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On the Effects of Anisotropy in Marine CSEM

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SUMMARY

In marine CSEM (controlled source electromagnetic) exploration and SBL (SeaBed Logging), the seabed subsurface is investigated by emitting low-frequency signals from a dipole source close to the seabed. The resulting electromagnetic (EM) field is recorded by receivers that usually sit on the seafloor. The main goal is to describe possible thin resistive layers within the conductive surroundings beneath the seabed. In the following, various anisotropy effects in a stratified earth are studied. The synthetic data examples that are presented have been generated by a modelling tool for stratified media that handles arbitrary anisotropy models. The results show that a model without a thin resistive layer, but with anisotropy effects in the overburden, might resemble the response from a thin resistive layer in an isotropic model.

Introduction

SBL is an application of the marine CSEM method which seeks to directly detect and characterize thin resistive (hydrocarbon) layers. The application exploits that an EM field can be guided in a resistive layer contained within more conductive surroundings (Eidesmo et al., 2002). The presence of anisotropy may in some cases confuse the interpretation of the subsurface response if not carefully rendered. In EM surveying, anisotropic effects will almost certainly be encountered to some extent. In marine CSEM, the EM field propagation is governed by the conductivity properties in the earth. Anisotropy thus implies that the EM field response depends on a conductivity dyad which for a homogeneous region can be rotated into its principal coordinate frame where the conductive property is described in terms of three parameters. Transverse isotropy means that two of three parameters are equal.

Much of the work on anisotropic effects when measuring EM fields has been performed for media with stratification and transversal isotropy in the same direction, e.g. Kong (1972), Chlamtac and Abramovici (1981), and Tompkins (2005). Another type of anisotropy-configuration that has been studied is transversal isotropy in a direction normal to a layered structure, e.g. Everett and Constable (1999). There are many material configurations in the subsurface that might lead to anisotropy (Negi and Saraf, 1988). It might be that there are some preferred directions in the subsurface rocks, or some preferred orientation of grains in the sediments. Fine layering or a pronounced strike direction might lead to an effective anisotropy. Alternations of sandstone and shale may give reservoir anisotropies. A theoretical treatment of stratified media with arbitrary anisotropy is given in Løseth and Ursin (2007). From Maxwell's equations in stratified media, a set of ordinary differential equations in the frequency-wavenumber domain can be written in terms of a field vector, a system matrix, and a source vector. In each piecewise homogeneous region, the system matrix is given by the material properties and the horizontal wavenumbers. The vertical wavenumbers are given by the eigenvalues of the system matrix. A diagonalization of the system matrix thus transforms the field vector into a mode-field that contains upgoing and downgoing field constituents. From considering propagation of the mode-field in a homogeneous region, across a source, across an interface, or a stack of layers, expressions for the EM field anywhere in the layered system are obtained. In homogeneous regions the differential equation is decoupled, and from the boundary conditions a description of reflection and transmission in terms of the eigenvector-matrices at each side can be obtained. The reflection and transmission in a stack of layers can be described by a recursive scheme which avoids the numerical problem with exponentially large terms. There are several reasons for studying plane layered media. The calculation of EM fields in such media is often useful in order to simplify a problem for interpretational purposes. The added complication to the interpretation in case of anisotropy makes it worthwhile to study anisotropy-effects in layered media.

Model

Consider the stratified model depicted in Figure 1. A horizontal electric dipole (HED) source emits EM signals with frequency 0.25 Hz, and the source height above the seafloor is $h_s = 30$ m. The resulting EM field is measured by a line of receivers in the inline direction of the source antenna. The receivers are positioned on the seafloor ($h_r = 0$ m), and in Figure 1, one of these receivers is sketched. The seawater depth is $d_w = 300$ m, and the conductivity of the seawater is $\sigma = 3.2$ S/m. The thickness of the overburden is $d_1 = 1000$ m, and for the reservoir, $d_2 = 100$ m. Anisotropic effects in the overburden and reservoir are considered separately and for the two different cases of having a resistive reservoir and a conductive reservoir. The isotropic conductivities are $\sigma_1 = 1.0$ S/m for the overburden, $\sigma_2 = 0.01$ S/m for the resistive reservoir case, and $\sigma_2 = 0.5$ S/m for the conductive case. The anisotropy-considerations are for simplicity restricted to transversally isotropic models. The direction that has different conductivity compared to the two others in the principal system of the

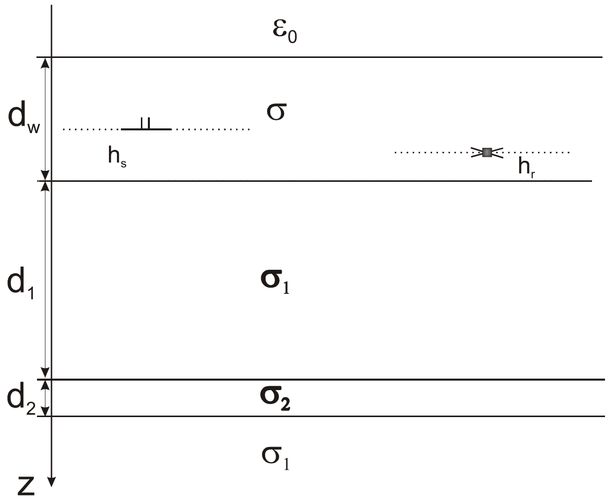

Figure 1. Sketch of the stratified anisotropic model for an overburden with TID.

