# Reservoir simulation as a tool to validate and constrain 4-D seismic analysis

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The ultimate way to validate the interpretation of 4-D seismic analysis and inversion described previously in this series is the "ground truth": drill and recover bypassed hydrocarbons detected by 4-D seismic analysis. But to lower the risk that bypassed hydrocarbons might be missed, reservoir simulation techniques can be used to validate and constrain 4-D seismic interpretation before spudding a well.

Reservoir simulation is a low-cost solution to validate, independently, a 4-D analysis that uses legacy seismic datasets in which different orientation, processing and quality can potentially introduce noise into the interpretation. The main objectives of a reservoir simulation are to reproduce the drainage pattern of reservoir fluids during production, and provide guidance and financial assessment of future production. The added mission of reservoir simulation in 4-D analysis is to relate this drainage interpretation to changes in seismic attributes, especially seismic impedance.

Seismic impedance changes are directly related to both changes in density and velocity of wave propagation within the reservoir. During reservoir simulation, the parameters monitored and replicated by multiphase fluid flow equations are pore pressure, and oil, gas and water saturations within the pore spaces as they change over time, during production. Since changes in impedance, mapped by 4-D seismic interpretation, are directly related to changes in the above mentioned parameters, predicted changes in fluid saturations and pressure over time by the reservoir simulator can be qualitatively compared to the observed 4-D seismic impedance change, Fig. 24.

A quantitative comparison requires estimation of the difference between a seismic impedance map obtained from the reservoir simulation, and a seismic impedance map obtained from 4-D seismic analysis. A reservoir simulation-derived seismic impedance map can be estimated by using some form of the Biot-Gassman equations to compute seismic attribute changes associated with variations in pressure and fluid saturation during production.

### EI 330 CASE STUDY AREA

The Eugene Island (EI) 330 field has been one of the most thoroughly studied in the Gulf of Mexico (GOM). Located about 110 mi southwest of New Orleans, EI 330 has produced more than 600 million bbl of hydrocarbon liquids from a classic Gulf Coast rollover anticline, trapped against a large growth fault (see Fig. 4, Part 1)

