High Resolution 3-D Crosswell Reflection Imaging in the presence of anisotropy: the Santa Rosa gas field, Eastern Venezuela

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Summary

Seismic anisotropy in sand/shale sequences causes structural imaging problems when an isotropic earth is assumed. Three high resolution crosswell seismic profiles were acquired in the Santa Rosa gas field in eastern Venezuela. The main objective is to gain detailed structural images in a seismically difficult data zone, where the deep target horizons are obscured by a near-surface gas column. Isotropic imaging techniques were applied to the crosswell data with relatively poor results. The imaging target comprises sands from 5 to 50 ft thick in a 1800 ft thick deltaic, mainly shaley sequence unconformably overlying a predominantly fluvial Oligocene sand-rich sequence. The abundance of shales and fine layering has resulted in significant anisotropy. We have performed perhaps the first 3-D anisotropic reflection imaging of crosswell seismic data. Due to the structure and well deviations we use a fully 3-D modeling and imaging framework to produce both velocity and crosswell reflection images. Initial tomographic inversion revealed strong evidence of anisotropy, which correlated well with sonic log information. Differences between vertical and horizontal velocities range from 16-23% in the upper shale-rich sequence, dropping to less than 5% in the lower sands.

Is this paper we show that accurate depth imaging using crosswell reflection data is possible in the presence of anisotropy. A companion paper, ("Evidence of anisotropy from 3-D crosswell tomography in a giant gas field, Venezuela", Washbourne *et al.*, 2000) presents the overall theory and application to high resolution velocity imaging.

Introduction

The Santa Rosa gas field is located east of Anaco, Anzoátegui state in eastern Venezuela. Three wells are involved in this crosswell seismic survey including an injector well and two gas producers. Well spacing ranges from 1191 to 1598 ft with a vertical imaging interval from 7200 to 9600 ft below surface. Three complete crosswell profiles were acquired between three wells in a triangular pattern. Crosswell seismic operations require a well in which the seismic source is placed, and one or more receiver wells where sensors are placed to record the data. Data acquisition is run as a wireline operation where a piezo-electric source sweeps during logging. The data acquired for these crosswell profiles used source sweep frequencies from 100 to 1400 Hz.

Figure 1 illustrates the geometry of the wells and vertical projections of the wellbore deviations. In this Figure, the arrows indicate a crosswell profile with the base of the arrow at the source well and the point of the arrow at the receiver well. Note that wellbore deviation and significant structure are present.

Reflection Imaging in the presence of anisotropy

Crosswell seismic reflection imaging requires an accurate velocity model for mapping data from the time domain into their correct depth locations. In structurally complex areas, or where well deviations are significant, a 3-D framework is needed to derive a good velocity model. Although in Santa Rosa field structural complexity is not present at the intervals studied here, the lenticular nature of the sands and the presence of normal faults affecting the reservoir sands set the frame for using unconventional processing techniques for crosswell tomography. Tomography used here follows the continuation constraint technique applied to 3-D traveltime velocity inversion by Washbourne and Bube (1998) and modified to include anisotropy by Washbourne *et al*. (2000).

Estimates of vertical to horizontal velocity ratios were derived by inverting narrow angle slices of travel time picks and comparing these velocities with vertical velocities derived from sonic logs. Eight angle slice tomograms were derived, providing enough information to accurately estimate how velocity varies with angle at each depth (Washbourne, et al., 2000).

Typical crosswell reflection imaging involves VSP-CDP mapping of the data from the time domain to the depth domain between the locations. The mapped data are then angle transformed, giving a seismic data volume whose vertical axis is depth, and whose horizontal axes are distance between the wells and reflection angle. These data are then stacked over an angle range from about 50 to 75 degrees (as measured from the vertical).

In an isotropic earth with horizontal reflectors, the reflections remain horizontal when mapping from the time domain to the mid-depth domain between the wells. If the model used for VSP-CDP mapping is isotropic, and the true earth is anisotropic, significant distortions will occur in the trajectories used in the mapping. Both the actual reflections and the modeled reflection times may not be flat, even when the horizons themselves are flat. Since the distribution of angle coverage between the wells varies as a function of distance from the wells, and the rays are affected by velocity errors which also vary in magnitude with angle and depth, the stack will give false structural indications as well as it will lower the overall signal to noise ratio in the presence of anisotropy. This can result in very poor results, even when reflections are clearly visible in the raw data (Figure 2).