conductivity dyad will be referred to as the direction of anisotropy. Scenarios with transversal isotropy in the vertical direction (TIV), transversal isotropy in the horizontal direction (TIH), dipping transversal isotropy (TID), and isotropy are modeled. The conductivity in the anisotropy direction is taken to be one-fourth of the isotropic conductivity. In a model with a TIV-overburden, the vertical conductivity is thus σ_{1v} = 0.25 S/m whereas the horizontal conductivity is σ_{1h} = 1.0 S/m. For the resistive reservoir case, the vertical conductivity in a TIV-model is σ_{2v} = 0.0025 S/m, whereas the horizontal conductivity is σ_{2h} = 0.01 S/m. In the TIH-model, the azimuth angle between the direction of the source and anisotropy is 15 degrees. When the model has dipping transversal isotropy (TID), the anisotropy direction has a 30 degrees tilt from the vertical axis in the direction of the source.

Results

In Figure 2, magnitude versus offset (MVO) and phase versus offset (PVO) for the resistive reservoir case (HC) have been plotted for various anisotropy scenarios in the overburden. The black, red, green, and blue curves represent the response from a model with isotropy, TIV, TIH, and TID respectively. The MVO plot shows an increase in response when anisotropy is present. This is due to the conductivity being less than in the isotropic case. Moreover, the response is largest for a TIH-overburden since it is this direction that has the strongest support of field propagation between the seafloor and the reservoir. Based on the same reasoning, the effect of a dipping anisotropy should have a magnitude in between the TIV- and the TIH-cases as shown in Figure 2. The phase behaviour is a bit more involved. The signals propagate faster when anisotropy is present since they experience less conductivity. In consistency with the amplitude responses, the TIH-model leads to faster propagation than a TID-model. The TID-model supports faster propagation than a TIV-model at large distance. At intermediate distances, the behaviour is a more complicated since, in this case, the response from the guiding in the reservoir and the reflection from the reservoir have nearly equal magnitude.

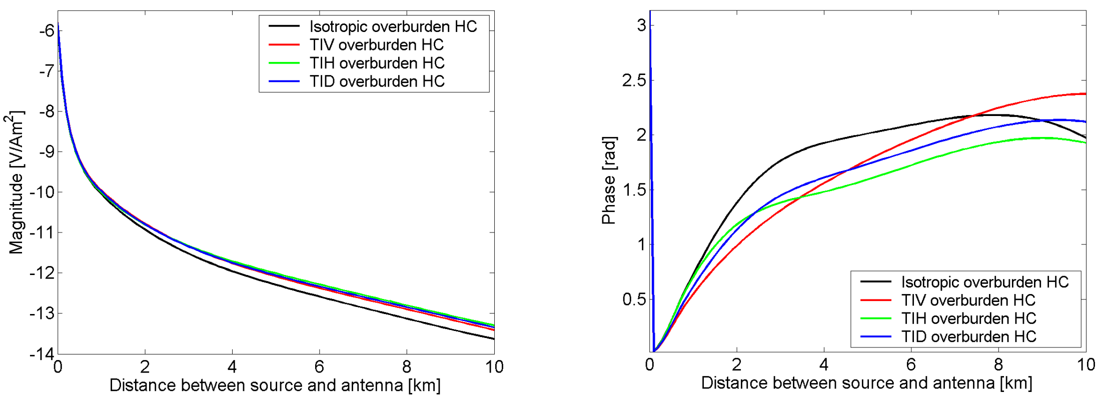

Figure 2. MVO and PVO response from a thin resistive layer for various overburden-anisotropy scenarios.

Figure 3 shows the responses when the overburden is isotropic and the resistive reservoir is anisotropic. A rough interpretation of the consequences of anisotropy in the reservoir can be made as follows: The response from the thin resistive layer is due to propagation in the horizontal direction of the reservoir. The important electric field parameter in the reservoir is the vertical electric field component. The TIV-reservoir has less conductivity in the vertical direction than the isotropic model, and thus, the TIV-case should be expected to give an increase in the reservoir response. The same effect, but less, should be expected for the TID-reservoir, whereas the TIH-anisotropy should not influence the response to any particular extent. The dip in the phase curves for the isotropic and TIH-case is due to the sea-surface.

