Seismic waveform inversion at the reservoir scale- current state of the art and the future directions

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Summary

Waveform inversion of single component seismic data under an isotropic assumption has been proved to be an effective tool for reservoir characterization. With the recent interests in exploring and exploiting the naturally fractured and unconventional hydrocarbon reservoirs, an understanding of the subsurface azimuthal anisotropy has become crucial and attempts have been made in developing methodologies for estimating the subsurface anisotropic properties from single and multicomponent pre-stack seismic waveform data. These isotropic and anisotropic waveform inversions are computationally challenging and require careful implementation of the inversion algorithm in a high-performance parallel computing environment. While these inversions could be applicable to real seismic data at the reservoir scale over geologically simple areas by assuming a locally one-dimensional (1D) structure at each common mid/conversion point (CMP/CCP) location, extending such methodology to complex three dimensional (3D) structures offer new sets of computational challenges. This paper reviews the current developments in the isotropic and anisotropic waveform inversion methods under 1D assumptions and outlines a practical approach of extending such methodology to complex 3D structures as the future of reservoir characterization.

Introduction

Amplitude-variation-with-offset (AVO) inversion is the current state-of-the-art that is routinely practiced by the oil and gas industry for reservoir characterization. Although quite successful, the assumptions behind AVO are strictly valid at relatively small (less than 30°) incidence angles (Mallick, 2007). Geophysics community is well aware of this limitation and AVO interpretation is always made in combination with other rock-physics and geological constraints. With recent advances in the acquisition and processing technology allowing the extraction of reliable reflection amplitudes out to large source-to-receiver offsets (incidence angles), and to broad frequency bandwidth, there are now attempts to go beyond the AVO and use wave equation based methods for inversion, which led to the emergence of a new technologies such as the full waveform inversion (FWI) and pre-stack waveform inversion (PWI). All inversions require optimization of an objective, given as the similarity or difference between the observed seismic data and the predicted data. Stating from an initial model of a set of models, they compute the predicted or synthetic data from these models and match with the observed data. These models are then iteratively modified until the match between the observed and predicted data is maximized or the mismatch between them is minimized. While AVO inversions use the AVO equations for computing the synthetic data, FWI and PWI use wave equation based methods to compute them. Although elegant in principle, applying waveform inversions to real seismic data is challenging. They are much more computationally demanding than the AVO and require careful implementation in a parallel computing environment. Keeping such computational challenges in mind, there have been two major trends in the waveform inversion development. One trend, known as the FWI, attempts to solve the full 3D wave equation using an approximate method based on finite differences or finite elements as the forward modeling engine (Pratt, 1999; Liu et al., 2012; Guasch et. al., 2012; Warner et al., 2013, among others). The second approach, known as PWI assumes a 1D structure for each CMP/CCP and uses an analytical approach as the forward modeling engine (Sen and Stoffa, 1991; Stoffa and Sen, 1991; Mallick, 1995, 1999, 2000; Sen and Roy, 2003; Gisolf et al., 2012, 2014; Tetyukhina et al., 2014, Padhi and Mallick, 2014; Li and Mallick 2015a; Mallick and Adhikari, 2015; Pafeng and Mallick, 2015, among others). Because computing 3D forward synthetics using finite-difference or finite-element method is expensive, FWI is yet to be applied at the reservoir scale and it is mostly used in resolving accurate low-frequency velocity fields for the imaging related applications. PWI, on the other hand, although compute-intense, a careful and parallel implementation of the methodology allows estimation of the subsurface properties at the reservoir scale from two-dimensional (2D) and even 3D seismic data.

Here, the application of PWI under isotropic subsurface assumption on real 2D and 3D seismic data is first reviewed and its superiority over AVO based inversion is demonstrated. This is followed by an application of anisotropic PWI on noisy synthetic data and a discussion on how such an anisotropic PWI could be applied to real 2D and 3D seismic data. Next, a 3D forward modeling methodology for fully anisotropic medium is outlined. Finally, a hybrid approach for combining PWI with FWI is proposed as a practical means for the future direction to a 3D seismic waveform inversion at the reservoir scale.

