Buena Vista Hills 3-D attenuation and velocity tomography

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Summary

We processed four crosswell seismic profiles from Chevron's Buena Vista Hills field in Southern California. Direct arrival travel times and estimates of frequency dispersion were extracted and analyzed for purposes of tomographic velocity and attenuation imaging. The profiles were initially processed with a 2-D tomographic algorithm, but it was immediately discovered that the significant deviation of the receiver well severely limited the applicability of the 2-D model, so an ambitious 3-D tomographic inversion effort was undertaken. This paper provides a summary of both the 2-D and 3-D inversion results. Because of computer limitations, the 3-D results shown herein incorporate only about 25% of the trave ltime and dispersion data. Our 3-D inversion model incorporates nodes on a prismatic mesh. The slowness and attenuation estimates between the wells are estimated from the separate inversion of the arrival times and dispersion data, respectively, from the four crosswell surveys.

Introduction

The fundamental goal of reservoir characterization is to obtain 3-D information on reservoir porosity and permeability. Potentially these properties can be estimated from the acoustic properties of the rock. Traditional crosswell travel time tomography estimates the slowness field (inverse velocity). When multiple profiles are available from the same field, their tomograms are typically computed independently despite the fact that they may have been taken with wells in common. In such cases, several factors related to geology and wellbore geometry combine to cause unsatisfactorily ties at the common wells. Crosswell data, however, is the highest frequency seismic data available at the interwell scale. Any attempt at high-resolution seismic reservoir characterization at this scale should provide a consistent way of processing multiple data sets to obtain true 3-D information. This is the situation for the Buena Vista Hills surveys.

The acquisition geometry (see Figure 1) at Buena Vista Hills provides the first opportunity to test 3-D inversion from crosswell data. An advantage of a 3-D inversion is its ability to use the exact borehole geometry to estimate 3-D variations in interwell heterogeneity. An exact representation of the source and receiver acquisition geometry can help reduce the types of artifacts that result from 2-D approximations.

The Propagation Model

In the usual travel time tomography model, velocity is taken to be a real constant; therefore waveforms propagate without change in shape. In practice, changes in the pulse waveform are easily observed, so velocity should be modeled as frequency dependent. A frequency-dependent velocity causes dispersion and accompanying attenuation. This combined dispersion-attenuation alters both the shape and travel time of finite length acoustic pulses in the medium.

In our model, we assume that a pulse propagates in a locally homogeneous medium. Causality requires that the complex phase function of the pulse signal be analytic. It can be proven that the real part of the phase (related to velocity) can be determined by the imaginary part (related to attenuation), or visa versa, if enough bandwidth is available. The relation can be expressed as the Kramers-Kronig condition or through a Hilbert transform. Thus, velocity and attenuation are related through the Hilbert transform. In order to establish an explicit form between the two, a fractional dispersion model (Figure 2) for the velocity is chosen. From this velocity dispersion model one can derive its counterpart, the attenuation.

The main effect of attenuation is to weaken the amplitude of arrivals at late times. Though evident in the data, this reduction in amplitude is difficult to use for estimating attenuation. Another important effect of this model is to lower the high frequency content of later arrivals relative to early arrivals, i.e., frequency shifts. These relative changes in frequency content also affect rise time of the pulses. The frequency shift and the rise time are both manifestations of the attenuation-dispersion phenomena, one in the frequency domain, the other in the time domain. Moreover, the causality requirement forces the real part of the velocity to be slightly frequency-dependent. This slight frequency dependence is also evidenced by slight changes in the ''rise time" of each pulse. Short rise time means that the high frequencies are traveling faster than the low frequencies. The cumulative attenuation due to dispersion is related to the rise time, which is defined by extrapolating the tangent to the point with has maximum gradient.

