THE EFFECT OF RESISTIVITY ANISOTROPY ON EARTH IMPULSE RESPONSES

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ABSTRACT

Multi-transient electromagnetic (MTEM) is a dipole-dipole time-domain galvanic electromagnetic technology, implemented in land, transition zone and shallow marine environments, suitable for mapping subsurface resistors, such as petroleum reservoirs across multiple terrains. Because MTEM is a full bandwidth, high resolution, field-optimized technology it is an ideal complement to seismic data. Most previous electromagnetic studies considered only isotropic resistivity. This new study evaluates the implications of resistivity anisotropy that when included in MTEM models results in more accurate depth inversions. The effects of microscopic (intrinsic) and macroscopic (effective) anisotropy on the VTI or polar anisotropy are evaluated in this study. Intrinsic anisotropy arises from rocks having flat minerals layered parallel with the bedding, whereas effective anisotropy arises when lithologies of different resistivity are inter-bedded. Earth electromagnetic responses to a transient source are greatly dependent on resistivity anisotropy. There is no isotropic solution to an anisotropic halfspace, and a multi-trace isotropic inversion of synthetic data arising from an anisotropic model will lead to misleading results, such as target depth estimated too shallow, exaggerated transverse resistivity for the target zone, and underestimated background resistivities. High levels of background anisotropy can obscure the target at a fixed offset which can be solved by increasing offset distance. There is a tradeoff in acquisition cost though, since signal strength decreases with increased offset. Anisotropy must therefore be accounted for and included in inversion schemes. A practical way to estimate the effective anisotropy directly from the data is shown based on the early and late parts of the step response providing values for the horizontal resistivity and the geometric mean resistivity.

INTRODUCTION

Resistivity anisotropy arises through a variety of scales. Micro scale anisotropy is referred to as intrinsic, where rock layers are horizontal and parallel, as in shale. Intrinsic anisotropy leads to lower resistivity parallel to bedding and higher resistivity normal to bedding. Since electromagnetic current paths in sedimentary rocks are provided by interconnected water-filled pore throats, vertical current paths are longer and more tortuous in rock exhibiting intrinsic anisotropy. Macro scale anisotropy results from interbedded heterolithic rock layers, such as sand-shale sequences, particularly with high resistivity hydrocarbon-bearing layers. Where individual beds are too thin to be resolved, the anisotropy is referred to as effective.

The degree of anisotropy may also vary directionally. This paper addresses only transversely isotropic rocks with a vertical axis of symmetry (VTI) such that resistivity at a given point has a constant magnitude in any horizontal (azimuthal) direction. If we define the vertical resistivity as \( \rho_v \) and the horizontal resistivity as \( \rho_h \), the anisotropy factor \( \lambda \) is then defined as: \( \lambda = (\rho_v/\rho_h)^{1/2} \). The geometric mean resistivity (\( \rho_m \)) is evaluated by classic direct current (DC)-resistivity sounding and defined as: \( \rho_m = (\rho_v \rho_h)^{1/2} \). Typical anisotropy factor values for brine charged sandstones are 1 to 2 and for shales 2 to 3. When hydrocarbon charged sandstones are interbedded with shales, the resistivity factor may reach as high as 6, and shales that are interbedded with anhydrite can reach values of up to 7.5.

New tri-axial logging tools available to industry are capable of measuring both vertical and horizontal resistivity, hence providing a direct evaluation of anisotropy in the wellbore. Wireline and measurement while drilling resistivity logs in vertical wells may be used to examine VTI. Borehole resistivity measurements often differ from

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indirect determinations of resistivity through DC-resistivity and general electromagnetic surveying. This is due in part to the differences in the scale (volume) of rock through which the electromagnetic waves travel. Surface MTEM measurements are affected by larger lateral variations than borehole measurements that are limited to relatively smaller depth of investigation surrounding the wellbore. Most previous electromagnetic studies only considered isotropic resistivity models. However, today there is great emphasis in including anisotropy in modeling and inversion studies. In this paper we consider the effects of transversely isotropic rocks with a vertical axis of symmetry (VTI), also known as polar anisotropy, on the earth’s electromagnetic impulse and step responses.

