Incontrovertible Evidence of Anisotropy in Crosswell Data

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Summary. Crosswell seismic data collected at BP's test site near Devine, Texas show clear evidence of P-wave anisotropy (v_x/v_z up to 1.3) confined to shale layers in a shale/carbonate sequence. Tomograms made assuming isotropy are severely degraded, but could be mistakenly interpreted as indicating (nonexistent) low velocity zones within the carbonates. The effects of the anisotropy are directly evident in the raw data once headwaves and internally reflected waves are correctly identified. Inversion for a layered, transversely isotropic, anisotropic medium yields a model that fits the data to the accuracy of the time picking.

1. Introduction. Crosswell data were collected using a piezoelectric pressure source with hydrophone receivers at BP's test site near Devine, Texas. Source and receiver wells were vertical with a separation of 100m. The peak frequency of the received signal was approximately 800Hz. A full 56 by 56 "tomographic scan" was run with source and receiver depths at 1.5m intervals between 771.0 and 853.5m. Figure 1 shows a sonic log, a common-shot gather, and a common-depth gather ($z_{source} = z_{receiver}$), all plotted on the same vertical scale. From top to bottom, the formations encountered were the Austin Chalk, Eagle Ford Shale (top at 777m), Buda Limestone (796m), Del Rio Clay (a shale) (823m), and Georgetown Limestone (848m).

In the limestone zones, the direct arrival times predicted by the log agree well with the first arrivals in the common-depth gather; in the shales, the first arrivals are headwaves. Figure 2 shows an expanded view of the zone around the Del Rio Clay, with the log superimposed on the common-depth gather at a scale to allow direct comparison. In this zone, headwave arrivals are clearly evident in both the shot gather and the common-depth gather (marked "H" in Figure 2). The vertical event at 33ms marked "B" on the common-depth gather fits well with the direct arrival time predicted by the log and has been interpreted as such in a previous study (Harris, 1988) when only a common-depth gather was available. However, there is no vertical event evident in the shot gather at this time. In the shot gather, the earlier event ("A") has the moveout pattern one would expect for a direct arrival if the formation had a velocity 15 to 30 percent higher than that suggested by the log (and increasing slightly with depth).

When direct arrival times (following "A" in Figure 2) are picked and inverted by standard time tomographic methods, the resulting velocity tomogram (Figure 3) shows a disturbing deviation from the expected layered solution. The problem is clear when one considers residual times obtained by subtracting from measured times the times predicted by ray-tracing through a layered model built from the times picked for the common-depth traces. The residuals are all positive; they increase as the ray angles (measured from horizontal) increase and reach highly significant values (3.6ms, almost three wavelengths). In the tomographic inversion, these residuals translate to excess slowness backprojected along the steepest rays.

The above observations raise a number of questions: If event "A" is the direct arrival in the shale layer, what is event "B"? Why does the model built from these times disagree with the log? Why does it do such a bad job of predicting times for source-receiver pairs at significant offsets in depth? If event "B" is the direct arrival, what is event "A"? Why does "B" look like the intersection of a downgoing event with an upgoing event in the shot gather?

2. Analysis. In this section we will argue that simple, self-consistent answers to these questions can be obtained if, and only if, we admit the possibility that the shales are anisotropic.

Consider first the question of whether the direct arrival is event "A" or "B". Note that event "H" is continuous with the first arrival in the Georgetown limestone in both the shot gather and in the common-depth gather and that its apparent vertical slowness ($\Delta t/\Delta z$) in the common-depth gather is twice as large as in the shot gather. Event "H" is undoubtedly a headwave generated at the boundary between the slow Del Rio clay and the faster Georgetown limestone. Note further that event "A" has a smaller apparent vertical slowness in the shot gather than does "H". The underlying wave event must, therefore, have a larger horizontal slowness (and a more horizontal ray vector). However, the headwave has a maximum horizontal slowness among (longitudinal) waves propagating in the limestone (*i.e.* the P-wave slowness of the limestone). PSP headwaves are ruled out by the known shear velocity (0.38ms/m) of limestone. It follows that the wave giving rise to "A" must have propagated entirely within the Del Rio clay. As it is the first such event in the data, it must be labeled "direct arrival".

Now consider P-wave energy propagating in the shale that is multiply-reflected from the top and bottom of the layer. Writing "D" for the direct wave, "T" for the wave reflecting once at the top, "TB" for the wave reflecting once at the top and once at the bottom, etc., the arrival times for these waves should show a characteristic crisscross pattern in a common-shot gather as illustrated in Figure 4a (here for a homogeneous layer). On the common-depth gather the same arrivals show the pattern illustrated in Figure 4b. Note that the even multiples have a null apparent vertical slowness. This observation depends only on the assumption that the medium is laterally invariant (not necessarily homogeneous). The point is that as the source and receiver are shifted up together, the ray segment removed from the near source leg is added to the near receiver leg of the total raypath, so the shifted total ray has the same ray parameter and total length as the original.

