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| Please fill in your manuscript title. | Geostatistical Inversion In Carbonate Reservoirs To Map Reservoir Quality With High Predictability – A Case Study From Onshore Abu Dhabi |

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# Abstract


The Thamama group of reservoirs consist of porous carbonates laminated with tight carbonates, with pronounced lateral heterogeneities in porosity, permeability, and reservoir thickness. The main objective of our study was mapping variations and reservoir quality prediction away from well control. As the reservoirs were thin and beyond seismic resolution, it was vital that the facies and porosity be mapped in high resolution, with a high predictability, for successful placement of horizontal wells for future development of the field.

We established a unified workflow of geostatistical inversion and rock physics to characterize the reservoirs. Geostatistical inversion was run in static models that were converted from depth to time domain. A robust two-way velocity model was built to map the depth grid and its zones on the time seismic data. This ensured correct placement of the predicted high-resolution elastic attributes in the depth static model. Rock physics modeling and Bayesian classification were used to convert the elastic properties into porosity and lithology (static rock-type (SRT)), which were validated in blind wells and used to rank the multiple realizations.

In the geostatistical pre-stack inversion, the elastic property prediction was constrained by the seismic data and controlled by variograms, probability distributions and a guide model. The deterministic inversion was used as a guide or prior model and served as a laterally varying mean. Initially, unconstrained inversion was tested by keeping all wells as blind and the predictions were optimized by updating the input parameters. The stochastic inversion results were also frequency filtered in several frequency bands, to understand the impact of seismic data and variograms on the prediction. Finally, 30 wells were used as input, to generate 80 realizations of P-impedance, S-impedance, Vp/Vs, and density. After converting back to depth, 30 additional blind wells were used to validate the predicted porosity, with a high correlation of more than 0.8. The realizations were ranked based on the porosity predictability in blind wells combined with the pore volume histograms. Realizations with high predictability and close to the P10, P50 and P90

cases (of pore volume) were selected for further use. Based on the rock physics analysis, the predicted lithology classes were associated with the geological rock-types (SRT) for incorporation in the static model.

The study presents an innovative approach to successfully integrate geostatistical inversion and rock physics with static modeling. This workflow will generate seismically constrained high-resolution reservoir properties for thin reservoirs, such as porosity and lithology, which are seamlessly mapped in the depth domain for optimized development of the field. It will also account for the uncertainties in the reservoir model through the generation of multiple equiprobable realizations or scenarios.

## Introduction

The field, under study, is a mature faulted anticlinal onshore oil field, located near Abu Dhabi, with an area of around 1300 $km^2$. The field is producing oil from several stacked reservoir intervals of the Lower Cretaceous Thamama group of reservoirs, which are a cyclic sequence of porous and tight carbonates. Horizontal wells are being drilled in the reservoir zones to enhance development of the field. To ensure proper placement of the wells, it was vital that the facies and porosity be mapped in high resolution, with a high predictability, as the reservoirs were thin and beyond seismic resolution. This was achieved by performing pre-stack deterministic and geostatistical inversion in the field. The study also relied on effective integration of all available information and data. As the future development would extend towards the flanks of the anticline, a special focus was given to this area.

## General Geology of the Area

The Thamama Group was deposited in a large carbonate ramp system on the Arabian shelf and comprises some 1500-2000 ft of open-shelf to shallow-water carbonates. (Oswald et al. 1995; Basu et al. 2013). The producing zones are several stacked reservoirs of the Lower Cretaceous series deposited during the in the Barremian to Late Aptian age. The stratigraphy of the reservoirs consists of laminations of high porosity shelf carbonates (primarily rudstone, floatstone and grainstone) with sealing, non-porous argillaceous limestones (Oswald et al. 1995; Salahuddin et al. 2016). They display pronounced lateral heterogeneities in porosity, permeability, and reservoir thickness. The porosity deteriorates down flank, from the producing crestal part of anticlines, due to increased stylolitization and a general thinning of the reservoir zones (Azer 1993; Oswald et al. 1995). The reservoir zones within the Thamama Group are sub-divided into several smaller reservoir units separated by zones of very low porosity and permeability, referred to as dense zones (Strohmenger et al. 2007).

No syn-Thamama structural development is evident in the study area. The anticline developed in two stages related to later tectonic events. The earlier tectonic event was related to the regional ophiolites obduction along the Arabian shelf during the late Turonian, which lead to reactivation of older structures along the inner shelf. The final structural event corresponded to the Zagros tectonism and occurred during Late Tertiary (Oswald et al. 1995).

