

**CROSSWELL WAVEFORM TOMOGRAPHY IN FINE-LAYERED SEDIMENTS:
MEETING THE CHALLENGES OF ANISOTROPY**

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Summary (200 Words)

During June, 2004, BP carried out a crosswell seismic survey in the Rocky Mountains. The crosswell data were acquired in finely layered clastic sediments in the Mesozoic section. The reservoir sands are known to vary laterally in quality, and the crosswell survey was conducted in order to provide a high resolution, sub-seismic image of the target. High-resolution velocity images were obtained using Waveform Tomography. This was particularly challenging due to low signal-to-noise ratios, high intrinsic attenuation, and significant, variable, an-elliptic anisotropy with a vertical transverse isotropy (TIV) symmetry. The final Waveform Tomography results show we can resolve layers down to the order of 4 m in thickness, and that we can accurately track these layers across the target zone. A subtle change in dip in the geology is revealed below a known unconformity. The variability of the anisotropy played a critical role, and the development of fully anisotropic Waveform Tomography is a logical next step.

Major objectives

The objectives were to obtain a velocity model consistent with the detailed waveform data in this extensive, low signal-to-noise crosswell survey in layered clastics. The effective TIV anisotropy of the fine-layered sediments played a critical role, and careful attention to the detailed waveform fit at each stage of the inversion was essential.

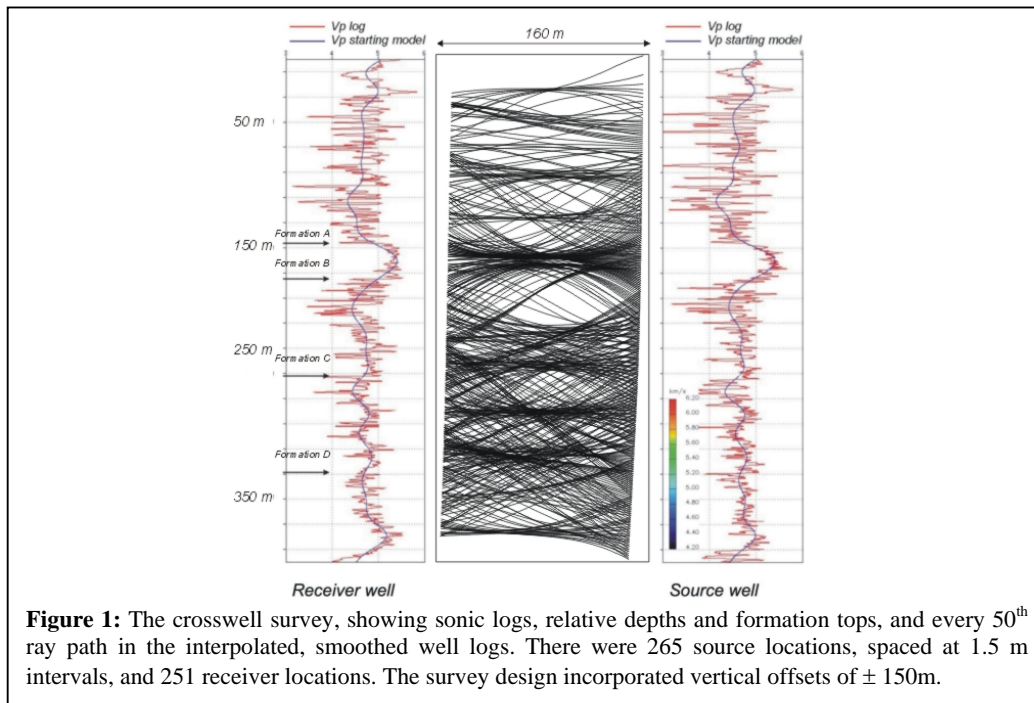
New Aspects covered

Waveform tomography for crosswell data is complicated by the presence of effective TIV anisotropy in fine-layered clastics. Our approach was to invoke a layer-based TIV anisotropy that varied throughout the model. We show that this attention to anisotropy is critical in obtaining successful tomographic images of the sediments.

