ROCK PHYSICS MODELING: KEY TO DE-RISKING FRONTIER EXPLORATION OPPORTUNITIES, OFFSHORE ARGENTINA

Natt Srisutthiyakorn[1], Stephan Gelinsky[2], Mario A. Gutiérrez[3] and Rafael Ceteno[4]

1: Shell International Exploration and Production Inc. n.srisutthiyakorn@shell.com

2: Shell International Exploration and Production Inc. stephan.gelinsky@shell.com

3: Shell International Exploration and Production Inc. mario.gutierrez@shell.com

4: Shell International Exploration and Production Inc. rafael.centeno@shell.com

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ABSTRACT

Los exploradores en cuencas frontera se enfrentan con definir y establecer el potencial económico de oportunidades exploratorias usando amplitudes sísmicas. Esta validación requiere de un marco de trabajo predictivo necesario para calibrar las propiedades de las rocas a las amplitudes sísmicas y el modelamiento de escenarios. Dos preguntas claves:

1) ¿Entendemos las propiedades de las rocas y fluidos y su impacto en la calidad del yacimiento y la respuesta sísmica, dado un control de pozos disperso y lejos del área prospectiva?
2) ¿Están los objetivos exploratorios Cretácicos soportados por amplitudes?

Para contestar estas preguntas, creamos un marco predictivo usando técnicas de interpretación cuantitativa para la detección y evaluación de prospectos en la Cuenca Colorado. El nuevo marco predictivo es integrado con petrología, predicción de presión de poro, petrofisica, y modelado de cuenca, y ha sido usado para la identificación e interpretación confiables de respuestas de amplitudes sísmicas en términos de litología, porosidad, y fluidos.

Nuestro enfoque tiene cuatro pasos: 1) control de calidad y acondicionamiento de los datos, 2) clasificación de litología y escalamiento, 3) formulación de modelo de física de rocas, y 4) generación del marco de interpretación. Con el modelo de física de rocas se clasificaron por categorías las respuestas sísmicas para escenarios de litologías y fluidos. Este flujo fue aplicado a escala regional y de prospecto para cuantificar el riesgo de la presencia de yacimiento e hidrocarburos, y es una parte importante del enfoque de Shell para clasificar y valorar los prospectos, estudios de riesgos geológicos someros y diseño de pozos.

INTRODUCTION

The goal of our study is to create a predictive framework for Mesozoic exploration plays in the Colorado Basin, offshore Argentina, especially on the Colorado formation (Early to Late Cretaceous). Argentina is one of South America's largest producers of natural gas and crude oil.

During the First Offshore Licensing Round in April 2019, the Argentinian government successfully implemented tender processes for offshore exploration blocks in the North Argentina frontier basin. Shell was awarded the exploration rights for blocks CAN-107 and CAN- 109 as operator with 60% interest and with Qatar Petroleum holding 40% (Figure 1). In January 2021, Shell farmed into the CAN-100 Block holding 30% interest, whereas the operator Equinor and majority state-owned Argentine YPF each hold 35%.

Validating the economic viability of prospects in frontier basin using seismic amplitudes is a major exploration challenge, especially if outboard acreage can only be derisked with far-inboard and sparse wells. The presented exploration model calibration required the development and implementation of a predictive framework for calibrating rock properties to seismic responses. Without a thorough understanding of the major geological drivers on elastic properties, seismic responses cannot be reliably predicted. Differences in rock composition and texture related to sediment source and depositional environment are important, and so is the possible diagenetic overprint related to the rock's burial history which relates to the effects of the temperature and stress evolution over geologic times.

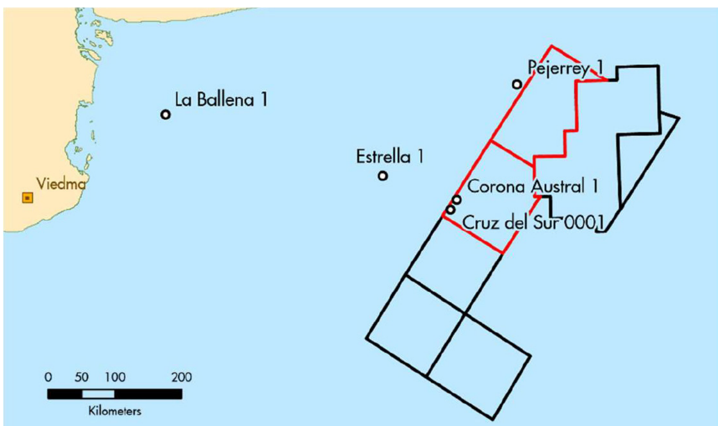

Figure 1. Map of the Colorado basin, Argentina showing the location of the blocks Shell and its partners won after the first offshore licensing round in April 2019. The wells plotted are used for rock physics model calibration.