The Multi-Transient Electromagnetic Method

The MTEM method is described by Wright et al. (2001, 2002 and 2005). It is a time domain, galvanic technology implemented in land, transition zone and marine environments (currently up to 500 m water depth), typically employing a transient broadband source signal known as a pseudo random binary sequence (PRBS). Similar to a vibroseis sweep utilized in seismic where the source signal bandwidth is matched to what the earth returns, the bandwidth of the PRBS is matched to what can be recovered at the receiver end at any particular offset. MTEM is unique in that the source and receiver signals are recorded simultaneously allowing deterministic deconvolution to recover the earth’s impulse response. Integration of the impulse response yields the earth’s step response. By employing deconvolution in combination with the PRBS source signal, the desired signal-to-noise ratio (S/N) at a target level is achieved in the shortest possible time.

The entire shape of the impulse or step response holds the information about the distribution of resistors in the subsurface, but the peak amplitude of the impulse response and the travel-time of that peak are important attributes, similar to trace attributes in seismic, that are used for real time assessments revealing both the potential presence of a resistor and the lateral terminations of that resistor. A full waveform inversion is always the final deliverable.

Land data is typically acquired with 100 m receiver station interval, reduced to 50 m for shallow targets and increased to 200 m for deep targets. Marine data is acquired with a 200 m receiver spacing resulting in a signal strength approximately 25 times greater than autonomous seafloor receiver pods currently employed by deepwater controlled source electromagnetic surveys.

Data acquisition is optimized to achieve the required S/N at target level as quickly as possible. Each source receiver offset yields one impulse response with a bandwidth that decreases quickly with increasing offset. The entire frequency range typically covers four orders of magnitude, so the offset range is grouped into three or four sub-ranges where the bandwidth of the PRBS is modified to optimally match each sub-range. At the same time as the bandwidth decreases with increasing offsets, the strength of the source, referred to as the dipole moment and defined as the product of injected current and the dipole length, is increased for each sub-range by successive lengthening of the source dipole.

The incoming data is quality controlled and pre-processed real time in both land and marine acquisition allowing the buildup of S/N to be monitored continuously at the target level, eliminating the need for adding redundant acquisition time, as is done when data is recorded blindly in autonomous sea-bottom pods. Clock-drift issues in the recording equipment is eliminated by full time access to Global Positioning System satellite time signals as a time reference.

Earth Step and Impulse Responses

The form of earth response functions may be illustrated by calculating the step and impulse responses at some offset for the simplest case of a uniform, isotropic halfspace. Example step and impulse responses for land data are shown in Figures 1 and 2 respectively. A step response is converted to an impulse response by taking the derivative, and the impulse response is converted to a step response by integration.

The step response is characterized by the instantaneous arrival of the airwave followed by the gradual buildup in subsurface response flattening out and asymptotically approaching a level that corresponds to the DC-resistivity sounding response sensitive to the geometric mean resistivity.

The land impulse response comprises the airwave (which travels along the ground/air interface near the speed of light and so arrives at time t=0) followed by a response resulting from diffusion through the resistive subsurface. These two components are immediately separable. The travel time of the
impulse response peak is proportional to the average resistivity.

**The Effects of Anisotropy**

The anisotropy under consideration is the simplest and most geologically common. The vertical direction is perpendicular to bedding and has the higher resistivity, and the horizontal plane parallel with bedding exhibits the lowest resistivity and is equal at all azimuths. This model is referred to as VTI.