Introduction

During June, 2004, BP carried out a crosswell seismic survey in the Rocky Mountains. The crosswell data were acquired in primary zones of interest in the Mesozoic section. These formations consist of finely layered beds of clastic sediments. Although the geological structures are predominantly horizontal, the sands are known to vary laterally in quality, and the crosswell survey was conducted in order to provide a high resolution, sub-seismic image of the target. The nominal distance between source and receiver wells was 160 m. ZSeis Reservoir Seismic conducted the survey, using a downhole piezoelectric source with sweep frequencies from 100 Hz to 2000 Hz.

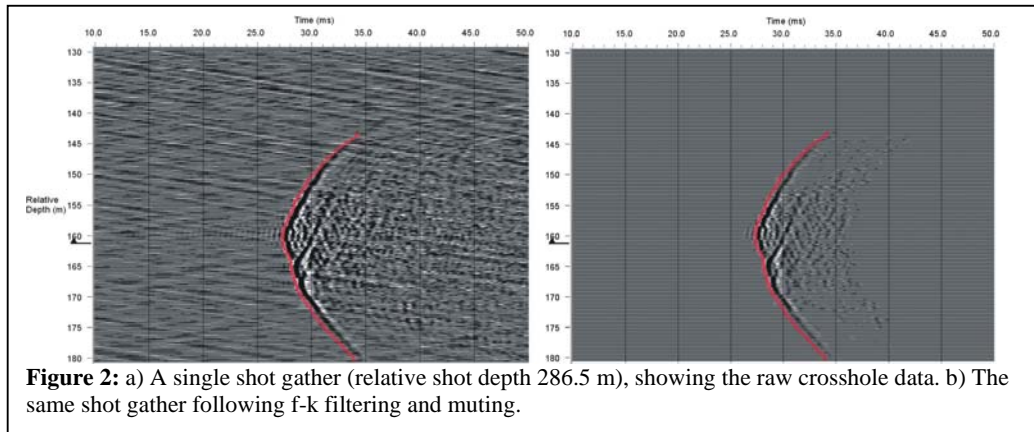
This paper describes the reprocessing of the crosswell data to extract high-resolution velocity images using seismic Waveform Tomography (Pratt, 1999). This extensive reprocessing effort was particularly challenging due to low signal-to-noise ratios, high intrinsic attenuation, and significant, variable, an-elliptic anisotropy with a vertical transverse isotropy (TIV) symmetry. Strong horizontal layering in the geology created a highly complex wavefield, showing evidence of multi-pathing, diffraction and refraction arrivals. In order to initiate Waveform Tomography, a starting velocity model was created using iterative, curved-ray, Anisotropic Traveltime Tomography (Pratt and Chapman, 1992). Variable TIV Anisotropy levels of the order of 10-15% were recovered for the P-wave arrivals. The anisotropy model was carried over to the Waveform Tomography stage, in order to account for the variable anisotropy within each vertical layer in the model. The final Waveform Tomography velocity models allow us to resolve layers to thicknesses of less than 4 m, and to track these layers across the target zone.



Data Description

The crosswell survey is illustrated schematically in Figure 1, and a representative shot gather from the survey is shown in Figure 2a. The predominantly horizontal nature of the sediments may be inferred from the high degree of correlation of the two sonic logs. The survey design incorporated vertical source-receiver offsets of ± 150 m. However the signal quality varied

considerably throughout the survey; for the shallow part of the section the offset range containing useful data was restricted to ± 60 m. For the deeper section, signal quality was acceptable to a range of ± 120 m. Travel times were manually repicked for the entire dataset, using shot gathers, receiver gathers and offset gathers repeatedly to ensure consistency. The entire survey consisted of approximately 45,000 traces, of which approximately 25,000 were successfully picked.



Anisotropic Traveltime Tomography

Strongly layered sediments are known to have anisotropic seismic velocities due to layer-induced long-wave equivalent anisotropy (see Pratt and Sams, 1996, and many other papers). In order to account for this expected anisotropy, a curved ray, regularized, anisotropic traveltimes tomography approach was used (after Pratt and Chapman, 1992). As the layering was predominantly horizontal, a transverse isotropy symmetry system was assumed with a vertical symmetry axis (“TIV” symmetry). The anisotropic traveltimes inverse problem is very poorly conditioned, and careful regularization is required. Constraints used in this phase of the inversion include first and second vertical and horizontal derivative constraints, and damping constraints on the deviation from the (homogeneous, isotropic) starting model. Several iterations of inversion followed by curved ray tracing were used to ensure the non-linearity of the problem was properly handled. A series of parameter tests were used to determine optimal weighting levels for each of the constraints.

