Play scale seismic characterization – Using basin models as an input to seismic characterization in new and emerging plays

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Summary

Basin simulations, reservoir simulations, laboratory measurements and field measurements are crucial details needed for making good operational decisions in frontier areas. Seismic reservoir characterization is the task that combines engineering, geological and geophysical data. Basin simulation gives the geoscientist the opportunity to incorporate sophisticated modeling into their predictions of subsurface properties. This simulation technique normally uses a regional seismic interpretation as an endpoint for a compaction, temperature, pressure or mineralogical forward model that has engineering and geophysical calibrations. Reservoir characterization work often produces multiple interpretations, using various techniques, of the same volume of the earth. How should these interpretations be combined? Which interpretations should carry more influence?

The technological challenge of using basin simulation output with traditional seismic inversion is that the exact location of facies is not accurate. Therefore, the derived static low frequency model constructed using rock physics transforms leads to an inversion product with unphysical artifacts at worst and at best, a reiteration of the basin model with slight property variations from the seismic amplitude input conspicuously overlying.

We present an inversion that utilizes a Bayesian framework to iteratively constructs a facies and impedance model using prior estimates of facies distribution and impedance uncertainty. This framework allows the spatial variability of properties from the basin model to be included in the inversion without introducing localized artifacts. The benefit of using a Bayesian framework in deterministic inversion at seismic resolution is that priors may be considered in order to disqualify unphysical or unlikely yet acceptable solutions from the non-unique solution space. In this application, the prior is constructed using facies specific porosity compaction trends, cement profiles based on temperature and timing and pore pressures, transformed with rock physics models to elastic properties. With these facies property volumes, we produce unique probability density functions at every seismic sample. Given the seismic input and additional priors, the inversion produces a most probable facies volume and impedances (Vp-Vs-Density). The resulting properties are thus an integration of a complex basin simulation model with a deterministic seismic inversion.

Introduction

We present a technique that has been developed to allow basin simulation output to be used as an input to jointly invert seismic data for impedances and facies with a Bayesian simultaneous inversion. We demonstrate this using the SEAM pore pressure prediction dataset, which is a Gulf of Mexico inspired geological model. The model is comprised of a 3D vShale volume (volume proportion of shale, quartz is complimentary) that was constructed considering varying depositional settings and an active salt history (Fehler and Keliher 2011). The vShale model and geological horizons were used as an endpoint for a basin simulation that evolved smectite/illite ratio, temperature, porosity and effective pressure over a depositional period from the Cretaceous to the present.

Elastic and Seismic Model Construction

A rock physics model was produced to combine and transform these properties into a self-consistent TI elastic model, generally calibrated to a deep Gulf of Mexico well: MC_727 Poseidon 1 (Mur and Payne 2017). This model produces a stress dependent shale and sand endmember stiffness tensor that is mixed, volumetrically, by the SEAM vShale volume. The mixed stiffness tensor and density volume is sampled to produce isotropic or anisotropic velocities. We review the model components and synthetic seismic dataset below.

The shale component of the model uses the basin-simulated shale porosity volume and pressure sensitive brine (FLAG fluid calculator (Han 2011)) as inputs to an isotropic shale compressional and shear velocity model (Vernik and Kachanov 2010). A background anisotropy model is produced by using a smectite-illite ratio volume to represent the smectite or illite rich shale at a baseline confining pressure. Anisotropy parameters were calibrated with the Wang shale database samples G30 for smectite-rich and G32 for illite-rich shale (Wang 2002). The background anisotropy model was then used, along with the initial isotropic C33, C44 values to populate a transversely isotropic (TI) stiffness tensor. The related TI compliance tensor is then perturbed with the basin model effective pressure values using the Pervukhina (Pervukhina, Gurevich et al. 2011) implementation of the Sayers and Kachanov (Sayers and Kachanov 1995) non-interactive approximation. This is a theoretical approach where distributed cracks are modeled with consideration of specific tangential compliance, specific normal compliance, specific surface area of cracks per

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unit and crack orientation. The density of cracks along a particular plane may be reduced with the normal stress acting on that particular plane, thus we produce a compliance perturbation at each address of the TI compliance tensor.

