THE AMERICAN OIL & GAS REPORTER®
JULY 2016
The “Better Business” Publication Serving the Exploration / Drilling / Production Industry

FWI Unravels Near-Surface Velocities

By Anthony A. Vassiliou, Robert A. Meek, Rodney Stromberg and Lionel Woog

HOUSTON–The Spraberry/Wolfcamp play in the Midland Basin holds an estimated resource potential of more than 75 billion barrels of oil equivalent, ranking as the largest oil field in the United States and the second-largest in the world. Pioneer Natural Resources is the largest operator in the Spraberry/Wolfcamp with an inventory of more than 20,000 untapped horizontal drilling locations.

Over the past five years, Pioneer has transformed its Spraberry/Wolfcamp acreage into a world-class horizontal resource play, successfully developing highly prospective stacked intervals within its 785,000-acre lease position in the Midland sub-basin of the greater Permian Basin, which spans some 20 West Texas counties.

Pioneer’s drilling program targets multiple, oil-rich intervals using advanced horizontal drilling and hydraulic fracturing techniques for optimal well performance and capital efficiency. The Wolfcamp B has been the company’s primary target in both its northern and southern areas, but to date, Pioneer has successfully appraised six productive intervals within its Spraberry/Wolfcamp leasehold: the Wolfcamp A, B and D shale intervals, the Lower and Middle Spraberry intervals, and the Jo Mill. The Lower Spraberry is estimated to have the most oil in place of all the Midland Basin intervals.

While the subsurface depths of these reservoir intervals range from 6,700 to 11,300 feet, the success of seismic imaging at reservoir depth in the Spraberry/Wolfcamp play is highly dependent on detailed imaging of the near-surface. Consequently, Pioneer undertook a study in the southern part of the Midland Basin to apply state-of-the-art 3-D acoustic full-waveform inversion (FWI) to create a detailed velocity model of the near-surface using a wide-azimuth 3-D dataset acquired over the study area.

Alternating Velocities

Shallow sonic logs indicate that the near-surface consists of alternating layers of significantly slow and fast velocities. However, a refraction statics model could not delineate the slower velocities in the Midland Basin study area. Therefore, the FWI-derived velocity model was used as the input model in the prestack depth migration to delineate the near-surface geology and subtle image reflections, including the shallow Santa Rosa formation.

Located at depths between 800 and 1,200 feet, the Santa Rosa is a brackish-water-bearing sandstone and conglomerate within the lower section of the Tertiary-aged Dockum group. Hydrologically separated from shallow freshwater aquifers located at 300-600 feet, the brackish water from Santa Rosa fluvial sandstone has become a primary source of water used to perform hydraulic fracturing stimulations in area wells after it is treated to remove sulfates and reduce its salinity.

The Santa Rosa is difficult to map on seismic. However, the operator recognized that successfully delineating the sandstone would not only allow more productive

FIGURE 1

Differences between Modeled Isotropic Down-Going (Blue) And Picked (Red) Travel Times on Offset VSP

