Seismic gather modeling and far-offset well-ties - West Africa study

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Summary

Six seismic gather modeling algorithms are run on 20 reservoirs from 11 West Africa wells to determine the most effective modeling algorithm in tying far-offset responses modeled from well data to the processed seismic data. Full wave equation solutions to the one-dimensional wave equation do not significantly improve far-offset well ties compared to their ray theoretical counterparts. Thus, mode conversions and inter-bed multiples do not appear to contribute significant energy to the seismic data for the modeled reservoirs. Isotropic modeling using a predicted shear log improves far-offset well ties relative to isotropic modeling with measured shear logs, particularly for high impedance reservoirs. However, anisotropic modeling can honor the recorded shear log and produce even better far-offset well ties than isotropic modeling with predicted shear logs in the high impedance reservoirs. In these cases, the development of a polarity reversal from near to far offsets causes the modeled data to tie the recorded data much better. This dramatic change in reflectivity with offset can cause positive amplitude anomalies at near offset to become negative amplitude anomalies at far offset (strong class IIp AVO). This observation is consistent in both oil-bearing and wet sands. Lack of critical angle effects in the recorded data also could be a result of an anisotropic Earth.

Introduction

Seismic to well ties are a fundamental part of seismic data analysis. In both processing and interpretation, well ties provide an important link between the data we record and the physics we believe to be occurring. At near offset, the physics is relatively simple, and an adequate well tie is often achieved by simply convolving a wavelet with a reflectivity series. As offsets increase, incidence angles also increase, and the physics become more complex. Converted waves, interbed multiples, AVO, attenuation, anisotropy, and NMO stretch are some of the more significant effects that can complicate analyses of far-offset data. This study performs detailed gather modeling to assess the impact of these various physical phenomena on the quality of far-offset well ties.

For the purposes of this study, the geologic setting addressed is mixed impedance deep-water reservoirs in West Africa. The standard approach to far-offset well ties is to model a synthetic gather using recorded well logs. Typically P-wave velocity (V_P), S-wave velocity (V_S), and density (ρ) are feed into a raytracing algorithm to get a primaries only P-wave reflectivity series which we then convolve with a wavelet to generate a synthetic gather.

Typically, this process yields an adequate near-offset tie, and a poorer, but still adequate far-offset tie. However, in the presence of high impedance reservoirs, the far-offset tie can often become very poor. The purpose of this study is to perform a series of controlled modeling experiments to assess the significance of various possible explanations for the poor quality far-offset tie for 20 separate reservoir intervals in 11 West Africa wells. These experiments are designed to answer 4 questions:

- Are mode conversions and inter-bed multiples important to model?
- Are measured shear logs reliable?
- Is modeling anisotropy important?
- Is stress-induced anisotropy evident in recorded data?

The seismic responses of recorded and predicted well logs are modeled using ray theoretical, and wave-equation solutions to the isotropic and anisotropic wave equation and compared with the processed seismic data. Appropriate comparisons allow these questions to be addressed.

Theory and Method

One possible explanation for poor far-offset well ties is that the measured shear log is of poor quality or is not measuring the seismically relevant quantity. To test this assumption, we generate synthetic seismograms using shear logs predicted using the ExxonMobil micro-porosity rock physics model.

The ExxonMobil micro-porosity model builds on the observation that sand pores tend to be rounder and less compliant than shale pores (Xu and White 1995). First a matrix is comprised of sand and clay minerals. Then the effects of shale porosity and sand porosity are handled separately. The pore geometry and fluid content depend on whether it is a shale pore or sand pore (shale pores are flatter and water-bound, sand pores are round and empty). Then Gassmann's equations are used to fill the sand porosity with the reservoir fluid (Gassmann 1951). From the moduli of the saturated rock, V_P, V_S, and ρ are calculated. Using the Xu-White model with measured V_P and ρ we can calculate the shale volume (V_{SHALE}) and then calculate a shear log (Xu and White 1996). In unconsolidated sands, this predicted shear log consistently gives a lower V_P-V_S ratio than the measured shear log and, using isotropic modeling, has been shown to better tie recorded seismic data (White et. al. 1998).