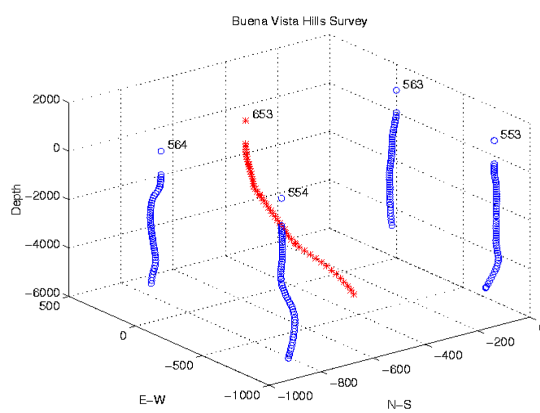

Figure 1. Borehole geometry at the Buena Vista Hills site. Notice that the central borehole is significantly deviated.

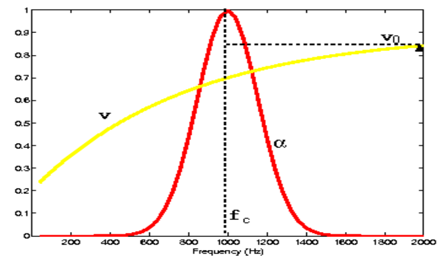

Figure 2. A dispersion model, where fc is the resonant frequency, □ is the attenuation coefficient, and v is velocity.

The dispersion model we've used also involves a characteristic frequency f_c. This characteristic frequency should be a function of the medium parameters such as porosity, viscosity, permeability, density and etc. For homogeneous media, the characteristic frequency and the velocity are correlated thus we may use the travel time to predict characteristic frequency and rise time. For heterogeneous media, this estimate of rise time is then adjusted by analyzing the actual data. In practice this adjustment is done in the frequency domain using the power spectrum taken with a windowed FFT around the first arrival. We have automated this process in ProMAX, and picked travel times and rise times for approximately 150,000 traces for the four surveys used in this study.

The four surveys were collected between 553 to 653z, 554 to 653z, 563 to 653z and 564 and 653z. Figure 3 displays the travel time picks for all four surveys. Figure 4 shows the corresponding rise time estimated using the procedure described above.

3-D Model Parameterization and Inversion

Our 3-D model is defined at the nodes of a prismatic mesh. The slowness value or attenuation value at any point inside a triangular prismatic cell is interpolated using the six corner slowness values of that cell. Barycentric interpolation at the top and bottom of the cell is followed by linear interpolation in the vertical direction. Joint inversion of multiple crosswell surveys for a 3-D slowness model requires prior information or constraints in order to form a well-posed inversion problem. The finest scale heterogeneity allowed in the 3-D solution is therefore restricted in order to compensate for the lack of uniform 3-D volumetric ray coverage. The model parameterization employed using nodes (Harris, 1993) in a natural way to impose this constraint. This node parameterization offers two important advantages. First, it is possible to control the scale of heterogeneity allowed by adjusting the distance between adjacent nodes. Second, the number of parameters defining the model is considerably less than normally required using 3-D rectangular voxels. Figure 5 depicts the well locations and the mesh used in the inversion.

Parameterizing the ray with cubic b-splines, and using Fermat's principle to obtain the spline coefficients easily permits two point raytracing between a source and a receiver. This is a straightforward extension of Moser et al. (1992) to 3-D. The computation of the raypath is reduced to determining the coordinates of the vertices. Our method provides a robust approach for obtaining 3-D raypaths with the typical trade-off between speed and accuracy. This trade-off is controlled through the choice of the number of vertices in the b-spline polygon. More vertices results in a higher degree of accuracy but also more computational time. In the work presented here we use 5 vertices because the velocity variations are not large. The manner in which this value was chosen was to compare the percent travel time difference for rays calculated in a test model using different numbers of vertices and choosing the optimal value. The non-linear inversion is solved through successive linearizations (Bube and Langan, 1994). Additional regularization constraints force lateral smoothness. The regularization weight is relaxed during the iterations following the continuation method (Bube and Langan, 1997).