METHODOLOGY & RESULT

This study primarily aimed at answering the following two questions:

1. Do we understand the rock and fluid properties and their impact on reservoir quality and seismic response well enough for Quantitative Interpretation (QI) derisking of outboard acreage, given the challenge that we have only sparse well control far inboard from the prospective area?
2. Are the deeper and older Cretaceous exploration plays possibly amplitude-supported if hydrocarbon bearing and can seismic QI hence help to derisk the presence or absence of reservoir and/or hydrocarbons in prospective outboard areas?

To answer both questions, we created a predictive exploration derisking framework. Key workflow steps included: (1) data QC and conditioning, (2) lithology classification and upscaling, (3) rock physics model formulation, and (4) generation of an interpretation framework. In summary, we built rock physics models leveraging the local well database and tested out AVO response modeling for multiple rocks and fluid scenarios. The predictive framework was created based on five inboard wells shown in Figure 1 (Corona Austral 1, Cruz Del Sur 1, Estrella 1, La Ballena 1, Pejerrey 1). The overall workflow followed closely the path outlined by Gutierrez and Dvorkin (2010) and Gutierrez (2018).

1. Data QC and Conditioning

QC of all the relevant, selected data is always a crucial first step for building the predictive framework. We investigated bad borehole areas as indicated by caliper and density log correction curves and removed any spurious log data on density, compressional and shear velocity. We interpolated the log for any small intervals of bad log and used regression or later the emerging rock physics models to fill larger gaps. Composite and mud logs are also useful to verify and improve the accuracy of the log-based lithology and fluid phase assessment.

The data is further visualized in the crossplot domain for QC purposes. For example, we investigated porosity vs. density to understand how the legacy porosity log was derived and what densities of grain and fluid the porosity evaluation assumed (Figure 2a). Vp vs. density is plotted to visualize the lithology effect on both variable that often leads to good discrimination between various lithologies in this domain. We plotted reference lines such as Gardner sandstone or Gardner shale to compare to the data color coded by volume of shale. We often see shales plotting at higher densities at a given Vp, as compared to porous sands (Figure 2b). Volcanic rock and carbonate often have their own data clusters on this crossplot. Neutron and density are crossplotted to petrophysically analyze the shaliness of the reservoir units (Figure 2c).

The local calibration well data quality was found to be generally poor, and this required us to iteratively create a lithology classification. The first iteration utilized preliminary regional trends to fill in any data gaps and allowed to then investigate additional zones of poor data that were not identified in the first iteration. For example, some low density intervals that initially were identified as sand- or siltstones with naturally lower density were subsequently re-classified as (washed-out) shales and then corrected. Figure 3 shows an example of our iterative lithology classification on the log panel seeing the change on lithology from the original petrophysics evaluation.