Velocity anisotropy is frequently observed to be important in seismic imaging, especially in the presence of a thick shale section (Schmid et. al. 1998). It can, however, also be important in angle dependent reflectivity (Figure 1). Furthermore, the unconsolidated sands in shallow reservoirs may be subject to stress-induced anisotropy. This theory and laboratory measurements have been discussed in depth in a number of papers (e.g. Nur and Simmons 1969, Lockner et al. 1977, Zamora and Poirier 1990, Yin 1992), so we will omit discussion of this theory in this document.

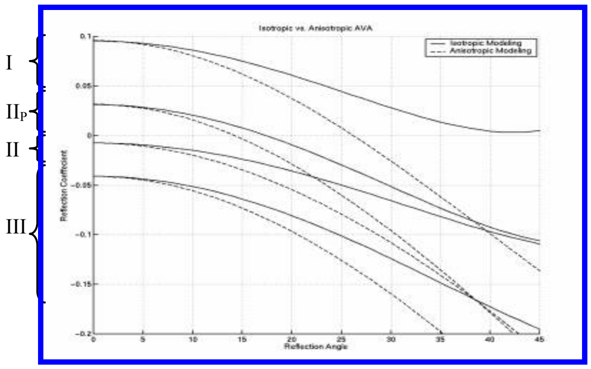

Figure 1. Isotropic and anisotropic reflectivity as a function of angle for varying rock and fluid properties. Isotropic modeling (solid lines) is by the Aki-Richards 3 term approximation to the Zoeppritz equations. The anisotropic modeling (dashed lines) is the full Zoeppritz solution. The standard AVO classes are noted in the left margin. In the anisotropic case, as incidence angles increase, the shale becomes faster and the sand becomes slower. This causes increasingly negative reflectivity - beyond the trends observed in the isotropic case. The basic effect is that AVO trends are exaggerated. This can cause polarity reversals for some high impedance reservoirs.

In view of these observations, another possible explanation for poor far-offset ties is that the earth is actually anisotropic. We test this possibility by generating anisotropic synthetic seismograms and comparing them to the real gathers. The anisotropic parameters required to generate the synthetic seismograms are generated from the measured logs using the enhanced anisotropic ExxonMobil micro-porosity rock physics model. The ExxonMobil micro-porosity rock physics model has been enhanced to predict anisotropic parameters for sands and shales by introducing a pore orientation distribution parameter for the shale pores and a crack orientation distribution parameter for the sands. This model was developed to explain the anomalously high Vp/Vs ratios observed in many hydrocarbon saturated unconsolidated sands in West Africa wells (Xu, 2002). One purpose of this study, is to test whether this rock physics model can also predict reflectivity observed in the seismic data.

For each reservoir, three modeling algorithms are used: ray-trace, p-wave primaries only (Isotropic), wave-equation (Isotropic), and wave-equation (Anisotropic). The ray-trace method uses the Aki and Rickards (1980) approximation to the Zoeppritz (1919) equations. The Aki-Richards approximation better matches recorded data, and implications of this are discussed later. In both the isotropic modeling algorithms, we do two separate models - one using the measured shear log and one with the shear log predicted by the isotropic ExxonMobil micro-porosity rock physics model. For the anisotropic modeling we also do two separate models - one with the shale having positive anisotropic parameters and the sand having negative anisotropic parameters (as in the stress-induced anisotropic model) and one with the sand anisotropic parameters zeroed (sands assumed to be isotropic). Thus for each well, there are a total of 6 models run.

Examples

Far-offset correlation coefficients for each reservoir in the study are shown in Figure 2. Each bar represents the cross-correlation for a given far-offset stacked model and the corresponding recorded far-offset stack. Comparing isotropic ray-trace and isotropic wave-equation modeling, there is no apparent uplift observed when using wave-equation modeling. In some reservoirs, using wave-equation modeling actually deteriorates the tie. This observation suggests that inter-bed multiples and mode conversions are not important to model in this data.