## Workflow

A robust and integrated workflow was established to characterize the thin reservoirs, within the stacked Thamama zones (Fig. 1a). The seismic and well log data were conditioned and checked for field-wise consistency. Approximately 30 wells were used as input to the study, which were vertical to near-vertical and had measured elastic logs. Pre-stack deterministic inversion was performed to generate elastic properties at the seismic resolution, which would guide the geostatistical inversion, to resolve the thin reservoirs. The conditioning and inversion workflows were optimized for the broadband seismic data.

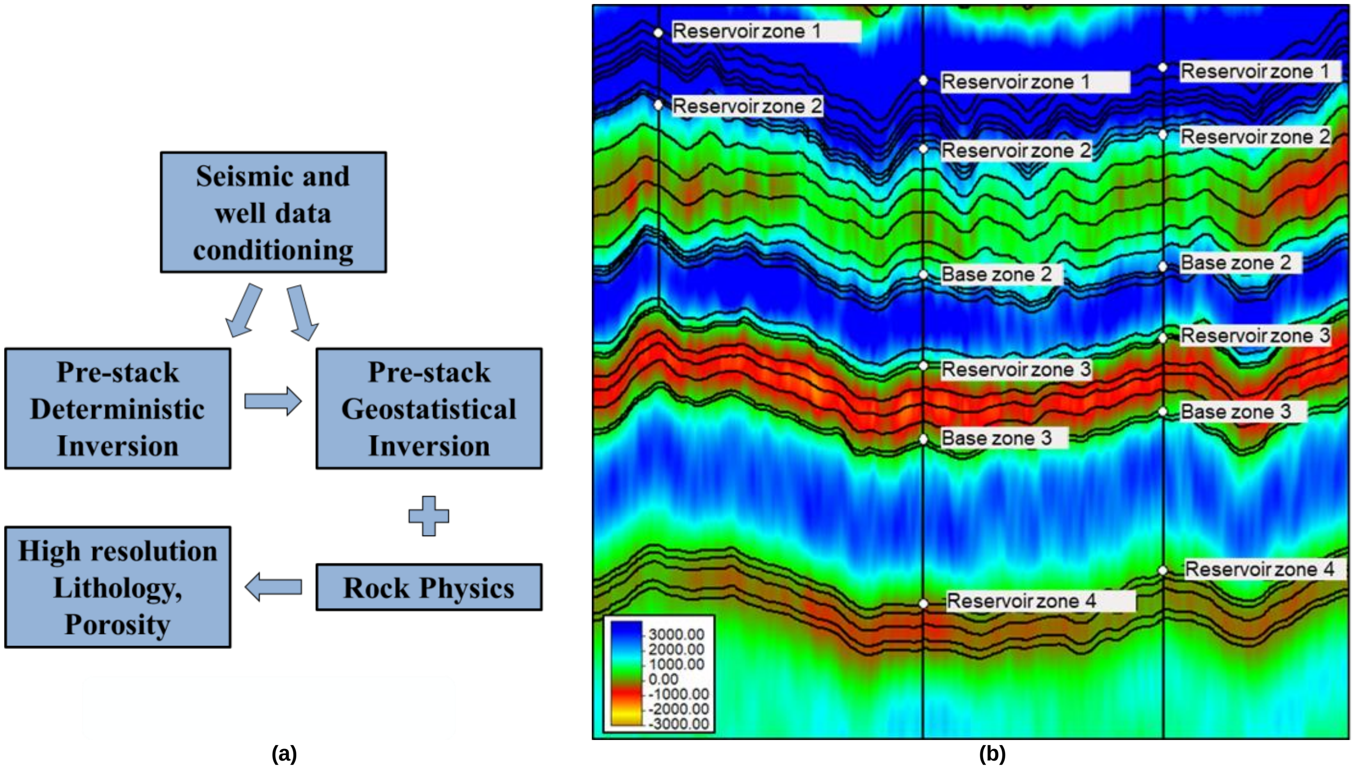


**Fig. 1: (a) Integrated workflow used in the study; (b) Reservoir zones on a section through three wells, with relative P-impedance (at seismic resolution) in the background. The surfaces within the reservoir zones define the thinner reservoir sub-units.**