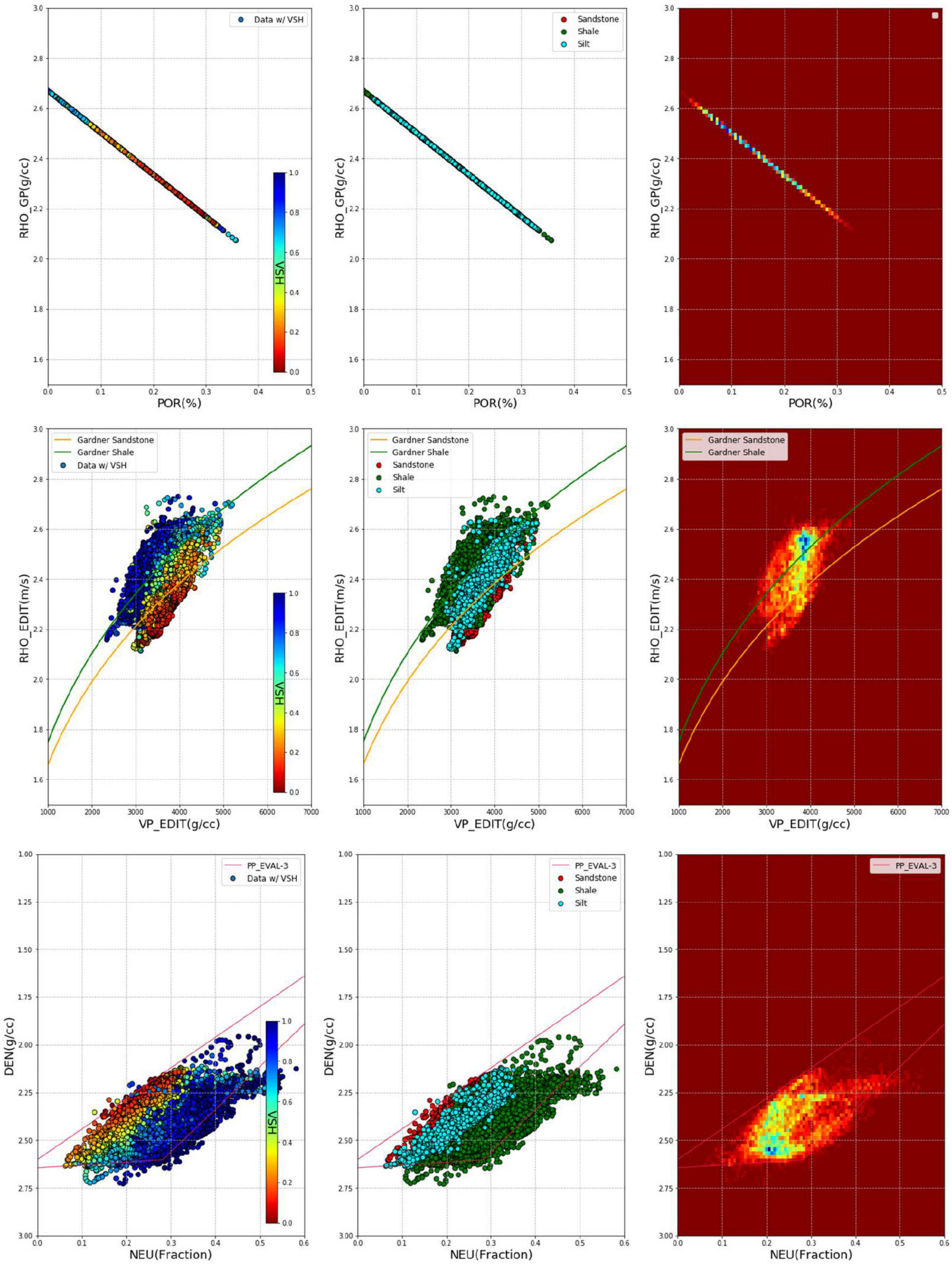

Figure 2. Example of crossplots for QC purposes for both sand and shale lithologies in Colorado formation. ((a) porosity vs. density, (b) vp vs. density, and (c) neutron vs density).

