Stochastic seismic-wavelet inversion toward carbonate quantitative interpretation

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Abstract

A seismic inversion algorithm is proposed to simultaneously retrieve P&S-wave velocities, density, and wavelet characteristics (shape and phase). Conditioned and NMO-corrected pre-stack seismic gathers in time and slowness domains are the main input. Inversion process can be executed in two different modes by replicating either NMO-corrected or raw synthetic gathers. In the latter mode, raw gathers are generated and NMO-correction is applied internally on raw gathers using intermediate P-wave velocity in each iteration. Full elastic reflectivity is the forward modelling algorithm utilized to replicate pre-stack seismic gathers. Very fast simulated annealing (VFSA) is the special global optimization algorithm employed to minimize objective function. The optimization algorithm is stochastic in nature and is enable to estimate uncertainty in model parameters. Unlike commercial software, no assumption is made on correlations between P&S-wave velocities and density. No smoothed background model is needed and only bounds on model parameters are necessary. The proposed workflow is claimed to recover sharp boundaries. This is due to the fact that non-liner full elastic reflectivity is used instead of linearized Zoeppritz equations. Thin beds are also recovered for the same reason and because of high resolution model parameters provided by stochastic component of the workflow.

Introduction

A major portion of the world's oil and gas reserves are in carbonate reservoirs. However, the development of forward models for predicting the physical properties of carbonate rocks has not been as successful as similar efforts for clastic reservoirs. This is a result of the large influence of diagenesis which often plays the primary role in defining the character of a carbonate rock.

Myers and Hathon (2012) developed a Staged Differential Effective Medium (SDEM) methodology to model elastic moduli. In fact, SDEM is a general technique for modelling the impact of mineralogy and texture on permeability, resistivity, and acoustic measurements.

To demonstrate the advantages and applicability of SDEM, Shahin et al. (2017) made three independent porosity measurements (Archimedes, µCT, and NMR) on twelve carbonate core plugs from northern Niagaran reef. They modelled two pore types, micro-pore and vugs. Electrical-resistivity, P& S-wave ultrasonic measurement of the same brine saturated core plugs were made. The joint modelling of resistivity and velocities was performed using SDEM technique. The parameters in the resistivity and velocity models were optimized using Very Fast Simulated Annealing (VFSA) algorithm (Ingber, 1989). Optimization algorithm was able to fine tune the model parameters of resistivity and velocities to provide vuggy and micro-porosities close to independently measured porosities using NMR and µCT.

Shahin et al. (2019) integrated SDEM multiphysics modelling technique to construct resistivity, elastic, and density borehole-derived well logs for complex carbonates. An inversion algorithm was developed to jointly convert resistivity, density, and sonic well logs into petrophysical properties. For doing so, they also utilized VFSA, a global optimization machine. Primary porosity (intergranular), secondary porosity (vugs), water saturation, matrix's density, matrix's bulk & shear moduli, salinity, critical porosity, resistivity lithology exponents of primary and secondary pore systems, and elastic intergranular length scales were petrophysical quantities, matrix and fluid properties, and model parameters which were recovered.

In this paper, we first utilize SDEM technique (already applied on core data and well logs) to replicate P& S-wave well logs. Then, we use full elastic reflectivity algorithm (Kennett, 1983) to simulate pre-stack seismic gathers. Finally, a novel stochastic seismic inversion method is designed to retrieve elastic properties and bulk density along with wavelet characteristics (Shape and phase).

Staged Differential Effective Medium (SDEM) theory

Historically Reuss and Voight averages have been used to relate the modulus of the components of a rock to it's the resultant modulus of the mixture. They represent bounds on the moduli of the material mixtures. The actual modulus usually lies somewhere in between these bounds. To further refine these averaging techniques and by including additional textural information, Myers and Hathon (2012), developed a SDEM model and applied it to velocities. This model calculates the properties of a dilute mixture. Inclusions are added to a host while assuming they only feel the average properties of the host and neglecting interaction terms between the inclusions. Critical concentration models (Nur et al. 1995) are naturally included in these models. The first integration step is from pure host to the critical concentration (iso-stress Reuss average). Then the integration is extended to the final porosity. This is a two-stage SDEM model for the rock.

A dual porosity carbonate can be simulated by adding an addition integration step to model the vugs (Myers, Hathon 2012). The intergranular and vuggy's parameters can be obtained from the non-linear optimization of core measurements (Shahin et al., 2017) or from well logs (Shahin et al., 2019).