The sand component of the model uses bulk and shear moduli maxima (K_∞ and μ_∞, respectively) based on the Mavko stiff sand model and calibrated to the MC-727 Poseidon well (Mavko, Mukerji et al. 1998). These values are perturbed following Macbeth (MacBeth 2004). Stress sensitivity parameters vary with porosity and are determined by a polynomial fit through laboratory measurements of Gulf Coast, Miocene sands (Gregory 1976). An isotropic stiffness tensor is then populated for the sand endmember. Figure 1 shows a section view of the shale and sand endmember models, isotropically sampled Vp, Vs, and density (Rho).

For this study, we produced a 4 ms sampled synthetic seismic model by convolving a broad band wavelet (approximately 5-70 Hz) with the reflectivies derived from the isotropic equivalent (C_{33}, C_{44}, and density) mixed sand and shale properties from the above described SEAM elastic model, using a 3 term, Vp-Vs-Density, reflectivity model (Aki and Richards 1980). The inversion is performed on 5° angle stacks from 0-50° incidence with a seismic noise assumption of 10%.

Joint Impedance and Facies Inversion.

We use a Bayesian simultaneous inversion that takes seismic amplitude data and jointly solves for impedances and facies consistent to rock physics trends. Input data consist of: seismic amplitude data, associated wavelets, zones defined by horizons, prior facies proportion estimates per zone, rock property depth trends, per-facies rock physics relationships and uncertainties of the elastic models.