Geostatistical inversion and rock physics analysis were performed considering the static model, such that the high-resolution results could be directly integrated into the reservoir modeling workflows. Hence, geostatistical inversion was performed in the structural grid of the static model, constrained by the seismic and guided by the deterministic inversion and variograms. A two-way velocity model was used to map the depth structural grid in the time domain, to perform the inversion. Detailed rock-physics analysis was performed to characterize the reservoirs and relate the elastic properties to petrophysical properties, such as porosity and water saturation. Bayesian classification was performed individually for each Thamama sub-zone to predict lithology, which was synchronized with the static rock-types (SRT). Initially, unconstrained inversion was tested by keeping all wells as blind and the predictions were optimized by updating the input parameters. The stochastic inversion results were also frequency filtered in several frequency bands, to understand the impact of seismic data and variograms on the prediction.

Several quality control (QC) steps were designed to validate the results of geostatistical inversion. Workflows such as unconstrained inversion were tested, where no well data was input and predictions were validated at the wells. The high-resolution elastic properties were also frequency filtered in several frequency bands, to compare with the seismic data. Additional blind wells were used to validate the predicted porosity and lithology, after converting the results back to depth domain.

As geostatistical inversion is stochastic in nature, it generated multiple equiprobable realizations of elastic and petrophysical properties. The high-resolution lithology and porosity were ranked based on the porosity predictability in the additional blind wells and the pore volume. Realizations with high predictability values and closer to the P10, P50 and P90 cases, in the pore volume histogram, were selected for further use in the static model.

The stacked reservoirs analyzed in this study were reservoir zone 1, reservoir zone 2, reservoir zone 3, reservoir zone 4, reservoir zone 5 and reservoir zone 6. The reservoir zone 2 and zone 3 were around 150 ft and 80 ft in thickness, respectively, and were within the seismic resolution. The remaining zones were around 35 to 45 ft in thickness and were beyond the seismic resolution. They were separated by thick dense zone of tight carbonates. The workflow was applied separately to each of the six reservoir zones, such that the parameters and inputs could be optimized individually. Separate static models were also used for each reservoir zone, to perform geostatistical inversion. Each reservoir zone was further sub-divided into smaller reservoir sub-units separated by thin dense zones of tight carbonates, with low porosity and permeability (Fig. 1b). The reservoir units were thin and beyond seismic resolution and could only be resolved through geostatistical inversion.

## Seismic and Well Data Conditioning

A full-azimuth high-resolution broadband seismic dataset was used in the study. The acquisition of this new dataset utilized the system with single-sensor geophone accelerometers, point source DX80 vibrators using the maximum displacement sweep design with an enhancement of low frequencies. The key specifications for seismic acquisition include a full azimuth high-density single-source/single-sensor data with 100m line spacing and 10m point spacing for sources and receivers, long offsets to 4km and a broadband vibroseis sweep that retains low frequencies down to 2Hz at -3db. The single-sensor single-source technology and the full azimuth dense geometry (5x5m grid) was designed for an optimum subsurface imaging for this survey. The relevant details of the acquisition system are shown in Table 1.

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| Source | DX-80 vibroseis, 80,000 lbt |
| Vibroseis sweep frequency | 1.8Hz to 120Hz |
| Receivers | Geophone Accelerometer (GAC) |
| Source station interval | 10m |
| Receiver station interval | 10m |
| Source lines / receiver lines interval | 100m |
| Maximum inline / crossline offset | 4.0km |
| Maximum absolute offset | 5.2km |
| Nominal fold | 1600 |

**Table 1: Key seismic acquisition parameters for broadband full azimuth land data**

The broadband seismic data was conditioned, to be fit for seismic inversion. The residual multiple reflections in the seismic data, were attenuated, leaving cleaner primary reflections. The gathers were flattened for better stacking power on stacked section. The gathers were converted to angle stacks and the stacks were aligned, using non-rigid matching (Nickel et al. 1999). The preconditioning workflow improved the seismic response of amplitude variation with angle (AVA) and returned consistent amplitude and phase spectra and better seismic to well ties.

