3D acoustic full waveform inversion of 3-D seismic data and PSDM: A near-surface Midland Basin study

Anthony Vassiliou, GeoEnergy, Inc.; Robert Meek, Pioneer Natural Resources; Rodney Stromberg, Lionel Woog, GeoEnergy, Inc.*

Summary

3D acoustic full waveform inversion (FWI) is used to create a detailed velocity model of the near surface using a 3D survey acquired in the Midland Basin. Shallow sonic logs show that the near surface comprises alternating layers of significantly low and fast velocities. A refraction statics model would not delineate the slower velocities. The FWI derived velocity model is used as input model in the prestack depth migration to delineate the near surface and subtle image reflections one of which is the brackish water bearing Santa Rosa formation. The Santa Rosa fluvial sandstone, which is difficult to map on seismic, is one of the water sources used in nearby hydraulic stimulations. By successfully delineating the sand, more productive water wells can be drilled. In addition to improving the shallow seismic response the velocity model can be used as input into a prestack depth migration to more accurately map the Wolfcamp formations.

Introduction

The success of seismic imaging is highly dependent on the detailed imaging of the near surface. In the present study, near-surface complexity and velocity inversions require the application of advanced wave equation based methods for near-surface velocity estimation. Full waveform inversion was first developed in the 1980s (Tarantola, 1984) and it has mostly been applied to marine 3D seismic data (Sirgue, 2009). There have been very few published studies on 3D seismic land data sets (McNeely, et. al., 2012).

In this study, we present what is to our knowledge the first application of acoustic 3D waveform inversion to a non-conventional producing reservoir in the Midland Basin. This was achieved without the use of any well information. We also show that the full waveform methodology used for 3D marine seismic data sets is not applicable to the land 3D seismic data set used in this study.

The shallow geology in the Permian Basin comprises Quaternary alluvial and aeolian deposits overlying the high velocity Cretaceous Edwards limestone. Below the limestone are (a) low velocity Cretaceous Trinity sands, (b) Triassic Copper Canyon, Trujillo, and Tecova sands and shales, (c) Santa Rosa Sandstone, (d) Permian Anhydrites and (e) dolomites in the Grayburg and San Andres formations as shown in Figure 1. The Santa Rosa is a brackish aquifer and is used as a water source for hydraulic stimulation. The underlying San Andres sand is used as a water disposal aquifer. Because of the alternating fast and slow velocities in this area refraction statics derived velocity models are not adequate for resolving the low velocity layers and lead to incorrect ray paths for imaging. The delineation of the Santa Rosa and San Andres formations is important in accurately placing water producing and disposal wells. Furthermore detailed shallow velocity models are needed to properly image underlying Wolfcamp horizontal targets.

Method

The land 3D seismic data used in this study is a subset of a larger survey and includes 4892 Vibroseis shots and 4245 channels. The 3D seismic data acquisition is wide azimuth and with maximum offsets of 18,000 feet. The seismic bandwidth is 3-95 Hz and the CDP bin spacing 82.5 feet. The raw field shot gathers are first geometry checked and a spherical divergence correction applied with a picked brute velocity. The first arrival traveltimes are then picked on the data set and subsequently inverted with a non-linear tomography from topography. The resulting tomography traveltime RMS error is 14.5 ms. After the traveltime tomography, the following steps are performed: (a) tomostatics application, (b) minimum phase conversion, (c) surface consistent deconvolution with 180 ms operator and 24 ms gap, (d) three passes of velocity analysis at 0.5 x 0.5 mile spacing, (e) surface consistent scaling. The full waveform inversion cannot estimate velocities in the presence of residual reflection statics. Therefore the computed residual reflection statics must be applied to the shot gathers prior to the FWI.

Since the used FWI is acoustic, surface waves need to be removed; a process that is performed with wavelet packets-based denoising (Woog, et. al., 2005). The denoising parametrization is designed to avoid attenuation of refracted, diving waves and remove only surface waves.

From previous VSP studies in the area, VTI anisotropy appears to be minimal in this area. An offset VSP was acquired for offsets 0 to 8000 feet as shown in Figure 2. The downgoing P-waves are picked to analyze vertical transverse isotropy (VTI). The picked events are shown in red color, and the calculated events from a computed isotropic model are shown in blue. The blue and the red picks overlap each other indicating a negligible VTI. Therefore, acoustic anisotropic FWI needs not be considered for this study.