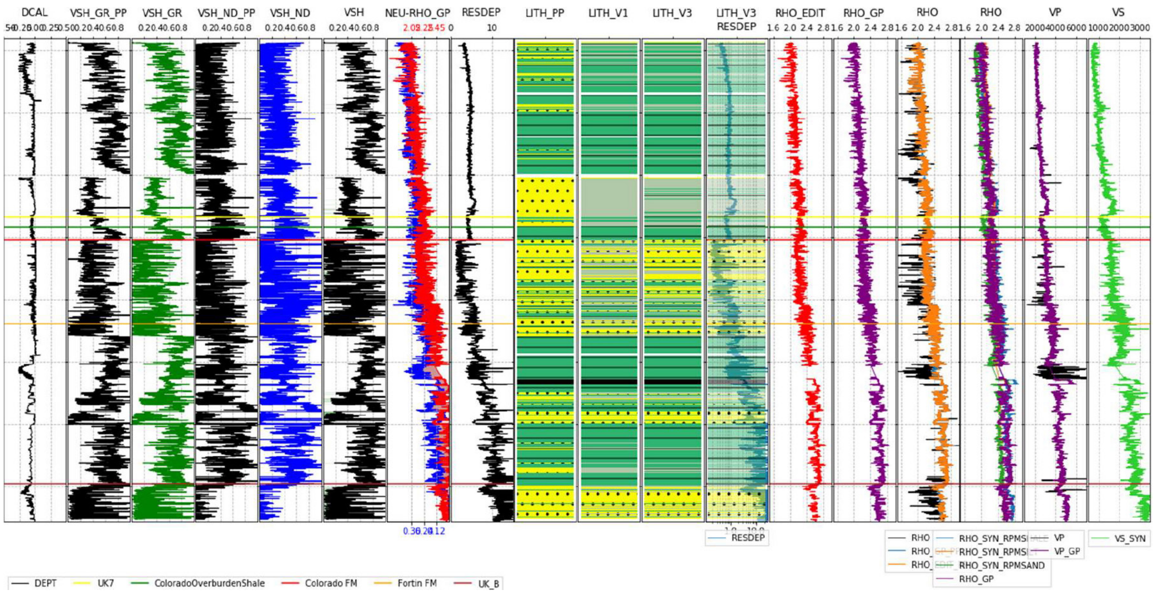

Figure 3. Example of our iterative lithology classification on the log panel, before upscaling. The y axis is in depth. The unit of NEU porosity is in %. RESDEP stands for deep resistivity and the unit of density (RHO) is in g/cc and the unit of velocity (VP and VS) are in m/s.

2. Lithology Classification and Upscaling

For the Colorado formation in the Colorado basin, we focused on identifying its key constituent lithologies, namely sandstone, shale, silt, and volcanics. Lithology classification ideally includes looking at different data such as thin section and cutting descriptions along with the well log data. This classification process is often iterative as we typically learn more about rock properties when we interrogate the emerging rock typing scheme in elastic property crossplot space (especially leveraging lithology-driven clustering on Vp-Den or AI-VpVs ratio crossplots).

A predictive framework should be able to capture uncertainties for all key lithologies at the seismic scale. Therefore, well logs must be upscaled from log-scale to seismic-scale. The running harmonic average (the Backus average) must be used to average elastic properties such as compressional and shear velocities (Figure 4). This was done by first calculating bulk and shear moduli for inputs for Backus average equation. For other logs, the running arithmetic average is employed (Mavko *et al.*, 2009; Gutierrez and Dvorkin, 2010).

3. Rock Physics Models Formulation

We formulated rock physics models for each of the four key end member lithologies: (1) sandstone, (2) silt, (3) shale, and (4) volcanic. The quality of any of these rock physics models can be quantified using descriptive error statistics with respect to its calibration dataset (mis)

