Inversion of 4-D seismic changes to find bypassed pay

Wei He, Roger N. Anderson, Albert Boulanger, Yu-Chiung Teng, and **Liqing Xu,** Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York; and **Randall Neal** and **Billy Meadow,** 4D Technology, Inc., Dallas, Texas

4-D differences between seismic amplitudes derived from multiple vintages of 3-D seismic reflection surveys can be used to identify hydrocarbon migration and drainage pathways in oil and gas fields. As we have seen in parts 1–3 of this series, 4-D rapid analysis results in a match between surveys, and a general view of drainage over time within reservoirs. The next step is to quantify the changes over time, in terms of oil, gas and water saturations, and derive a specific view of drainage. Then the value of 4-D can be realized by the operator through the placement of wells to recover new oil from old fields.

INTRODUCTION

The steps to quantitative processing come through the introduction of

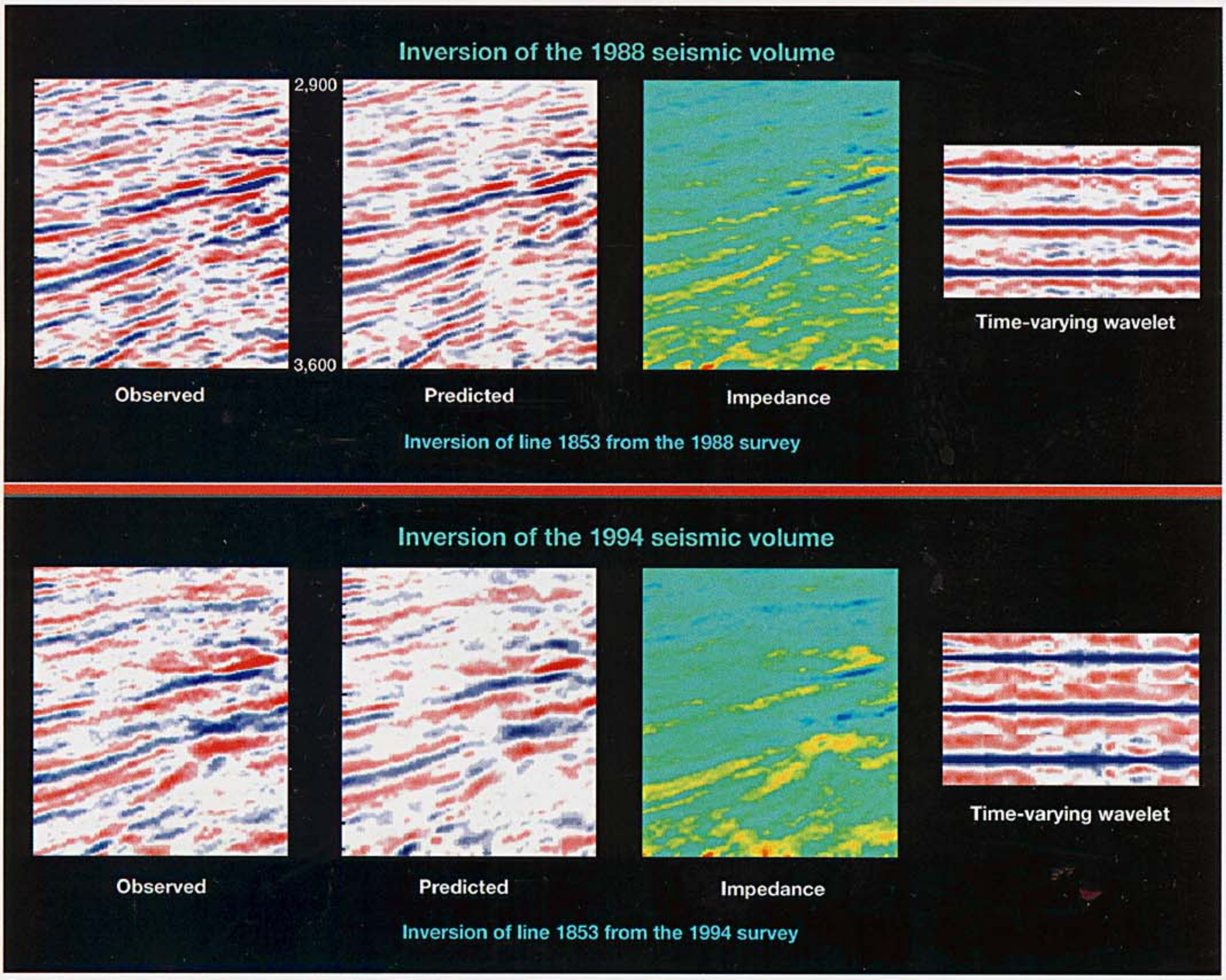

Fig. 18. Inversion of a collocated seismic section extracted from a set of time-lapse seismic surveys.