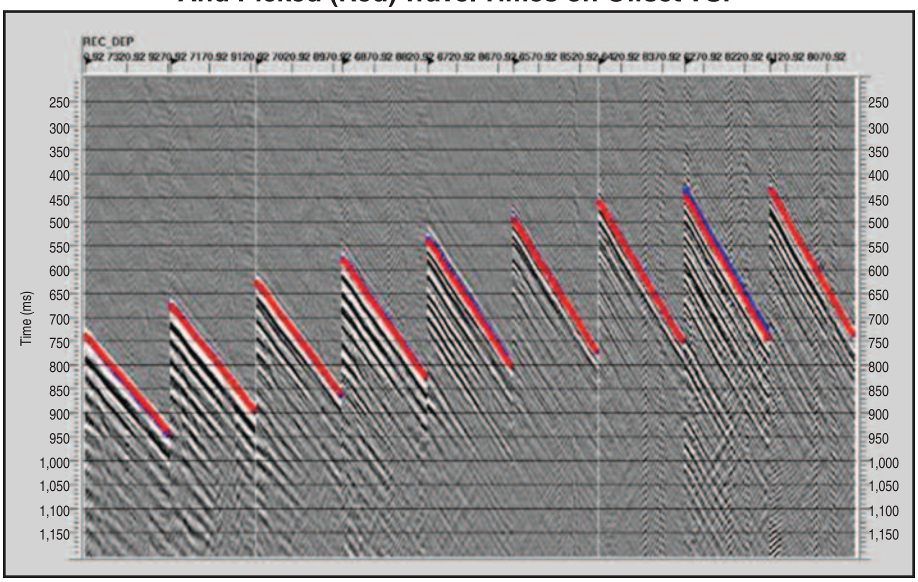
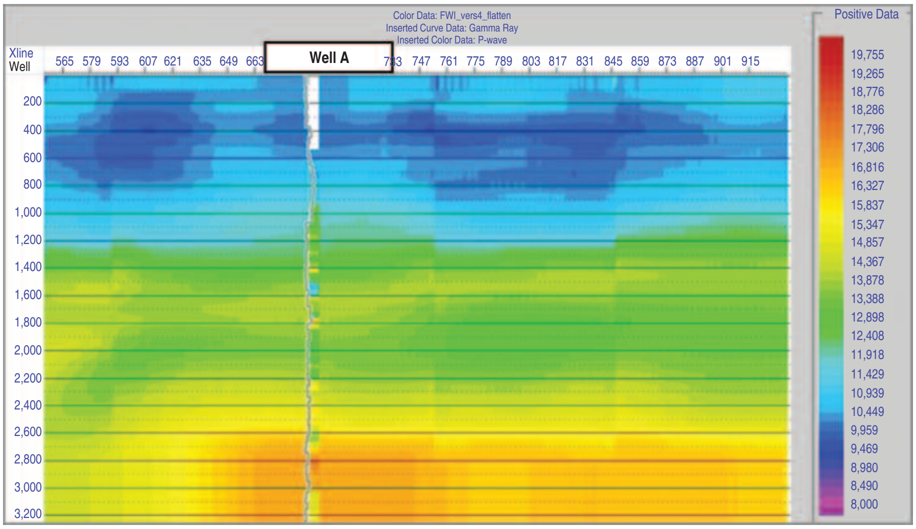


FIGURE 2

Full-Waveform Inversion and Shallow Well Velocities



shallow velocity models necessary to properly image the deeper Spraberry/Wolfcamp horizontal targets.

The 3-D seismic data used in the study are a subset of a larger wide-azimuth survey. The dataset includes 4,892 vibroseis shots and 4,245 channels, and was acquired with maximum offsets of 18,000 feet. The seismic bandwidth is 3-95 hertz, and the common depth point (CDP) bin spacing is 82.5 feet.

After the raw field shot gathers were geometry-checked, a spherical divergence correction was applied with a picked brute velocity. The first-arrival travel times were picked on the dataset and subsequently inverted with nonlinear tomography from topography. The resulting tomography travel time root mean square error was 14.5 milliseconds.

After the travel time tomography, five main steps were performed to apply:

- Tomostatics;
- Minimum phase conversion;
- Surface-consistent deconvolution with a 180-millisecond operator and a 24-millisecond gap;
- Three passes of velocity analysis at 0.5- x 0.5-mile spacing; and
- Surface-consistent scaling.

Since the full-waveform inversion could not estimate velocities in the presence of residual reflection statics, the computed residual reflection statics were applied to the shot gathers prior to FWI.

The FWI technique applied in the Midland Basin is acoustic, so surface waves had to be removed. This consisted

water wells to be drilled, but the improved shallow seismic response also would allow the velocity model to be used as input into the prestack depth migration to more accurately map the underlying Spraberry/Wolfcamp formations.

To accomplish this, near-surface complexity and velocity inversions required advanced wave equation-based methods to estimate near-surface velocities. Full-waveform inversion is a relatively recent development in oil and gas geophysics technology, and has been applied mostly to marine 3-D seismic data. In fact, there have been very few studies published on using full-waveform inversion on 3-D land datasets, and to the best of our knowledge, Pioneer's study was the first application of acoustic 3-D waveform inversion to an unconventional producing reservoir in the Midland Basin.

It is important to note that the project achieved these objectives without using any well information. The study also demonstrated that the full-waveform methodology used for 3-D marine seismic datasets is not applicable to the land 3-D seismic dataset used in this study.

Acoustic FWI Technique

The Permian Basin's shallow geology consists of Quaternary alluvial and aeolian deposits overlying the high-velocity Cretaceous Edwards Limestone. Below the limestone are low-velocity Cretaceous Trinity sands; Triassic Copper Canyon, Trujillo and Tecova sands and shales; the Triassic Santa Rosa sandstone; Permian Anhydrites; and Permian-age dolomites in the Grayburg and San Andres formations. 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.