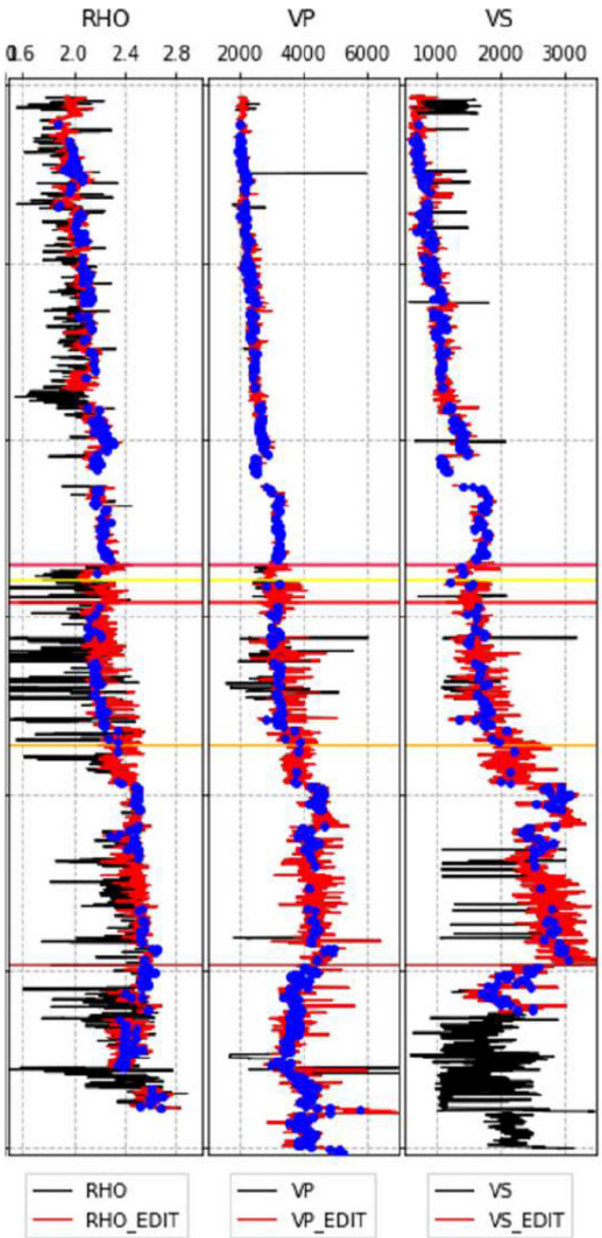

Figure 4. Example of upscaled Vp, Vs, and density in blue dots plotted on top of the well logs. The black lines represent original logs and the red lines represent the log after editing in which we used for calculating bulk and shear moduli for Backus average. The unit of density (RHO) is in g/cc and the unit of velocity (VP and VS) are in m/s.

fit such as RMS error, minimum, maximum, mean, and standard deviation of the error. The misfit is generally larger for the fitting of depth below mudline vs. porosity (mean error of 1.5%) than VP vs. porosity (mean error of 0.07%) and VP vs. VS. in Colorado formation (mean error of 0.06%) (Figure 5).

For sandstone, the main reservoir target within the Colorado formation has overall good porosity (15-35%). In the deeper and older Fortin formation, the porosity drops sharply due to compaction and quartz cementation. We initiate our reservoir rock physics model with porosity as a function of depth below mudline. Then, we model compressional velocity as a function of porosity and shear velocity as a function of compressional velocity subsequently.

For shale and silt, we initiate the model via a compaction trend, starting with compressional velocity as a function of depth below mudline. Next, we model density and shear velocity as functions of compressional velocity. For shale, we observe a tight fit between data and model regression. The shale overburden of the Colorado formation is generally much softer than other regional shale units and is heavily washed out in most wells, which required careful data qc. It should be noted that at times a seismically-relevant harder heterolithic unit overlays the porous Colorado reservoir section.

The rock physics model for volcanics is difficult in the Colorado basin. Volcanic velocity and density depend on lithological composition (basalt vs. tuff) more than compaction. Therefore, we recommend using a range of velocity and density to represent basalt and tuff properties.

We extracted the pressure and temperature trends from basin modeling at the lead location to be used for fluid trends. The pressure trend is aligned with hydrostatic pressure.

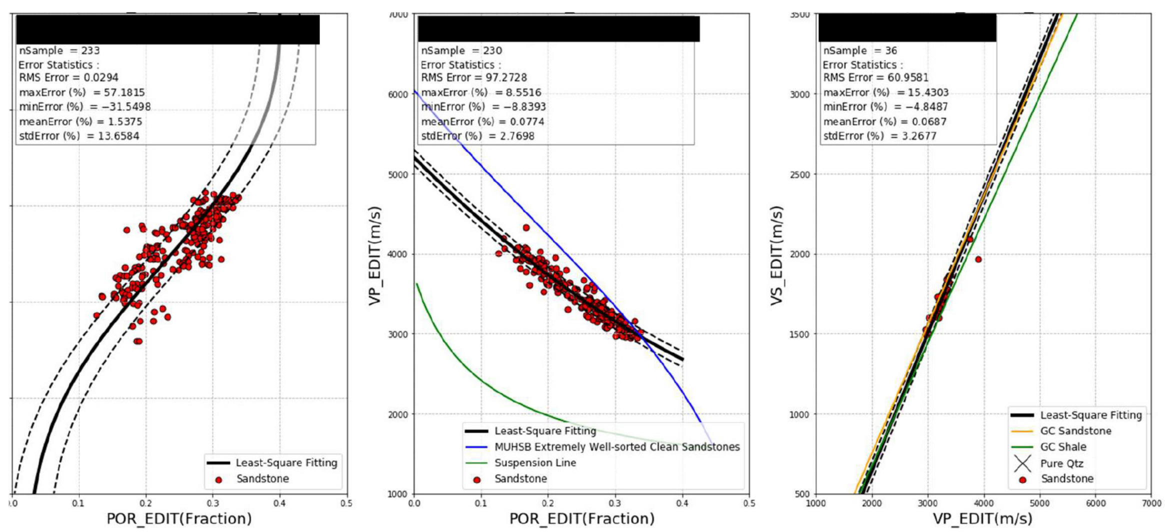

Figure 5. Example of rock physics model formulation for sandstone in Colorado formation. For the first figure, y axis is depth below mudline.

