4-D seismic reservoir simulation

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Oil companies face many production risks. The engineering technologies that are currently used (primarily 2-D map and graph based) allow discovery of production problems usually after they occur, so that a large amount of valuable resources are expended as reactions to contain problems as best as they can. With 4-D reservoir monitoring technology, production-reducing risks can be anticipated (and therefore proactively minimized) or in some cases completely avoided, e.g., decide to drill an injector well in a different location. In the future, even more risky and exceedingly challenging engineering problems face oil companies trying to efficiently drain difficult reserves, especially in the ultra-deepwaters of the world. This final article in the series will discuss seismic simulation, the remaining 4-D technology needed to integrate all the time lapse data into a dependable reservoir management tool.

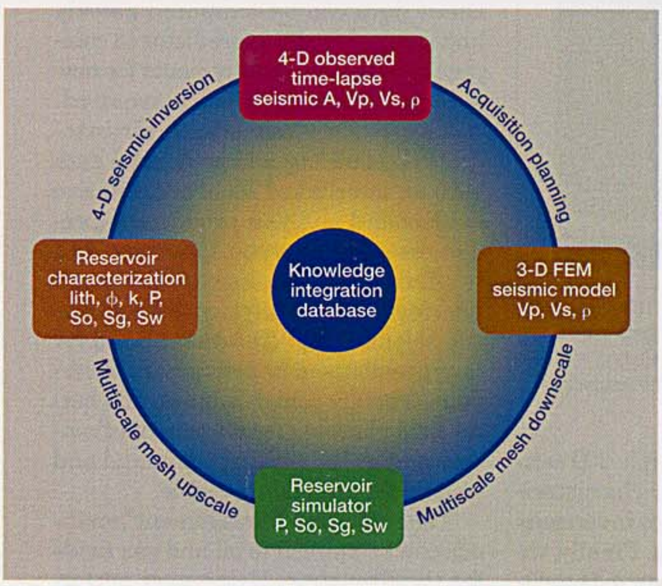

Fig. 29. Seismic reservoir simulation loop. Actual time-lapse 3-D seismic surveys enter the loop at top, travel through seismic inversion to reservoir characterization (left), then through mesh upscaling to the reservoir fluid simulator (bottom).Next, mesh downscaling to the 3-D finite element seismic modeler (right) and finally through an acquisition/planning of new data and drilling phase.

REDUCED PRODUCTION RISKS

All new technologies aim to lead to the production of more oil and gas for the end-user and more profit for the supplier. New developments in 4-D seismic acquisition and processing, reservoir characterization, reservoir simulation, and seismic modeling have each led to substantial improvements in recovery efficiency. That is, substantial technological progress has been made in getting more oil from old fields. Yet, these new data manipulation and interpretation tasks, in which both real and synthetic data are integrated, have not been inverted into a single, most-likely earth model. This nexus—analyses of real data and models of several species of geological, geophysical and engineering datasets—is just now becoming interpretable because computers finally have the capacity to perform the inversion.

New 4-D technologies will make use of vastly more, and diverse, volumes of data and models than ever before, to characterize subsurface fluid extraction. Models will simulate flow with the same resolution as subsurface seismic mapping so that the acoustic, thermal and pressure consequences of extraction can be accurately identified, and production efficiency maximized.

