Simultaneous Inversion of the Ladybug prospect and derivation of a lithotype volume

Jim Fowler and Mark Bogaards, Jason Geosystems; Gale Jenkins, Texaco Worldwide Exploration and Production, Inc.*

Summary

Two offset angle seismic stacks from the Ladybug prospect (offshore Gulf of Mexico) have been inverted with a new Simultaneous Inversion algorithm, ultimately converting the seismic amplitudes into rock property models of lithotype (lithology and fluid) and porosity. To assess its effectiveness, the results of this inversion and analysis workflow were compared to those of traditional AVO analysis tools. It was determined that the Simultaneous Inversion methodology extracts a more dynamic range of information from offset seismic stacks, and results in an improved response to reservoir identification and mapping over that of traditional seismic AVO analysis.

The Simultaneous Inversion generated three new volumes: acoustic impedance (Zp), shear impedance (Zs), and estimated density (ρ). These data sets then underwent further interpretive analysis of lithology and porosity to identify prospective hydrocarbon zones within the target layers.

Introduction

The full Simultaneous Inversion workflow transforms seismic data to rock property models of lithotype (lithology and fluid) and porosity. The input data necessary for Simultaneous Inversion itself are multiple angle-stack seismic data sets. As initial products of the inversion, acoustic and shear impedance and density volumes are generated. These volumes may be used for direct estimation of other elastic rock properties, such as lithotype identification (based on rock type and pore fluid content) and the Lamé parameters lambda-rho and mu-rho.

The Simultaneous Inversion methodology was applied to the Ladybug prospect, Garden Banks Block 409, offshore Gulf of Mexico. This 1997 discovery is approximately 135 miles southwest of New Orleans in about 1600 ft of water. The prospective interval consists of Pleistocene (Yarmouth) age clastics filling a salt-withdrawal basin. Well control consists of the Texaco #1 discovery well and the Texaco #2 and #3 delineation wells. The oil and gas accumulation is on the margin of the basin, and there is no well control in the basin proper. The hydrocarbon-bearing sands focused on for this study are approximately 200 ms (500 ft) thick and found at a depth of 6000 ft subsea.

This study's objective was to determine the extent, geometry and fluid content of these sands as they extend into the basin, and therefore to better understand the reservoir volumes, geometry and connectivity. To that end, two angle stack seismic data sets were inverted with the new Simultaneous Constrained Sparse Spike Inversion (S-CSSI) algorithm, and the output data sets were examined with a variety of qualitative and quantitative analysis tools. The results of this analysis were compared to those of a more traditional AVO workflow, primarily gradient and intercept plots and cross plots. The conclusion of the authors is that the impedance volumes reveal a more dynamic range of diagnostic information, including lithology and fluid content, than can be determined with traditional seismic AVO analysis alone.

Data

Shear and compressional velocity logs and density logs are necessary for as many wells as possible over the window of interest to ensure a reliable appraisal of AVO behavior and to generate a stable estimate of the wavelets corresponding to each input stack. For this project, a shear log was available only for a small interval around the target reservoir for only one of the three project wells. To address this data limitation, the existing s-sonic, p-sonic and density logs were edited, conditioned and processed for velocity synthesis and fluid substitution with a rock physics analysis and modeling tool. This tool generates an elastic rock properties model, updates it to optimize the fit with measured data, and then applies it to produce synthesized p- and s-sonic logs over the full time window of interest, for all the project wells.

A good quality 60 fold 3D seismic data set was used for this project. The data has been prestack migrated (20 offset bins), with angle stacks of zero to 18 degrees and 19 to 35 degrees. The offsets available range from 123 to 19,803 ft and provide a suitable range of angle information at the target interval. A 3D seismic-derived velocity field was also used to calibrate the inversion velocity model.

Prior to inversion, the multiple seismic volumes were vertically aligned with a trace-by-trace stretch and squeeze algorithm, to correct for residual NMO and other processing artifacts. Minor phase differentials were accounted for in the wavelet estimation and inversion.

Method

An elastic impedance (EI) curve as a function of offset angle θ is computed for each well. This log is derived with an Aki-Richards algorithm which analyzes the p-impedance (density divided by p-sonic) and s-impedance (density divided by s-sonic) logs with respect to θ (Connolly, 1999). With these synthetic EI logs, a wavelet is estimated for each seismic data set. These wavelets match the phase, amplitude and frequency content of their respective offset data set. The offset volumes are then inverted with a Simultaneous Constrained Sparse Spike Inversion (S-CSSI) algorithm. This algorithm is an extension of the zero-offset CSSI method, in which a single volume of stacked seismic is inverted into a normal incident acoustic impedance (AI) data set (Pendrel and van Riel, 1997). This conversion is accomplished through minimization of a core objective function involving the L-1 sparsity norm of the reflection coefficients and the seismic-to-synthetic misfit. For this study, the CSSI algorithm is modified to simultaneously invert multiple seismic data sets with different angle ranges, where the objective function now involves angle dependent reflection coefficients and data fit to all input stacks.