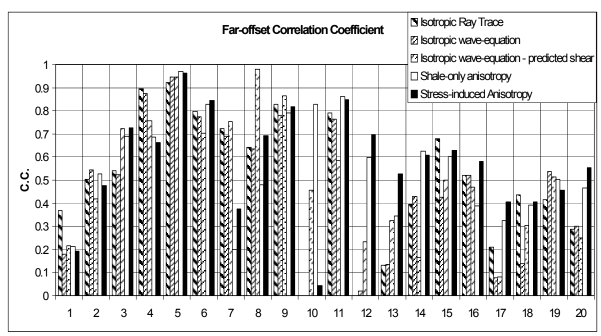

Figure 2. Results from study. For each reservoir, correlation coefficients are plotted (left-right): isotropic ray trace, isotropic wave equation, isotropic wave equation w/ predicted log, shale-only anisotropy, and stress-induced anisotropy. As a whole, there is little uplift using wave-equation modeling vs. raytrace. Using the predicted shear improves the far-offset tie vs. the measured shear using isotropic modeling, but modeling the effects of stress-induced anisotropy improves the far-offset tie significantly in a number of wells.

In a number of reservoirs, there is increased uplift when using the isotropic modeling with the predicted shear log. Further improvements are observed when shale-only anisotropic modeling is used, and using the stress-induced anisotropic model gives the best far-offset ties in a number of wells. In the reservoirs modeled, the most uplift using the predicted shear log or anisotropic modeling is in mixed or high impedance reservoirs. The isotropic rock physics model tends to predict a higher V_S than the measured log in the sands. This will then lower the V_P-V_S ratio of the sands. The V_P-V_S ratio, specifically the V_P-V_S ratio contrast with the overlying rock, determines the amount of AVO a reflector will have (Hilterman 1989). If the V_P-V_S ratio of the sand is lowered, the contrast is greater and the reflector will have more negative amplitude with offset. Modeling with shale-only anisotropy will yield a similar effect. Modeling with stress-induced anisotropy will further exaggerate this effect. The basic result is that modeling with the predicted shear log or modeling with anisotropy will yield a similar effect - increasing negative reflectivity at larger angles.

The effect of increased reflectivity on correlation coefficient depends on the relative impedance of a reservoir. Low impedance reservoir reflectivity does not change polarity with offset. Including the effects of anisotropy increases reflectivity with offset, and the correlation coefficient will not change. However, is there is a polarity reversal on the data, the far-offset correlation coefficient depends on if that flip is modeled. Figure 3 shows a wet reservoir interval (*reservoir 13*) in which wet sands exhibit strong class IIp AVO. Isotropic modeling fails to account for the observed polarity reversal. Anisotropic modeling accounts for this reversal, and the correlation coefficient is significantly improved (.82 vs. -.37).

As mentioned in the methodology section, Aki-Richards is the method used to approximate the Zoeppritz equations in the isotropic modeling, yielding better results than the Zoeppritz equations themselves. The Aki-Richards approximation accounts less for the "pre critical angle amplitude bloom". In the data used in this study, this pre-critical amplitude anomaly is not observed, so the Aki-Richards method better matched the recorded data. The lack of this amplitude anomaly in the recorded data could be because the critical angle changes in an isotropic Earth vs. an anisotropic Earth. A positively anisotropic shale overlying a negatively anisotropic sand causes the critical angle to be larger (or nonexistent) than in the isotropic case. The critical angle (when anisotropy is considered) is so large that it is beyond the range of incidence angles recorded in the seismic survey, at least at the depths of the reservoirs. Thus, the critical angle effects are not recorded for the reservoir intervals.

AVO attribute analysis frequently employs the two-term Shuey approximation of the Zoeppritz equation (Shuey 1985) is used. These properties can be directly measured from moved out CDP's or migrated image gathers. Figure 4 shows the isotropic Zoeppritz, Aki-Richards, and Shuey reflectivity for a high-impedance wet sand. Plotted in the same figure is the anisotropic Zoeppritz solution for the same sand. At near-offset, the reflectivity is the same for all algorithms. At far-offset the two-term Shuey approximation is closest to the anisotropic reflectivity. AVO analysis has been applied in a number of cases in this geologic setting. If the rocks are actually anisotropic, the successfulness of AVO analysis could be a coincidental result of using the isotropic reflectivity approximation that turns out to best match anisotropic reflectivity at offset.