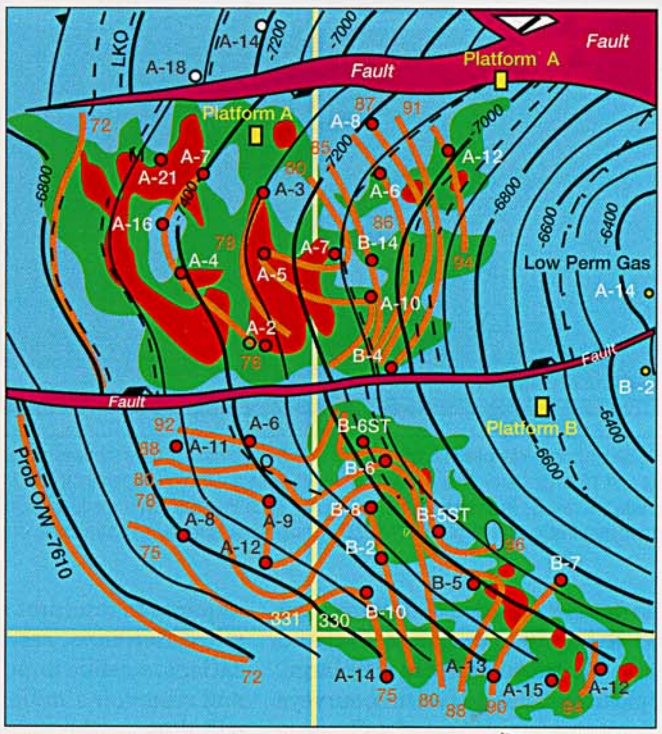

Fig. 30. Summary of 4-D seismic amplitude differences from 1985 to 1992 in El 330 field. Orange contours are timing of the watering events in wells. Green is sustained high seismic amplitude over time and red is actual brightening of amplitudes over time. Blue background is all reservoir thought to be water-wet. Fault block A is at bottom and Fault block B is at top.