Reflection ray tracing is used to create a time-depth map relating reflection times in the time domain data to reflector positions in depth. This information is used in VSP-CDP mapping and migration.

Figure 3a shows reflection positions predicted by standard isotropic raytracing for the Santa Rosa crosswell data. Clearly, both the direct arrival and reflection trajectories do not follow the actual seismic arrivals. The velocity model used for ray tracing was derived via tomography assuming an isotropic earth. This means that velocities estimated for near-horizontal arrivals may be too slow (hence times will be too late) and velocities estimated for more vertical arrivals will be too fast (times will be too early). The resulting velocity model will be an average over a small range of angles depending on the range of angles used to derive it.

Such an incorrect velocity model degrades the reflection stack in several ways: 1) reflection energy before the predicted direct arrival at near zero offset will be lost during mapping, 2) energy at long offsets after the predicted direct arrival, but before the actual direct arrival (noise) will be mapped into the final image, 3) reflections will not be mapped into their correct positions, and 4) reflections will not be flat after mapping which will limit the quality of the final stacked image. Figure 3b shows the same common receiver gather with reflection times calculated by taking into account the presence of anisotropy. This correction for anisotropy is depth and structure dependent and performed over all the angles used in the final image. Note that the predicted direct arrival times and reflection times nearly exactly match those of the observed data.

Imaging Results

The ideal solution to take into account anisotropy would be to fully model the effects in a 3-D sense. Our initial approach to take into account the anisotropy involved deriving a velocity model via tomography using direct arrivals over a small angle range similar to the angles used in the reflection stack (*i.e.* non-zero offset arrivals). Such a velocity model is intermediate between the horizontal and vertical velocities and is relatively close to the medium velocities at the angle ranges over we wish to map and stack the crosswell data. VSP-CDP mapping with such a model does not give a satisfactory result. If a fully 3-D anisotropic velocity model is derived using an elliptical or transversely isotropic modeling framework then VSP-CDP mapping can be performed correctly. Figure 3 shows the improved results from reflection raytracing by taking into account 3-D structure and depth and angle dependent velocities (anisotropy) caused by the presence of large shaley intervals. In this case the anisotropy estimates varied from 18-23% in the shale section (Colorado member) down to 0-5% in the fluvial sand-rich Merecure Formation below about 8800 ft.

Figure 4 shows the result of mapping and stacking using the fully 3-D anisotropic velocity model. During VSP-CDP mapping, angle dependent velocity corrections are made at each layer in the model to take into account the anisotropy and how it varies with depth. Comparing the reflections with density logs for each well reveals a strong correlation with known reflectors/formation members. Figure 4 also shows 3-D depth migrated surface seismic extracted near the right hand well location. A marked improvement in resolution is visible when comparing the crosswell seismic image with the surface seismic image. Frequencies in the surface data vary between 10 to 50 Hz whereas frequencies recovered in the crosswell data cover the range 100 to 1200 Hz.

Summary

Significant anisotropy, of the order of 20-25% can severely affect conventional depth imaging. The crosswell seismic data can provide high resolution information even in seismically difficult areas where surface imaging techniques are restricted by near-surface gas accumulations, or where the imaging targets are deep and surface data reveal little about subtle structural features. Crosswell seismic data reveal significant changes in reflection character from one geological unit to another, revealing features not visible on surface seismic data, particularly when comparing the continuity of sand layers in the upper Colorado member and deeper Merecure Formations.

We have performed high resolution 3-D crosswell reflection imaging in the presence of significant anisotropy. Conventional isotropic processing can result in poor reflection images in the presence of anisotropy, even where the structure is not complicated. Assuming transverse isotropy in the reflection and direct arrival ray tracing can result in much more accurate VSP-CDP mapping compared to conventional 2-D and 3-D isotropic imaging. Crosswell reflection images show vastly improved resolution over surface seismic and will enable better reservoir characterization.

The crosswell imaging method has achieved much higher resolution seismic images than would have been possible with surface-based seismic imaging techniques such as VSP and other conventional seismic methods. The ability to image sub-seismic faulting and fine structural and stratigraphic detail below 15 feet vertical resolution is shown here as feasible, especially when crosswell data is used integrated with geologic and conventional geophysical information.

