Multi-step Inversion and Single Loop Inversion Techniques - Two Tools for Seismic Reservoir Characterization

D. Grana* (Stanford University), T. Mukerji (Stanford University) & J. Dvorkin (Stanford University)

SUMMARY

The main objective of this work is to present a strategy for integrating seismic information and, potentially, other types of geophysical measurements in seismically-derived reservoir models of rock facies discriminated, e.g., by porosity, mineralogy, and fluid. Even though seismic data do not directly provide information for reservoir properties, such as facies distribution, porosity and net-to-gross, these data can be used to quantitatively constrain reservoir models away from well control. We illustrate here two techniques for estimating facies distribution and rock properties from seismic amplitudes following a probabilistic approach and integrating them into reservoir models via geostatistical methods. This use of geostatistics allows us to obtain several realizations of high resolution models of facies and reservoir properties. We then show how to combine the two techniques to obtain fine-scaled models which honor seismic data. The resulting integrated method represents a closed loop strategy for reservoir modeling and it can be extended to incorporate various types of data.
Introduction

Reservoir models are usually based on geostatistical simulations of facies and the associated petrophysical properties, such as porosity, permeability, net-to-gross, and fluid saturation. Typically, the only available data to constrain reservoir models far away from the wells are seismic traveltimes and amplitudes. Seismic data do not provide direct information about reservoir properties but rather reflect the elastic contrasts in the subsurface. Thus, several techniques, deterministic and stochastic, have been developed to estimate reservoir properties from seismic data (Bosch et al., 2010; Doyen, 2007). We classify these methods into two main categories (Figure 1): (1) multistep inversion (e.g., Grana and Della Rossa, 2010), and (2) single loop inversion (e.g., Gonzales et al., 2008).

In multistep inversion, the final reservoir model is the result of concatenated inversion/estimation steps: typically, seismic elastic inversion is first performed on seismic data to derive volumes of P- and S-wave impedances or velocities; then, a rock physics model is used to estimate the spatial distributions of rock properties from seismic-derived elastic properties; finally, facies classification is obtained from the volumes of rock properties previously derived. If a probabilistic approach is applied at each step of the inversion process (e.g. Grana and Della Rossa, 2010), or in the classification step (e.g. Mukerji et al., 2001) the result is a set of volumes of probabilities of facies and rock properties. The resolution of the resulting most probable facies volume is the same as that of the seismic data. As a subsequent step (Mukerji et al., 2001) the seismically-derived probabilities could be used as soft-probabilities in a geostatistical simulations to get realizations of high-resolution reservoir model.

Single loop inversion is mainly based on the iterative application of a forward model and the inversion step is performed using deterministic or stochastic optimization techniques. In general, high-resolution models of reservoir properties are generated (for example using Sequential Indicator Simulation (SISim) as described in Journel and Gomez-Hernandez, 1989); then physical models are applied to derive synthetic seismic volumes: rock physics transforms are first applied to the simulated volumes to generate the corresponding elastic properties; then synthetic seismic traces are computed by a convolutional model. Finally, the so-obtained synthetic seismic traces are compared to real seismic to evaluate the mismatch; the procedure is iterated by modifying the initial set of models till a good match between synthetic and real seismic amplitudes is obtained. This step is performed here, by using a stochastic optimization technique: the Probability Perturbation Method, (Caers and Hoffman, 2006). This approach provides a high-resolution reservoir model, which honors seismic data.

Here, both methodologies and the associated advantages and limitations are presented and the comparison of the corresponding results at a well location is shown. Finally we propose a strategy for the integration of the two techniques.

Method and Theory: Multi-step inversion

The probabilistic approach to seismic facies classification and petrophysical properties estimation consists of three main steps (Figure 1): seismic inversion to recover elastic attributes from seismic amplitudes; estimation of petrophysical from elastic attributes; and facies classification to classify seismic facies from petrophysical properties. This method is based on different physical-mathematical models: rock physics models, seismic convolution, and linear approximations of Zoeppritz equation. These models cannot be deterministically inverted because the solution is not unique, which requires a probabilistic approach.

The first step of the method is an elastic inversion based on Bayesian approach (Buland and Omre, 2003) to obtain a set of volumes of probability of elastic properties (velocities or impedances) conditioned by seismic amplitudes. Then we establish, at the calibration well, a rock physics model which links elastic properties to petrophysics. Such a model cannot be inverted deterministically but it can be used to derive the conditional probability of elastic attributes conditioned by petrophysical properties (the rock physics likelihood function). By combining the probability volumes of elastic properties obtained in the first step, with the rock physics likelihood function, we can derive the probability of petrophysical properties in the whole 3D volume. Finally the last step consists in a Bayesian classification of facies from the probability volume of petrophysical properties obtained in the previous step.
The methodology overcomes the common assumption of Gaussian distribution of petroelastic properties by using Gaussian Mixture Model (Grana and Della Rossa, 2010).