Figure (1) illustrates a thick dual-porosity carbonate which is partially saturated with oil for the upper part of the formation. The residual water saturation in the upper portion is about 10%. The lower portion is fully water saturated. The middle part is the transition zone. To model the density log, calcite with density of 2.71 gr/cm3, brine with density of 1.05 gr/cm3, and oil with density of 0.75 gr/cm3 are used. P&S-wave velocities are modelled using SDEM, matrix bulk and shear moduli of 77 and 32 GPa and a critical porosity of 0.45.

Figure (2) shows the rock physics cross plots for dual-porosity carbonate formation displayed in figure (1). As seen, water leg and oil column can be separated using the left panel. Gradual decrease in acoustic impedance and increase in Poisson's ratio are the indication of increase in intergranular porosity (right panel).

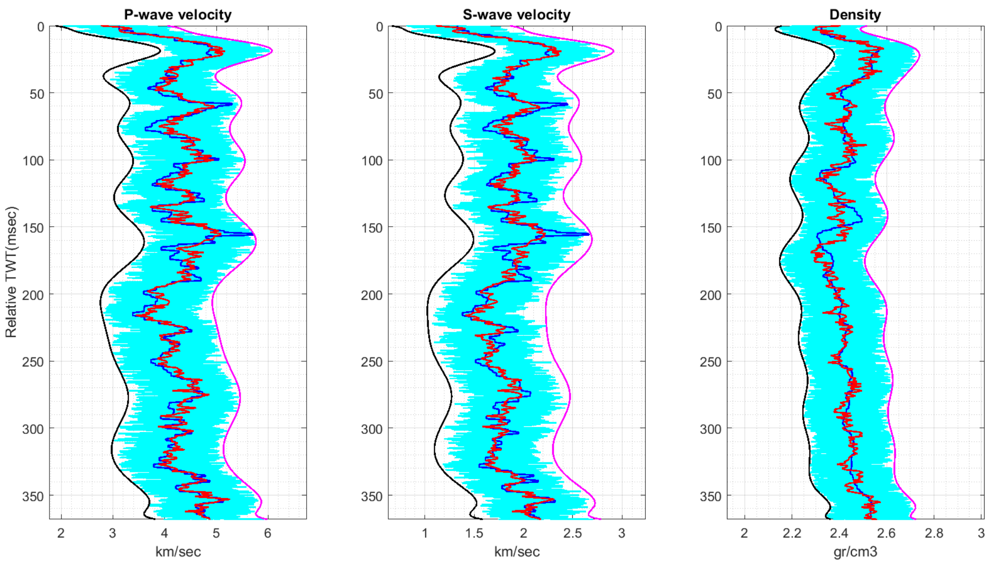

Figure 1 *Plots of the true well log responses and their inverted values over a thick dual-porosity carbonate formation containing intergranular and vuggy pores. In all tracks, blue curves are true well log responses, red curves are inverted properties obtained from the averaging of 50 independent realizations. Soft and stiff bounds are also displayed in black and pink, respectively.*

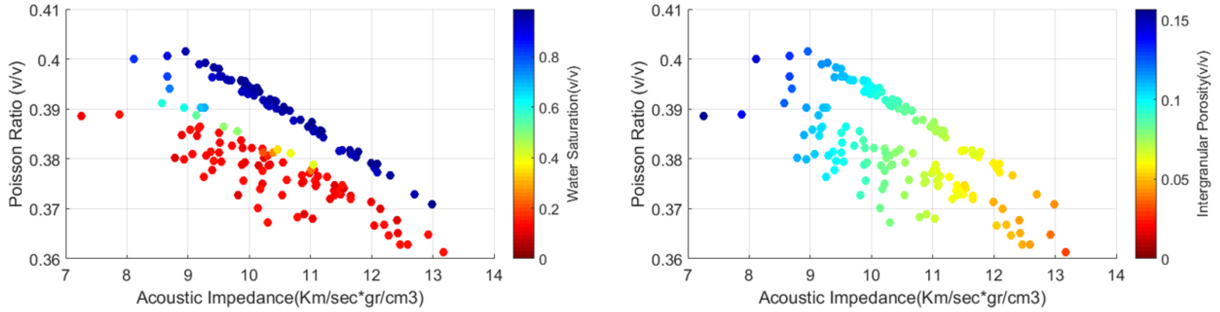

Figure 2 *Cross plots of the true well log responses for the dual-porosity carbonate formation containing intergranular and vuggy pores. Left panel is color-coded with water saturation and right panel with intergranular porosity.*

Full elastic reflectivity seismic modeling

Full elastic reflectivity algorithm (Kennett, 1983) is the forward modelling algorithm utilized to replicate pre-stack seismic gathers. Input are P&S-wave velocities and bulk density and outputs are NMO-corrected or raw pre-stack seismic gathers in time and slowness domains.