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References

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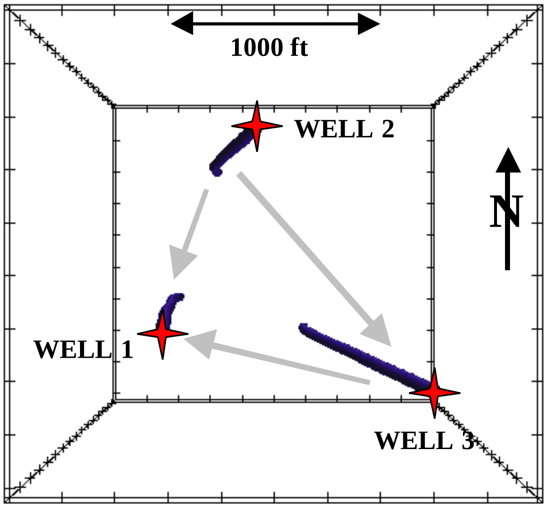
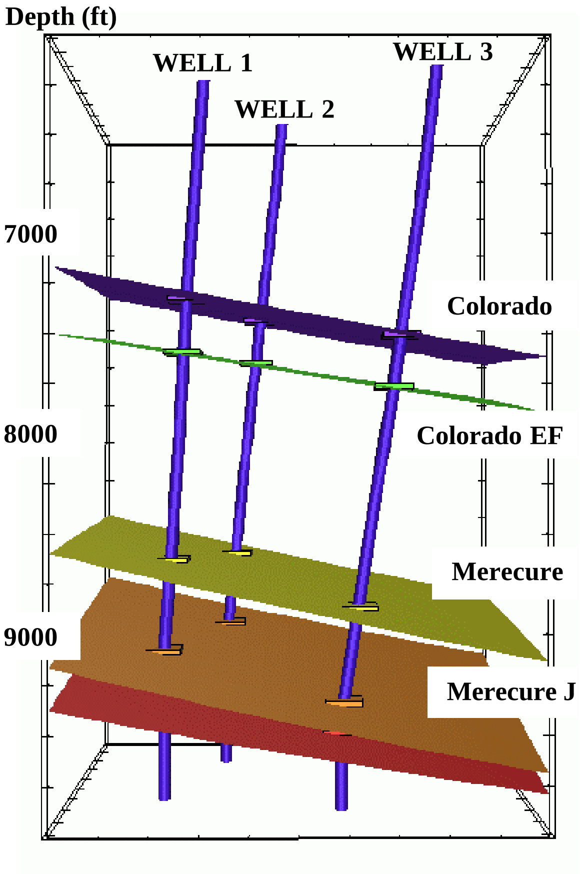


(a)



(b)

Figure 1. (a) Plan view and (b) cross-sectional views of the crosswell survey geometry at Santa Rosa gas field, eastern Venezuela showing formation boundaries. Red stars indicate surface well locations. Grey arrows point from source wells to receiver wells.

