A case study for detecting thin Upper Morrow fluvial sands in the United States Mid-continent from geostatistical simultaneous AVO inversion
Jeff Zawila, EOG Resources, Inc. Howard Titchmarsh, John Pendrel and Art Valdez, Fugro-Jason, Inc.

Summary

The consolidated rocks comprising the Upper Morrow fluvial sandstones of the Mid-continent are high risk targets due to a lack of acoustic contrast with respect to their adjacent shales. They are, however, very prolific oil and gas reservoirs. In log data, the Upper Morrow sandstones are easily distinguished from other lithologies in cross-plots of P-Impedance vs. S-Impedance, colored by rock properties such as V-shale, effective porosity, Sw and lithology. These elastic log plots imply an AVO effect in the seismic reflection data. The analysis of the field data using a simultaneous AVO inversion algorithm enabled reservoir sands to be highlighted in cross-plot space, thus enabling geobodies of reservoir sand to be captured in inverted 3D volumes. Seventy-eight percent (78%) of the wells that penetrated the geobodies encountered thick Upper Morrow sandstone whereas only seventeen percent (17%) of the wells drilled outside of the geobodies encountered significant sandstone.

Introduction

Upper Morrow fluvial sandstones of the Mid-continent are prolific oil and gas reservoirs, but are traditionally difficult to identify on conventional seismic data. These sandstones have low to no seismic amplitude contrast at vertical incidence with respect to the adjoining shales, thereby making the sandstones indistinguishable from the shales on conventional seismic stacks. Furthermore, bed thicknesses are as small as 20’ to 30’ which is beyond the resolution of typical seismic. Subtle changes in seismic amplitudes image geomorphic shapes that are interpreted as different components within a fluvial environment such as sand/shale point bar fill, channel fill, and abandoned channel fill. These geomorphic shapes help reduce the prospect risk but they cannot determine whether an interpreted point bar complex is sand or shale-filled because they give no indication of absolute reservoir rock property. Petrophysical analysis and interpretation together with robust rock physics modeling of well logs suggests that Upper Morrow sandstones have a distinct elastic response that separates the reservoir sands from other lithologies. These cross-plot observations were valid at both log and seismic resolution, enabling the establishment of a reservoir-defining cross-plot polygon. The separation of rock properties observed in the cross-plots implied a seismic AVO effect and that shear wave information obtained from offset seismic data was essential to distinguish sandstones from shales. Full-stack seismic had no such distinguishing power. Simultaneous AVO inversion algorithms were investigated for their utility in the identification of thick Upper Morrow sandstones. Analyses using both deterministic (best single answer) and geostatistical (sets of possible answers) were completed. The latter had the added advantages of higher resolution and an estimation of uncertainties associated with the rock properties from which probabilities could be calculated. At the well locations, the geostatistical inversion identified reservoir sandstones of around 30’ and accurately predicted a 28’ thick Upper Morrow sand in a blind well. Away from the wells, the inversion indicated bodies as thin as 20’.

Figure 1: Basemap of area of interest. Wells A, B and C were utilized as input controls for seismic inversion. Wells A and B encountered a 20- and 13- foot thick Upper Morrow sand, respectively, while well B encountered thick shale channel fill.

The objectives of the project were to:
1. Confirm and evaluate drilling locations.
2. Reduce the risk associated with drilling wells.
3. Delineate thin sands within the Upper Morrow and identify porosity.
4. Produce high-detail inversion results that image internal bed layering and reservoir compartmentalization.
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5. Produce 3-D distributions of sands and porosity.
6. Qualify the success of the inversion as a predictor of rock properties by incorporating a blind test well.

Methodology

A twenty-three square-mile 3D seismic dataset and three wells, two of which contained dipole sonic logs, comprised the input data (Figure 1). Of the two wells containing dipole logs, one well (Well A) encountered a 20-foot thick Upper Morrow point bar sand while the other well (Well B) encountered thick shale channel fill. The third well (Well C) encountered a 13-foot thick sand.

The project comprised three main phases. The first phase was to determine if the objective of the project could be met with elastic properties established from well logs. The primary objective was to delineate thin sands within the Upper Morrow Formation and identify porosity. Good separation in elastic cross-plot space between Upper Morrow sand and other lithologies was confirmed. When the cross-plots were high-cut filtered to the seismic band, the separation was reduced and it was established that a geostatistical AVO inversion would be required to identify the thinnest of the sands. Petrophysical conditioning of the wire line data removed artifacts created by borehole effects and environmental corrections. Volumetric analysis of mineralogical components together with porosity and fluid fractions were also established prior to rock physics modeling of elastic moduli. Reservoir rock was established with an effective porosity cutoff >= 8% wherever VQuartz >= 60%. Figures 2 and 3 display elastic property cross-plots from the Morrow interval, incorporating data from the three project wells. The Morrow pay sand and quartz sand separate from other Morrow lithologies encountered in the wells.