Four vintages of 3-D seismic surveys have been acquired over the field,

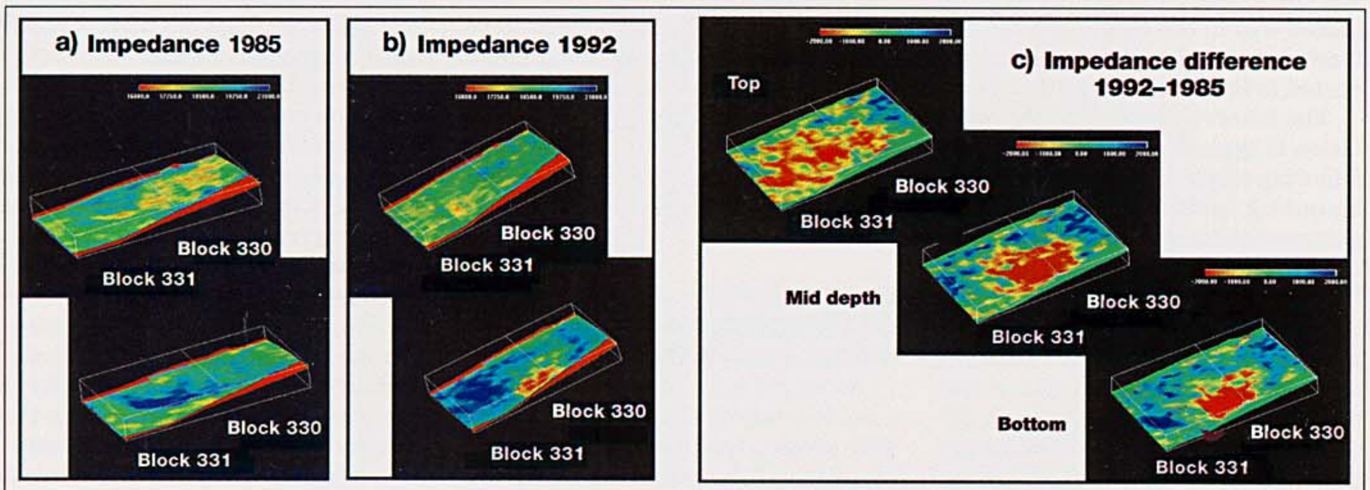


**Fig. 24.** Impedance maps over LF sand, Eugene Island 330 field, inverted from 3-D seismic surveys acquired in 1985 (a) and 1992 (b). 4-D time-lapse seismic differences observed between 1985 and 1992 (c) show a decrease in impedance (red), interpreted as an increase in gas saturation down-dip (to the left).

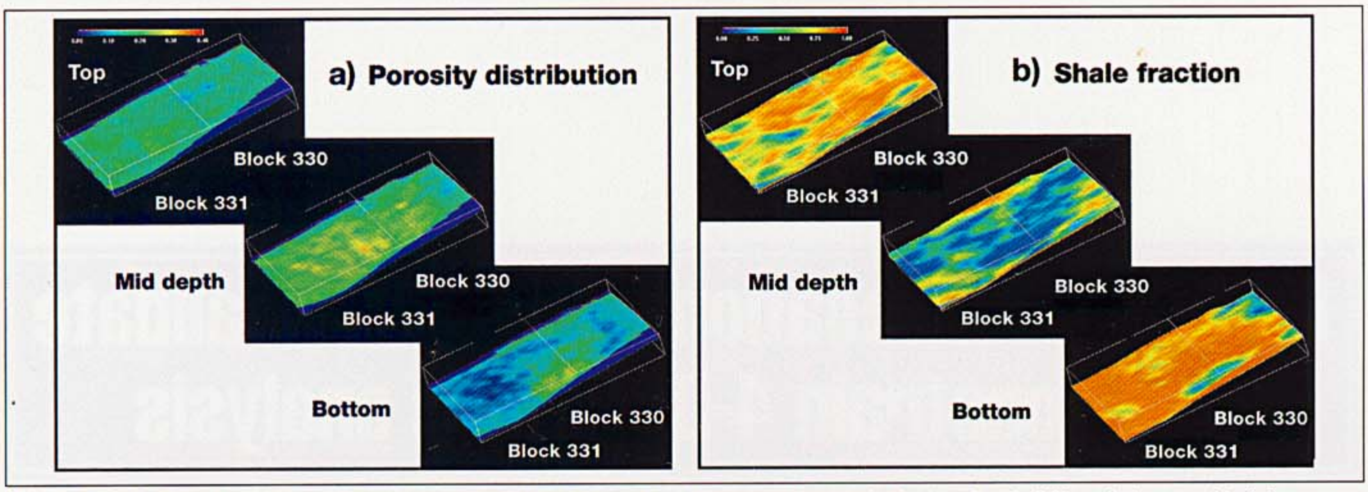


**Fig. 25.** Porosity (a) and lithology or shale volume fraction (b) derived from the 4-D reservoir characterization (see Part 4 of this series) are used to define properties of numerical reservoir simulation model.

which consists primarily of EI Blocks 330 and 331. The 1985 and 1992 surveys are used in this analysis. The reservoir simulation study is confined to the most prolific oil producer in the field, the LF reservoir, a Pleistocene deltaic sandstone thickening from about 80 ft toward the eastern closure in EI 330 to more than 120 ft downdip (to the west) in EI 331. The crest of the anticline is shaled-out.

## METHODOLOGY FOR RESERVOIR SIMULATION

Reservoir simulation is a powerful tool to understand and use to attempt to reproduce the drainage of oil, gas and water within a reservoir by matching production history and associated pressure changes. This is done by applying the equations of multiphase fluid mechanics in porous media to an oil-gas-water mixture within a 3-D numerical mesh, describing the geometry and properties of the rocks comprising the reservoir. Wells active during the production period are also placed within the mesh, and the perforated sections of the wells are connected to the adjacent mesh nodes.