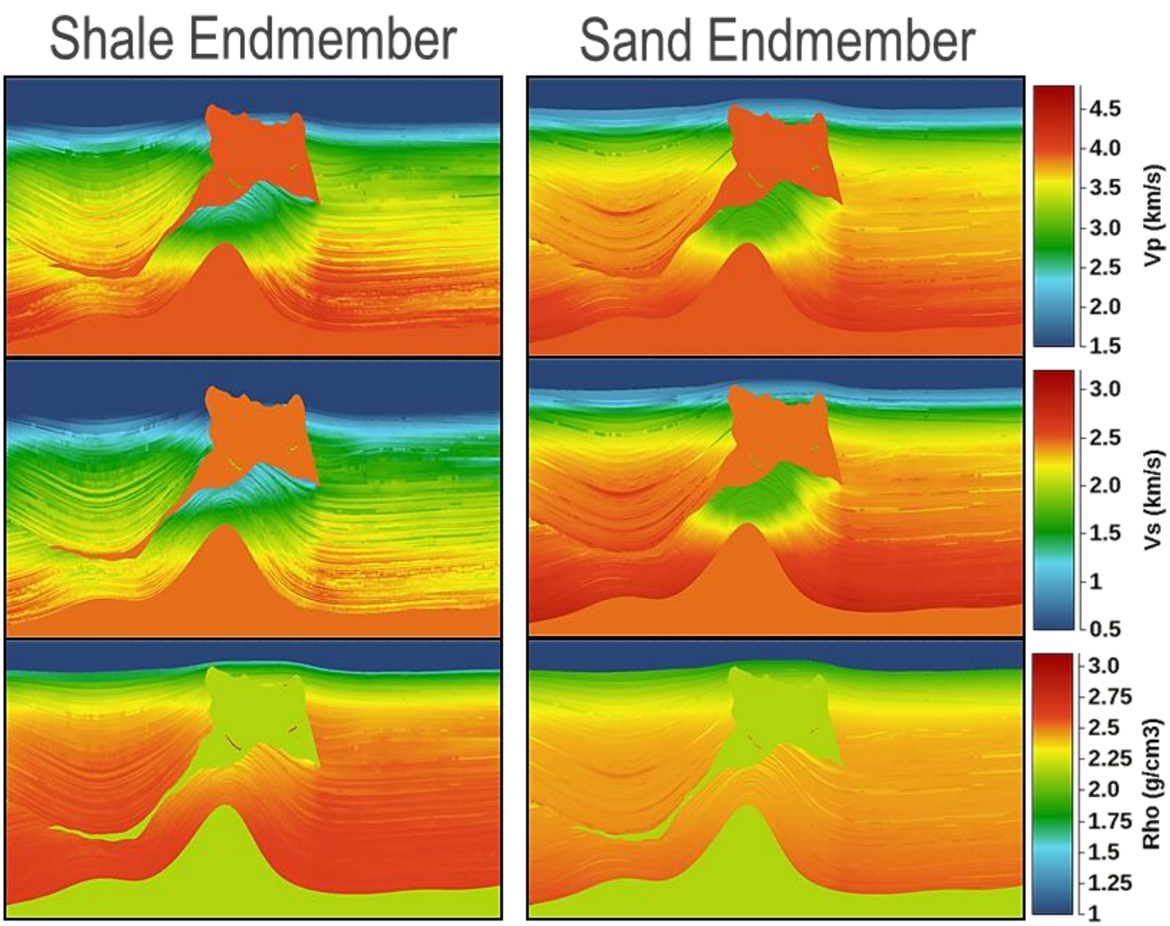

Figure 1: Endmember shale (right) and sand (left) Vp-Vs-Rho values. The two models consider pressure, porosity, temperature, and mineralogy. The area under the salt intrusion tends to have higher porosity and increased pore pressure. To the right of the salt intrusion, the model contains areas of over- and under-pressure.

Bayesian Priors and Inversion Results

We are able to test different facies definitions based on varying mixes of the sand and shale endmember models. After successfully solving a binary sand and shale scenario, we refined the facies model to delineate clean and mixed facies. We find that impedance and facies match to the model is best when four facies are targeted in the inversion. For the four facies scheme, facies and facies trends are defined by the cutoffs in table 1. Figure 2 (right) shows the derived prior elastic trends in acoustic impedance (AI) versus velocity ratio (Vp/Vs) space. With increasing depth, facies AI values increase, shales have Vp/Vs ratios greater than those of sands. Figure 3 shows a comparison of the reference facies and impedances with the inversion results. Figure 4 gives a closer view of the fine details imaged with the facies inversion. Beds thinner than 8 meters and the cleanest sand and shale volumes are successfully delineated.

Table 1 Facies and trend volume construction parameters

Facies	Cutoff	Sand/Shale Property Ratio
Clean Sand	Vshale <=20%	90% Sand, 10% Shale
Shaley Sand	Vshale > 20% and <=50%	65% Sand, 35% Shale
Sandy Shale	Vshale < 50% and <80%	35% Sand, 65% Shale
Clean Shale	Vshale >=80%	10% Sand, 90% Shale