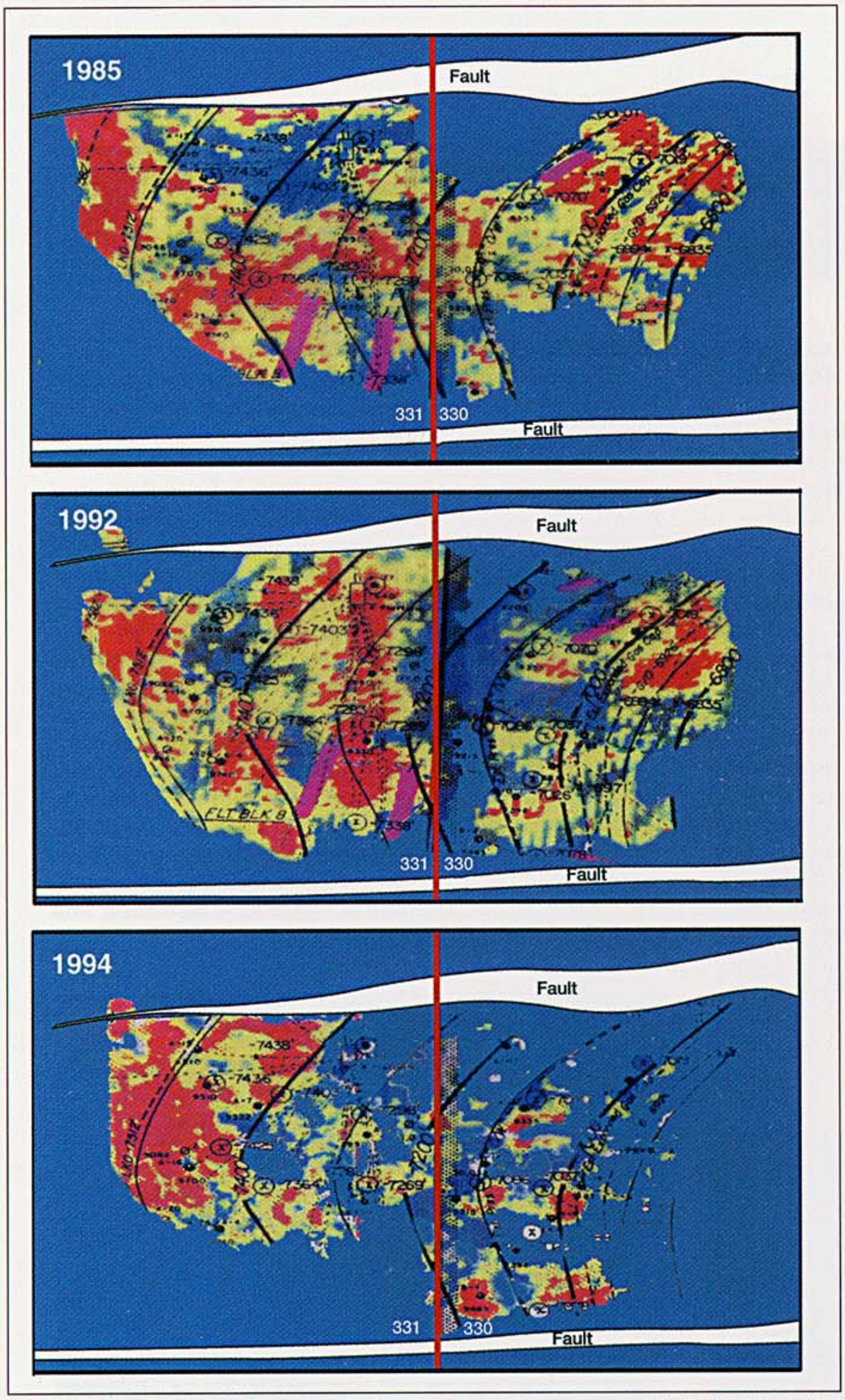

Fig. 31. Seismic impedances in Fault block B of EI 330 computed from surveys acquired in 1985 (top), 1992 (middle) and 1994 (bottom). Red is low impedance and blue is high impedance. Differences between top and middle images results in image shown in Fig. 34. Note that the low impedance zones move downdip over time, a characteristic sign of gas coming out of solution as pressure continues to drop in the reservoir.

The datasets needed to describe and predict the optimal drainage of oil and gas from the subsurface are very large. Multiple time-lapse 3-D seismic surveys that form the foundation of 4-D reservoir monitoring are just now becoming widely available to oil companies.

In Parts 1–5 of this series we have discussed the software workflow required to interpret multiple 3-D seismic differences, reservoir characterizations, seismic impedance inversions and reservoir simulations. Finally, we will discuss the remaining 4-D technology required to produce the fully integrated earth model of drainage—seismic simulation, Fig. 29.

The 4-D reservoir monitoring environment of the future will require a new form of reservoir simulator—a seismic reservoir simulator—designed specifically for the future planning of both production and monitoring programs. This is the last fundamental component necessary to integrate 4-D technologies into a predictive, and self-learning, reservoir management system.

4-D SEISMIC SIMULATION

Increases in computational speed and memory capabilities of supercomputers have made a 10-million-node, 3-D-finite-element, elastic model of 4-D seismic changes finally solvable. Even at that, only a reservoir stack of about 3,000×3,000×3,000 ft can be modeled accurately, though that size is expected to grow systematically in the future.

Full 3-D seismic modeling capability is required due to dispersion of seismic waves as they pass downward, then upward through stacked pay reservoirs. The simulator must be extremely computer efficient, so that it will run quickly on multiple nodes of a parallel supercomputer, or overnight on a ring of high-end workstations. Also, shear as well as compressional waves must be computed in a full, elastic solution so that attenuation as well as dispersion can be properly modeled.

To handle multiple timesteps (inherent in 4-D drainage mapping over time), the simulator must be customized and connected to 4-D data analysis software. Then, similarities and differences between field and synthetic data can be computed quickly and easily. Finally, a predictor to compute repeat-time requirements for new seismic field acquisitions is required.

The 4-D seismic simulator integrates seismic, log and production data with an interlinked set of quantitative models and analysis products to predict reservoir acoustic dynamics. And it offers a methodology to link engineering with geophysics. This closes the seismic loop! Iteration allows for improvements in understanding reservoir structure and dynamics, and better field planning for placement of sensors and wells, making command and control for oil fields possible.