The reservoir model for the simulation is typically constructed in the following steps: 1) reservoir geometry, bounding faults and internal compartmentation are defined by seismic-stratigraphic interpretation using the best 3-D seismic dataset available; 2) spatial distribution of the reservoir's physical properties such as lithology, porosity and permeability are estimated for the 3-D numerical mesh during the reservoir characterization process that involves geostatistics and geostochastic simulations using well logs as hard data and seismic attributes as soft data; 3) defining fluid-rock properties, e.g., bubble point, viscosity, capillary curves, relative permeability, from lab experiments such as PVT analysis of formation fluids; 4) defining initial and boundary conditions for the reservoir; and 5) adding production history and pressure changes from each well over time.

The simulation is then run repeatedly, and some refinements are made for poorly constrained parameters in the model (such as permeability distribution) until satisfactory matches to pressure and produced fluid history are computed. Such is the complexity of a petroleum reservoir that any realistic fluid flow simulation requires the knowledge of a vast array of chemical and geophysical parameters.

Unfortunately, at the present state of technological expertise of the industry, acquisition over time of all critical parameters for the reservoir simulation model is incompatible with the realities of economic production of oil and gas. Therefore, independent comparison of the simulation results to 4-D seismic impedance variations observed in the field offers great promise to significantly improve the accuracy of both techniques. Ultimately, they are both imaging the same thing, drainage of oil and gas in reservoirs.

## LF RESERVOIR CHARACTERIZATION/ MODEL PARAMETERS

As an independent test of the 4-D seismic interpretation loop, the reservoir simulation begins with construction of the 3-D mesh using the 4-D reservoir characterization described in detail in Part 4 of this series. Therefore, spatial resolution of the reservoir simulation and the 4-D seismic interpretation are the same, and qualitative comparison of results can be immediate. For computational efficiency (time and computer memory savings), and for fast primary model calibration, the mesh can also be upscaled in the first stages of the simulation.

Porosity and permeability distribution within, and surrounding, the reservoir are the key parameters necessary to be discretized in a 3-D mesh representative of the heterogeneity of the geological depositional environment, Fig. 25. Direct measurement of porosity and permeability can be obtained from lab analysis of well core and side wall formation tests. This data is very reliable, but concentrated in few locations. Well logs also provide valuable data for porosity estimations. However, it is very difficult to have evenly distributed, reliable data covering large segments of the reservoir.

To solve this problem, data mining techniques are used to find embedded rules among reservoir attributes for the reservoir-wide estimation of properties, such as porosity and permeability. For the LF reservoir, a clear relationship between permeability and porosity was obtained using lab measurements on core samples of sandstone, Fig. 26. However, the presence of shale, heterogeneously distributed within the reservoir, can reduce permeability considerably, without affecting porosity significantly, thus limiting the validity of such an ideal relationship only to the reservoir sands. Therefore, it is necessary to correct the permeability used in the model by including shale content (shaliness attribute). A simple formu-

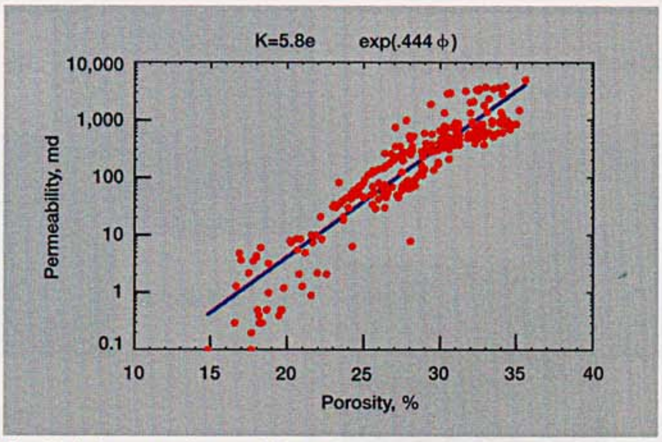

**Fig. 26.** Lab measured permeability and porosity data for LF sand samples. Logarithmic regression fit determines permeability variation operator in model from porosity distribution derived by reservoir characterization analysis in Fig. 25.

lation was used in the simulation presented here; it consists of applying the permeability vs. porosity regression from Fig. 26 to calculated porosity, and then weighting resulting permeability with the shale fraction.