Isotropic PWI

PWI uses an analytical forward modeling based on reflectivity method (Fuchs and Müller, 1971; Kennett, 1983; Fryer and Frazer, 1984; Mallick and Frazer, 1987, 1988, 1990, 1991, among others) as forward modeling engine. Being waveform based, PWI is compute-intense with multiple sets of non-unique solutions. Although it has been successfully applied to both synthetic and real seismic data using a linearized gradient based approach (for example, Sen and Roy, 2003), to avoid convergence to a local optimum such gradient based inversion schemes require an initial model to be sufficiently close to the true model (Mallick, 1995). Consequently, a non-linear inversion such as genetic algorithm (GA) or simulated annealing (SA) is a preferred choice for PWI. It must however be noted GA or SA is much more computationally demanding than a gradient-based approach and they require efficient implementation in a high performance parallel computing architecture. For inverting single component (P-wave) seismic data under isotropic assumptions, Mallick and Adhikari (2015) and Padhi et al. (2015) outlined a multi-level parallelization of GA in which all the processors were subdivided into M sets with N processors in each set (i.e., $M \times N$ is the total number of available processors). Each set then simultaneously inverts data from M different locations using N processors in each location. Such a multilevel parallelization scheme is capable of efficient handling of 2D (Mallick and Adhikari, 2015; Padhi et al., 2015) and even 3D (Pafeng and Mallick, 2015) seismic data. Figure 1 is the comparison of the Poisson's ratio estimated from AVO inversion with that from PWI on a real seismic data from the Rock-Springs uplift (RSU), Wyoming, USA. A 2D line from the RSU 3D seismic data was extracted, and the Poisson's ratio estimated from both inversion methods on this extracted 2D line is shown in Figure 1. In addition, formation tops of some key lithologies interpreted from the well data are also identified and marked on Figure 1.

Superiority of PWI over AVO inversion is clearly evident in Figure 1. The formation boundaries are much clearly identifiable on the PWI than the AVO (compare Figures 1a and 1b). The striping patterns on the right and the wavy patterns on the left of the AVO inversion result are caused from an incorrect low-frequency model and are not consistent with the RSU geology. These artifacts are completely absent on the PWI. Overall, PWI is much superior to AVO not only in identifying different formation boundaries but also in estimating a model that is geologically consistent.

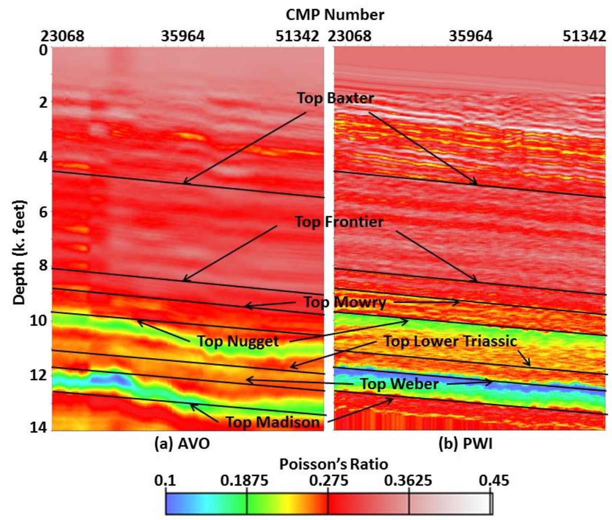

Figure 1: Comparison of the estimated Poisson's ratio from (a) AVO inversion and (b) PWI. Some of the formation tops, interpreted from the RSU-1 well data and RSU geology are also marked.

