Well-to-seismic mistie: A valuable indicator of seismic anisotropy for subsalt velocity model update. A case study in a deviated subsalt well in the deepwater Gulf of Mexico

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Summary

The well-to-seismic tie is not only the best way to tie seismic data back to a ground truth by comparison with well-log data using synthetic seismograms for seismic interpretation purposes, but it also provides very valuable seismic anisotropy information. In this paper, we present our concepts and an example of use of a well-to-seismic tie to indicate seismic anisotropy. In addition, rock-physics analyses were incorporated to update the subsalt velocity in a deepwater area of the Gulf of Mexico.

Introduction

The well-to-seismic tie, which is the best way to tie seismic data back to a ground truth by comparison with well-log data using synthetics seismograms, is also widely used for seismic interpretation. Additionally, when the final product from seismic data processing is delivered in the depth domain, it provides very important seismic anisotropy information.

Generally, the value of the seismic-to-well tie depends on the seismic data quality, the well data, and the time/depth relationship. The usual way to tie well information to seismic data in depth is to convert them to time, tie them, and convert them back to depth. However, this process can introduce additional uncertainty because the velocities used to transform each data set to depth can be different. One of the most important variables affecting the well-to-seismic tie is the migration velocity, because incorrect velocities result in lateral and vertical reflection mispositioning. One factor that can significantly affect the velocities is the presence of anisotropy. Incorrectly accounting for anisotropy manifests itself as an incorrect vertical seismic velocity, causing the data to mistie.

In this paper, we address how to identify anisotropy from the seismic-to-well tie that can then be used to get the data sets to match by using that information to reimage the seismic data. Additionally, we also incorporate a rock-physics model into the process to assist in estimating the anisotropy. To update the subsalt velocity model at the well location, this process was performed in each well in the study area. Then, we incorporate all anisotropic functions from the wells to build a new velocity model for depth imaging. We will show an example of how to use the well-seismic mistie and rock-property analyses to update the subsalt velocity model with new anisotropy.

Study area

We conducted analyses of the well-to-seismic tie for anisotropy for some deepwater wells in an area that covers approximately 50 Minerals Management Service (MMS) lease blocks in the Green Canyon area of the Gulf of Mexico (Figure 1). In this area, discoveries have been made in a large number of Plio-Pleistocene minibasins and subsalt in Miocene-aged reservoirs. Though many giant discoveries have been found, such as BP's Atlantis and Chevron’s Tahiti, there is still plenty of promising territory for future exploration.

Other issues that make the tie between the well and seismic data difficult in this area are: (a) many of the wells are deviated; (b) the beds have significant dip, especially in the minibasin play types; and (c) the seismically derived velocities can be quite different from well velocities. Figure 2 shows a depth-migrated seismic section through two deepwater subsalt wells.

Figure 1: The study area (red box) in the Green Canyon area, Gulf of Mexico, U.S. Continental Shelf.

Synthetic seismograms

Synthetic seismograms can be used to create a link between rock properties and seismic data by using the convolution model of the earth’s reflectivity response, \( R \), the seismic wavelet, \( W \), and a compensation factor accounting for wavelet attenuation, \( Q \). Hence, the seismic signals, \( S \), can be expressed as:

\[
S(t) = R(t) \ast W(t) \ast Q(t)
\]

\[
S(f) = R(f) \times W(f) \times Q(f),
\]

(1)
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where \( S(f) \) and \( R(f) \) are the frequency-domain Fourier transforms of the time-domain responses \( S(t) \) and \( R(t) \), respectively.

Seismic inversion aims to determine the earth reflectivity response, and hence, the acoustic impedance. We must determine the wavelets for a well-to-seismic tie for all suitable wells. After generation, crosscorrelation and validation can be used to select one wavelet to use in the inversion. In general, vertical wells are the best to use for generating reliable wavelets. However, most of the deepwater wells are deviated or logged in the reservoir section that may also include impedance anomalies (Henry, 2000), both of which must be accounted for in the wavelet extraction process. Therefore, we must choose the waveform and length carefully, and either maximize the crosscorrelation or minimize the relative misfit between synthetic and real seismic data, particularly for strong reflections (Mandal and Mitchell, 1986).

When making ties in time, the data can be stretched and squeezed to accomplish the tie; however, in depth, the misties must be accounted for by updates to the seismic velocity model that also must include a description of the anisotropy factors.

Case study

The well under consideration is in Block 640 of the Green Canyon area (Well 1 in Figure 2). It is almost vertical when reaching the top of salt at 8,620 ft. The salt exists in the well section from 8,620 ft to 19,230 ft. The well is strongly deviated to a maximum of 30° below the salt. The well penetrated Oligocene sediments at the bottom of the hole. The original well-log data were edited for borehole conditions and tool corrections. The sonic logs were corrected with checkshot information to adjust the time-depth curves. The well data were then converted to time using a checkshot-calibrated time-depth curve. The depth-migrated seismic data were also converted to time using the migration velocities. We then established the well-to-seismic tie in time by using a Ricker-based (10 Hz) wavelet that was extracted from the data. To get the best wavelet, several extraction methods were tried, such as extended White (White, 1997) and ISIS time and frequency wavelet extraction methods that are based on minimizing the prediction error (Akaike, 1969). Wavelets were estimated for each input trace for each start time, so there is a 3D volume of estimated wavelets. The predictability measures the quality of the estimated wavelet for each point in this 3D volume and can be generally computed as

\[
Pr_{\text{editability}} = \frac{100 + \sum \text{Acorr.1(t)} \cdot \sum \text{Acorr.2(t)}}{\sum \text{Acorr.1(t)} + \sum \text{Acorr.2(t)}} \tag{2}
\]

Where \( \text{Acorr.1} \) is the auto-correlation of synthetics, \( \text{Acorr.2} \) is auto-correlation of seismic data, and \( \text{Xcorr.} \) is the crosscorrelation of well and seismic data.

