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Study of complex behavior of marine controlled-source electromagnetic (CSEM) fields for anisotropic media through model simulation

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Summary

Several hundred marine controlled-source electromagnetic (CSEM) projects have been completed world wide in last few years but the results often surprise the interpreter due to several complex behaviors of sub-surface formations. Anisotropy is one of them. Most of the sedimentary formations are anisotropic. The current study reveals that if anisotropy is not considered, the interpretation of CSEM data can even create a false reservoir or may kill a reservoir response. The CSEM response produced using horizontal resistivity (R_t) of well logs in an anisotropic media is widely different from the actual. However, replacement of R_t with vertical resistivity response is the near approximation to the anisotropic response though not exactly equal. The study shows that consideration of anisotropy is very important in CSEM data interpretation for better interpretation.

Introduction

Controlled Source Electromagnetic (CSEM) surveying has emerged as an important exploration tool for mapping hydrocarbon reservoirs since last decade. CSEM investigate the sub-seabed resistivity by measuring the deformation of electric and magnetic fields of a low-frequency electromagnetic (EM) signals emitted from a Horizontal Electric Dipole (HED) source close to the seabed. The deformations are recorded by receivers placed on the seafloor (Fig.1) and are used to create a resistivity model of the sub-surface. CSEM can identify the higher resistive hydrocarbon saturated reservoirs within the conductive brine saturated sediments and thus can be used as a de-risking tool in hydrocarbon exploration. The main objective of CSEM survey is to detect the presence of possible thin resistive reservoirs. Recorded electric and magnetic fields can be resolved into two components, radial and azimuthal (Fig.2). The radial component of the electric field is more sensitive to the thin horizontal resistors (constable and Weiss, 2006) than the azimuthal. The interaction of the fields with the sub-surface formations are quite complex and the complexity increases with the increased nonlinear behavior of the media.

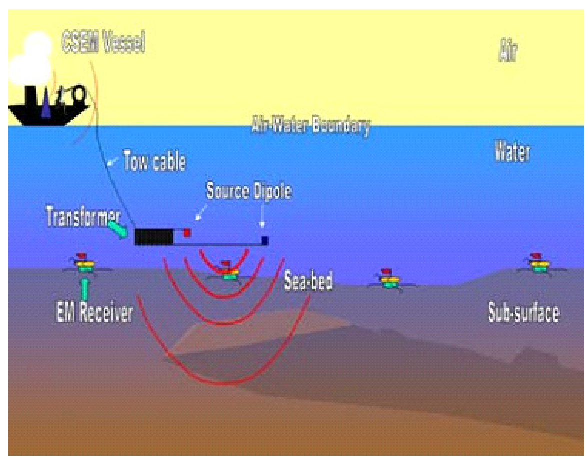

Figure 1: CSEM survey Layout

Anisotropy is one of common complex behavior of the sedimentary layers. Anisotropy means a direction dependent variation of physical properties at a particular point of the media. We define the resistivity anisotropy as the variation of resistivity in X, Y and Z-direction of an artesian coordinate system. Resistivity anisotropy (λ) can

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be defined from well log data as the square root of the ratio of Vertical Resistivity (R_v) and Horizontal resistivity (R_t or R_H). The synthetic studies have been carried on anisotropic homogeneous half-space and 1D subsurface model to understand the CSEM sensitivity to anisotropy.