The S-CSSI algorithm generates broadband elastic parameter results. In the inversion the low frequency component may be stabilized with a background model, typically derived from well logs or seismic velocity control. Experience with the S-CSSI algorithm shows that the density component is generally poorly resolved from the input seismic data. To alleviate this instability, the Gardner equation is invoked as a soft constraint to the algorithm, and the output density volume is calibrated to well control. Additionally, the Mudrock relationship may be applied to stabilize the inversion further, but this relationship is generally not required.

The inversion achieves several key results with respect to subsequent interpretation. First, through the wavelet estimation procedure, the inverted data sets are amplitude calibrated to the available well control. Second, the inversion is generally very successful in reducing tuning and the offset dependence of tuning. The inverted volumes may thus be used for quantitative interpretation with significantly increased accuracy and resolution than achieved from interpreting seismic data. A further key advantage is that the inversion products are layer based rock property cubes rather than seismic reflection cubes. Because of this, interpretation of the inverted volumes can be readily guided by the direct link to well control.

The fact that the data sets are well log calibrated, layer based rock property volumes leads to the application of a very powerful, highly automated volume-based interpretation methodology. This procedure starts with a well log analysis of the elastic and other petrophysical logs to determine how lithologies, fluid types and porosity ranges are discriminated from each other in the Zp-Zs domain. The effectiveness of such an approach is enhanced by including the results of fluid substitution modeling. The methodology itself is typically achieved through crossplot analysis where zones of interest are examined. The relationships established through the well logs then are carried over to the 3D volumes to automatically find all points in space meeting the well log derived criteria, thus calibrating the seismic derived rock property cubes to well control. Subsequently, and automatically, the spatial points are analyzed for connectivity to generate geobodies of connected points. These geobodies can be viewed in 3D to gain an understanding of their geometry and extent, and how they relate to the depositional and structural environment. Because the "body checking" procedure is automatic, different scenarios and sensitivity are readily tested. As a final step, the geobodies can be "wrapped" with horizons, automatically generating top, base and thickness maps of the bodies. As this workflow is highly automated, it greatly improves interpretation accuracy and productivity, and valuable interpretation efforts can now focused on analyzing log and spatial relationships.

To further enhance this interpretive process, the results of studies by Goodway et al. (1997), Dufour et al. (1998), and Pendrel et al. (1999) are utilized. Their works show that in many cases Lamé parameters can more readily discriminate lithology and fluids. For the Ladybug study, the output acoustic and shear impedance and density volumes are used to compute two Lamé Parameter data sets, based on the following relationships:

$$\text{lambda-rho} = Zp^2 - 2\cdot Zs^2$$
$$\text{mu-rho} = Zs^2$$

where Zp = acoustic (compressional) impedance and Zs = shear (elastic) impedance.

Lambda-rho is a pore fluid indicator with low values indicative of hydrocarbons, and mu-rho is a lithology indicator with high values indicative of sands. After generating the Lamé parameters, the above described volume interpretation procedure is again applied. Spatially corresponding samples from each Lamé volume are cross plotted, and those samples which exhibit the desired lambda-rho to mu-rho relationship (low lambda-rho, high mu-rho) are detected and mapped, discriminating prospective pay sands within the target layers. These Lamé cross plots are found to be more discrete in isolating pay sands than are similar Zp vs. Zs cross plots. The pay-prospect samples then are isolated with the geobody connectivity tool, allowing the potential reservoir sand bodies to be mapped and quantified.

These predicted geobodies are measured against known production zones at well control, and the workflow utilized in this study, where Simultaneous Inversion is combined with volume based interpretation, is found to be highly accurate in predicting these zones. There is a high degree of confidence in this methodology's ability to predict similar productive zones in regions of the target basin not constrained by well control.

As a final step, a new lithotype volume consisting of lithology and fluid information is generated, based on relationships between the Zp, Zs and density volumes derived in the Simultaneous Inversion and rock moduli derived with the rock physics tool. To do this, characteristic Zp, Zs, density, gamma ray and porosity relationships are established for a number of lithotypes (shale, wet sand, gas sand, etc.). Similar relationships between porosity and bulk and shear moduli are also established. From these relationships the likelihood of each lithotype occurring at a given sample is measured, with the most likely candidate being assigned as the predicted lithotype. In a like manner, the highest probability porosity is calculated. The rock property output volumes from Simultaneous Inversion are analyzed sample by sample using this statistical classification approach, and a full lithotype volume incorporating rock type, porosity and fluid fill is generated to further enhance the reservoir description.

Conclusions

The Simultaneous Inversion of two offset seismic data sets has produced a succession of 3D rock property volumes. They allow for an analysis of the Ladybug reservoir system with a greater degree of resolution and response than is available from traditional seismic based AVO analysis. The inversion results are in the layer domain, are calibrated to well control and (offset dependent) tuning is greatly reduced. The primary output volumes, compressional and shear impedance and estimated density, are used to derive Lamé parameter volumes (lambda-rho and mu-rho) which are diagnostic of both rock matrix and fluid fill. These output cubes are interpreted with a highly efficient volume interpretation and connectivity analysis tool. As a final interpretation step, a rock physics model driven statistical classification procedure is applied. This results in spatial cubes where each point is assigned the highest probability lithotype and corresponding porosity. These results support enhanced geobody capturing, mapping and volumetric analysis of potential hydrocarbon reservoirs.

References

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