Prediction of Reservoir Properties by Integration of Seismic Stochastic Inversion and Coherency Attributes in Super Giant Ghawar Field

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SUMMARY

Oil production from the Arab D Reservoir in the super giant Ghawar Field is affected by extreme flow rates at the wellbore from very thin geologic intervals. Reservoir flood front management in these areas is extremely challenging since the reservoir fluids, including injected water, follow these pathways at unpredictable velocities. As the field matures it has become more important to understand the distribution of these features and the extent of their fluid communication. New types of data such as 3D seismic and borehole image logging, as well as more integrated methods of interpreting traditional wireline logs and production data are being employed. New mathematical methods of building geological models have also been utilized. The result has been a more sophisticated model of flow interaction between high permeability rock types and a fracture system whose impact was previously underestimated. Modeling the reservoir matrix heterogeneities and overlaying them with the fractures has yielded the most promising results. These changes suggest that calculations of OOIP (original oil in place) and ultimate recovery may be substantially different when taken into account. In the present study 3D stochastic models of reservoir attributes including, lithology, porosity, and permeability were developed to investigate the nature and distribution of high permeability in the Arab D reservoir. Wells logs, core analyses, and production logs constitute the hard data. Acoustic impedance from a stochastic inversion of 3D seismic data is used to constrain the simulation of well data. In addition, coherency attributes from the 3D seismic and the 3D acoustic impedance were used to interpret the subtle faults and fracture swarms that affected the fluid flow. Good correlation between flow and fracture-swarms highlight the interaction between high permeability lithologies and hydraulically active fractures.

INTRODUCTION

The Ghawar Field in northeast Saudi Arabia is the largest and most prolific oil field in the world. It is approximately 250-km north south and 30 km east west. The gross reservoir interval is approximately 300 feet thick at a depth of 6500 feet. Production is from the Upper Jurassic Arab-D shelf carbonate reservoir. The reservoir pressure is supported with peripheral water injection in both east and west flanks The Arab-D reservoir is a cyclical shelf carbonate which is extremely heterogeneous. Post-depositional dolomitization from carbonate diagenesis, cementation and fracture swarms distributed sporadically throughout the field (Daetwyler, Hagerty et al, 1987). The reservoir is being developed with a well spacing of approximately 1-km. Due to this well spacing in Ghawar, much of the interwell heterogeneity in the reservoir is under sampled. Thus the 3D seismic data along with the computed attributes from it play an important role in providing control between the wells for constructing reservoir characterization model for Arab-D.

The goal of reservoir characterization is to derive a model of interwell heterogeneity. This is achieved by integration and analysis of all available seismic data, core measurements, borehole image logs, petrophysical and dynamic data such as production index, pressure decline or water breakthrough information. The model is visualized and manipulated in three dimensions and provides a better understanding of the reservoir heterogeneities. Detailed, accurate reservoir characterization in three dimensions plays a vital role in developing and managing a reservoir and optimizing production.

Prediction of Reservoir Properties by Integration of Seismic Stochastic Inversion

Acoustic impedance computed from stochastic inversion of 3D seismic data provides the porosity and reservoir quality distribution between the well control points. Seismic data also provides the structural and stratigraphic framework for the subsurface reservoir. Faults and fracture swarms are interpreted from 3D seismic attributes like coherency, dip-azimuth, curvature analysis and calibrated using borehole image logs. It is critical to understand the fracture and fault distribution and their orientation to plan the drilling and completion of production and injection wells.

3D STOCHASTIC INVERSION

The study area was over 700 square km. in the Uthmaniyah sector in the Ghawar Field. A 3D seismic survey was acquired over the area, resulting in 192 fold 25x25-meter bins. The relative amplitude preserved processing sequence produced a post stack migrated 3D seismic volume, with a moderate to good seismic signal quality at the objective Arab-D event. This data volume constituted the input to the seismic inversion process. Both deterministic and stochastic inversion of the seismic traces was performed in order to estimate the acoustic impedance for modeling reservoir heterogeneity between wells. The seismic inversion process is defined in the flow chart in Figure 1.