Coupled seismic-wavelet inversion

We intend to use VFSA which naturally has a higher chance to find the global optimum of the objective function. In this paper, an objective function is defined as the root mean square of differences between simulated and observed pre-stack seismic gathers. There are two sets of model parameters to be retrieved. The first set, called global parameters, are constant over the time interval of interest. These global variables are wavelet shape (amplitude spectrum) and wavelet phase (from zero to 360 degree). The second sets of model parameters are locally time-dependent variables. These parameters are P-wave velocity, S-wave velocity, and density. During the optimizations process appropriate constraints are applied.

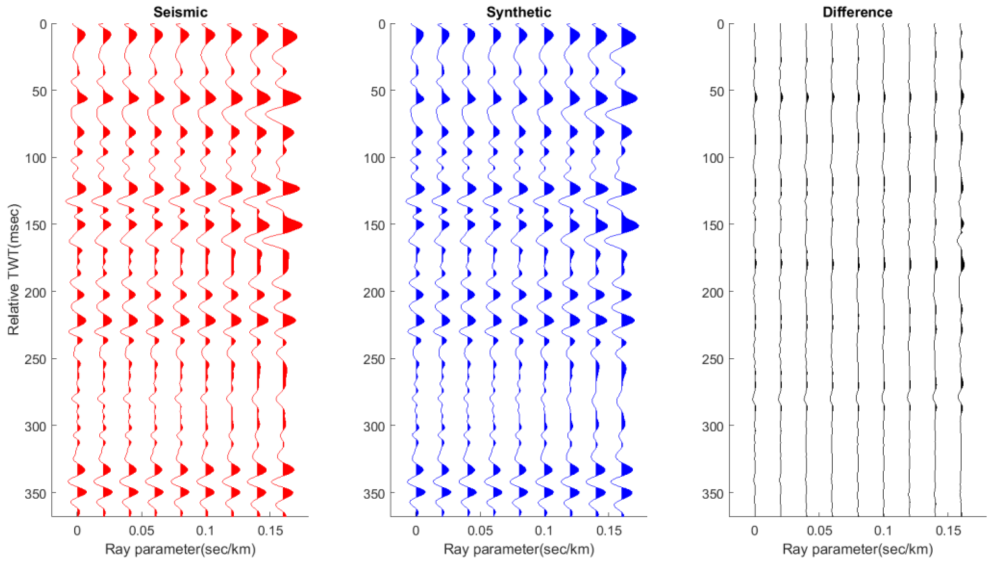

Figure 3 *Plots of the true (left track) and synthetic seismic (middle track) responses over the dual-porosity carbonate formation. Full elastic reflectivity is utilized as the modeling algorithm. The right track is the difference between true and synthetic seismic. Note that synthetic response is simulated for P&S-wave velocities and density obtained from the averaging of 50 independent realizations.*

As can be seen in Figure (1), the inversion workflow is capable of matching the model for the three portions of carbonate formation (water leg, oil column, and transition zone) and retrieving P-wave velocity, S-wave velocity, and density with high precision. Note that the mean value of 50 realizations is very close to the true value of properties.

Figure (3) shows the performance of inversion workflow to match true and synthetic pre-stack seismic gathers. As seen, the difference between true and mean synthetic gathers are close to zero and this emphasizes the power of the inversion machine.

Figure (4) shows the performance of inversion workflow to retrieve wavelet in time and frequency domains. True wavelet is a 45-degree phase rotated and band-limited Sinc function. The wavelet length is 71 msec and it has the minimum and maximum frequencies of 5 Hz and 115 Hz, respectively. Note that the mean value of 50 realizations is very close to the true wavelet (shape and phase).

Conclusions

Elastic and density well logs have been constructed using SDEM and mass balance equations for a thick dual-porosity carbonate reservoir. Then, pre-stack seismic gathers are simulated using full elastic reflectivity seismic modelling. Finally, a stochastic global optimization algorithm has been designed to invert pre-stack seismic gathers. Locally time-dependent P&S-wave velocities and density are the main properties estimated via this inversion algorithm. Wavelet shape and phase are global parameters retrieved. Uncertainty estimation of retrieved properties is a natural outcome of the proposed workflow. Uncertainty of these properties will be quantified via independent implementation of the stochastic optimization initialized with random model parameters. The next logical step is to extend this methodology to directly invert pre-stack seismic data back to pore-type, porosity, and saturation.