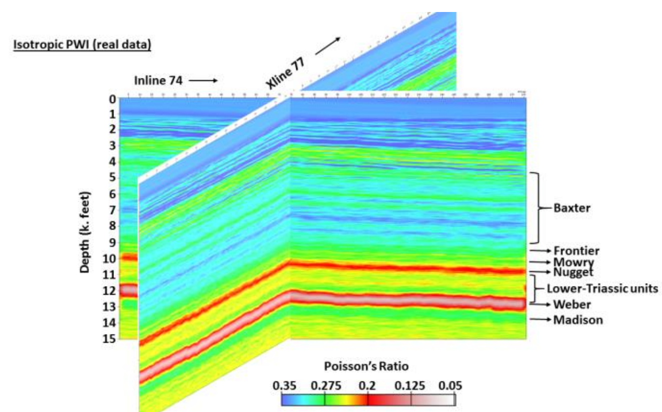

Figure 2: Example of 3D PWI applied to RSU 3D seismic data with interpreted formation tops. Notice the difference in the color scale between Figure 1 and 2.

The 2D inversion shown in Figure 1 has been further extended to the RSU 3D data by Pafeng and Mallick

(2015), shown in Figure 2. Notice that the 3D PWI also provides a very good result.

Anisotropic PWI

With recent interests in exploring and exploiting the naturally fractured and unconventional hydrocarbon reservoirs, estimation of subsurface anisotropy is important because they allow estimating the directions of the existing permeable fractures or the directions along which they are likely to occur during hydraulic fracturing (Zoback, 2010). While isotropic PWI is complex, it is even more complex when it is extended for anisotropy. Because anisotropy is better detected from multicomponent seismic data than the single component (P-wave) data (Thomsen, 1988; Stewart et al, 2002, among others), a multicomponent PWI is necessary for accurate estimation of anisotropy. Such multicomponent seismic inversion require optimization of multiple objectives, one for each data component. Such multi-objective optimizations are in principle are non-unique with multiple sets of solutions, known as the Pareto-optimal solutions.

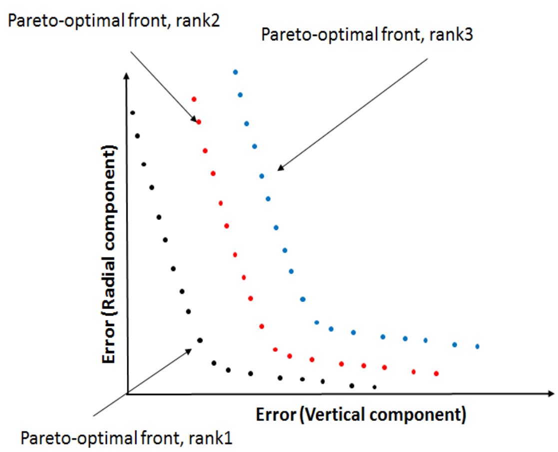

Figure 3: Demonstration of the Pareto-optimal set of solutions.

To demonstrate the concept of Pareto-optimality, consider inversion of two component (vertical and horizontal radial) seismic data. Also consider that the inversion is cast as a minimization problem, i.e., the mismatch or the error between observed and predicted data are minimized. For inversion of two component data, there are two objectives, (1) the error of the vertical component and (2) the error of the horizontal (radial) component. Now, consider plotting solutions for all models generated in course of the inversion in the objective space as shown by Figure 3. Note that the solutions shown as black dots equally satisfy both objectives because none of them could be considered better than the other in terms of satisfying both objectives. The set of solutions shown respectively as red and blue dots in Figure 3 behave in a similar fashion but the red solutions are not better than the black solutions but they are better than the blue solutions. In multi-objective optimization, these different sets of solutions belong to different Pareto-optimal sets. In the objective space, they each form a front which are called the Pareto-optimal fronts. The best set of solutions, shown as black dots in Figure 3 is the Pareto-optimal front of rank 1, the next best set, shown as red rots in Figure 3 is the Pareto-optimal front of rank 2 and so on.
For inverting multicomponent seismic data, typically a single objective is defined as a weighted sum of the objectives of each component, which is then followed by a single objective optimization (for example, see Mallick, 2000; Chang and McMechan, 2009). Such an approach provides a single solution out of the entire Pareto-optimal set which may be biased by the choice of the weights being used to define the objective. It is thus advisable to treat the entire set of objectives as a vector and simultaneously optimize all its components to estimate the entire Pareto-optimal set. The fast non-dominated sorting genetic algorithm or NSGA II outlined by Deb et al. (2002) is such a multi-objective optimization method.