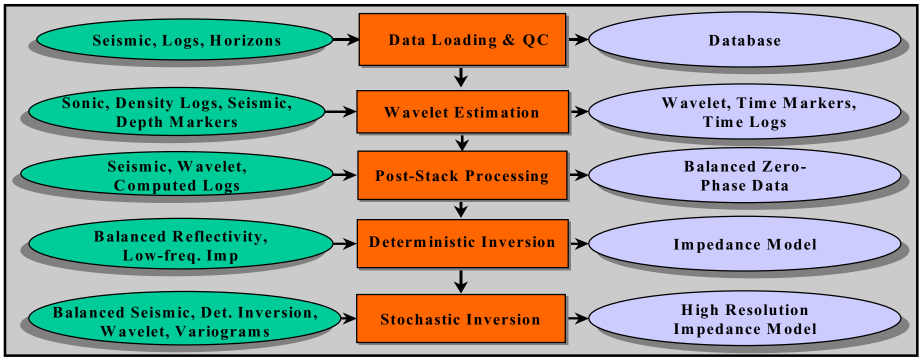

Figure 1. Workflow for Stochastic Seismic Inversion

The first step in the inversion process is the integration of the log data and seismic traces at the well locations. Within the study area, 125 of the 300 wells have sonic and density logs needed for correlating the well and seismic data. Reflectivity series and synthetic seismograms were generated from these well logs, and were used for performing the well to seismic tie, updating the time-depth relationships, and estimating a wavelet from the seismic data. The resulting "best" wavelet was used to design a phase-only filter to convert the seismic traces to zero-phase.

Prior to deterministic inversion, a sparse-spike estimation was applied to the zero-phase seismic data. This uses a criterion that minimizes the number of reflectors represented in the reflectivity series and produces a broadband reflectivity data. A model of the reflectivity envelopes, constructed from the reflectivity envelopes computed at the well locations, was used to scale the broadband reflectivity traces to realistic reflectivity values, as well as to compensate for any residual non-geologic amplitude variations. Similarly, a low-frequency impedance model was constructed from low-frequency impedance logs generated at the well locations. The scaled reflectivity estimates and low-frequency impedance models were input to the recursive deterministic inversion process, producing an absolute

impedance model with a vertical resolution similar to that of the input seismic data. This deterministic inversion result is used as input in the stochastic inversion process.

The stochastic inversion process simulates a large number of "equiprobable" impedance traces at every trace location (Haas and Dubrule, 1994). Reflectivity series are generated from these simulated impedance logs, and are convolved with a user-selected wavelet to generate a corresponding number of equiprobable synthetic seismic traces. The synthetic seismic traces are correlated with the actual seismic trace recorded at that location, and the impedance trace which produced the synthetic with the largest correlation coefficient is retained as the inversion result at that trace location. All seismic traces are visited in a random order, and the results from the inversion of an individual trace are then used as additional well (pseudo-well) data for subsequent inversion calculations along the random path. The inversion process thus integrates and honors log data and seismic data. In addition, the impedance model from deterministic inversion was used as a constraint on the simulated impedance.

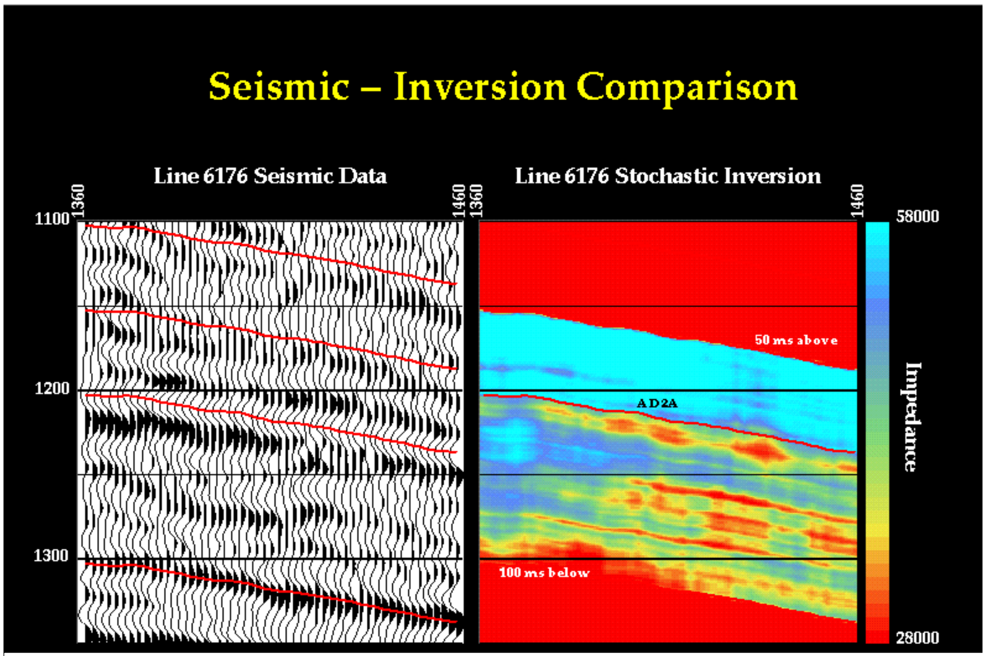

Figure 2 Results of Stochastic Inversion and the Seismic Traces

Figure 2 shows a comparison between the vertical resolution from seismic data with the stochastic inversion acoustic impedance data. The impedance in stochastic inversion realizations approaches a resolution close to log scale (on the order of 6 feet in this case). This high resolution is a result of forward modeling at a very fine sample rate (typically less than 1 ms), thus providing the increased vertical resolution.

