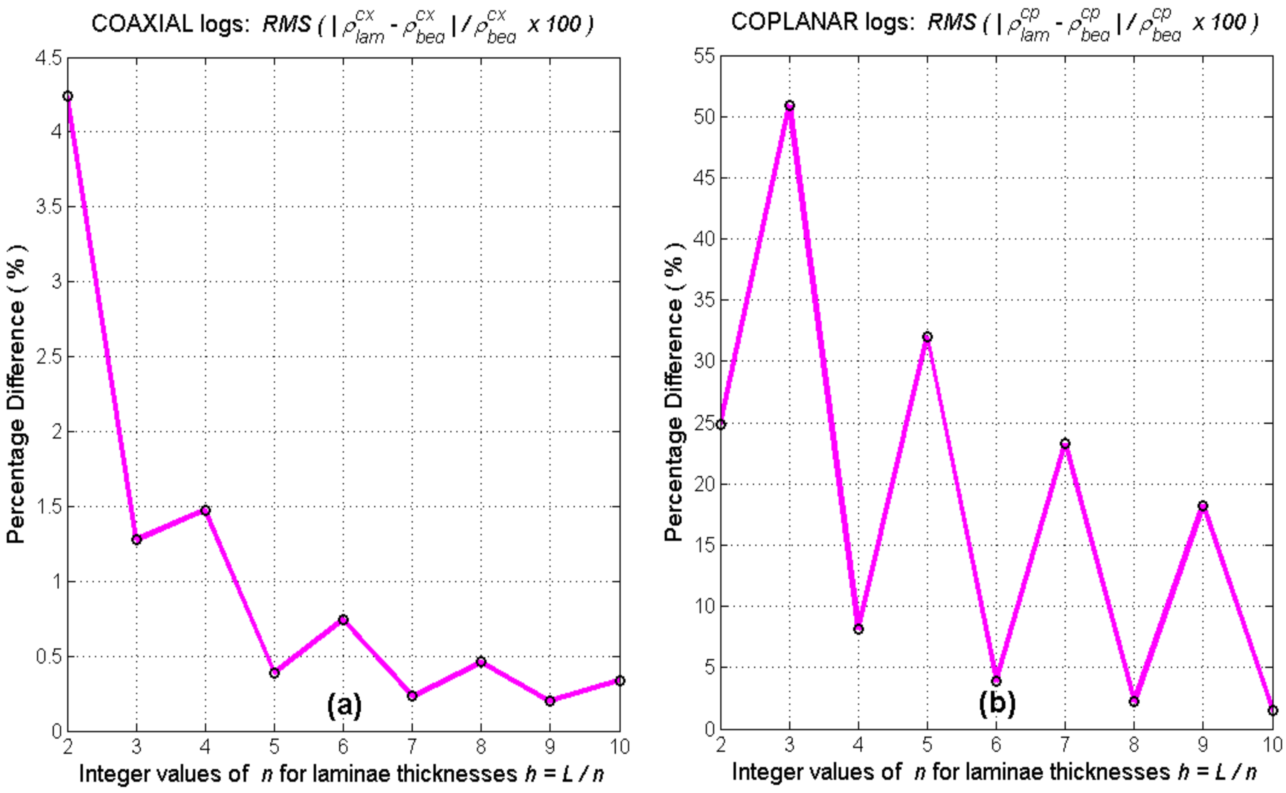

Figure 2 – Relative difference (%) between the laminated formation and the equivalent anisotropic bed responses to the coaxial (a) and coplanar (b) corrected logs with reduction of the laminae thicknesses.

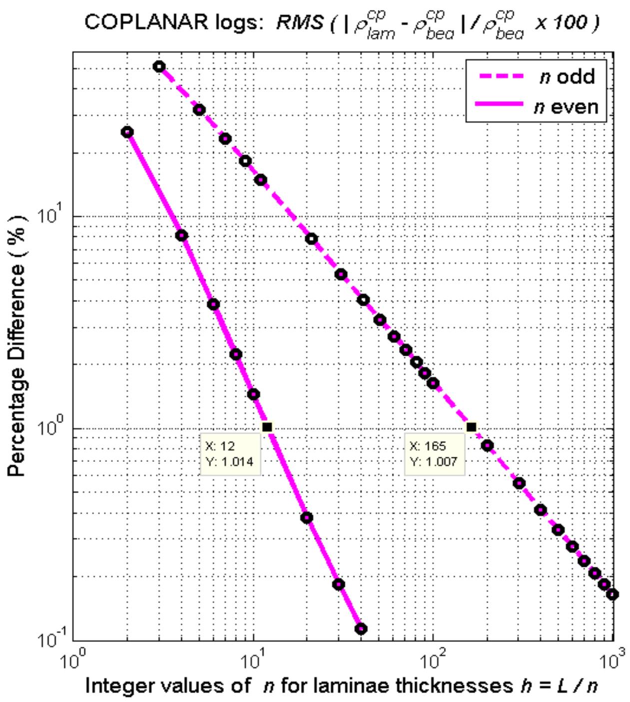

Figure 3 – Relative difference (%) between the laminated formation and the equivalent anisotropic bed responses to the coplanar corrected logs with reduction of the laminae thicknesses.

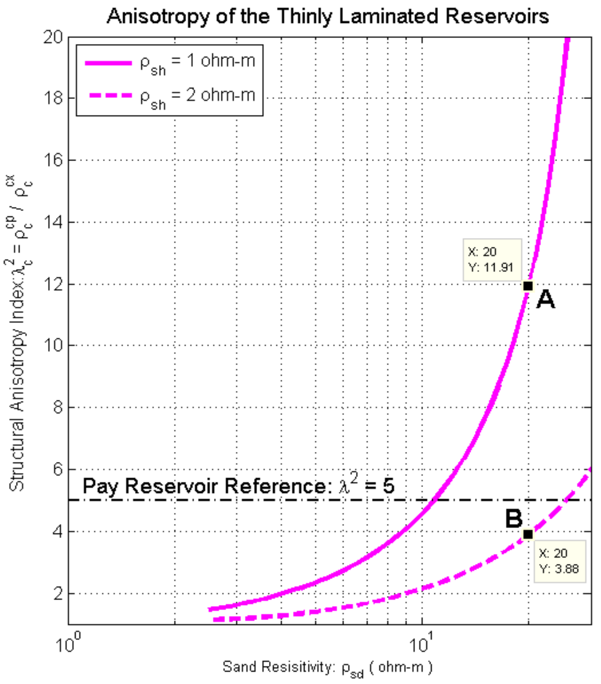

Figure 4 – Structural anisotropy index within thinly laminated formations (h = L/165) versus the sand-shale laminae resistivities.