"Total Quality Management" methods can be applied to oil and gas fields for the first time. Using past performance (seismic and production data) to predict future performance allows accurate planning for further seismic acquisition layout and timing, and well

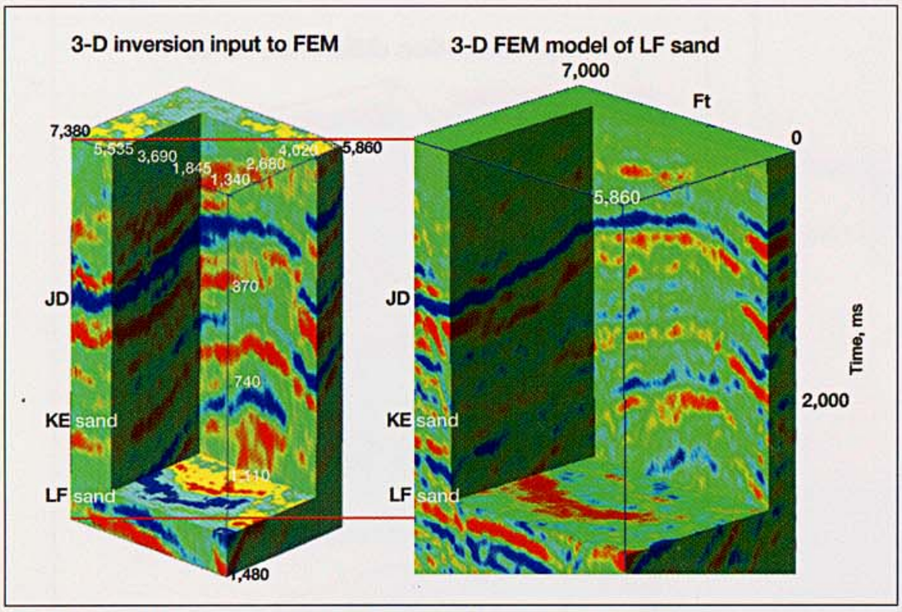

Fig. 32. Actual 1992 impedances for EI 330 (left) are fed into the 3-D finite element model to generate predicted seismic amplitudes (right). Note blue on left is low impedance and blue on right is low amplitude—an apparent phase reversal is evident.

remediation before major problems arise, see accompanying table.

REQUIREMENTS TO CLOSE THE SIMULATION LOOP

The computational efficiencies of 4-D seismic modeling, inversion, differencing, reservoir simulation and characterization codes have made it possible to predict and reproduce 4-D seismic and fluid flow changes observed in oil and gas fields during drainage. The 4-D simulation environment is keyed to the linkage of five different technologies:

1. Seismic inversion and geostatistical reservoir characterization link logs (hard data) and 3-D seismic observations (soft data) so that a volumetric prediction of rock physics and fluid parameters at each element of the volume, at each time of observation, is possible. Porosity, lithology, compressional and shear velocity, density, gas, oil and water saturation, and anisotropic permeability must be predicted at each element of a several-million-node mesh.

2. This static description of the field at fixed snapshots in time is then fed into a parallel reservoir fluid flow simulator that adds history matching of production and pressure changes from wells in the field to predict specific oil/gas/water drainage behavior over time.

3. Reservoir simulator results are then fed into the several-million-element mesh of a seismic model that predicts seismic response over time. To deal with dispersion and attenuation in stacked pay, and acoustically complex reservoirs (most oil fields), the 3-D model must be elastic. Five independent elastic constants are required to vary among each volume element over time to compute realistic synthetic waveforms.

4. Seismic model predictions must then be compared and differenced with observed changes in repeated 3-D seismic, and other physical properties of the field, using an "operator" to converge on a "most-likely" solution that satisfies both observations and models.

5. The "man/machine" workflow to support the computing infrastructure must closely parallel the developments and linkages of other tasks throughout all of the above.

4-D SEISMIC RESERVOIR MANAGEMENT

FEATURES	ADVANTAGES
Links rock physics and acoustics	Offers for the first time integration of all seismic log and production data with an interlinked set of quantative models and analysis products to predict reservoir acoustic dynamics. Offers a methodology to link engineering with geophysics.
Closes seismic loop	Iteration allows for improvements in understanding reservoir structure and dynamics as well as better field planning for sensors and well placement. Makes possible command and control for fields.
Quantitative approach to reservoir management	Best practice "Total Quality Management" methods can be applied across the board for the first time.
Predicts future/past	100s of synthetic wells can be placed. Planning for further seismic acquisition layout/timing and well remediation.