Approximately 30 wells which were vertical to near-vertical were used in the study. All the wells had measured density and compressional sonic logs. Most of the wells had measured shear sonic log and the shear velocity was estimated for the remaining wells. The well log data was edited and checked for field-wide consistency and calibrated in order to be prepared for synthetic generation, wavelet estimation and seismic inversion. Multi-linear regressions were used to predict data for missing intervals and to replace erroneous log data, affected by large variations in the diameter and shape of the borehole and drilling fluid invasion. Borehole wash-out zones were defined based on the caliper log readings and invasion intervals were identified based on the difference in water saturation of uninvaded zones compared to flushed zones. Gassmann's fluid substitution equations (Gassmann 1951) were used to correct for the drilling fluid invasion. Conditioning of the sonic and density logs is critical to restore the logs to true formation response, prior to use in the seismic inversion study.

For shear velocity estimation, initially the hydrocarbon fluid effect was removed from the density and sonic logs, to prepare a prediction model for the wet shear sonic using zone-specific multi-linear regressions. Once the shear log with 100% brine saturation had been predicted, the hydrocarbon effect was added back using the Gassmann's fluid substitution equation. QC of the conditioned logs was done by comparing them with the standard rock physics templates. The dynamic range of the elastic and petrophysical logs was validated using histograms and field wide data consistency plots were generated (Fig. 2).

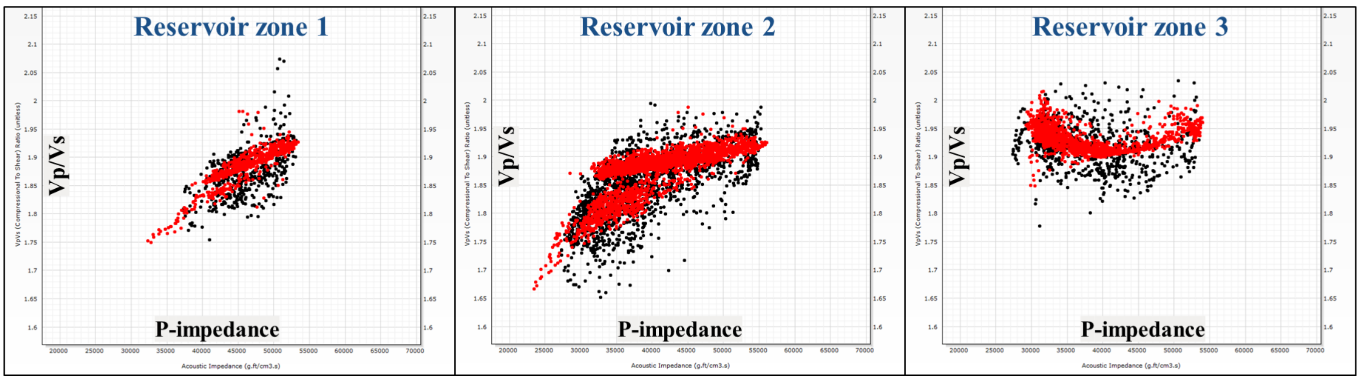


**Fig. 2: Shear estimation QC: P-impedance vs Vp/Vs cross-plots for reservoir zone 1, zone 2 and zone 3, with the Vp/Vs generated from measured shear log in black overlain by Vp/Vs generated from the synthetic shear logs in red. The synthetic shear was able to capture the reservoir heterogeneities.**

## Pre-stack Deterministic Inversion

Pre-stack inversion was performed on the conditioned seismic data to generate elastic properties of P-Impedance, S-Impedance, and density, for all the reservoir zones. As the low frequency information is missing in the seismic data, a low-frequency model (LFM) is required to be input into the seismic inversion process, as a prior model. The LFM, up to 4 Hz frequency, was built through population of well logs within in a structural framework, guided by the seismic interval velocity. Pre-stack simultaneous seismic inversion was performed using the angle stacks ranges of 10°-18°, 17°-25°, 24°-32°, 31°-39° and 38°-46°, with their extracted wavelets. The inversion results were validated based on the correlation between the well logs (resampled to seismic resolution) and the inverted traces. A high correlation was observed and the elastic properties derived from deterministic seismic inversion were used as guide models in the geostatistical inversion.

## Rock Physics

The petrophysical properties, such as lithology, porosity, and water saturation, are essential for reservoir characterization and are used to define the reservoir in a static model and calculate the hydrocarbon volumetrics. They are also input into the reservoir simulation workflow. Rock physics analysis is key to define the relationships between the elastic properties, generated through seismic inversion and petrophysical properties. Through rock physics, the inversion outputs of P-impedance, S-impedance, and