The final results from Anisotropic Traveltime Tomography comprise a series of 2D images of the vertical and horizontal velocities, and the two “Thomson parameters”, ϵ and δ . Figure 3a shows the horizontal velocity model from this process. The final anisotropic model fits the picked traveltimes to an RMS level of less than 0.1 ms, which was consistent with the estimated picking accuracy of the data.

Waveform preprocessing and frequency domain file preparation

Before waveform tomography could be carried out, the data were reduced to a form suitable for the forward and inverse modelling algorithms (Figure 2b). Preprocessing steps included:

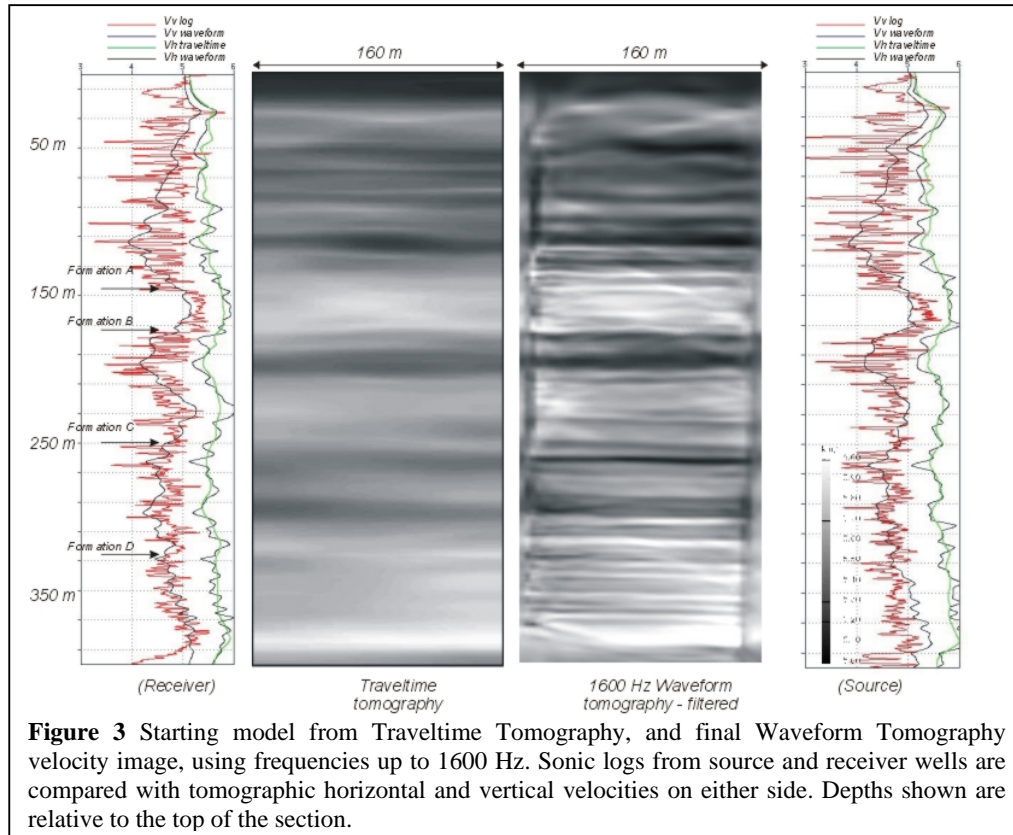
1. Suppression of the tube waves by the application of masks in the f-k domain.
2. Muting of the data to remove all waveforms for which no traveltimes pick is available.
3. Lowpass filtering of data frequencies 1000 Hz (removed at a later stage)
4. Time muting to remove signals arriving later than 10 ms after the first arrival times.

The Waveform Tomography approach operates on the waveform data one frequency at a time (see Pratt, 1999). The input data are prepared by transforming the filtered, time-windowed

time domain shot gather data (as in Figure 2b) into a set of input data files, one frequency at a time. Every source-receiver pair in the survey thus contributes a single, complex-valued data point to each file. The generation of the frequency domain files is carried out using a standard discrete Fourier summation. However, we actually calculate this summation and all subsequent Fourier quantities using a complex value of ω given by

$$\omega = 2\pi f - i \frac{1}{\tau},$$

where f is the frequency, and τ is a time damping term used to damp later arrivals in the data.