Figure 3 shows a three dimensional perspective view of the impedance model derived from the stochastic inversion process.

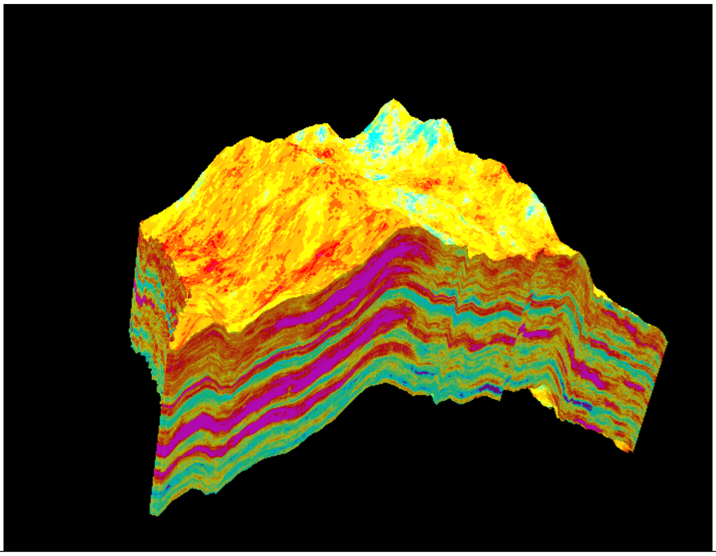

Figure 3. Impedance Volume from Stochastic Inversion

RESERVOIR CHARACTERIZATION BY DATA INTEGRATION

Variations in acoustic impedance computed from the seismic volume can be related to reservoir properties, such as porosity and lithofacies. Utilizing geostatistical techniques, seismic data and log data can be combined to produce a reservoir characterization model that honors both seismic and petrophysical data. In this study, the stochastic inversion impedance data were combined with well data to generate lithofacies and porosity models. The acoustic impedance computed in the stochastic inversion provided a much finer vertical resolution than the seismic amplitude or the deterministic inversion results.

The Arab D reservoir is composed of two major lithofacies - limestone and dolomite. Computed facies logs describe the distribution of these facies in the wells. Analysis of the univariate distributions of impedance as a function of lithofacies indicated an overlap in the observed impedance values of these two lithologies. This precluded the direct application of seismic impedance data to derive lithofacies models. Therefore, univariant distributions of impedance for each lithofacies within each reservoir layer were used to develop a probability function describing the probability of each facies as a function of impedance value within the respective reservoir layer. Using this probability function, it was possible to combine the seismic impedance data with the lithofacies logs to model the limestone and dolomite distribution within the reservoir.

For comparison, lithofacies models were built using only the well data. The dolomite distribution in models using well data show a lithofacies geometry markedly different from that derived from incorporating seismic impedance data in the modeling process. The influence of integrating seismic data appears as local differences in dolomite geometry.

As is typical in carbonates, porosity and impedance exhibit an inverse linear correlation - increases in porosity are manifested as decreases in impedance. In this situation, the seismic impedance data can be incorporated directly in the porosity modeling. Porosity was modeled by facies-dependant Gaussian simulation using acoustic impedance as a soft constraint. The difference in areal porosity distribution between models generated using only well log data versus models incorporating both well and seismic impedance data indicates that integration of seismic data produces a more geologically realistic porosity distribution.

The matrix permeability is modeled by a cloud transform of facies-based porosity to permeability, using a transform of log porosity to core permeability.

The seismic traces and the impedance volume were processed for coherency attributes and the resulting lineaments from the coherency were interpreted for faults and fracture swarms at the reservoir interval. These were calibrated with image logs from wells to verify the nature and orientation of the linear features identified from the seismic data. The dynamic data such as water cut, flow meter logs and production indices were also used to validate the permeability models. The effective permeability derived from this analysis using faults and fractures indicated areas of higher permeability that are consistent with patterns of water movement in the reservoir. In general most fluid flow is bottom drive and there is complex interaction between vertical fractures/faults and horizontal stratiform permeability (Pham et al, 1999). The permeability has been enhanced in the reservoir because of this interaction.

CONCLUSIONS

The integration of muti-disciplinery data has created a synergy in the three-dimensional reservoir modeling process. Structural and stratigraphic control from 3D seismic were amalgamated with the geological models and engineering data to arrive at reservoir model parameters that are supported by reservoir performance (Pham et al ,1999). Reservoir porosity and permeability distributions are enhanced between wells by the integration of seismic, petrophysical, core and fluid flow data. High permeability elements attributed to diagenesis and fracturing were identified. Adding these features into the reservoir simulation model should improve the history match and reservoir prediction capabilities. The effective permeability model developed honors diverse data types and helps to explain the dichotomy between core measured permeability and the permeability demonstrated from reservoir fluid flow performance.

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