It is clear that the data of Figure 2 show the patterns illustrated in Figure 4 and that event "B" is the "BT=TB" reflection. Further confirmation comes from a qualitative consideration of amplitudes — the TB arrival is strong because the reflections are postcritical. The direct arrival fades (fairly abruptly) as it approaches the base of the clay because the horizontal velocity is increasing with depth. This implies that the rays for the direct arrival dive slightly. When the source is deep enough that the diving rays meet the fast Georgetown limestone, energy is lost from the direct arrival and added to the headwave.

A problem arises, however, when one attempts to fit the arrival times for all the identified events using predictions made from isotropic models. The uniformity and verticality of event "B", together with the match between logs from the two wells argue strongly in favor of a laterally invariant model. Figure 5 shows the predictions from an isotropic model that fits the direct arrival together with predictions from the anisotropic model described in the following section. The isotropic model seriously mispredicts both the headwave and the multiply-reflected arrival. Similarly, predictions from a model that fits the headwave arrival seriously miss the direct arrival. Predictions from the anisotropic model fit all the arrivals consistently. Only the direct arrivals (and some log data) were used in the derivation of the model. The fit with the headwave and the internally reflected arrivals provide corroborative support for the accuracy of the model.

3. Synthesis. The close match of the logs from the two wells, together with preliminary forward raytracing calculations suggest that the data can be well accounted for by the simplest kind of anisotropy consistent with the elastic wave equation — a transversely isotropic (TI) medium with a vertical axis of symmetry.

Chapman and Pratt (1990) have shown that traveltimes in an anisotropic medium can be approximately computed by a method that is particularly well-suited to traveltime inversion. In this approach, one assumes that the anisotropic "true" model is a small perturbation of a background isotropic model. Rays are traced in the background medium and times are computed by adding to the background times a perturbation computed by integrating along the ray a function that depends linearly upon the perturbations in the elastic moduli. For quasi-P waves in a homogeneous TI medium with a vertical symmetry axis, this approach yields a total traveltime approximation of the form:

$$T = dl\, s_\theta$$

where dl is the length of the ray and s_θ is an angle-dependent (group) slowness of the form:

$$s_\theta = A\cos^4(\theta) + B\cos^2(\theta)\sin^2(\theta) + C\sin^4(\theta) \qquad (1)$$

with

$$A = s_x, \quad C = s_z, \quad B = 4s_{45} - (s_x + s_z).$$

For the purpose of inverting the Devine crosswell data, we considered models consisting of 56 homogeneous, TI anisotropic layers centered at the source/receiver depths. Each layer is characterized by three parameters, $s_x(i)$, $s_z(i)$, $s_{45}(i)$, from which all $s_\theta(i)$ can be computed using equation (1). Supposing that background isotropic velocities for each layer are chosen and that rays connecting each source to each receiver are traced, let dl_{ijk} and θ_{ijk} respectively denote the length and angle in layer i of the ray connecting source j to receiver k. Then the approximate traveltime computations described above lead to a sparse, overdetermined system

$$T_{jk} = \sum_i a_{ijk}s_x(i) + \sum_i b_{ijk}s_z(i) + \sum_i c_{ijk}s_{45}(i)$$

where T_{jk} is the measured traveltime from the jth receiver to the kth source, and

$$\begin{aligned}
a_{ijk} &= dl_{ijk}(\cos^4(\theta_{ijk}) - \cos^2(\theta_{ijk})\sin^2(\theta_{ijk})) \\
b_{ijk} &= dl_{ijk}(\sin^4(\theta_{ijk}) - \cos^2(\theta_{ijk})\sin^2(\theta_{ijk})) \\
c_{ijk} &= dl_{ijk}(4\cos^2(\theta_{ijk})\sin^2(\theta_{ijk})) \qquad (2)
\end{aligned}$$

The system has 56×56 equations in 56×3 unknowns. Additional equations of the form

$$\gamma_1(s_z(i) - s_{log}(i)) = 0$$

and

$$\gamma_2(s_\theta(i) - s_\theta(i+1)) = 0$$

were added as soft constraints favoring a match of vertical slowness to the logged values and favoring solutions that were vertically smooth except at picked layer boundaries. The $\gamma's$ are adjustable weights for the constraints. The system was solved using a standard conjugate gradient algorithm.