4. Generation of Interpretation Framework

Figure 6 shows depth trend summary for Colorado formation. After having rock physics model for wet sandstone, we used Gassmann fluid substitution to model different hydrocarbon bearing sandstones for half space modeling shown in Figure 7. The half space modeling allows us to model AVO class of reservoir-seal pair. Figure 7a suggests that wet sand AVO response could be Class IV in the Colorado formation. On the other hand, figure 7b suggests the pay sand AVO response could be Class III in the Colorado formation, indicating the possibility of identifying hydrocarbon presence through amplitude support. However, the model also shows that, at certain depths, the AVO response could also be flat with minimal change between the near and far amplitude. We compared the result from modeling to a synthetic seismogram response in Figure 8, which shows that there is an agreement between the depth trend based model amplitude response prediction and synthetic seismogram. For a hydrocarbon bearing reservoir, we expect to observe AVO Class III on top of the reservoir.

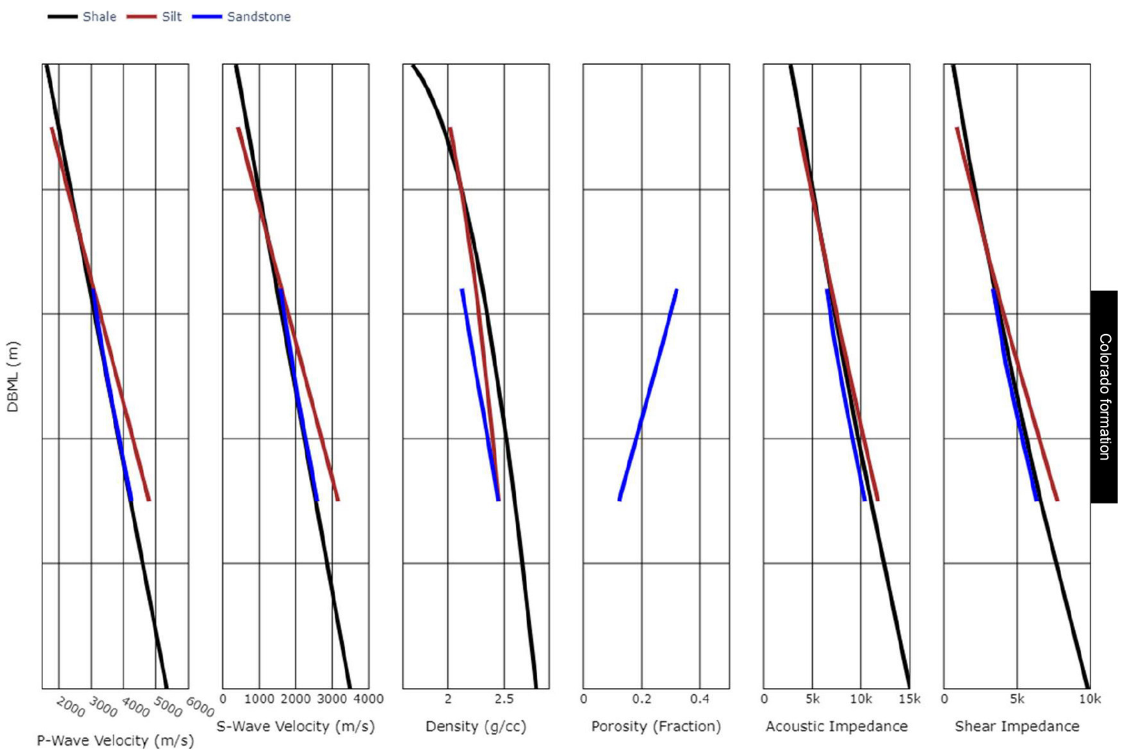

Figure 6. Depth trend summary for wet sandstone specifically calibrated for the Colorado formation (blue), shale(black) and silt (red). Y-axis is in depth below mudline (DBML).