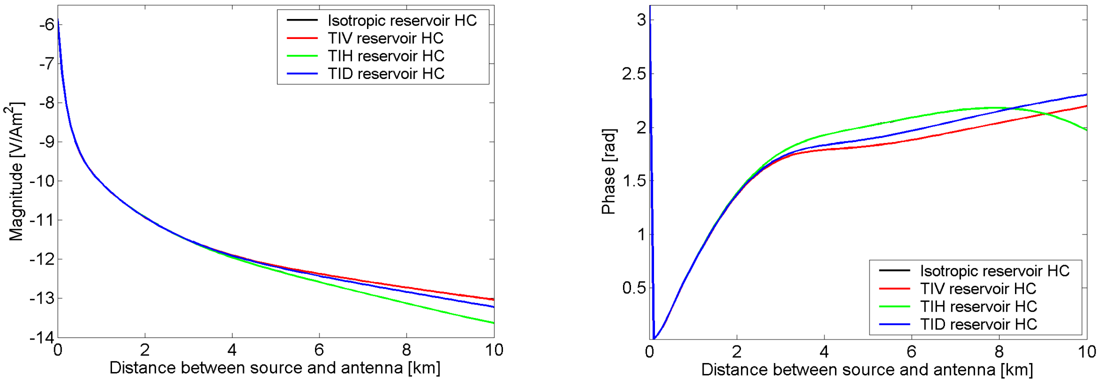

Figure 3. MVO and PVO response from a thin resistive layer for various reservoir-anisotropy scenarios.

In the conductive reservoir case (H_2O) the thin layer has almost the same resistivity as the surrounding overburden and underburden (half the value). From Figure 4 it can be observed that anisotropy in the overburden in this scenario has pronounced effects on the response. The small variation in the isotropic conductivities leads to larger sensitivity to the anisotropy-effects. The interplay between the lateral field propagation at the sea-surface and seafloor along with the reflection from the reservoir, leads to strong TIV-response for small distances and large TIH-response for larger distances.

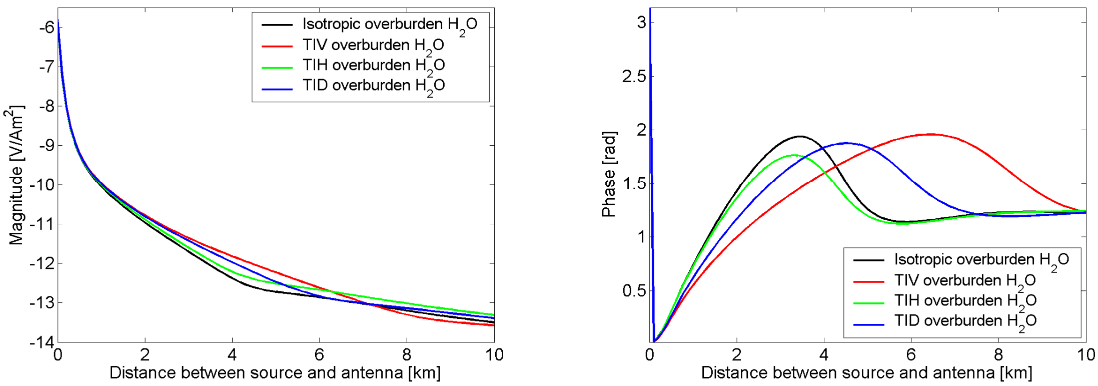

Figure 4. MVO and PVO response from a H_2O-reservoir for various overburden-anisotropy scenarios.

In Figure 5, the response from an isotropic model with a resistive reservoir (HC) and the responses from various overburden-anisotropy models are normalized to the isotropic conductive reservoir case (H_2O). It can be observed that at short and intermediate distances,

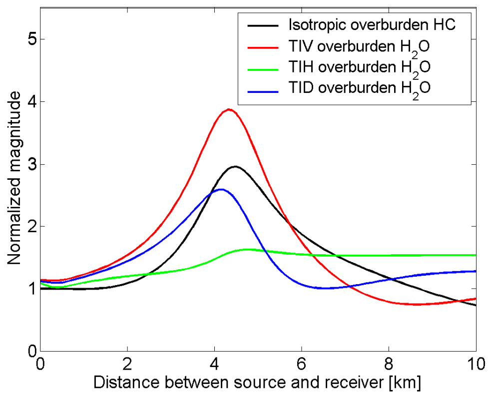

Figure 5. Normalized magnitude plots for scenarios with anisotropic overburden and conductive reservoir and an isotropic model with a resistive reservoir.

the response from an anisotropic overburden (red, green, and blue curves represent TIV, TIH, and TID respectively) resembles the response from the resistive reservoir (black curve). This suggests that care must be taken when interpreting real EM field data in areas with anisotropy, especially when interpreting normalized magnitude data.

Conclusions

The purpose of the modelling examples presented here has been to illustrate some effects of anisotropy in a stratified model. Even if responses from isotropic models can be made to resemble more complicated anisotropic models (by carefully selecting the conductivity parameters in the direction normal to the propagation direction of the strongest signal contribution), isotropic models will seldom account for all the anisotropy-effects. With one more degree of freedom, a TIV-model can obviously account for anisotropic effects better than an isotropic model, but not fully explain more complicated anisotropy-phenomena. The examples furthermore show that anisotropy effects in the overburden might confuse the interpretation of the response from a reservoir if not carefully rendered.

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