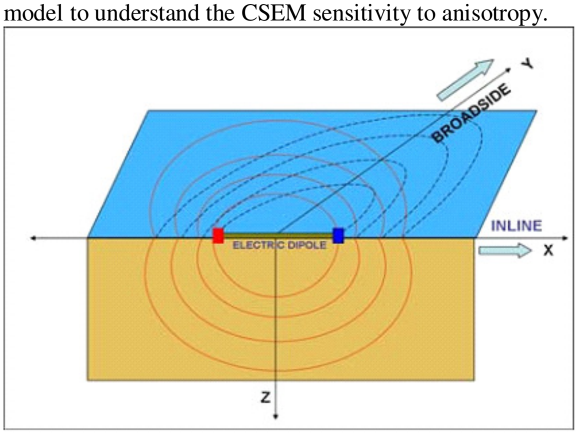

Figure 2: Diagram showing the radial and Azimuthal component of dipole field

Transverse Isotropic Models

Anisotropy in the sedimentary basin generally develops during deposition of clastic sediments due to variation of grain size and periodic layering. A sedimentary basin often contains alternate layers of shale and sand. Shale generally shows significant anisotropy due to lamination where as water saturated sands show less anisotropy. Though the reservoir generally consists sand layers, in most of the cases the anisotropy of thin reservoir is very high when it is saturated by hydrocarbons. In simple stratified earth, anisotropy is a vector measurement which has constant magnitude in any direction of a horizontal plane but the magnitude is different in the vertical direction. This type of formation is called Transverse Isotropy in the Vertical (TIV) direction (Fig.3). But the properties measured in a horizontal well that crosses a series of vertical fractures might have Transverse Isotropy with a Horizontal axis of symmetry (TIH).

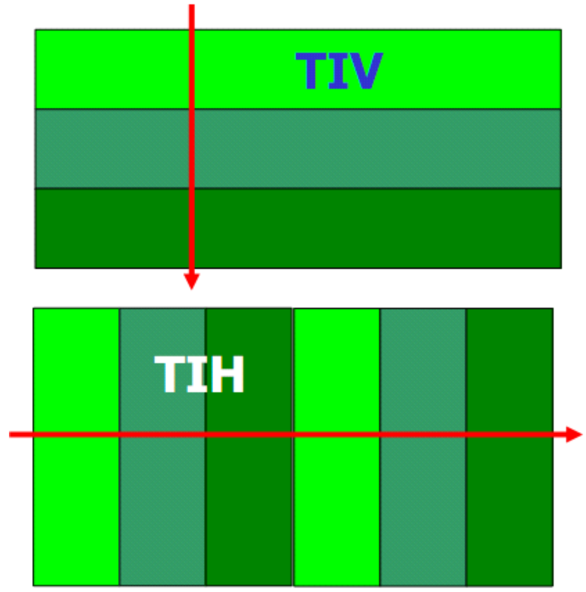

Figure 3: Diagram shows TIV and TIH of an anisotropic media. Variation of color indicates the variation of physical properties

All the anisotropic models used for the study have been considered TIV in nature. The resistivities of the models are fixed in X-Y plane but increase in vertical direction (Z).

Model Studies

Conventionally the well log data consists of only horizontal resistivity (R_t) measurements and lacks resistivity anisotropy information. In this study first we have tried to find out how CSEM response of an isotropic horizontal resistivity (IHR) model differs from the actual anisotropic response (obtained from both horizontal and vertical resistivity values). We have taken a uniform homogeneous half-space model (Fig.4a) with horizontal (X-Y plane) resistivity 1 Ohm-m and vertical (Z-direction) resistivity 1.5 ohm-m to calculate its CSEM response. The results (Fig.4b) show that the anisotropic response is significantly higher than IHR response. Thus CSEM is very much sensitive to resistivity anisotropy of the media. We have played with the isotropic horizontal model to understand the possible misinterpretation of the CSEM response if anisotropy is not considered. It is found that an addition of 30 m thick and 20 Ohm-m resistive layer at a depth of 750 m (Fig.4c) in the IHR model can only compensate the effect. Thus if the anisotropy is not considered, interpreter can create a reservoir from the CSEM response of an anisotropic uniform homogeneous half-space.

In next step, we tried to check if the similar difference in CSEM response would be observed for a reservoir model. We have also tried to find its sensitivity to vertical resistivity. We have added a 30 m thick resistivity layer at a depth of 1000 m in the anisotropic homogeneous half space model to create the 1D resistive reservoir model (Fig.5a). The horizontal resistivity has been assigned 20 Ohm-m for the reservoir and vertical resistivity 30 Ohm-m.

The result (Fig.5b) shows that CSEM response of an anisotropy reservoir model also repeats the similar deviation from IHR response. So, for reservoir case also anisotropy response is largely different from isotropic model with horizontal resistivity.

In the third step, we calculated the CSEM response of the isotropic vertical resistivity (IVR) model. The result show that IVR response is close to the anisotropic response with small deviation (~4%) for this model. Thus the study reveals that CSEM is more sensitive to vertical resistivity then the horizontal resistivity.