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The initial velocity model is derived using first arrival tomography. Following the surface wave denoising, low frequency band-pass filtering is applied to generate the input data for a frequency-based FWI. However, it is clear that due to the field production noise (Figure 3), the waveforms are distorted and therefore it is impossible to apply frequency based FWI. Instead of a frequency based FWI, we apply a time domain based FWI, using shot gathers bandpass filtered with a 0-2-22-24 Hz filter. Because of the near offset concentration of the residual surface wave energy, a range from 2000 to 15000 feet offset is selected after several forward modeling parameterizations. Early arrival muting is applied so that only refracted and diving waves are used, not reflected events. The starting interval velocity model is the non-linear tomography result. The wavelet employed for the FWI is a 11Hz Ricker wavelet. The model depth range was -3220 feet to +65 feet below mean sea level. Scaling is applied to the synthetic gathers to match the denoised bandpass filtered shot gathers only once before the FWI production run. The FWI finite difference modeling is then computed from topography. Results of raw (black) and modeled gathers (red) are shown in Figure 4.

As stated in the introduction, this study was undertaken without the availability and use of any well information. The results of this FWI study are compared to the well logs in Figure 5. The FWI results agree very closely with the shallow sonic logs. In particular, the velocity inversion zones are delineated very clearly with the FWI and match the well logs.

The denoised CDP gathers after zero phase corrections and the final velocity model from FWI are then input to a Kirchhoff PSDM. The Kirchhoff PSDM is run from the land topography and uses a 6,000 feet aperture and a maximum dip of 50 degrees. The results of the PSDM are compared to the gamma ray logs and Yates top in Figure 6. The Yates reflector is in agreement with the tops, indicating anew that the vertical transverse isotropy is negligible in this area. In Figure 7 the correlation to the well log synthetic seismogram is very high, with no stretching or squeezing applied. Compared with the original time migration result on the right in Figure 7, the PSDM image derived using this flow reveals mappable shallow reflectors.

Conclusion

Isotropic acoustic 3D FWI is successfully employed in a non-conventional reservoir in the South Midland Basin, without the availability of any well log information. The FWI results closely match the shallow sonic logs. Furthermore, the result of the PSDM with the FWI velocity model provides both a strong match with the known stratigraphic markers within the 3D survey area and a high correlation with the well log synthetic seismogram.

Acknowledgement

We would like to thank Pioneer Natural Resources for permission to present this paper and Tom Chambers for helpful discussions on the shallow geology in this area.

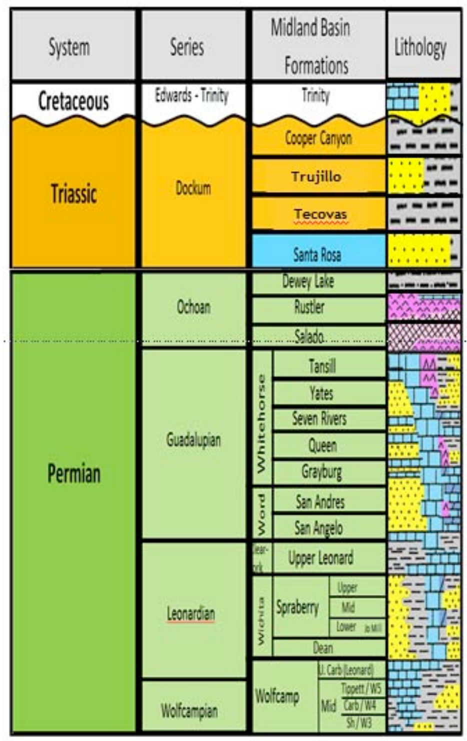

Figure 1. Stratigraphic chart of the shallow geology of the Midland Basin.

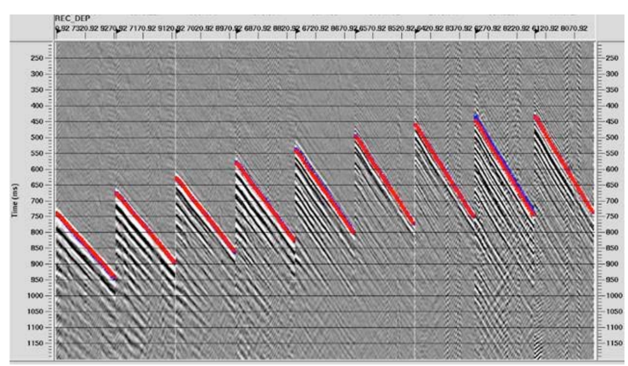

Figure 2. Minimal traveltime difference between the modeled isotropic downgoing traveltimes (blue) and the picked traveltimes (red) on this offset VSP indicates little VTI is present in this area.