In a VTI rock the vertical resistivity is referred to as \( \rho_v \) and the horizontal resistivity \( \rho_h \) and they define the anisotropy factor

\[
\lambda = \frac{\rho_v}{\sqrt{\rho_h}}
\]

with typical values between 1 and 5. The geometric mean resistivity is \( \rho_m = \sqrt{\rho_v \rho_h} \). We may now consider three special ways of varying anisotropy – keeping \( \rho_v, \rho_h \) or \( \rho_m \) constant. We describe these cases as:

- \( \rho_h^c \): \( \rho_h \) = constant, \( \rho_v \) and \( \rho_m \) increase with increasing \( \lambda \).
- \( \rho_v^c \): \( \rho_v \) = constant, \( \rho_h \) and \( \rho_m \) decrease with increasing \( \lambda \).
- \( \rho_m^c \): \( \rho_m \) = constant, \( \rho_h \) decreases and \( \rho_v \) increases with increasing \( \lambda \).

Effects on a uniform halfspace step response for these three cases of varying anisotropy on land are shown in Figure 3 and effects on land impulse responses are shown in Figure 4. The effects are dramatic. The airwave (initial step \( E(0) \)) depends only on the horizontal resistivity \( \rho_h \), whereas the late time DC value (\( E(\infty) \)) depends only on the geometric mean. Using results from Wilson (1997) for an isotropic halfspace of resistivity \( \rho \)

\[
E(0) = \frac{\rho}{2\pi r^2} \quad \text{and hence} \quad \frac{\rho_h}{2\pi r^3},
\]

\[
E(\infty) = \frac{\rho}{\pi r^3} \quad \text{and hence} \quad \sqrt{\rho_v \rho_h} \frac{1}{\pi r^3}.
\]

This provides a method of determining the anisotropy of the halfspace as

\[
\lambda = \frac{\sqrt{\rho_v \rho_h}}{\rho_h} = \frac{1}{2} \frac{E(\infty)}{E(0)}
\]

and this is then used as an initial start value in an inversion scheme.

It is easily seen in Figure 4 that the travel-time for the impulse response peak is mainly sensitive to the vertical resistivity \( \rho_v \) and this provides another opportunity to make sure the extracted vertical and horizontal resistivities, and the geometric mean provide a consistent solution.

**Implications for the Inversion of MTEM Data**

In the following section we discuss the implications of inverting MTEM data acquired over an anisotropic subsurface with an isotropic inversion routine. Figure 5 shows no impulse response is generated over an isotropic halfspace that matches the impulse response from an anisotropic halfspace, even when the anisotropy factor is as low as 2.0 considered to be a typical background value.

Anisotropic data were then generated from a model comprising a background geometric mean resistivity of 20 \( \Omega m \) with an embedded target layer 25 m thick with geometric mean resistivity 500 \( \Omega m \) whose top was at a depth of 500 m. Figure 6 shows the result for an anisotropic target embedded in an isotropic background. All impulse responses separate well with the peak amplitude increasing with increasing target anisotropy, and travel-time of the peak decreasing with increasing \( \rho_v \).

Next we examine the response when varying the anisotropy of the background where we also maintain the previous variation of anisotropy in the target layer while maintaining constant offset. Shown in the example to the left in Figure 7 is a repeat of Figure 6. The isotropic background allows wide separation between the anisotropic target responses. However, when anisotropy magnitude 2 is assigned to the background, the response curves are moved closer together as seen in the middle illustration, and at a background anisotropy magnitude of 3, the response from the half-space and the target overlap perfectly for target anisotropy factors 1, 2 and 3 while maintaining the geometric mean. We therefore conclude that for a fixed offset, an increase in background anisotropy can potentially obscure targets for all levels of anisotropy up to the magnitude of the background anisotropy.
The solution to this problem is shown in Figure 8. To the upper left is the case with all anisotropic targets obscured by the background anisotropy. In the following three images the offset is successively increased with all other parameters held constant, resulting in a successively increasing separation of the response curves.

Next we investigate the result of a uniformly anisotropic model ($\lambda = 2\square$) when a target layer is inverted under the assumption of isotropy. This model is shown in Figure 9 and the multi-offset Occam inversion results in Figure 10. The isotropic inversion results in the target being placed too shallow with a too high transverse resistance and the background resistivity too low.