Figure 6 shows the inversion obtained with the log constraint in force and using a background model chosen to match the logged slownesses. After inversion, except at isolated points, maximum residuals are less than a half wavelength and for most of the data, residuals are less than one quarter wavelength (0.325ms). In the output model, the anisotropy is confined to the shales. Other trials have shown that the results are fairly independent of the background model, and that the results for s_x and s_{45} are fairly independent of the log constraint.

4. Conclusions.

- The anisotropy really is incontrovertible. Even restricting attention to a single shot gather and to modes that propagate entirely within the Del Rio Clay, the data cannot be reconciled with any isotropic model.
- Tomograms made under the assumption of isotropy are so severely degraded as to be misleading.
- Inversion of the crosswell data for a layered anisotropic model accounts well for the variation in the data and yields a result which is isotropic in the limestone and highly anisotropic in the shales (v_x/v_z from 1.15 to 1.30).
- Proper event identification is difficult or impossible to perform using common-depth gathered data only.

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References.

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J. HARRIS, 1988, Cross-Well Seismic Measurements in Sedimentary Rocks, extended abstract, 58th Annual Meeting of the SEG, Anaheim, pp. 147-150.

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Figures.

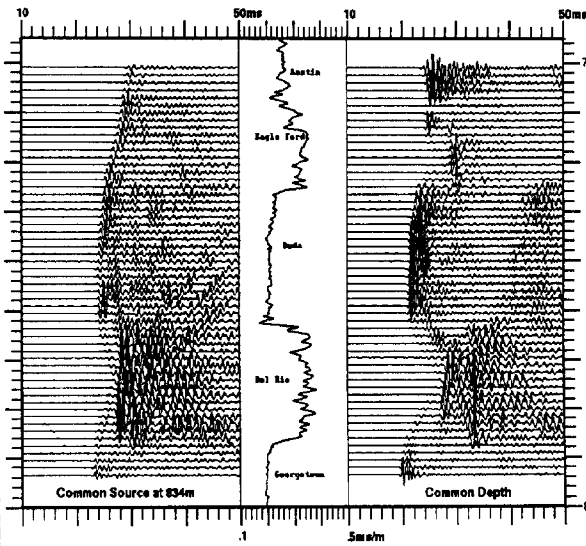

Figure 1. Common-source gather, sonic log, and common-depth gather. The trace at depth 834m is common to the two gathers.

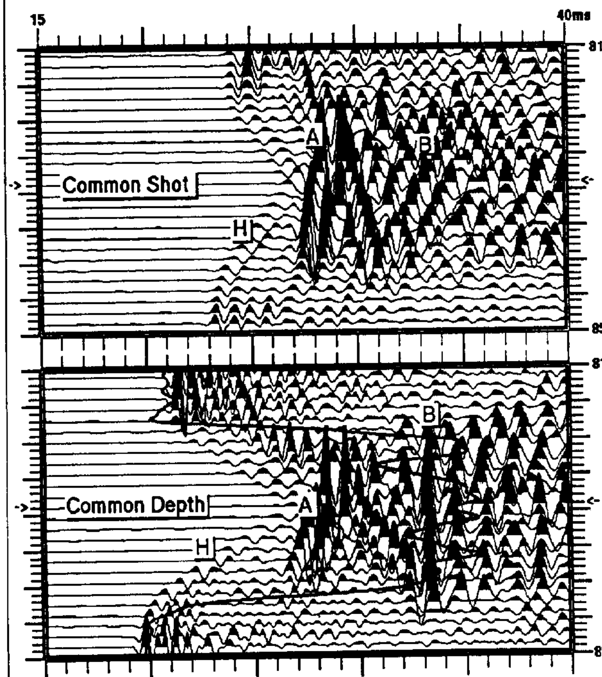

Figure 2. Enlarged view of the sections in the vicinity of the Del Rio Clay. The sonic log has been scaled to units of milliseconds per 100 meters and superimposed on the common-depth gather.

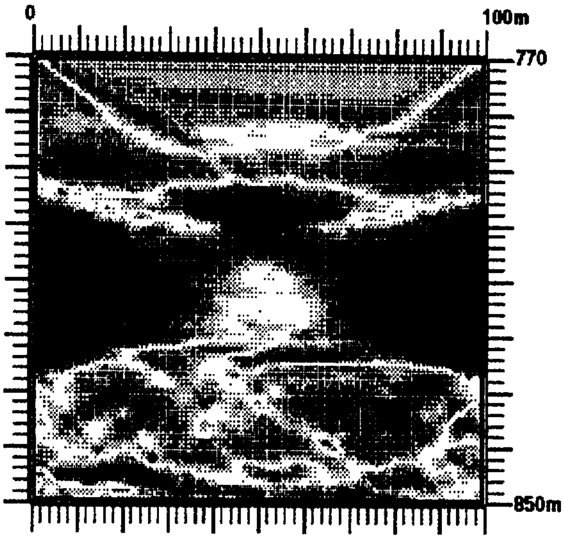

Figure 3. Bent-ray tomogram based on an isotropic background model.