Padhi and Mallick (2014) used NSGA II to successfully invert multi-component noisy synthetic seismic data for isotropic and transversely isotropic with vertical axis of symmetry (VTI) subsurface properties. Li and Mallick (2015a) parallelized NSGA II and successfully inverted three component noisy synthetic data along two azimuths (i.e., for a total number of six objectives) for estimating the subsurface anisotropic properties up to a complexity of an orthorhombic (ORT) symmetry. Figures 4 and 5 show the anisotropic PWI result of Li and Mallick (2015a). Note that all nine anisotropic parameters, density, and the direction of the anisotropic symmetry axis are accurately estimated from the inversion. In addition, the maximum likelihood estimates, shown in cyan background color in Figures 4 and 5 provide an estimate of the uncertainty associated with the estimation of each parameter.

Although anisotropic PWI has so far been demonstrated on synthetic data only, in principle the methodology could be easily applied to real data. Because real multicomponent seismic data are not easily available, here the demonstration of the methodology is restricted to synthetic data only. We are in fact trying to identify a real multicomponent seismic data and the results of inverting these data will be shown during the presentation. The primary advantage of the multicomponent PWI, cast as a multi-objective inverse problem is the fact that there are no restrictions to the number of objectives that are inverted. For example, the three-component example shown in Figures 4 and 5 could be easily extended to invert nine component seismic data from three component receiver and sources. In addition, such a multi-objective method could be easily used to jointly invert seismic data with other data such as gravity, magnetic, electromagnetic, etc. into an inversion that is not only multi-objective but also multi-physics.

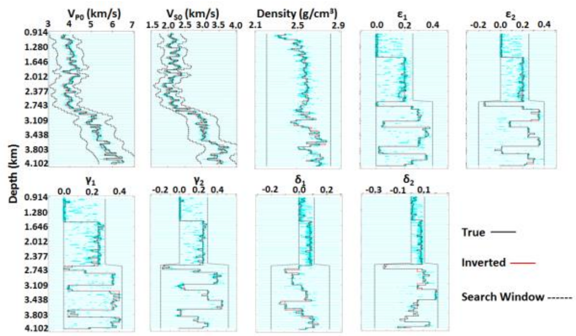

Figure 4: Demonstration of the anisotropic PWI. Estimation of the vertical P- and S-wave velocities (V_{P0}, V_{S0}), density, and the Thomsen-Tsavankin parameters (Thomsen, 1986; Tsavankin, 1997) ε_1, ε_2, γ_1, γ_2, δ_1, and δ_2 are shown.

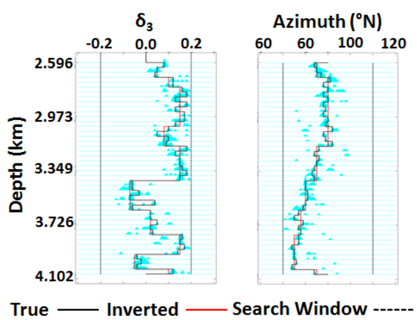

Figure 5: Same as Figure 5 but for the estimation of the Thomsen-Tsavankin parameter δ_3 and the principal anisotropy direction. Because only the lower part of the model was azimuthally anisotropic, these parameters were estimated and shown only for that part.

PWI to FWI- a practical approach

The isotropic and anisotropic PWI examples shown above assume a locally 1-D structure for each CMP/CCP. With this assumption PWI could be applicable to many areas with simple to moderately complex geology after the seismic data are pre-stack time or depth migrated. In the areas where the geology is complex, a local 1D assumption will not be valid and it is required to use a modeling methodology in the inversion that honors 3D structures. While there are many such modeling methods using finite differences or finite elements, most of them are valid for acoustic and/or isotropic elastic subsurface. A fully anisotropic modeling methodology using finite elements have been recently developed by Li and Mallick (2015b). This finite element modeling (FEM) is based on discretizing the model using second order tetrahedral elements in space and Newmark type scheme for time marching. In addition, high-order absorbing boundary conditions using special potential functions is implemented in this modeling methodology. Figure 6 is an example of this modeling method for a five-layer model.