In Figure 11 the effective anisotropy is estimated from step response data ($\rho_m/\rho_b$). As shown above, the horizontal resistivity is extracted from the electric field response immediately following the airwave pulse, and the geometric mean is seen in the asymptotic approach of the late time response to the DC sounding response resulting in an effective anisotropy factor $\lambda = 1.99$. The anisotropic inversion with an estimated effective anisotropy of $\lambda = 1.99$ results in the much improved Occam inversion illustrated in Figure 12, where the target is now placed at the accurate depth with a good estimate of transverse resistance, and the background resistivity is also better represented.

CONCLUSIONS

Proper interpretation of MTEM data requires anisotropy to be included as part of any inversion scheme. Inversion at a single offset cannot distinguish between isotropy and anisotropy and can result in target depth errors. Since inversion of single offset data cannot reveal anisotropy, simultaneous inversion of multi-offset data is necessary. By using the method outlined in this paper to estimate the effective anisotropy from the step response data, layer anisotropies can be included as initial parameters in forthcoming inversions. Where possible, a MTEM survey over a calibration well should be integrated to determine effective anisotropy values that yield the correct target depths.

Failure to account for anisotropy can lead to inversions that fail to converge since there is no isotropic halfspace equivalent to an anisotropic halfspace. In the case of a uniformly anisotropic subsurface with a target layer, an isotropic inversion will place the target too shallow, overemphasize the transverse resistance of the target and underestimate the background resistivity. Higher background anisotropies can mask the target for a range of target anisotropies for a fixed offset that can be solved by increasing the offset for successful target delineation.

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REFERENCES


Step response - land

The step response (the electric field) at a receiver on land starts with an instantaneous increase at time $t = 0$, followed by a period of little change after which the transient responds to the subsurface resistivity. The response varies with offset.

Figure 1 - The step response on land starts with an instantaneous rise followed by a brief period of little change after which the transient responds to subsurface resistivity. The response varies with offset.

Impulse response – land

After the initial delta-function the EM propagation responds to the resistivity of the subsurface. Shown here are the impulse response functions at a source-receiver separation of 1 km for a water-filled and a hydrocarbon-filled reservoir 25 m thick at a depth of 500 m.

The peak due to the hydrocarbons is larger and earlier.

Figure 2 - Following the instantaneous airwave, or delta-function, the EM propagation responds to the resistivity of the subsurface. The peak corresponding to the case where hydrocarbon is present is higher in amplitude and arrives earlier.
Land case:  Step responses

\[ \rho_h = \text{constant} \quad \lambda = 1, 2, 3 & 4 \]

\[ \rho_v = \text{constant} \quad \lambda = 1, 2, 3 & 4 \]

\[ \rho_m = \text{constant} \quad \lambda = 1, 2, 3 & 4 \]

Initial step is only dependent on \( \rho_h \)

Late time (d.c) value is only dependent on \( \rho_m \)

**Figure 3** - Step responses for different anisotropy factors \( \lambda \) where first the horizontal resistivity \( \rho_h \) is kept constant to the left, the vertical resistivity \( \rho_v \) is constant in the middle, and the geometric mean \( \rho_m \) is kept constant to the right. The step response is seen to be sensitive to the horizontal resistivity only, and the geometric mean is seen to be sensitive to the late time asymptotic response only.