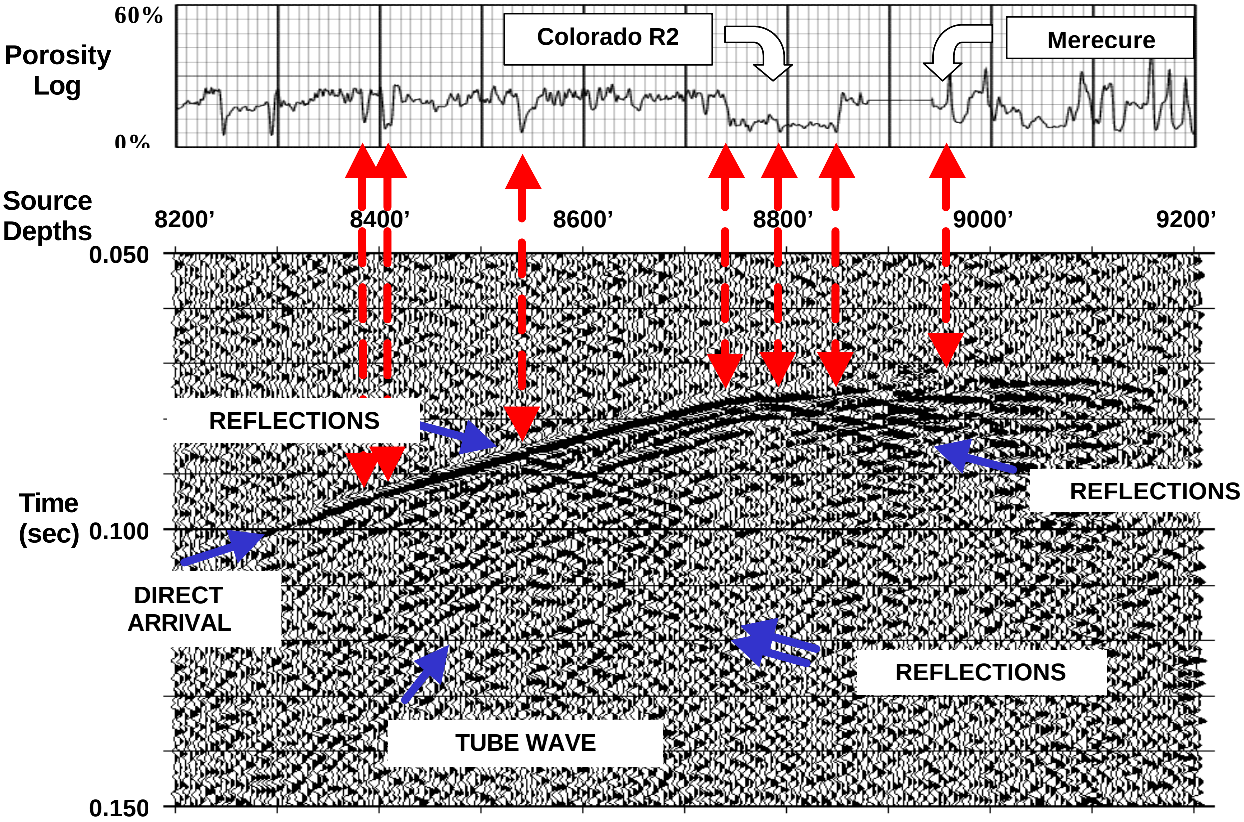
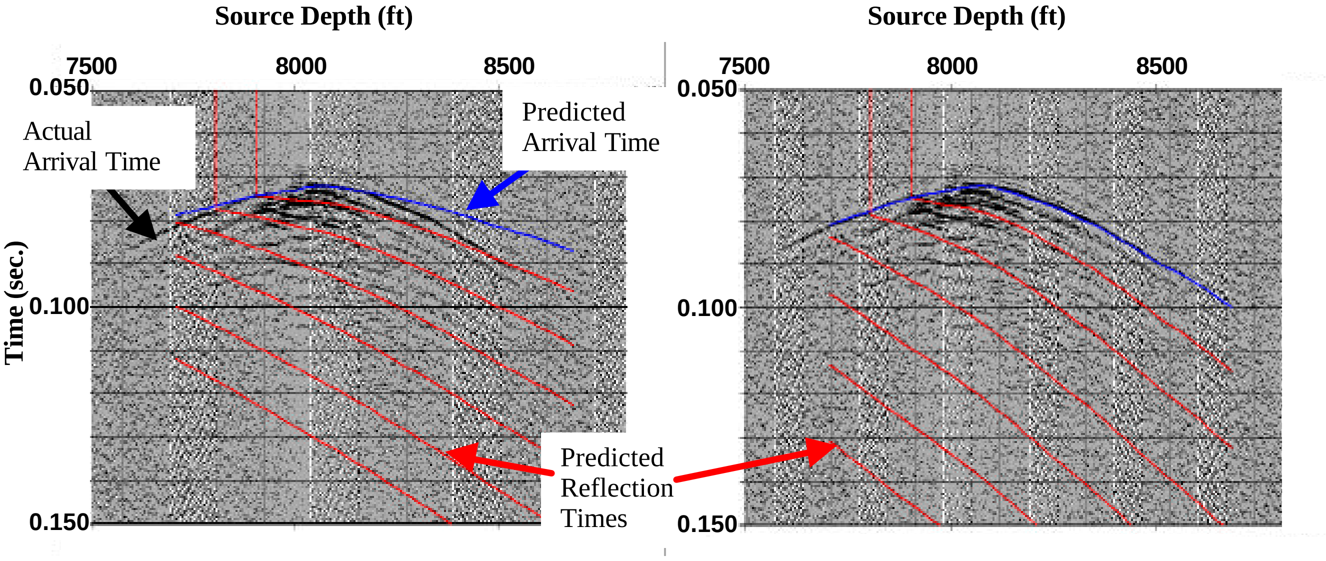


Figure 2. A common receiver gather at a depth of 8700 ft from the profile collect between wells 1 and 3 in the Santa Rosa gas field showing correlations between reflections and a porosity log from well 3



(a) (b)

Figure 3. A common receiver gather at a depth of 8000 ft from a profile collected between wells 1 to 2 showing (a) reflection times and direct arrival times predicted by isotropic ray tracing and (b) reflection times predicted by anisotropic ray tracing.