Other critical parameters necessary for reservoir simulation are the fluid-rock properties of any oil, gas and water present in the porous rock reservoir. PVT data, measured routinely on fluid samples, defines the fundamental fluid properties and their variations as a function of pressure, temperature and gas-oil ratio. These properties include density, viscosity, formation volume factors, and the relative permeability curves for the fluid phases present in the reservoir. While these fluid-rock properties have a tremendous influence on production, relative permeability curves are the most poorly constrained parameters in this model, necessitating adjustments in preliminary simulations during a series of iteration loops designed to converge to the appropriate match with observed pressure and production histories.

**Initial conditions and production history.** Oil, gas and water production volumes are recorded routinely during the life of producing wells, and the most direct control of the validity of the reservoir simulation is its ability to reproduce these production histories. A realistic simulation of reservoir fluids drainage, in the time interval between two consecutive 3-D seismic surveys, also requires that the model starts from accurate initial conditions. These conditions are the oil, gas and water saturations and the pore pressure throughout the reservoir at the time of the acquisition of the first 3-D seismic dataset.

For the majority of 4-D projects, multiple 3-D seismic surveys have been conducted after the reservoir had already been exploited for some time, and hence, it is not possible to determine completely accurate initial conditions. Therefore, it is necessary to start the simulation at the onset of initial production, when oil, gas and water are assumed to be in gravity-controlled equilibrium within the reservoir. Initial conditions can be simply defined by the original depths of the oil/water and oil/gas contacts.

**Simulation of LF reservoir, EI 330 field.** Consider an example of the 4-D interpretation loop linking the reservoir simulation to observed 4-D