**Figure 1** Flowchart of the two presented methodologies: (top) Multi-step inversion; (bottom) Single Loop Inversion

**Figure 2** Multi-step Inversion results: (from left to right) probability of litho-fluid classes conditioned by seismic amplitudes (oil sand in yellow, water sand in brown, shale in green), probability of porosity (red indicates high probability, blue low probability, the black curve is the actual well log), clay content, and water saturation, probability of P-impedance and S-impedance (blue curve is the actual log, red curves are the P25, P50, P75 of the pdf), predicted LFC profile and actual LFC profile.

An example of application is shown in Figure 2: the methodology has been applied to a real well dataset and the final results are the vertical profiles of litho-fluid class and probabilities of petrophysical properties. The main advantage of this technique is that it is very fast, whereas the main limitations are that it is a single trace approach which overlooks the lateral correlation of the properties and that the resolution of the litho-fluid model is the same as the resolution of the input seismic data.
Method and Theory: Single Loop inversion

Single Loop Inversion is an emerging technique in seismic reservoir characterization that aims at directly integrating the petroelastic model and facies classification in the seismic inversion workflow. A similar approach has been presented in Gonzales et al. (2008), for the direct inversion of facies with the integration of the rock physics model and multiple point geostatistics, but the optimization is performed directly on the realization and not on the associated probability distribution. In our approach we propose to combine two geostatistical techniques: Sequential Indicator Simulation to generate several facies models, and Probability Perturbation Method a stochastic optimization technique used to perturb the probability used in SISim.

The basic structure (Figure 1) of the algorithm can be described as follow: a) generate a facies model by sequential simulations; b) link the litho-fluid classes to elastic properties according to the rock physics model; c) compute the seismic response of elastic contrasts; d) evaluate the mismatch with the real seismic; and e) perturb the facies model and iterate the procedure till the convergence. The main challenge of this approach is how to directly perturb the facies model to obtain an improvement in the seismic response, while at the same time honouring the prior information and vertical spatial correlation. This problem is faced by adopting a technique developed for reservoir model optimization: the Probability Perturbation Method (Caers and Hoffman, 2006).

An example of its application is shown in Figure 3: the methodology has been applied to the same well dataset of Figure 2. The main advantage of this technique is that it provides high resolution models of litho-fluid classes and the associated properties. The method is faster than rejection sampling but with complex sequences, as the one presented in Figure 3, the convergence could be slow. For this reason we propose here to combine the two techniques: in order to speed up the convergence and at the same time honour the seismic data, a new probability is introduced, as a secondary information, in Probability perturbation method (Caers and Hoffman, 2006): the probability of litho-fluid classes conditioned by seismic data obtained in Multi-step inversion (Figure 3, left). The inverted model at the well location (Figure 3, right) shows a good match with the actual classification.

Discussion of the results

Both methodologies have been applied to a well log dataset. The extension to 3D case is straightforward because Multi-step inversion is a single trace method, whereas Sequential Indicator Simulation can be performed in 3D with a suitable choice of the variogram model to ensure the lateral correlation. In Figure 4 we show the result of the application of Multi-step inversion to a real reservoir...
study: in this case, the isoprobability surface of 70% of probability of detecting hydrocarbon sand from seismic data, is shown here. The integration of the two methodologies allows one to obtain high resolution reservoir models (facies and reservoir properties) avoiding high computational costs. Moreover the integration of the two methods also allows one to include different physical models and different data: seismic data, elastic attributes, petrophysical properties, facies classification as presented in the examples above, but it could also be extended to different types of data, such as crosswell seismic, or even electromagnetic data, with a suitable physical model to link resistivity to velocities.

**Figure 4** Isoprobability surface of 70% probability of oil-sand litho-fluid class.

**Conclusions**

In this work we compared and integrated two different techniques for seismic reservoir characterization. Multi-step inversion usually provides helpful information on the probability of facies and/or litho-fluid classes at seismic scale: the estimation is the result of a full Bayesian approach, and the use of parametric distribution such as Gaussian or Gaussian Mixture models allows for estimating the posterior probability analytically. However the estimated model cannot be used directly in reservoir modelling because it reflects the resolution of seismic data. For this reason we proposed a different approach based on geostatistical techniques (sequential indicator simulation and probability perturbation method) to generate high resolution facies models conditioned by seismic and well log data. The integration of the two methods provides reliable results in the presented application case.

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**References**