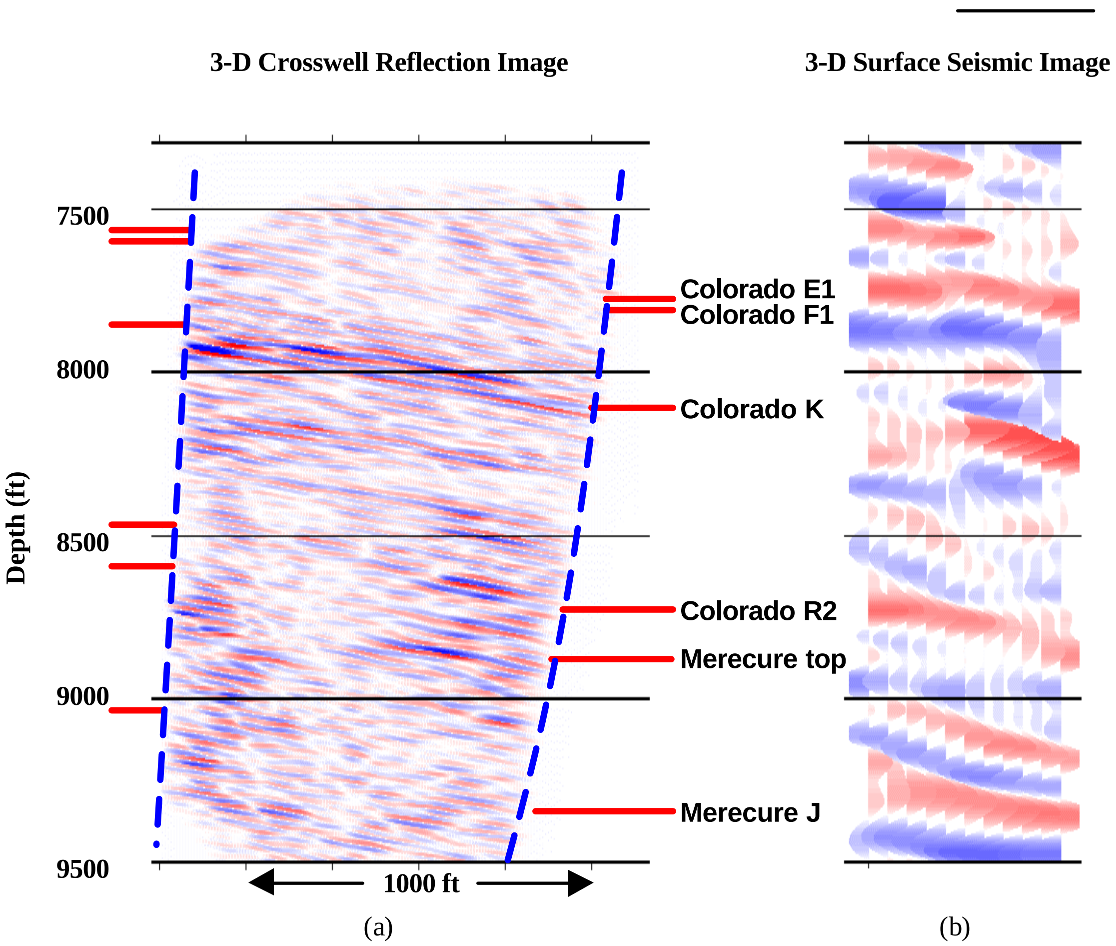


Figure 4. Crosswell reflection image from profile collected between wells 1 and 3 derived using anisotropic reflection ray tracing and a velocity model derived from 3-D anisotropic tomographic inversion. 3-D depth migrated surface seismic data extracted near the well on the right side is shown to the right for comparison. Vertical resolution contrast is about 15:1 between the two images. Well paths are marked with dashed blue lines.