While the brackish Santa Rosa aquifer is used as a water source for hydraulic stimulation, the underlying Guadalupian San Andres Sand often is used as a water disposal aquifer. The ability to accurately delineate the Santa Rosa and San Andres formations is important to accurately placing water-producing and disposal wells, as well as to provide the detailed

FIGURE 3

Prestack Depth Migration using FWI Velocity Model (Correlates with Yates Tops)

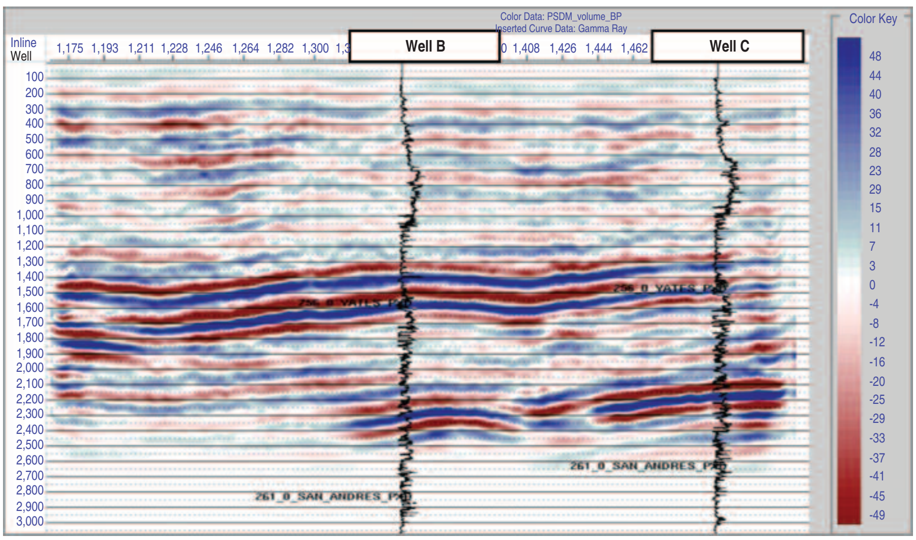
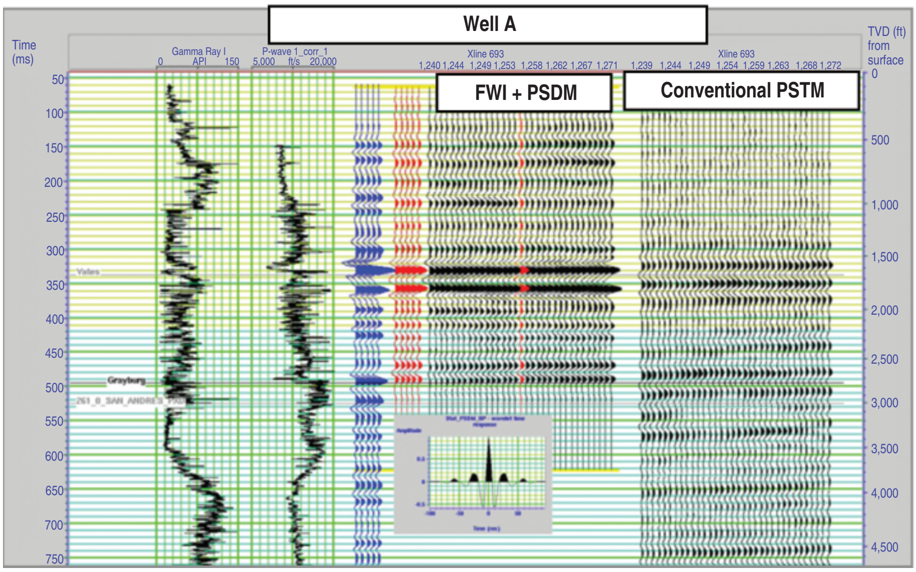


FIGURE 4

Well Log Synthetic (Blue) with 0.75 Correlation With Prestack Depth Migrated Seismic



of a process that was performed with wavelet packets-based "denoising." The denoising parametrization is designed to avoid the attenuation of refracted, diving waves and to remove only surface waves.

From previous vertical seismic profile studies in the area, vertical transverse isotropy (VTI) appeared to be minimal. An offset VSP was acquired for offsets from zero to 8,000 feet.