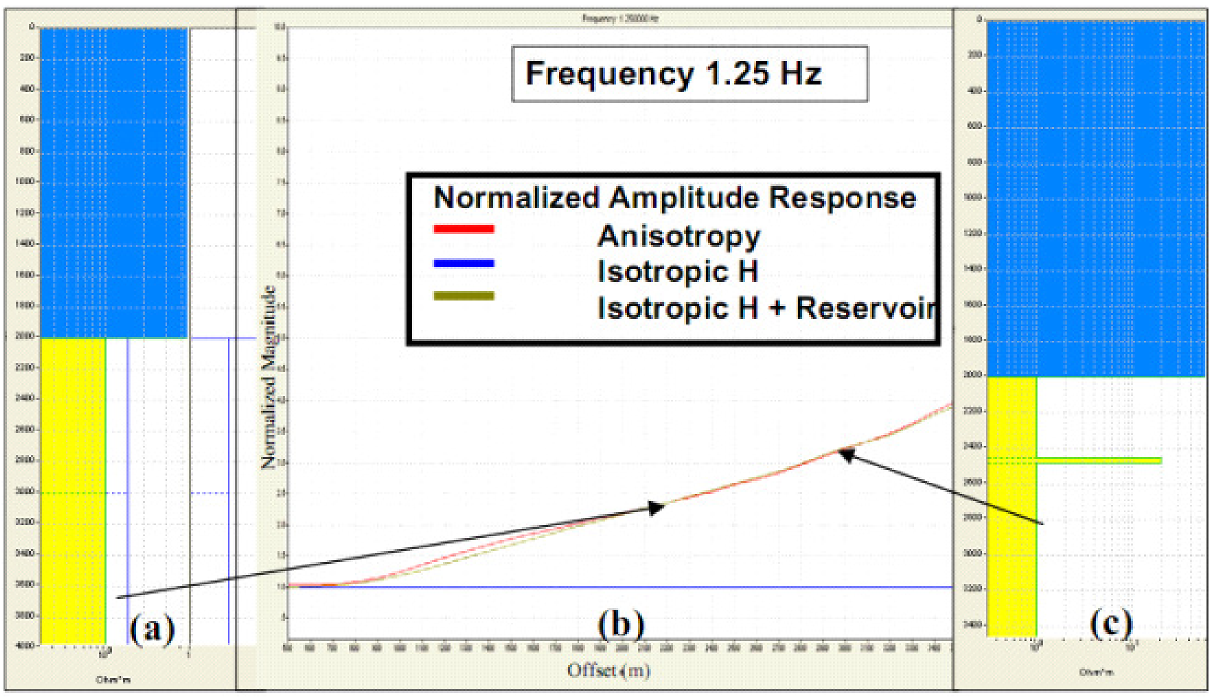

Figure 4: (a) Anisotropic uniform homogeneous half-space model with horizontal resistivity of 1 Ohm-m and vertical resistivity of 1.5 Ohm-m; (b) CSEM response of an anisotropic and isotropic reservoir model (c) with the response of horizontal isotropic resistivity model