CONCLUSION

In this paper, we showed the process of building a well data based predictive framework in support of frontier exploration. The predictive framework was fully integrated with petrology and basin modeling. The rock physics models were built for key lithologies, allowing us to model different scenarios of seismic full stack and AVO responses. Identifying the AVO anomaly class, comprehending the geologic risk factors, reviewing the seismic and rock physics data quality, and extensively analyzing multiple seismic anomaly features are all crucial tasks. Building this predictive framework helped us to better understand the regional rock and fluid properties and their seismic expressions. The scenario modeling indicated that it is possible to have an amplitude-supported play in the Colorado formation. Going forward, the presented integrated quantitative interpretation workflows can be applied at regional and prospect

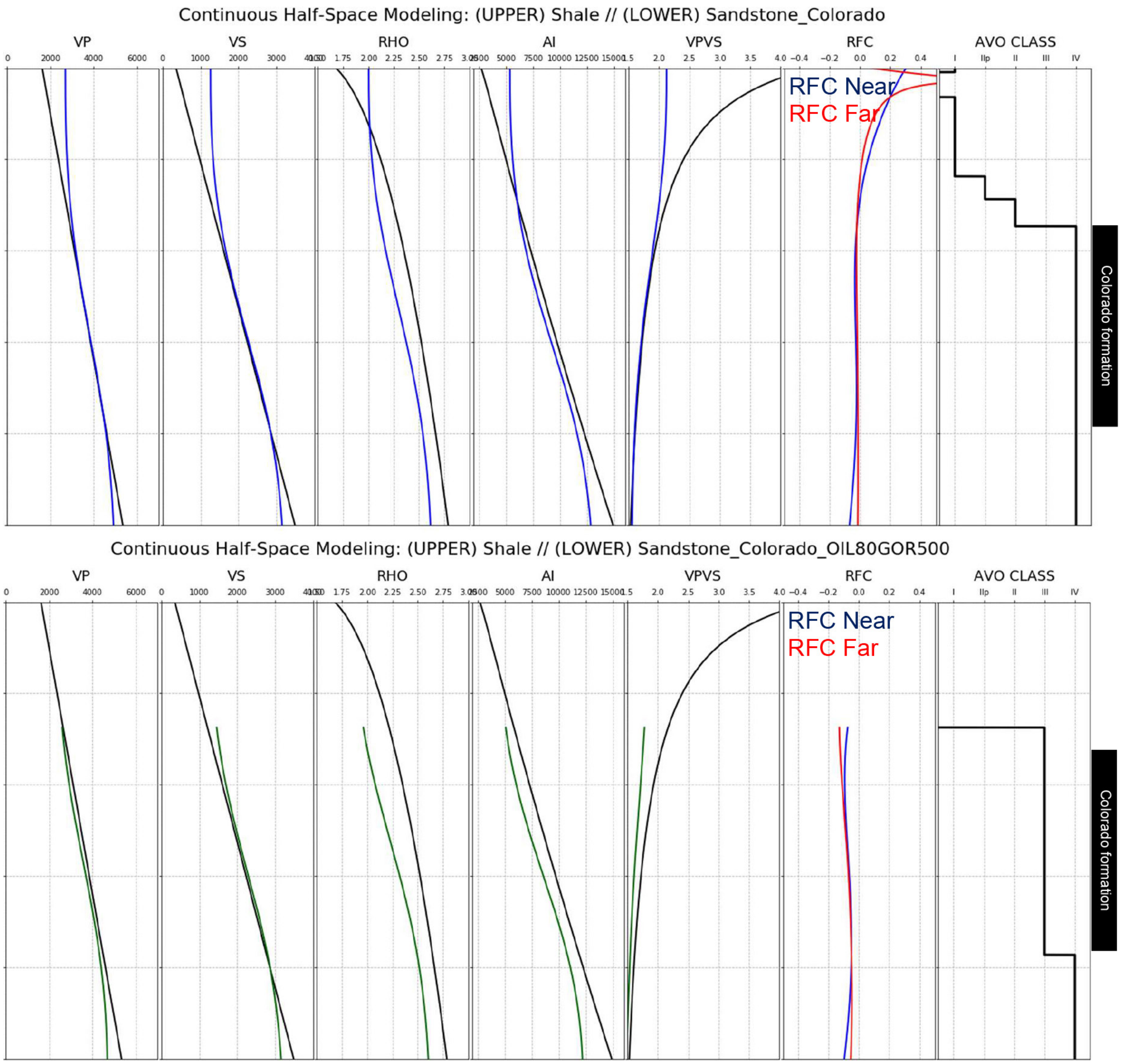

Figure 7. Depth trends with y-axis in depth below mudline (DBML). VP and VS unit are in m/s. RHO unit is in g/cc. (a) Depth trend showing shale in black and wet sandstone in blue. (b) Depth trend showing shale in black and hydrocarbon bearing sandstone saturated in dark green.

