Prestack waveform inversion: an onshore application in the US Gulf Coast

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Summary

Onshore exploration depends mostly on imaging to define structure and stratigraphy. The amplitude from stack cube or AVO response are used qualitatively to gauge fluid content. In this onshore case study, we have well control as well as proposed locations. The prestack waveform inversion was performed after our initial campaign of drilling so new well information could be incorporated in the model. The goal of the inversion is to help in evaluating whether to participate in a well or not. The inversion result gives us extra information to make such decision.

Prestack waveform inversion techology has seen a rather limited application over the last 20 years in the seismic industry. A few applications of prestack waveform inversion have been reported in the past few years (Mallick 1999, Roy, et. al 2004, Lau et al, 2005). The main reason for the limited application was the lack of robustness of the prestack waveform inversion and the computational inefficiency of the numerical optimization employed. This case study demonstrates the accuracy of the methodology by virtue of elastic parameter prediction ahead of the well drilling and its computational efficiency in terms of turn around time.

Introduction

There are several advantages of the prestack waveform inversion as compared to widely applied angle stack inversion methods. First, prestack waveform inversion is applied directly on prestack migrated gathers with NMO correction removed, therefore honoring all offset and seismic amplitude, phase information. Second, assuming long acquisition cable length prestack waveform inversion estimates directly compression velocity, shear wave velocity and density, which is not possible in angle stack inversion methods. Finally, prestack waveform inversion can work with either only primary reflections or with both primary and interbed multiple reflections

Recently there have been several advances in prestack waveform inversion, in particular in the area of the regularization part of the optimization which is absolutely critical in obtaining geologically meaningful results.

Prestack waveform inversion method

The prestack waveform inversion can be broadly subdivided into two parts, first the modeling and second the optimization. We apply the method on prestack time migrated gathers which have been denoised and conditioned prior to the NMO correction removal. We assume a local 1D earth model and we use the reflectivity method of Kennett (1983) for forward modeling. The Kennet reflectivity method generates upgoing and downgoing reflection matrices which deal with the primary reflection, multiple reflection and seismic transmission effects. For the Frechet derivative computation we employ a method similar to Randall (1989), in which perturbations in the elastic parameters of the 1-D earth model generate partial upward and downward reflection matrices which are then combined through finite differences to generate the Frechet derivative seismograms.

The numerical optimization is done through the minimization of an objective function which combines both the raw data misfit and the elastic model parameter norm as follows

$$E(\mathbf{m},\alpha)=(\mathbf{d}-\mathbf{g}(\mathbf{m}))^T\mathbf{C_d}^{-1}(\mathbf{d}-\mathbf{g}(\mathbf{m}))+\alpha(\mathbf{m}-\mathbf{m}_0)^T\mathbf{C_m}^{-1}(\mathbf{m}-\mathbf{m}_0)\quad(1)$$

where in the above equation (1) $\mathbf{d}$ is the data vector, $\mathbf{m}$ is the model vector, $\mathbf{g}$ relates the data vector to the model vector, $\mathbf{m}_o$ is the starting model, α is the regularization parameter and $\mathbf{C_d}$, $\mathbf{C_m}$ are the covariance matrices for the seismic data and the model. We employ a modified Gauss-Newton method for the minimization of the objective function in (1). Due to the starting elastic parameter model being very smooth we choose to terminate the iterative model update search which leads to additional regularization and computational speed in the method (Hanke, 1997). Finally for the computation of the regularization parameter we employ a variation of the discrepancy principle by Mozorov as it was modified by Engl (1987). The Engl discrepancy principle after further modifications has also been applied by Roy at al. (2004).