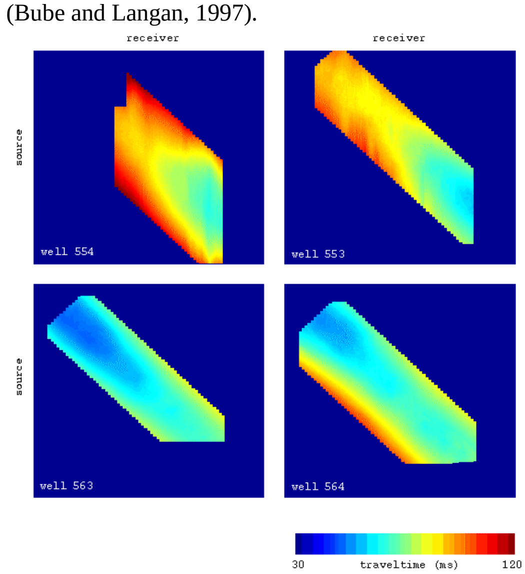

Figure 3. Travel time picks. The four BV Hills profiles, labeled by the source well, share a common receiver well, 653Z.

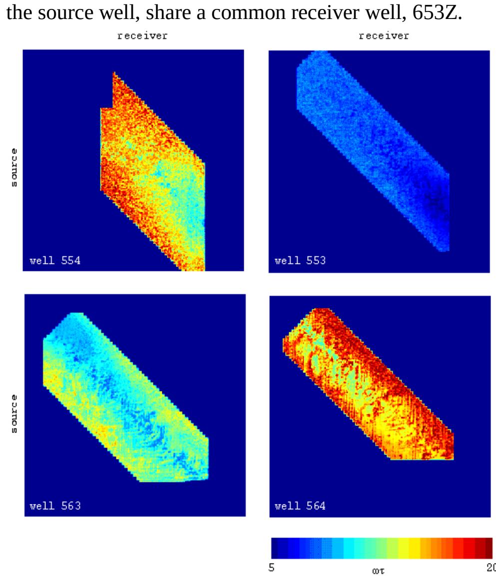

Figure 4. Rise times (ωt). The four BV Hills profiles, labeled by the source well, share a common receiver well, 653Z.

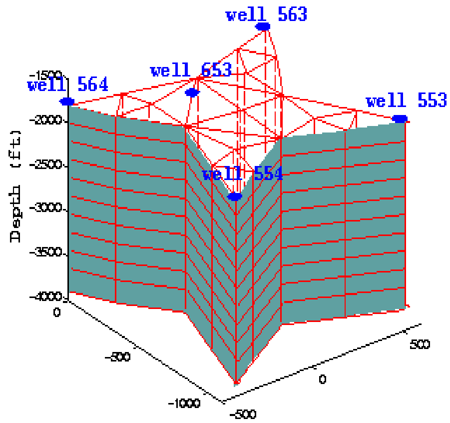

Figure 5. Well locations and mesh for 3-D inversion.

Inversion Results

Several tomographic inversion were performed on the data. We first used a conventional 2-D algorithm, where an average 2-D plane is selected to pass through the deviated wells. We also used the 3-D algorithm described herein on separate profiles. In this latter case, the 3-D well geometry is honored but the separate surveys are not forced to tie at the common receiver well. Finally, a single tomographic inversion was performed using all four datasets. In all cases, the inversions were first carried out for the direct-arrival travel time data to estimate a 3-D slowness model. The slowness image was then used to calculate the ray paths used for the attenuation (Q) inversion. Figure 6 shows a single perspective of the 3-D attenuation and velocity inversions. SP logs are plotted with the tomograms for correlation.