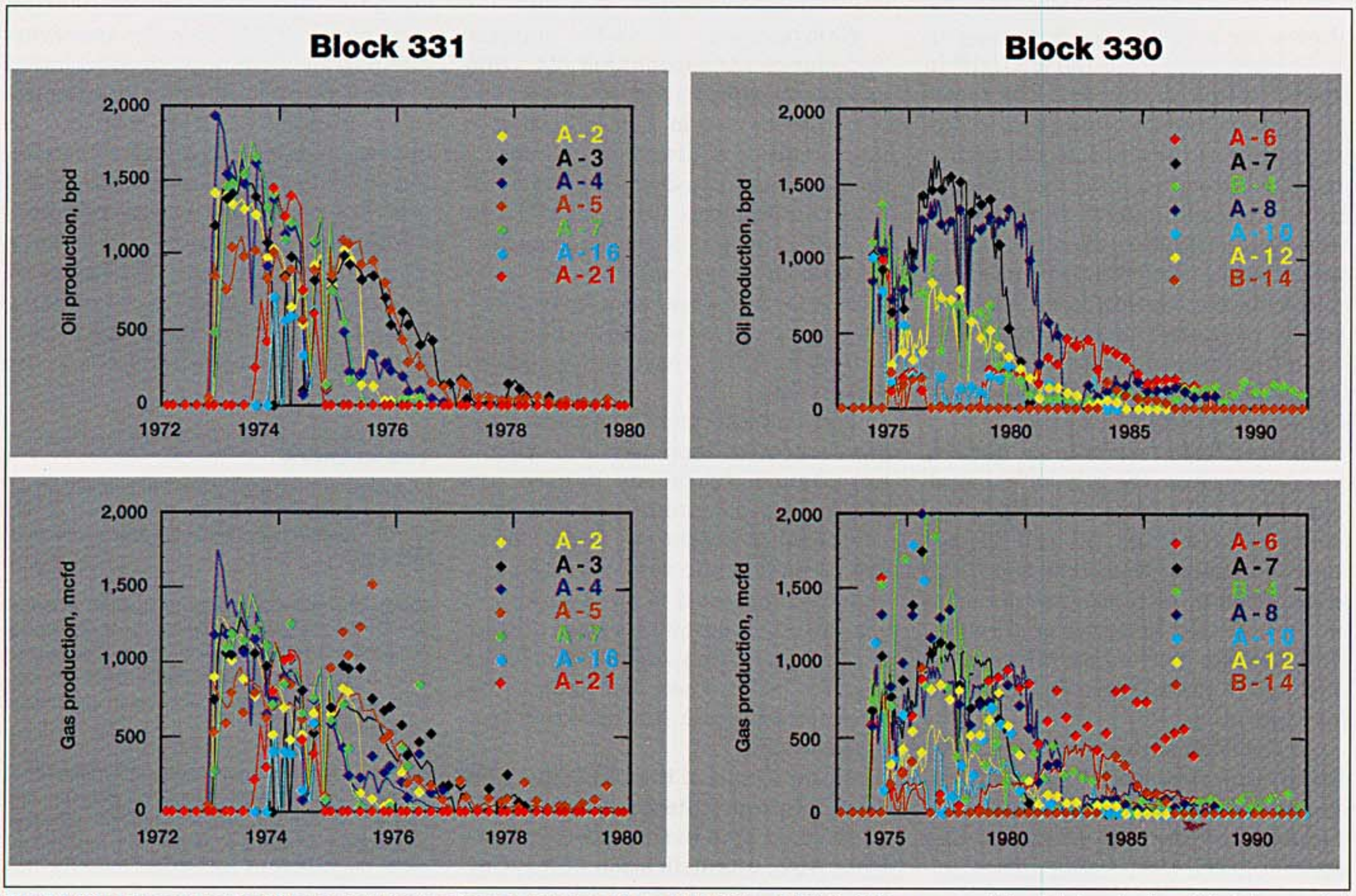

**Fig. 27.** Oil and gas production history match for all wells producing from LF sand in EI 330 and 331. Solid lines represent simulated production while dots are actual production values from wells.