EUGENE ISLAND 330 TESTBED

To give an example of this 4-D seismic reservoir simulation methodology we have been examining, in this series, bypassed hydrocarbon reserves present in the EI 330 field. We began with a static description of rock/fluid physics at the time of the 1992 seismic shoot, and then proceeded to attempt to reconstruct conditions in the field from the beginning of production in 1972, with the last seismic acquisition in 1994 (Parts 1 through 5). This study started in fault block A of EI 330 field (Part 1) and proceeded to examine fault block B, Fig. 30.

As 3-D seismic technology has evolved, the spatial resolution of 3-D seismic data has greatly improved the resolution of reservoir characterization, particularly in lateral resolution. As the integration of seismic and wireline logging data has evolved, modern reservoir characterization has become more and more accurate and reliable. As a result, heterogeneity and discontinuities in the LF reservoir were revealed that can be seen as the change in impedance from production that occurred between 1985, 1992 and 1994, Fig. 31, see also Parts 1 and 2.

These 4-D seismic images of the LF reservoir were iteratively analyzed to compute changes of petrophysical and fluid parameters. Lithology, porosity, pore fluid pressure, permeability, and gas/oil/water saturation were estimated at each element of the volume over the life of the field. Our method consisted of a combination of well log data analysis for lithology determination, spatial cross-correlation computations between lithology and acoustic impedance, and a robust stochastic simulation technique. The conditional stochastic simulation technique we used was a Markov-Bayes method (Part 3).

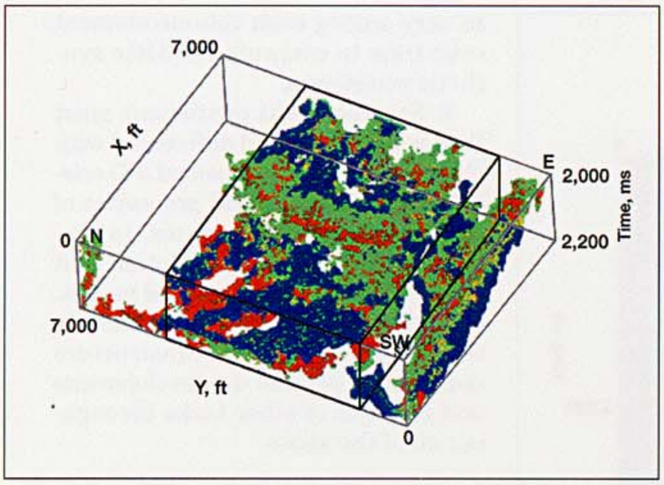

Fig. 33. Illustration of difference in 3-D finite element model seismic amplitude cubes computed for 1985 (not shown) and 1992 (Fig. 32). Red is increased, high amplitudes over time and blue is decreased amplitudes. Green areas are sustained, high amplitude intervals—compare to seismic impedance and computed gas saturation differences (Fig. 34) and to observed seismic amplitude differences (Fig. 30).

The bridge that connected these physical parameters with compressional (and eventually shear) velocity and density was 4-D seismic inversion. We tested several different inversions, including the Levenburg-Marquart method (Part 5, Fig. 24). Several scales of reservoir characterization and simulation mesh were tested, and the finding was that fine vertical scale was required to eliminate the ambiguities introduced by the mesh itself (Part 5).

Next, the reservoir characterization was input to a reservoir fluid flow simulator. We utilized two commercially available reservoir simulators (parallel Eclipse and parallel VIP) for prediction of time-dependent fluid flow required to history match previous production and pressure behavior of the field. A prediction of gas saturation values to compare with the impedance prediction was the result (Part 5, Fig. 28).

3-D seismic forward modeling was then used to compute a set of volumes with changes in seismic amplitude predicted at discrete time-intervals over the life of the field. Fig. 32 compares the observed seismic impedance volume in 1992 with the computed acoustic model, with drainage accounted for up to 1992.

We then differenced the model results computed for 1985 and 1992 and compared them with observed changes from the past, using the Lamont 4-D Software, Fig. 33. The similarities and differences between modeled and real acoustic responses within the reservoirs gives true predictive verification to the accuracy and precision of the model results. This difference between 1985 and 1992 seismic models should then be compared with the gas saturation difference over the same time interval from the reservoir simulator and the seismic inversion differences, Fig. 34. Only when these three representations of drainage in the LF reservoir from 1985 to 1992 have been reconciled can we believe in the accuracy of the 4-D predictions enough to place new 4-D seismic wells to drain bypassed oil and gas in EI 330.