scales to reduce reservoir and pore-fluid uncertainties of prospective acreage. Exploration uncertainty can be reduced by interpreting and risking seismic anomalies related to leads and prospects using this solid predictive framework, ultimately improving exploration decision quality. However, the fact that in the here described case study all well calibration was fairly far inboard from the deepwater exploration targets and the inboard Colorado reservoir penetrations were significantly deeper than the expected outboard counterparts both cause a significant derisking uncertainty to remain. To lower the uncertainties in the probability of geologic success and the range of resource estimations, this method requires a systematic, objective, and consistent workflow execution. It further requires careful adjustment of the

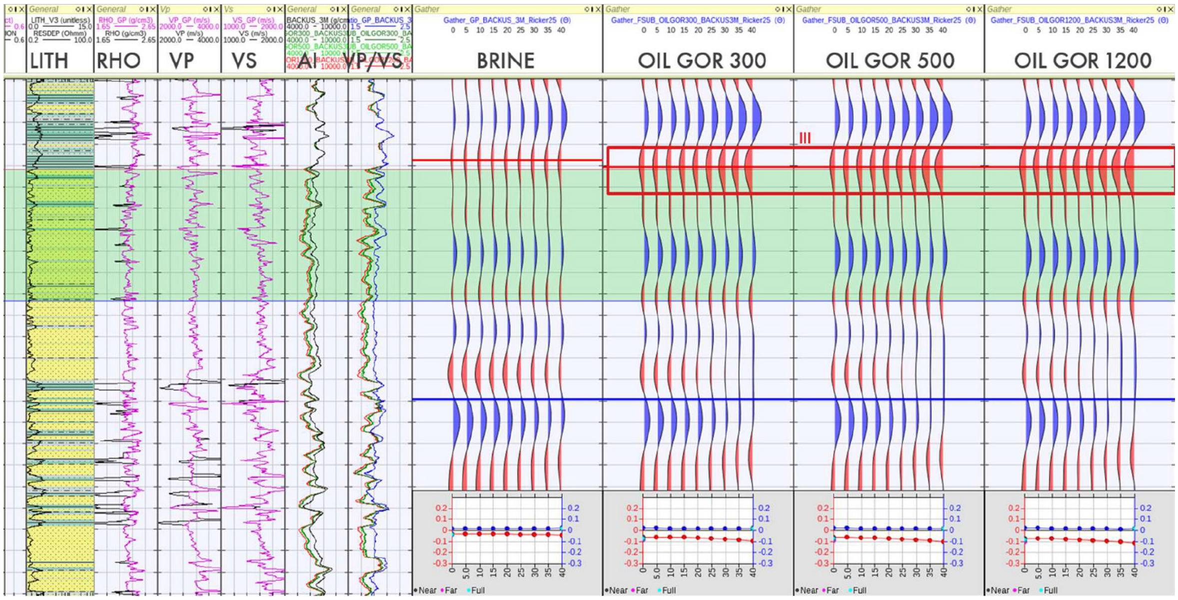

Figure 8. Features a well example with a synthetic seismogram response that is agreement with the depth trend based model amplitude response prediction. For a hydrocarbon bearing reservoir, we expect to observe AVO Class III on top of the reservoir.

model from the calibration to the prediction setting, taking possible differences in water depth, target depth, depositional environment, and burial histories into account. Leveraging seismic velocities in the prediction location can help to locally recalibrate the shale depth trends and to constrain the overall compaction state of the target section.

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