Simultaneous AVO seismic inversions composed the second phase of the project. Partial-angle stacks of near (2-20 degrees), mid (20-30 degrees), and far (26-36 degrees) traces were created from the seismic gathers. Next, a deterministic simultaneous AVO inversion was computed. This required tying the wells to the partial-angle stacks, generating wavelets and creating a low frequency model from stacking velocities and well logs to calibrate absolute elastic properties. The algorithm incorporates all the input data with exact solutions to the Zoeppritz equations to determine P-Impedance, S-Impedance and density simultaneously at each grid point in time and space (Pendrel et al., 2000). The far angle stack was not at a sufficiently high angle to determine density uniquely. It was therefore constrained to follow the P-Impedance in character. Since the algorithm was ‘blind’ to the well logs in the seismic band, the logs could be used as an effective quality control at the well locations. The deterministic inversion proved to be a good discriminator of the thicker sandstones from shales. However, the deterministic inversion ultimately becomes a biased estimator of thickness for thin sandstones, which require a broader frequency band. The Upper Morrow point bar fill in wells A and B approaches the limits of seismic resolution, hence the need for a more detailed inversion.

Simultaneous AVO seismic inversions as determined by volumetric processing (colored z-axis). Data points are sampled at 60 Hz seismic resolution from the modeled well logs within the zone of interest. Pay sands and quartz sands are captured within a triangular polygon.

The geostatistical inversion algorithm provided high resolution unbiased estimates of sandstone bodies. The algorithm used also incorporated all the features of a non-model-based simultaneous AVO inversion. Similar to all geostatistical simulation techniques, any number of images or realizations can be produced. This algorithm does this by using Bayesian inference to compute sets of probability density functions representing elastic properties and lithofacies. These are then sampled by a Markov Chain Monte Carlo (MCMC) technique. All of the realizations are constrained to be consistent with the input seismic...
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partial-angle stacks. The realizations can be averaged to obtain a robust estimate of reservoir properties and lithotypes or the variation between them can be used to estimate the probabilities of occurrence of lithotypes and elastic properties within any specified range. The input well logs can be used explicitly or held blind for quality control.

The third phase of the project was the interpretation of the outcomes of geostatistical inversion. The idea is to use the sandstone polygons in P-Impedance – S-Impedance space defined from the seismic-band log cross-plots to identify sandstone bodies from the high-resolution inversions. The mean of many realizations from the geostatistical simultaneous AVO inversion was used for this. This is achieved by linking the cross-plot polygons to a three-dimensional volume viewer, a cross-section and map display, and a well log viewer. Areas within the polygon are highlighted in all viewers to enable interpretation and accurate prospect generation as defined by the geobodies.

Results

Figure 4 shows an arbitrary line through the project and compares the full angle stack with the deterministic and geostatistical simultaneous AVO inversions. Clearly, the geostatistical result contains more detail. Figure 5 shows a close-up at the Well A location.

Detail becomes resolution when it is observed to be consistent from realization to realization. Thus, the mean of many realizations is a handy input to interpretation. The deterministic simultaneous inversion resolved bed thicknesses of around 40’ at best, but probably closer to 50’ – 60’. The geostatistical inversion provided an increase in detail between 20’ and 30’, in general.

The mean from 10 geostatistical realizations was selected for interpretation and prospect generation. This was achieved by capturing geobodies in the volumes related to the elastic cross-plot polygons (Figures 2, 3). The geobodies were checked for conformity with prior geologic interpretations. The polygons successfully discriminated Upper Morrow Sands. Figure 6 shows some of the larger bodies plotted in 3D perspective view.

Geobodies captured by the elastic cross-plots were compared to well control to determine the validity of the inversion results and to validate future drilling locations. Twenty-six wells were drilled within the 3D and are displayed in Figure 7. Nine wells were drilled near or inside the captured geobodies with seven wells encountering Upper Morrow sand. Sand thickness ranged between 8 and 41 feet with an average thickness of 28 feet. Three out of seventeen wells drilled outside of the captured geobodies encountered Upper Morrow sand. Sand thickness ranged between 6 and 13 feet with an average of 10 feet. In summary, seventy-eight percent (78%) of the wells drilled in or near captured geobodies encountered thick Upper Morrow sand whereas only seventeen percent (17%) of the wells drilled outside of the captured geobodies encountered thin Upper Morrow sand.
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Conclusions

Simultaneous deterministic and geostatistical AVO inversion results demonstrated that sand/shale separation in the well logs can be successfully extrapolated through body captures of elastic properties. Effective porosity identification was also achieved. The geostatistical inversion results showed a higher level of detail in rock properties than the seismic data or deterministic inversion, precisely resolving pay sand intervals less than 28 ft. in thickness.

Comparing the results of the geobody captures to existing well control demonstrated statistical significance in the successful identification of Upper Morrow sands in the United States Mid-continent area. Seventy-eight percent (78%) of the wells that penetrated the geobody captures encountered thick Upper Morrow sand with an average thickness of 28 feet, whereas only seventeen percent (17%) of the wells drilled outside of the captured geobodies encountered thin sand with an average thickness of only 10 feet. Additionally, three successful wells utilizing geobody captures were drilled since project completion and encountered thick Upper Morrow sand.

Acknowledgements

The authors wish to thank EOG Resources, Inc. for permission to publish this data. Assistance from the co-author colleagues at Fugro-Jason, Inc. is gratefully acknowledged.