While the nodal parameterization can be an effective way to parameterize a model it is not completely general. A node parameterization assumes a model with smooth lateral variations is sufficient to describe the data. Whenever the smooth lateral variation assumption is justified, this approach estimates a 3-D geological model from data taken in multiple surveys, and consistent with the true 3-D borehole geometry. Each survey has approximately 40,000 travel times. Together the four profiles have over 150,000 travel times, a problem too big for our computer workstation. As a result the 3-D inversion shown in Figure 6 used only about 25% of the travel times and rise times, i.e.; we used every other source position and receiver position. We are continuing to improve the images by developing a combined SIRT/CG solver for the large 3-D problem.

The interpretation of multiple 2-D tomograms is important for practical applications of crosswell tomography for high-resolution reservoir characterization. The proposed method is a consistent approach for the estimation of a 3-D slowness model from multiple crosswell surveys. The constraints on the scale of lateral variations do restrict the horizontal resolution of the solutions but at the crosswell scale these assumptions are still much better than surface seismic and better than simple interpolation of well logs.

Acknowledgements

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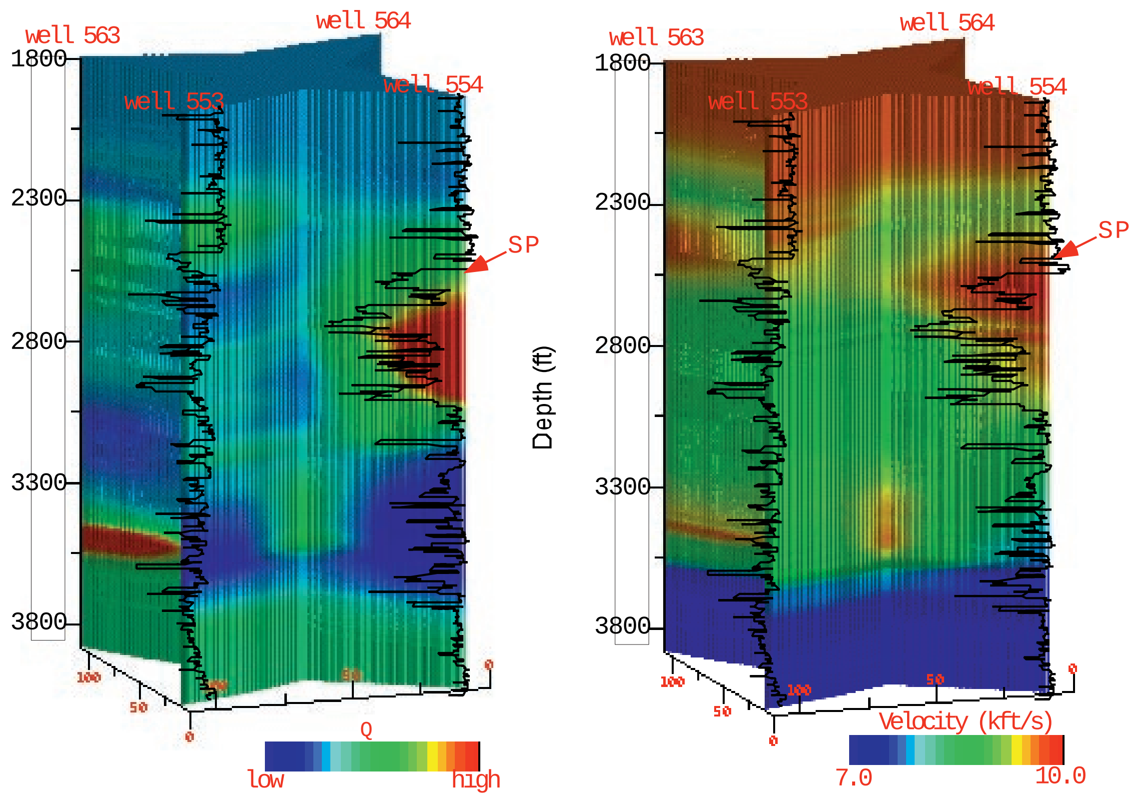

Figure 6. Attenuation (Q, left) and velocity (right) inversions. The images are viewed from the plane of well 554 and 564. The SP logs are plotted for correlation.