SUMMARY

We envision the oil and gas company of the future to have integrated, computationally rigorous control centers for all reservoirs in all important fields. These simulation and control centers will be constantly updated and recomputed to react to new sensor data coming in from 4-D surveillance of the fields, and from instrumented boreholes that contain pressure, temperature, and acoustic transducers that detect changes in production activity in the field—all in real time.

The 4-D seismic simulator component of this control environment is a parallelized, 3-D, finite element elastic model that will be used to produce forward models that interpret seismic changes in the field as they occur during the production process. The models and datasets reside on distributed, computational resources in multiple locations, and both the data and computational cycles are accessed remotely, and invisibly, by the control center operator, who sees and interacts through what will likely be a new generation of 3-D virtual reality visualizers. The 4-D seismic simulation rationalizes differences between observed seismic changes and predicted changes over time to maximize production efficiency in the field. Only when we can write the equations that rigorously describe the production of hydrocarbons (the modeling) will we be able to realize substantial improvement in the recovery of oil and gas from true 4-D reservoir management. **wo**

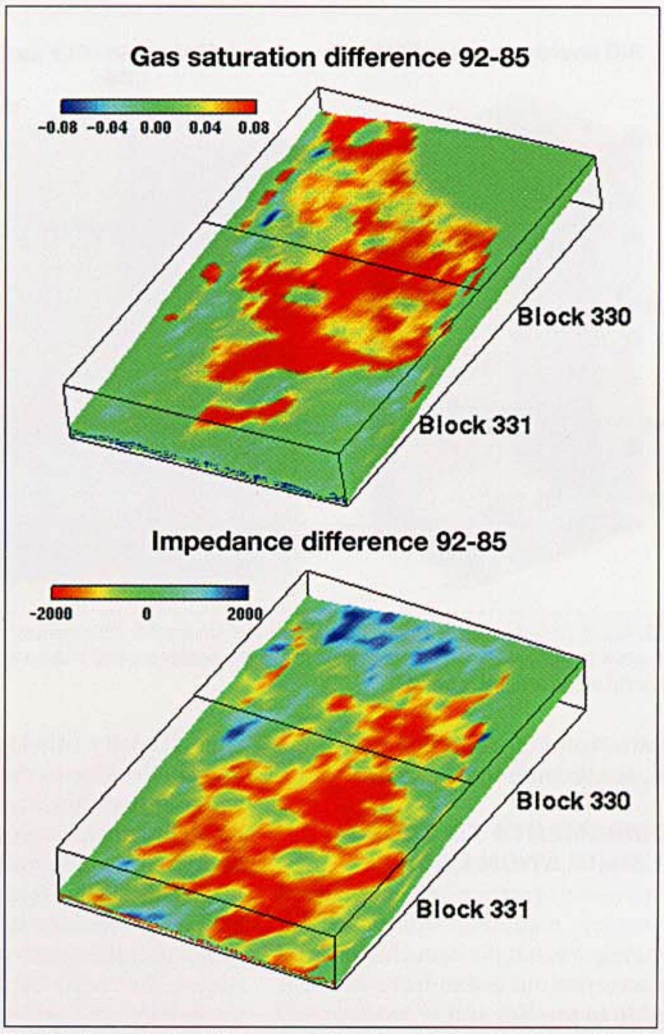

Fig. 34. Reservoir simulation computations from 1985 and 1992 result in differences (top) that predict regions of high gas concentrations (red). 4-D seismic observations of impedance changes (bottom) independently predict areas of high gas concentrations. Only when the locations of gas predicted by the seismic model (Fig. 33), reservoir simulation (top) and observed 4-D seismic impedance changes (bottom) agree can a new well to recover this bypassed pay be properly sited. Further iterations of the 4-D seismic simulation loop are required in EI 330 field.