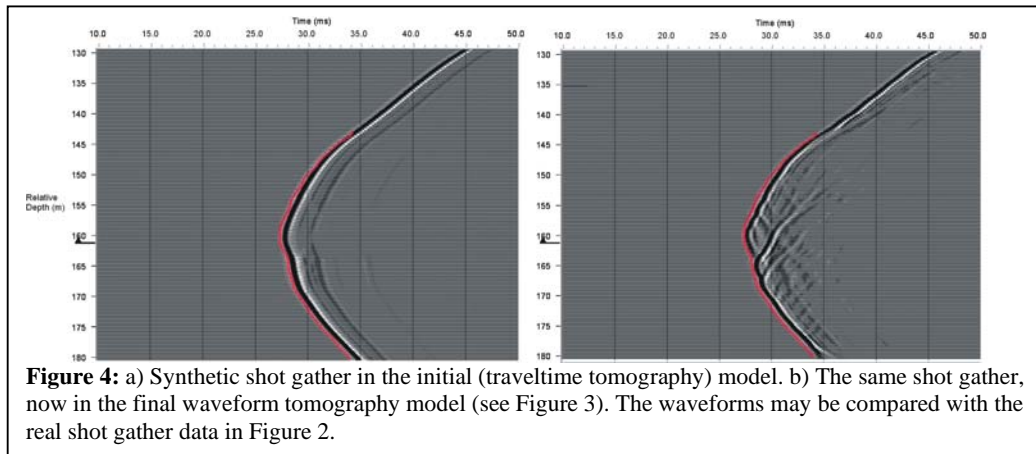


Waveform Tomography

Waveform Tomography potentially provides a significant improvement in resolution over Traveltime Tomography. However, Waveform Tomography requires a starting model that correctly predicts the first arrival to within a half-cycle (Sirgue and Pratt, 2004). Since the level of anisotropy for the crosswell data is significant (and variable), it was critical to use a Waveform Tomography approach that correctly handled this anisotropy. By stretching the 2D, isotropic, acoustic model vertically (after Dellinger, 1996) we were able to simulate an elliptical TIV anisotropy. The stretch factor was adjusted within each layer to match the layer anisotropy obtained from the anisotropic Traveltime result. This was a crucial stage in the inversion – without incorporating variable anisotropy from layer to layer, it was not possible to fit the waveform data with any reasonable velocity model.

Waveform Tomography was then carried out in stages, starting from the lowest useable frequency in the data (200 Hz), and moving up in steps of 50 Hz. Prior to Waveform Tomography, a source wavelet was estimated directly from the data using the (linear) approach of Pratt (1999); as the velocity model was improved on during the inversion, the source wavelet was periodically re-estimated and updated. Throughout the inversion good convergence was observed, and periodic checks were made that the models did indeed predict reasonable time-domain data that matched the original input data (see Figure 4). Final

waveform tomography results are presented in the right-hand side of Figure 3. An f-k filter was applied to the final result to remove steeply dipping artifacts in the final image (most likely caused by fine-scale anisotropy not accounted for in the method).



Discussion and conclusion

The final Waveform Tomography results shown in Figure 3 illustrate the advantages of using full waveform data, rather than traveltimes alone. The comparison with the sonic logs gives us confidence in the results, as does the fit between predicted waveforms in Figure 4, and the real data in Figure 2. Careful attention to the detailed waveform fit at each stage of the inversion is absolutely essential. The results show we can resolve layers down to the order of 4 m in thickness (well into the subseismic range), and that we can accurately track these layers across the target zone. A subtle change in dip in the geology is revealed below a known unconformity. The formation top at approximately 150 m relative depth is revealed as a subtle change in velocity, coupled with a strong change in the anisotropy (affecting the vertical velocities more than the horizontal velocities). The presence of artifacts related to the fine-scale anisotropy implies that subtle lateral variation in the velocities could neither be confirmed nor ruled out. The variability of the anisotropy played a critical role, and the development of fully anisotropic Waveform Tomography is a logical next step.

Acknowledgement

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