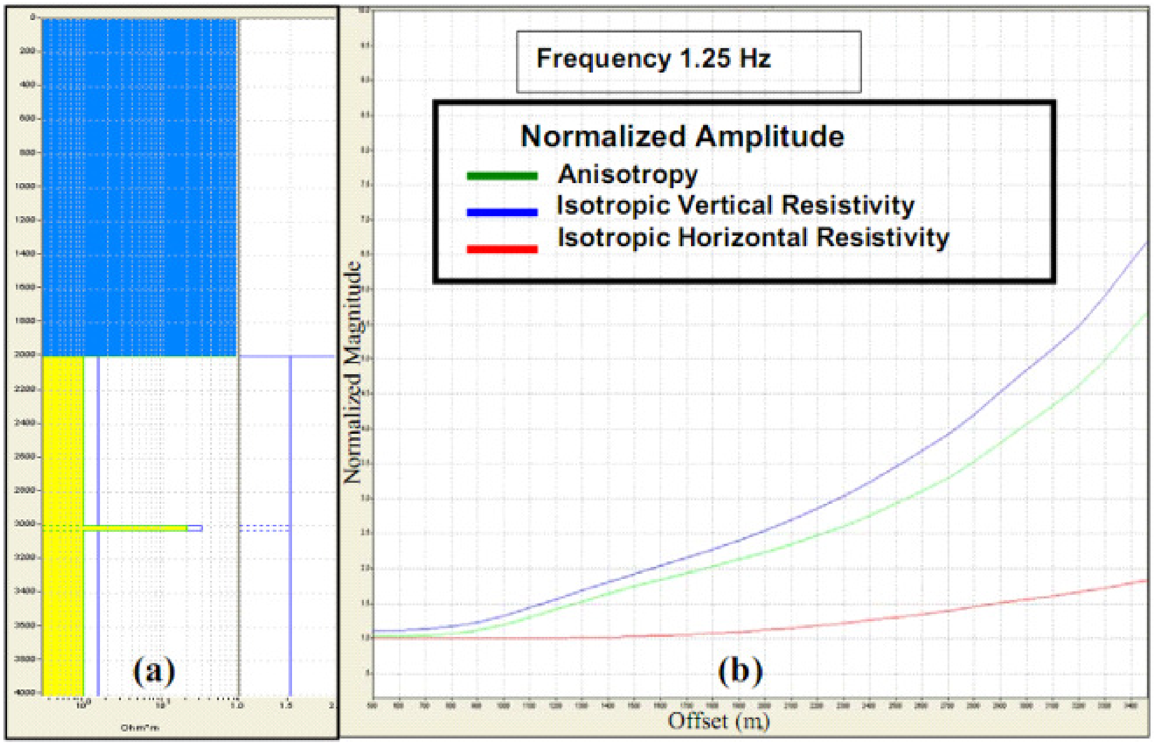

Figure 5: (a) 1D anisotropic model with 30 m thick reservoir; (b) CSEM response of reservoir model for anisotropy, isotropic vertical and isotropic horizontal resistivity

The anisotropy and IVR response are close but not exactly equal. Lastly, we tried to find out the relation between them with varying values of anisotropy in our homogeneous half-space model (Fig. 4a). The result (Fig 6) shows very complex relation between anisotropic and IVR response. With higher value of resistivity anisotropy ($\lambda^2=R_V/R_t > 2.2$) anisotropic model response is higher than the isotropic vertical resistivity response. On the other hand for lower anisotropy value ($\lambda^2 < 2.2$) it is lower than isotropic vertical resistivity response. Study confirms that replacing anisotropy with isotropic vertical resistivity may be approximate but consideration of anisotropy is very important to get actual result.

Lastly, we have tested the quantitative difference of CSEM response for anisotropic and IVR models of a realistic complex 1D reservoir model (Fig.7a) at Eastern Offshore, India. The model consist two shallow (< 600 m deep) reservoirs of varying resistivity and thickness. Analysis shows that 1.25 Hz frequency is most sensitive to the reservoirs and maximum 5 km offset can be obtained for this frequency. The effect of anisotropy has been found significantly large with increase of transmitter-receiver offset (Fig.7b). Though at smaller offset, the IVR response is more but at higher offset anisotropic response is about 18% higher than IVR response at offset 5 Km for this model. This difference of response may produce misleading resistivity section if anisotropy is not accounted in inversion scheme, particularly at longer offsets. The crossover between anisotropy and IVR occurs at nearer offset for higher anisotropy. Similar crossover also has been reported by Lu and Xia, 2007.

Conclusions

This study reveals that consideration of anisotropy is very important for the interpretation of CSEM data. CSEM response is more sensitive to vertical resistivity (R_v) of an anisotropic sub-surface and the response is widely different if only horizontal log resistivity (R_t) is used. In that case the higher values of anisotropic response can be misinterpreted as a reservoir response. However, vertical resistivity isotropic (IVR) model is close to anisotropic response but can not fully account for complex anisotropy phenomena, especially at longer offsets and may overestimate or underestimate the resistivity of sub-surface. Thus, consideration of anisotropy is recommended in inversion schemes for better CSEM data interpretation.