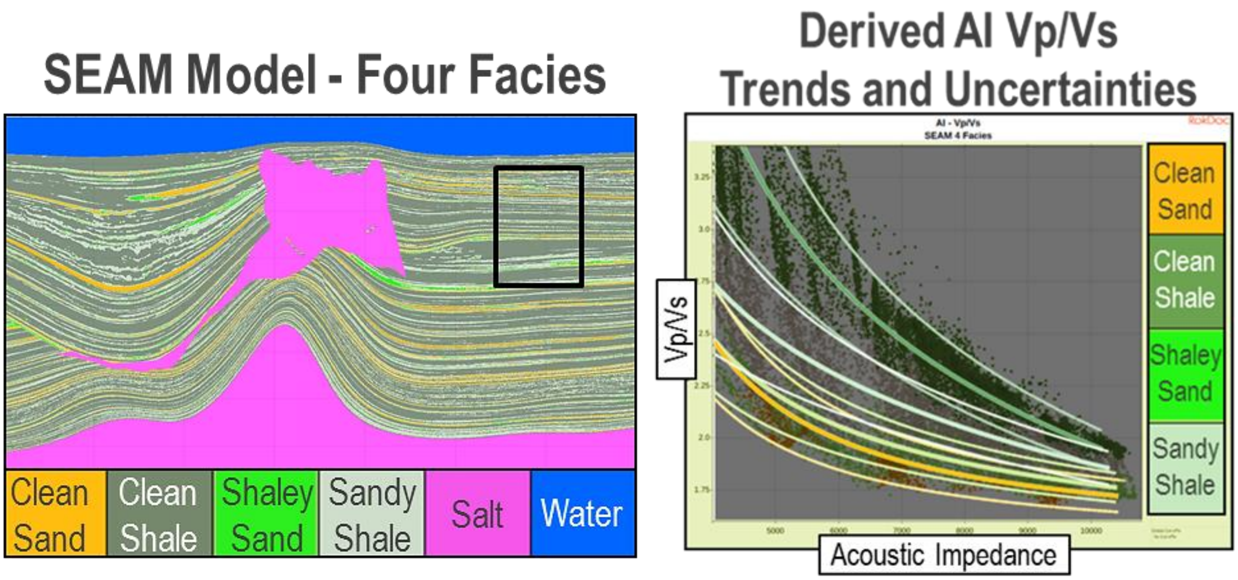

Figure 2: Facies and inversion window (left) and AI-Vp/Vs crossplot of properties modeled over the inversion window. Lines indicate the mean trend and uncertainties for each facies. Uncertainties for each facies were determined using a pseudo-well passing through the center of the inversion window.

Conclusions

Variability in the SEAM dataset comes from a number of modeled physical sources: pressure and temperature sensitive fluids in the pore space, clay mineral evolution, effective pressure variations and porosity. We successfully capture this variability in the uncertainties of the elastic facies' depth varying probability density functions and demonstrate that we can successfully produce accurate impedances without the support of a static low frequency background model. In this manner, we have successfully used a basin model as a prior in a Bayesian simultaneous inversion and have produced a highly detailed facies image that accurately classified beds as thinner than 8m. The embedded pore pressure signal is not directly predicted in this study, but it is of great interest to continue to test quantitative pore pressure prediction techniques in order to compare predictions to the truth case.

Acknowledgements

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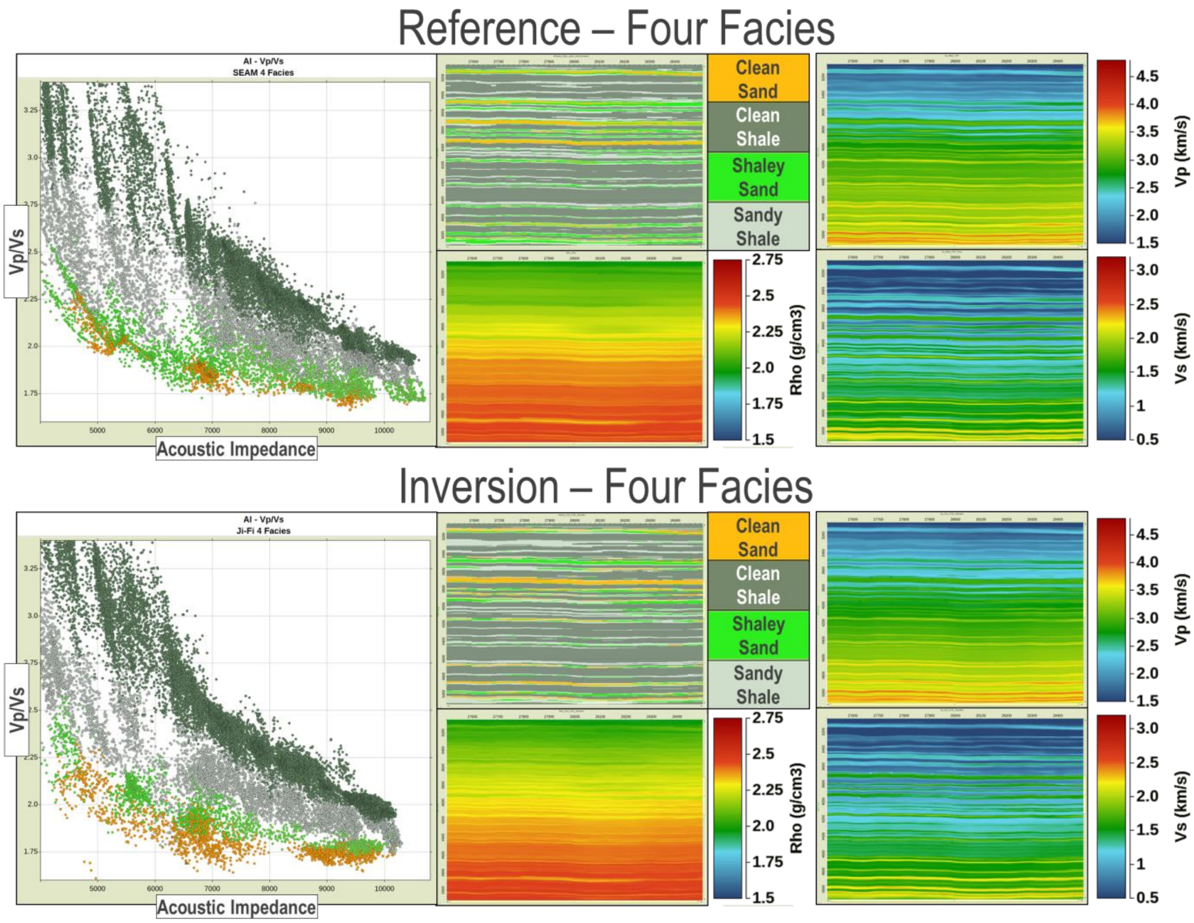