The wavelet was extracted from a composite seismic trace constructed from partial amplitude traces along the wellbore trajectory within a radius that depended on the data quality. Wavelet estimation method choice depends on the correlation between seismic and well-log data. Initially, we analyzed the time mistie between synthetics and the seismic data (Figure 3). The mistie values are then taken into account during anisotropy analysis. The time alignment of the well data to the seismic data was used for mistie analyses and to improve the extracted wavelet. The derived time-varying shifts were then applied to update the time-depth curve for the well. Figure 3 shows the synthetic seismogram tie to the seismic data. The synthetic ties very well with seismic data at the water bottom (position A). However, the mistie increased at the top and the bottom of the salt (positions B and C, respectively) and became very significant at the deeper part of the section (positions F and G) due to an incorrect anisotropic velocity model that was used to migrate the data. But, after applying the time shifts, the seismic events match quite well with the events on the synthetics.

Figure 4 (left panel) shows the comparison of the synthetic trace and the seismic data in time. They perfectly match in the time domain after time-variance shifts, but what about in the depth domain? We may not expect to see much difference between synthetics and seismic data in the depth domain if the structure is not complicated, the dip at the well location is not large, and the well is nearly vertical.
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However, these conditions are violated due to the highly deviated well and complex structure in this area (Figure 2), so we do not expect the depth tie computed in this fashion to be of high quality. We have tried several methods to extract the best wavelet at zero-phase for the seismic-to-well tie. We have extracted the wavelet after time alignment by using several methods to choose the most suitable one. The wavelet extracted by using the extended White method (White, 1997) is selected for this well with very high predictability.

To convert the synthetic data back to depth, we used the corrected seismic velocity and checkshot-calibrated well velocity (Figure 4b). In depth, the tie is very good at the water bottom, but over other depth intervals, especially at the top and the base of the salt, the quality of the tie degrades. There may be two main causes for this: (1) an incorrect well sonic velocity due to measurement and correction errors in creating the sonic log, or (2) the wrong earth model used for imaging the seismic data. In this case, because the well data have been audited carefully, the differences seen in Figure 4 are taken to be indicators of anisotropy.

Because shales and their related rocks constitute more than 75% of sedimentary rocks, they play a very important role in seismic wave propagation and fluid flow. Anisotropy from the earth formation that makes velocities of wave propagation in each direction different is mainly caused by intrinsic anisotropy from shales. Therefore, rock-physics analyses should be incorporated with seismic-to-well misties from synthetics to estimate anisotropy for well-to-seismic control. From analyzed results in wells in this study area, we observed that the formations that have high clay contents normally have high values of seismic anisotropy. Figure 5 shows crossplots of rock properties with lithology classification. We can observe how rock properties, especially their velocities, change with respect to lithology, or even in the same type of lithology, which contains different clay contents (dark blue and yellow sands in Figures 5a and 5b). Figure 6 shows the updated subsalt velocity at the well location after anisotropy correction. We only showed the corrected velocity for subsalt horizons. This process was done for each well in the study area. Hence, these results were used to correct the anisotropy model for reimaging the data; a discussion of which will be presented in our talk and more detail will be presented in a separate paper on velocity model building.

Figure 3: Establish the time-variant shifts for wavelet extraction. Negative value means shift down. Positive value means shift up. Copyright @2009 WesternGeco.

Figure 4: Comparison of synthetics and seismic data at well location shows perfect match in time (a). Figure 4b shows synthetic trace converted into depth by well (black) and corrected seismic (red) velocities. Copyright @2009 WesternGeco.
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Figure 5: Rockphysics analysis in the well. Figure 5a shows the relationship of porosity vs. P-velocity with ages. Figure 5b shows how clay volume variation influences velocity and porosity (Light blue: salt; Blue & light yellow: clean sand; Brown & red: high volume of shale).

Figure 6: Subsalt velocity update by using well mistier analyses. The red curve is seismic migrated velocity. The green curve is updated velocity at well location.

Conclusions
Using well-to-seismic ties for seismic interpretation by time alignment (stretching and squeezing) is a very well-known method that was used when all seismic processing products were in the time domain. However, when seismic processing started to be conducted in the depth domain, simple stretching and squeezing to match the seismic data to the well data became insufficient. Instead, we should do additional analyses to better understand the reasons for the mistie using synthetics created in both time and depth. Using the seismic-to-well misties analyses combined with lithologic constraints from rock-physics analyses was found to be very valuable in extracting information about seismic anisotropy, which can then be fed back to reimage the data and better position the seismic reflections.

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