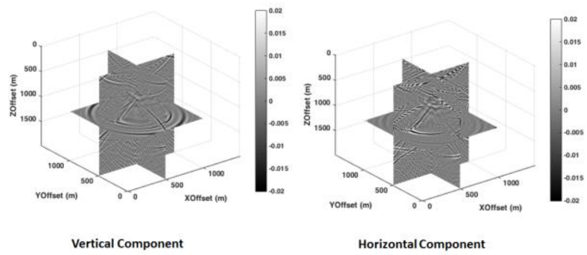

Figure 6: Vertical and horizontal component of response computed using 3D finite element modeling.

Although FEM allows to go past 1D and move from PWI to FWI such that the inversion is applicable to complex geological settings, it is computationally expensive. Therefore, using a multi-objective methodology such as NSGA II does not seem practical. The most one could expect in such FWI scheme is to define a single objective as weighted sum of its components followed by a gradient based inversion. As mentioned above, such a gradient based approach require an initial model to be close to the true model such that premature convergence to a local optimum could be avoided. It is however difficult to obtain such an initial model, especially for inverting multicomponent seismic data for anisotropic subsurface properties.

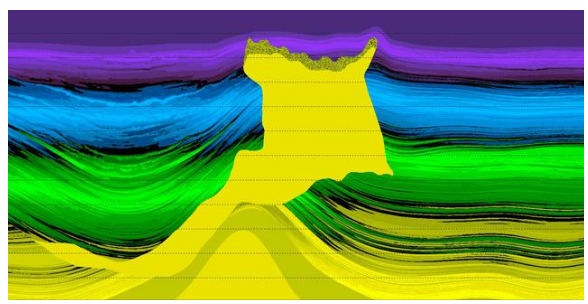

Figure 7: Example of the SEAM velocity model, courtesy Society of Exploration Geophysicists.

In most areas of exploration interest, geology is not complex throughout the area. As an example, Figure 7 is a 2D line extracted from the 3D SEG Advanced Seismic Modeling (SEAM) project. The SEAM model is based on real geology and therefore is a very good representative of the geological complexities that are expected in real world. As can be seen from Figure 7, although the geology is complex in the middle, there are certain areas, both on the left and the right of the section where the geology is relatively simple. Consequently, PWI using 1D assumption and a non-linear inversion scheme such as GA or NSGA II could be used to extract sufficiently accurate subsurface model over the geologically simple areas. These models could then be interpolated over the areas of complex geology to extract an accurate initial model for the gradient based FWI. Such a hybrid approach of combining PWI with FWI is possibly the most practical choice to the future of the waveform based seismic inversion at the reservoir scale.

Conclusions

Under isotropic assumptions PWI is clearly superior to the AVO inversion. Because a careful implementation of such an isotropic PWI allows application of the method to 3D data volumes, it should be the method of choice for the reservoir characterization applications in future. Additionally, isotropic PWI could be easily extended to include anisotropy and invert multicomponent seismic data cast as a multi-objective optimization. Such multi-objective optimization not only allows inverting multicomponent seismic data but it also provides an elegant methodology to jointly invert seismic with other data types as a multi-objective and multi-physics inversion.

Because PWI assumes 1D subsurface structure at each CMP/CCP, it is applicable only in areas that are not geologically complex. For complex geology, development of FWI with a forward modeling method honoring 3D subsurface structures is necessary. While FEM is an efficient method for 3D modeling, its computational complexity does not allow using a non-linear inversion scheme that could be implemented in PWI. However FWI could be combined with PWI in a hybrid approach. In such approach, PWI could be used to accurately estimate subsurface models in relatively simple areas, which, in turn, could be interpolated over the areas with complex geology to provide an accurate initial model for FWI. Such a hybrid approach could potentially be the future to the reservoir characterization using waveform based inversions.

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