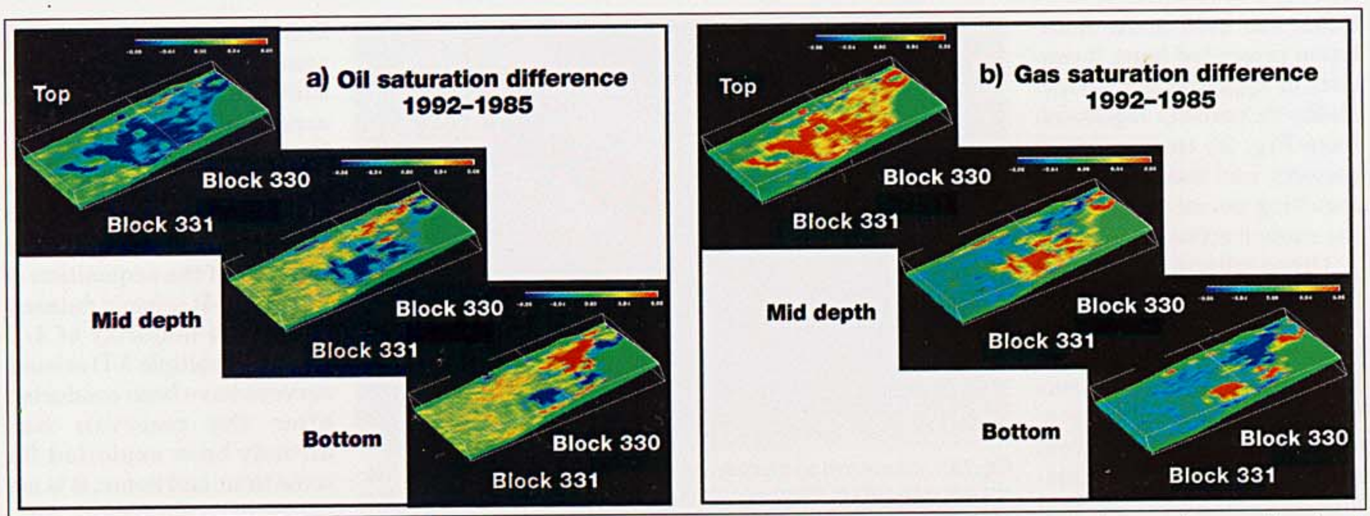


**Fig. 28.** Results of reservoir simulation in LF sand of EI 330 field. Difference in oil (a) and gas (b) saturation between 1992 and 1985. Increases in gas or oil are in red. Compare these reservoir simulation predictions with similar impedance difference patterns observed from 4-D time-lapse seismic impedance analysis in Fig. 24(c).

seismic impedance changes conducted by analyzing the LF sand in EI 330. Results presented here represent just the completion of the first loop that will be further refined later in this article.

This interpretation loop starts with observed 4-D seismic impedance changes resulting from analysis of the LF sand in EI 330 field. The difference between impedance maps inverted from 3-D seismic surveys recorded in 1985 and 1992, Fig. 24, shows an anomalous decrease in impedance over time DOWN-DIP in the LF reservoir (in red). The interpretation is that poor connectivity updip prevented the gas that was coming out of solution (as pressures dropped far below bubble point in the reservoir) from migrating up-dip to form a secondary gas cap. A major mission of reservoir simulation is to independently validate this interpretation, since the reservoir characterization from only one vintage 3-D seismic survey is used in the simulation.

In the EI 330 reservoir simulation, connectivity from the lithological analysis of the 3-D survey from 1992, and lab core data, Figs. 25 and 26, are matched against fluid flow equations in an attempt to reproduce pressure and production histories of all wells. Note that no production information was used in the 4-D seismic impedance interpretation.

At the time of the first 3-D survey (1985), the reservoir had been producing for over 13 years. To start the simulation within the 4-D time lapse interval (1985–1992) using correct, initial conditions, the actual simulation was initiated in 1972, from undisturbed, initial reservoir conditions.

Fig. 27 shows the simulated production vs. actual production rates of oil and gas in the 14 wells used in the simulation. In this simulation, excellent matches to both oil and gas production histories for wells in EI 331 and oil produced from EI 330 are reached. Reasonable agreement to gas production in EI 330 is also achieved, validating the simulation, overall, and making predicted oil and gas saturation changes consistent, Fig. 28.

Comparison of 4-D seismic impedance variations, Fig. 24c, and gas saturation variations from the reservoir simulation, Fig. 28b, confirms interpretation of the accumulation of a secondary gas cap down-dip in the LF reservoir between 1985 and 1992. In general, there is a good agreement between observed and reservoir-simulation-derived impedance maps. However, there are small-scale differences between the two independent 4-D analyses.

For example, both analyses show gas saturation increases and seismic impedance decreases, which are "striped," and running generally from southeast to northwest in the downdip portion of the reservoir. But the exact orientations of the stripes are somewhat different. A reconciliation of the two techniques would be required before a new well location can be settled upon to recover this bypassed gas.

A new iteration that adds the 1994 seismic interpretation is considered to be the next step in the interpretation loop. Also, quantification of the link between magnitude of impedance change observed, and extent of increased gas saturation through an analysis using Biot-Gassman equations, will better constrain the gas volumes likely to be causing the impedance anomaly.

## SUMMARY

This study completes, for the first time, the interpretation loop for the LF reservoir that proceeds from observed 4-D time-lapse seismic impedance changes, through prediction of oil/gas/water saturation changes derived from the reservoir simulation. Coupling the simulation to the 4-D interpretation loop results in a superior interpretation of bypassed oil location. Seismic modeling of this superior interpretation will provide a powerful new reservoir monitoring technology for the next century. The industry can only get better at recovery efficiency as these emerging technologies are perfected, one field at a time, over the next few years. ***wo***

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