Application of the prestack waveform inversion method

The prestack waveform inversion method was applied to a 3-D seismic data set in the Gulf Coast of United States. The input data set consisted of a set of prestack time migrated gathers tied to well log synthetics , the well log suite for a vertical well, a seismic wavelet estimate and the prestack migration velocity field. The prestack waveform inversion was done in the following steps:

First, the prestack time migrated gathers were denoised and were subsequently the NMO correction was removed. Second, the 3-D seismic data were scaled by matching the maximum amplitude of the CDP gather in the well log location to the maximum amplitude of the well-log synthetic seismogram and deriving a scalar factor, which was subsequently applied to the 3-D seismic data. Third, the starting Vp model was the migration velocity model; the starting model Vs was derived from the Greenberg/Castagna model (1992) and the starting bulk density model was a constant equal to 2.3 gm/cm^3. Fourth, we use the set previously derived starting Vp, Vs, Rho models for the iterative prestack waveform inversion on the well location. A few parameters were set such as the seismic bandwidth for the 1-D forward modeling, the number of iterations, wavelet shift. Fifth, after the inversion parameters are set for the well location we use the same parameters to start the inversion for the complete 3-D survey. Finally after 30 iterations of the prestack waveform inversion the final Vp, Vs, Rho, minimum and maximum Vp, Vs, Rho values and modeled gathers were generated.

Interpretation

After the prestack inversion was complete, the three volumes were loaded to further calibrate to well control. A well proposal from a partner to drill a location with both structural and amplitude support was studied. The P and S impedances indicated that the proposed location had sand but not fluid. Post-drill result confirmed the prestack inversion result.

Conclusion

We have used prestack inversion as a very useful piece of information. This was compared with what we knew about the setting based on geophysics, geology and reservoir engineering. In doing so, we were able to be more definitive in our decision making process of whether we should participate in a drilling location or not. Prestack inversion is not a silver bullet. It has to be interpreted in light of the existing well control, geologic framework and reservoir performance in analog wells.

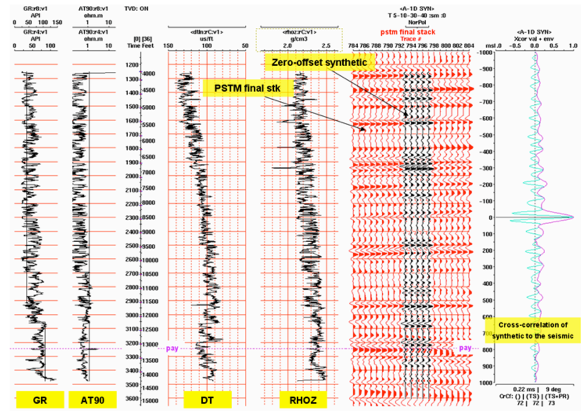

Figure 1. Well-to-seismic tie: zero-offset synthetic and PSTM final stack. Displayed panels are (L to R): gamma-ray log, resistivity log, sonic log, bulk density log, full-stack overlaid with zero-offset synthetic, cross-correlation of the synthetic to surface seismic.

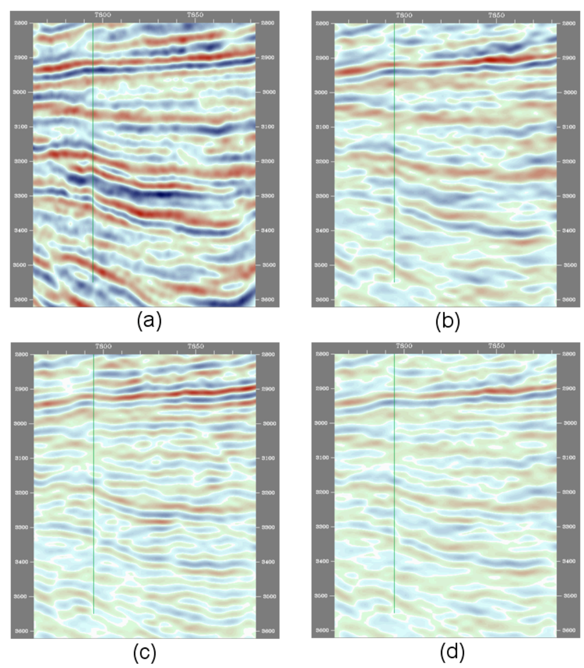

Figure 2. Pre-stack inversion results. (a) PSTM final stack; (b) P-impedance differentiated with respect to two-way time; (c) S-impedance differentiated with respect to two-way time; (d) bulk-density differentiated with respect to two-way time.