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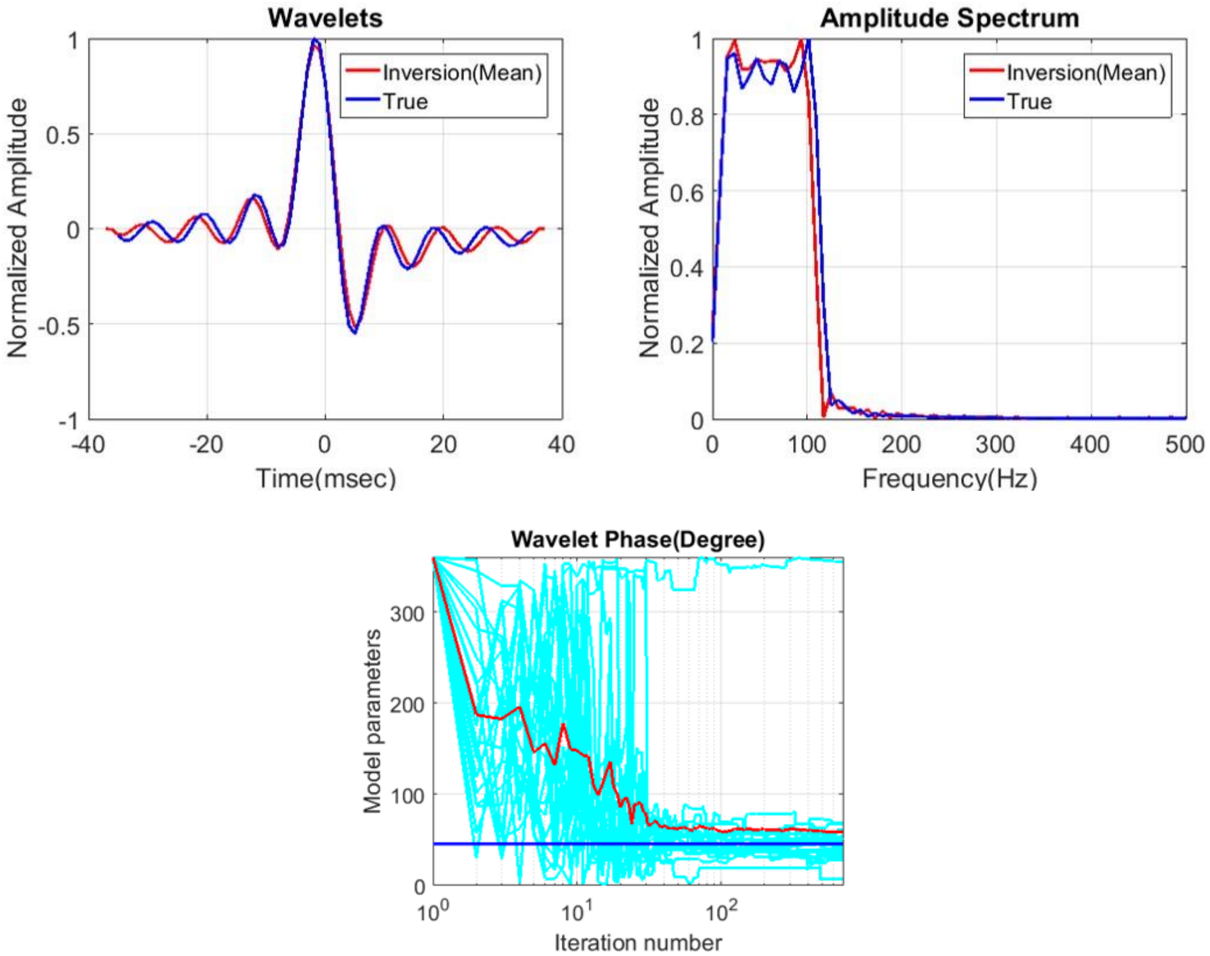

Figure 4 *Plots of a bandpass and phase rotated Sinc wavelet in time (upper left) and frequency (upper right) domains. In upper panels, blue curve is true wavelet, red curve is inverted wavelet obtained from the averaging of 50 independent realizations. The lower panel shows the evolution of wavelet phase versus iteration number. In this panel, blue straight line shows true phase (45 degrees), red curve is the averaging of 50 independent realizations shown in cyan.*