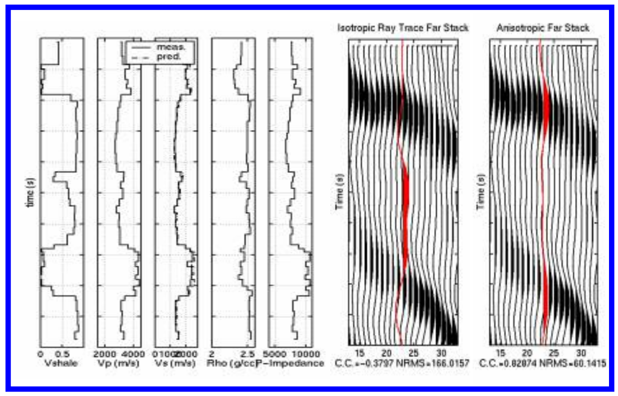

Figure 3. Logs and associated near and far-offset ties for *reservoir 13* in this study. The log panels from left to right are: V_{SHALE}, P-velocity, S-velocity (solid) overlain by predicted S-Velocity (dash-dot), density, and $P_{IMPEDANCE}$. The two far-offset ties are using the isotropic ray-trace model with the measured log (left) and the anisotropic wave-equation model (right). The polarity of the isotropic model seems wrong, and in fact, the anisotropic modeling has introduced a polarity flip from near to far which greatly improves the tie (C.C.=.82 vs. -.38).

Conclusions

Full wave equation solutions to the one-dimensional wave equation do not significantly improve far-offset well ties compared to their ray theoretical counterparts. Thus, mode conversions and inter-bed multiples do not appear to contribute significant energy to the seismic data for the modeled reservoirs.

In the case of high and mixed impedance reservoirs, isotropic modeling using a predicted shear log improves far-offset well ties relative to isotropic modeling with measured shear logs. However, anisotropic modeling can honor the recorded shear log and produce even better far offset well ties than isotropic modeling with predicted shear logs in the high impedance reservoirs. Modeling anisotropy in the shale and stress induced anisotropy in the sands consistently produces the best far offset ties for high impedance well ties. Similar results could be obtained by shifting all the anisotropy into the shales (i.e. make the shales more strongly anisotropic and the sands isotropic), but this would leave anomalously high Vp/Vs ratios in the hydrocarbon saturated sands.

The anisotropic modeling shows that high impedance wet sands can exhibit strong Class IIp behavior and become strong negative reflection coefficients at far offsets.

The large positive precritical amplitude blooms predicted by isotropic ray-trace modeling using Zoeppritz's equations and to a lesser extent by isotropic wave-equation solutions for high impedance reservoirs are not observed in the seismic data.

The rocks penetrated by the wells used in this study are all unconsolidated clastics and the conclusions should only be applied to similar rocks.

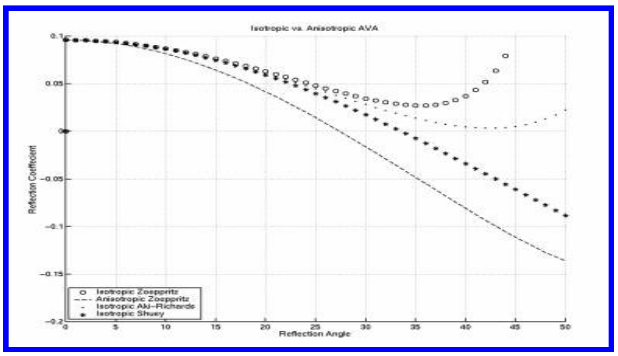

Figure 4. Exact Zoeppritz reflectivity (circles) and isotropic approximations for an arbitrary high impedance sand. The Aki-Richards 3-term approximation (dotted) begins to show the expected "pre-critical amplitude bloom" at far offset (past 40^{o}). Shuey's 2-term approximation (asterisks) does not show this wave-propagation phenomena. In the anisotropic Zoeppritz (dashed) solution, the critical angle is non-existent (at offset, $V_{SAND} < V_{SHALE}$). Because Shuey's approximation tracks the true anisotropic reflectivity, 2-term AVO analysis (intercept-gradient) and 2-term V_S inversion will often be successful even when rocks are anisotropic.

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