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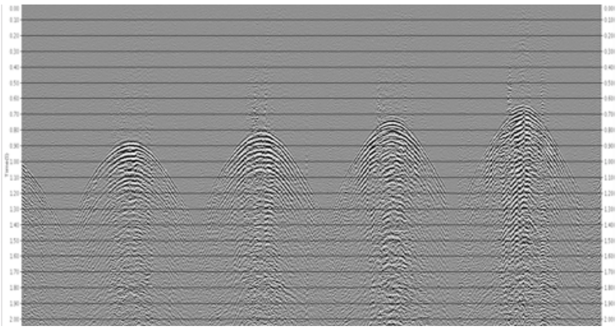

Figure 3. Raw shot gathers.

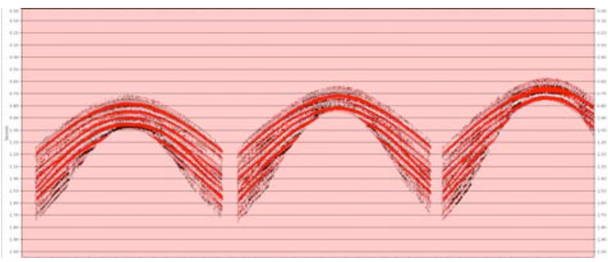

Figure 4. Overlay of the real muted shot record (black) with the FWI modeled shot record (red).

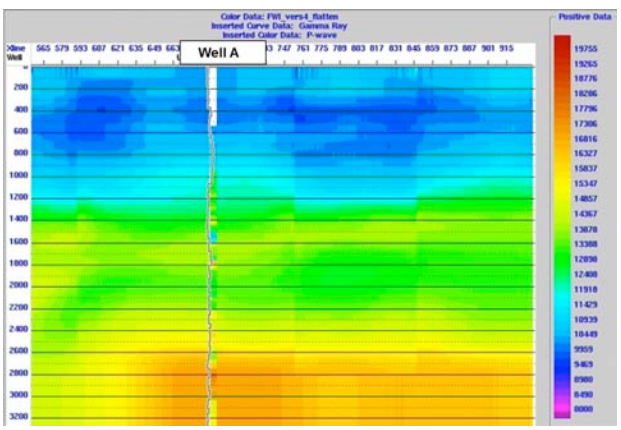

Figure 5. Full waveform inversion agrees with shallow well velocities.

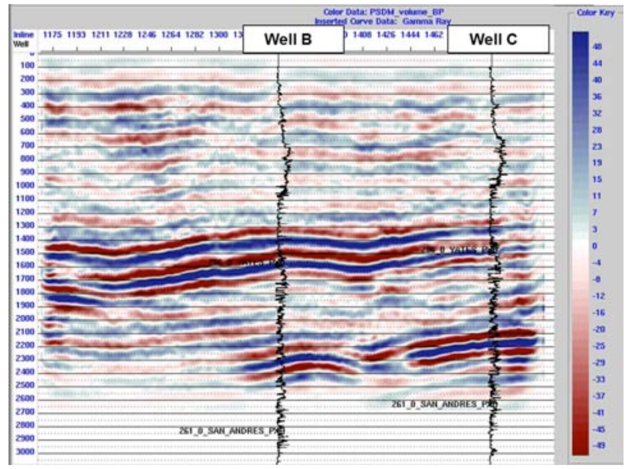

Figure 6. Prestack depth migration using the FWI velocity model resulted in an image that correlates well with Yate tops indicating an accurate depth image.

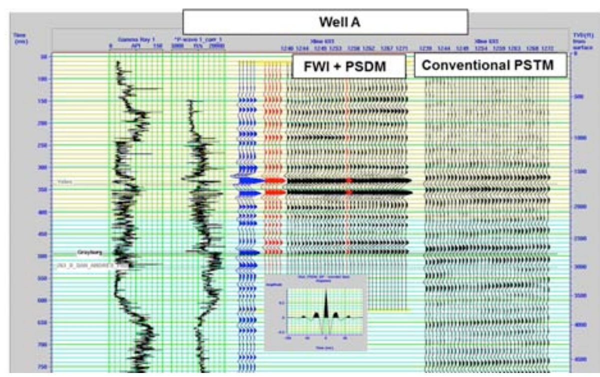

Figure 7. The well log synthetic (blue) has a .75 correlation with the prestack depth migrated seismic.