Study Results

The downward-propagating compressional (P) waves were picked to analyze VTI anisotropy. As shown in Figure 1, the picked events (shown in red) demonstrated minimal travel time difference to the calculated down-going events from the computed isotropic model (shown in blue). In fact, the blue and the red picks overlap, indicating a negligible VTI. Therefore, acoustic anisotropic FWI did not need to be considered for this study.

The initial velocity model was derived using first-arrival tomography. Following the surface wave denoising, low-frequency band-pass filtering was applied to generate the input data for a frequency-based FWI. However, it was clear that the waveforms were being distorted as a result of field production noise. It was, therefore, impossible to apply frequency-based FWI.

Accordingly, instead of frequency-based FWI, the study was conducted using a time domain-based FWI methodology that used shot gathers band-pass-filtered with a 0-2-22-24 hertz filter. Because of the near-offset concentration of the residual surface-wave energy, a range from 2,000 to 15,000 feet offset was selected after several forward-modeling parameterizations.

Early-arrival muting was applied so that only refracted and diving waves were used, and not reflected events. The starting interval velocity model was the nonlinear tomography result. An 11-hertz Ricker zero-phase wavelet was employed for the FWI. The model's depth ranged from -3,220 to +65 feet below mean sea level. Scaling was applied to the synthetic gathers to match the denoised band-pass-filtered shot gathers only once before the FWI production run. The FWI finite difference modeling then was computed from topography.

As noted, this study was undertaken without the availability or use of well information. Figure 2 compares the results of the FWI study with the actual well logs. As can be seen, the FWI results agree very closely with the shallow sonic logs. In particular, the velocity inversion zones are delineated clearly with the FWI and match the well logs.

The denoised CDP gathers after zero-phase corrections and the final velocity model from FWI were input into Kirchhoff prestack depth migration. The Kirchhoff PSDM was run from the land topography and used a 6,000-foot aperture and a maximum dip of 50 degrees. Figure 3 shows the results of the PSDM compared with the gamma ray logs and Yates top. The

ANTHONY A. VASSILIOU *is chief executive officer and president of GeoEnergy Inc. in Houston. He began his career in 1987 as a research geophysicist at Mobil Research & Development Corp., and later served as a senior research geophysicist at Amoco Production Research before founding GeoEnergy in 1998. The company specializes in seismic data processing, full-waveform inversion, seismic imaging, acoustic/elastic wave equation modeling, and denoising. Vassiliou holds a B.S. in geodesy from the National Technical University of Greece, and an M.S. and a Ph.D. in civil engineering from the University of Calgary.*

ROBERT A. MEEK *is a technical specialist in the geophysical technology group at Pioneer Natural Resources in Irving, Tx. His focus is on rock property estimation using prestack inversion, microseismic, and surface seismic data analysis. Meek began his career in 1987 as a geophysicist at Mobil Oil. After serving 10 years at Mobil, he joined Conoco, serving for seven years as a senior research geophysical scientist and geophysical adviser. Meek holds a B.S. in geology from the University of North Dakota and an M.S. in geophysics from Southern Methodist University.*

RODNEY STROMBERG *is a geophysicist at GeoEnergy Inc. Before joining the company, he held various positions and responsibilities with major oil and gas companies as well as service companies supporting exploration, related mostly to seismic data processing. Stromberg holds a B.S. in geological engineering from the University of Utah.*

LIONEL WOOG *is director of software development at GeoEnergy Inc. He joined the company in 2003, after previously serving at Adapted Wave Technologies and Fast Mathematical Algorithms & Hardware Corp. Woog's professional interests are in seismic denoising, depth imaging, and graphical processing unit software development. He holds a B.S. in computer engineering from Rochester Institute of Technology and a Ph.D. in computer science from Yale University.*

Yates reflector is in agreement with the tops, again indicating that the vertical transverse isotropy was negligible in this area.

In Figure 4, 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 4, the PSDM image derived using this workflow revealed mappable shallow reflectors.

As the Midland Basin project illustrates, isotropic acoustic 3-D FWI can be employed successfully in unconventional reservoirs without the availability of well log information. In this application, the FWI results closely matched the shallow sonic logs.

Furthermore, the results of PSDM with the FWI velocity model provided both a strong match with known stratigraphic markers within the 3-D survey area and a high correlation with the well log synthetic seismogram. ❒

Editor's Note: The preceding article was adapted from a technical paper presented at the 2015 Society of Exploration Geophysicists annual meeting, held Oct. 18-23 in New Orleans. For additional information, see SEG paper 5914651.