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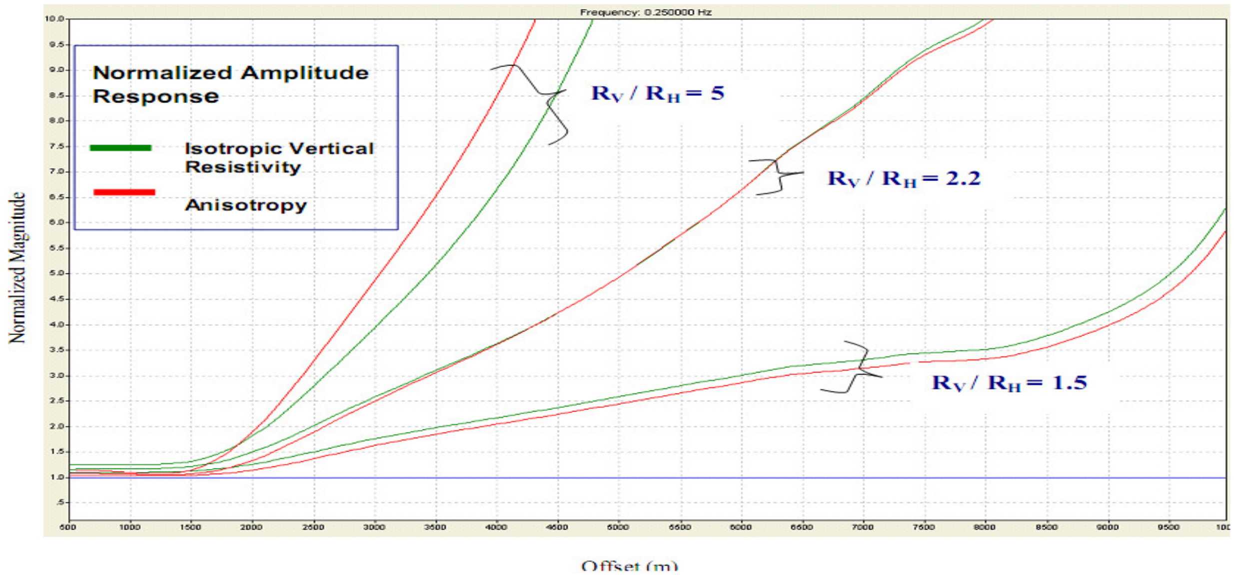

Figure 6: CSEM response of anisotropic uniform half-space model with varying values of anisotropy (constant horizontal resistivity 1 Ohm-m) which is normalized with isotropic horizontal resistivity response

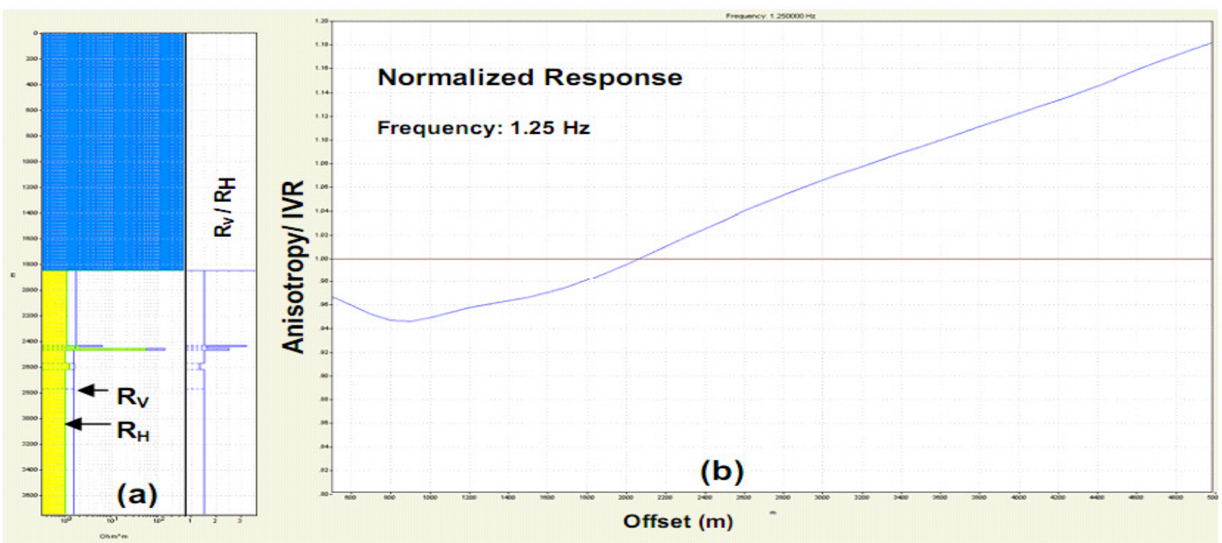

Figure 7: (a) Realistic 1D model with reservoir; (b) Anisotropic CSEM response (blue curve) normalized by IVR response of the complex reservoir model. Brown line represents the base line (1.0)