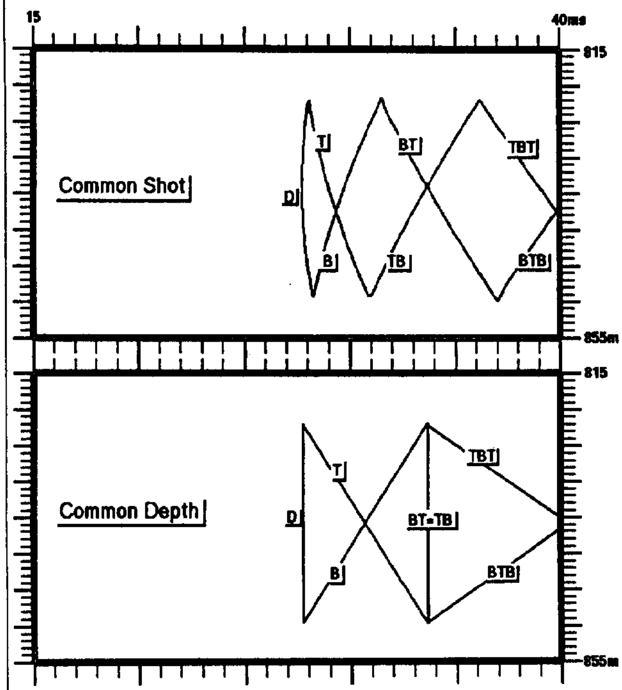

Figure 4. Pattern of reflected arrivals in a common-shot gather and in a common-depth gather.

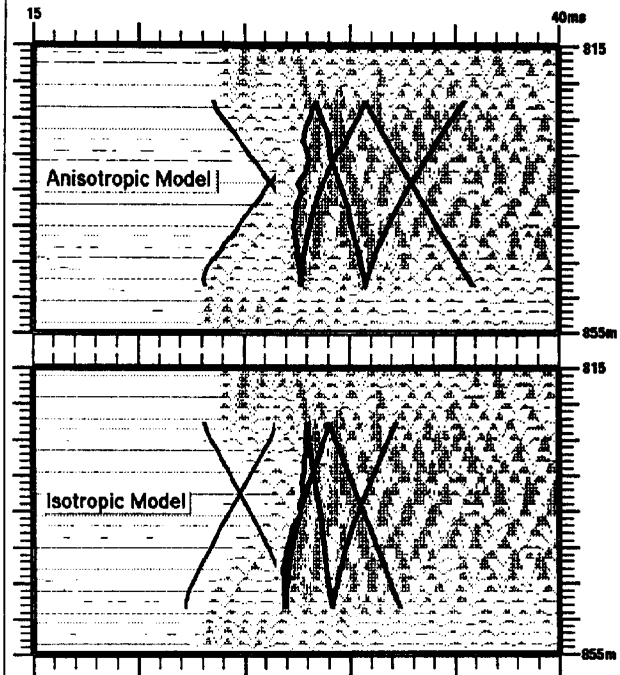

Figure 5. The common-shot gather with headwave, direct, and multiply reflected arrivals predicted (a) by the anisotropic model of Figure 6, (b) by the isotropic background model used for the tomogram in Figure 3.

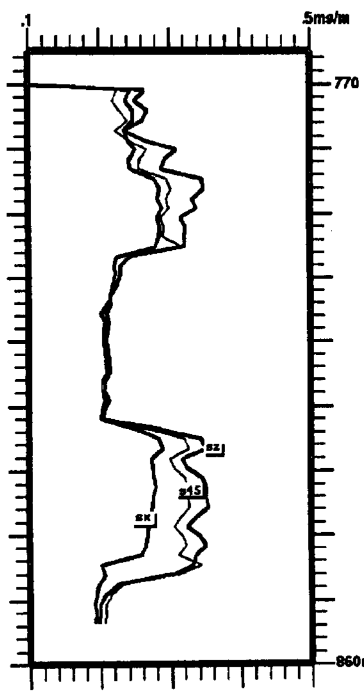

Figure 6. Anisotropic model resulting from the inversion. Three slowness parameters for horizontal, 45 degree, and vertical propagation are plotted as sonic logs.