Figure 3: Comparison of reference (top) and inversion result (bottom): AI-Vp/Vs crossplot and section views of Facies, Vp, Vs, Density. Intercept and gradient equivalent seismic properties (AI-Vp/Vs) are distributed correctly in the inversion results without the classic averaging artifacts seen in facies unaware inversions. Facies, Vp, Vs, and Rho values are sensible.

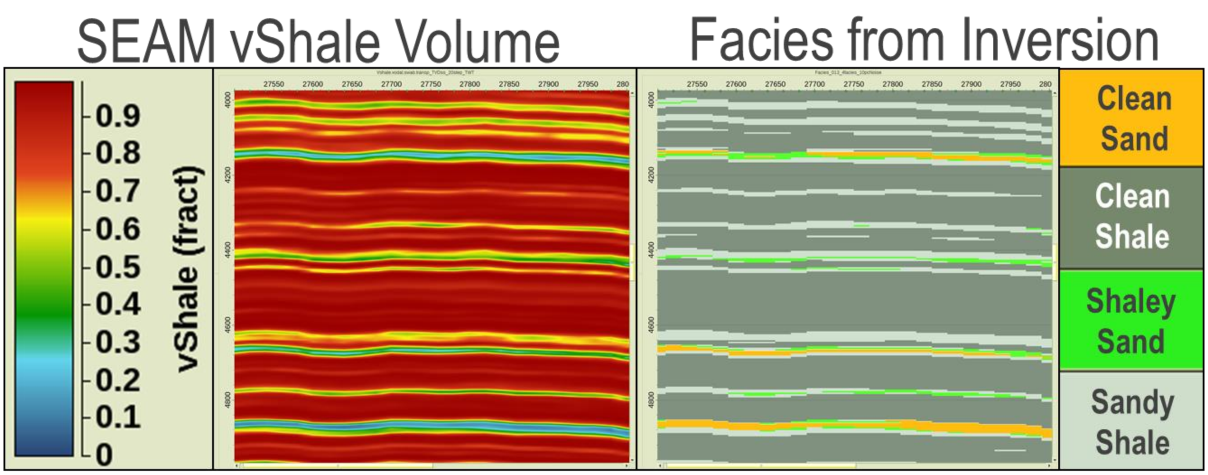

Figure 4: Detailed image of vShale volume (left) and inversion results (right). Thin, sandy shale beds have been identified and subtle sand-shaley sand variations are nicely captured in the joint facies inversion.

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