Land case:  Impulse responses

\[ \rho_h = \text{constant} \quad \lambda = 1, 2, 3 & 4 \]

\[ \rho_v = \text{constant} \quad \lambda = 1, 2, 3 & 4 \]

\[ \rho_m = \text{constant} \quad \lambda = 1, 2, 3 & 4 \]

**Figure 4** - Impulse responses for different anisotropy factors \( \lambda \) where first the horizontal resistivity \( \rho_h \) is kept constant to the left, the vertical resistivity \( \rho_v \) is constant in the middle, and the geometric mean \( \rho_m \) is kept constant to the right. The travel-time for the peak of the impulse response is only sensitive to vertical resistivity. When \( \rho_v \) is kept constant, as seen in the middle, there is no change in travel-time. To the far right a clear sensitivity to vertical resistivity is seen.
Isotropic versus anisotropic halfspace

There is no isotropic halfspace equivalent to an anisotropic halfspace

Figure 5 - The thick black line represents the impulse response from a halfspace with an anisotropy factor $\lambda = 2$. The other three curves represent the impulse responses from isotropic halfspaces. It is readily apparent that the isotropic solutions cannot be made to fit the anisotropic data.

Background versus target anisotropy

(a) $r = 1.5 \text{ km}; \lambda_0 = 1$

Figure 6 - Target with varying anisotropy with constant geometric mean resistivity $\rho_m$ embedded in an isotropic halfspace. All responses separate clearly, but for quantitative interpretation of target resistivity, the anisotropy must be known.
Background versus target anisotropy

For a fixed offset, increasing background anisotropy obscures target anisotropy

Figure 7 - The left illustration shows exactly the same model as in Figure 6 where a target with anisotropies 1, 2 & 3 is embedded in an isotropic background. In the middle the background anisotropy has been increased to 2.0 and the curves are now showing much less separation. To the right the background anisotropy has been increased to 3.0 and the impulse response from the halfspace coincides with all the impulse responses when the target is included with varying anisotropy. All results were generated for an offset of 1.5 km.

Background versus target anisotropy

Higher background anisotropy requires longer offsets for target delineation

Figure 8 - The solution to the problem showed in Figure 7. The upper left image shows that high background anisotropy can completely obscure a target of varying anisotropy. The next three images show how the separation between the models is increasingly restored by successive increases in offset from 1.5 km to 2.0, 2.5 and 3.0 km.
Anisotropic model with target layer

Mean resistivities:
- Background \( \rho_m = 20 \ \Omega m \)
- Target \( \rho_m = 500 \ \Omega m \)

Anisotropy of each layer: \( \lambda = 2 \)

What is the result of applying an isotropic inversion to an anisotropic model including a target layer?

**Figure 9** - Model used to generate the results in Figures 10 – 12 where the anisotropy \( \lambda \) of all layers is 2. The mean resistivities for the background and target are 20 ohm-m and 500 ohm-m respectively.

Isotropic inversion - models

For isotropic inversion:

- the target is placed too shallow
- the target transverse resistance is too high
- the background resistivity is too low

Inversion:
- Multi-offset with \( r = 2.5; 3.0 \) & 3.5 km

**Figure 10** - Isotropic inversion results from the anisotropic model described in Figure 9. The observed problems are: the target is placed too shallow, the target transverse resistance is too high, and the background resistivity is too low.
Anisotropic model with target layer

Mean Resistivity $\rho_m$

Mean resistivities:
- Background $\rho_m = 20 \ \Omega m$
- Target $\rho_m = 500 \ \Omega m$

Anisotropy of each layer: $\lambda = 2$

For offset $= 0.5 \ km$:

$\rho_h = 2 \pi r^3 B_x^0 = 10.0 \Omega m$

$\rho_m = 2 \pi r^3 B_x^\infty = 19.90 \Omega m$

Hence

$\lambda = 1.99$

Figure 11 - The effective anisotropy can be calculated from $\rho_m/\rho_h$, where the geometric mean resistivity $\rho_m$ is estimated from the late time asymptote of the step response, and the horizontal resistivity $\rho_h$ is estimated from the early step response.

Anisotropic inversion with $\lambda = 1.99$

Inversion with fixed anisotropy reveals a good estimate of target depth, transverse resistance and background resistivity

Figure 12 - When the model introduced in Figure 9 is inverted with an estimated effective anisotropy $\lambda = 1.99$, the results are very satisfactory. The anomaly is now placed on the correct depth with the correct transverse resistance, and the background is correctly represented also.