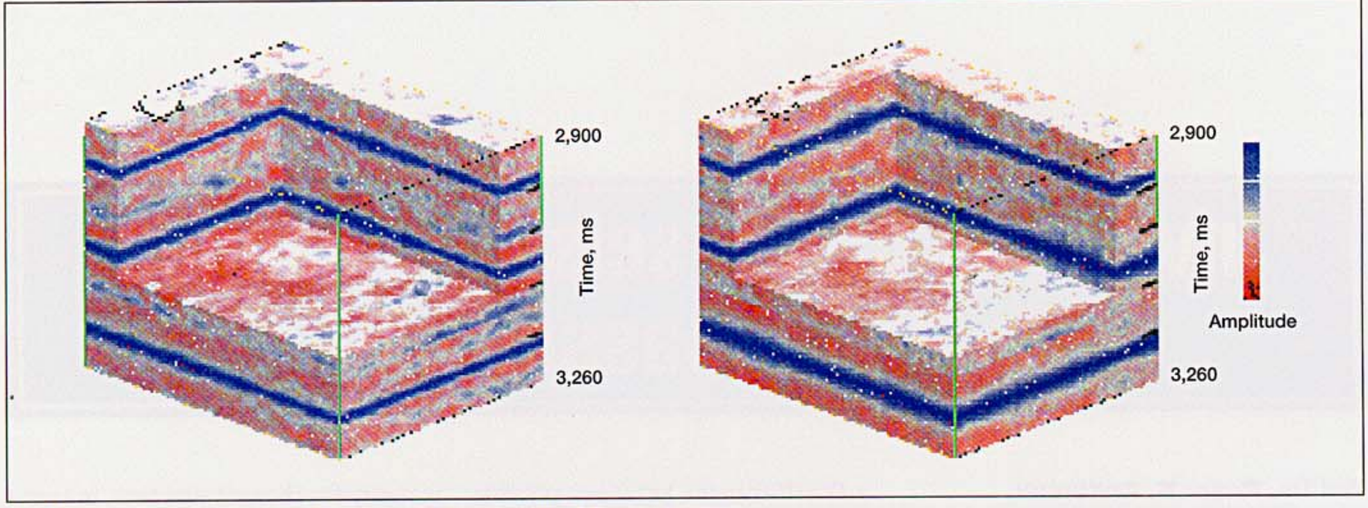

Fig. 19. Estimated data processing difference cube when inverting 4-D seismic dataset.

seismic inversion and reservoir characterization into the 4-D world. The integration of high lateral resolution from inverted acoustic impedance and high vertical resolution from sparsely-distributed, but highly sampled well logs is used to achieve this quantitative 4-D reservoir characterization picture of changes in oil and gas fields over time. However, to achieve this improvement requires much computational effort, as well as time.

The 4-D changes in acoustic impedance inverted from seismic waveforms make possible the connection to petrophysical property changes observed in wells. Unlike seismic amplitude, which measures relative changes between layers of the earth, acoustic impedance (velocity times density) can be directly associated with lithology, porosity and saturation of the reservoir. Thus, 4-D seismic inversion is the bridge connecting seismic differences to time-dependent changes in oil and gas volumes within reservoirs.

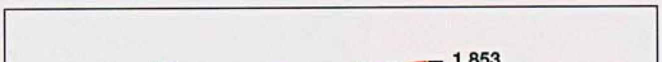

Fig. 20. 4-D impedance difference is region-grown to illustrate impedance changes in several turbidite sand reservoirs. Increase in impedance is shown in blue, indicating drainage. Decrease in impedance is show in red, indicating gas dissolution due to pore pressure decrease.

WHAT IS INVERSION?

Geophysical inversion is the estimate of a set of physical parameters which provides the best-guess description of an earth model based upon all the data provided to the inversion. That is, we try to derive a best-fit model to the complete set of observations from a field, using the inversion to sort out a most-likely answer from among inconsistencies among all the geological, geophysical and engineering data. A typical inverse problem matches a forward model, which is predicted by theory, and an inverse model, which finds the minimum misfit function between observations and theoretical predictions from the forward model , Fig. 18.

Why 4-D inversion? The inversion of seismic waveforms to derive rock and pore fluid elastic parameters is perhaps the most challenging problem encountered in the E&P world. Recently, many algorithms developed in applied mathematics and statistics have been successfully applied to seismic inversions as searching techniques. 4-D seismic inversion is new on the block, and adds to the computational complexity by modeling changes in acoustic impedance caused by fluid migration and drainage in the subsurface over time.

In forward modeling of the 4-D seismic response, a time-variant, dynamic wavelet extraction is specifically designed to eliminate differences caused by most of the acquisition and post-stack seismic processing variations among the various 3-D seismic datasets used in the 4-D analysis. Therefore, the use of inversion for determination of 4-D acoustic impedance volumes can quantitatively increase the accuracy of fluid drainage identification.

4-D inversion work flow. Acquisition and processing differences—the noise—must be corrected for, without removing changes caused by reservoir pressure and fluid saturation changes within reservoirs—the 4-D signal. To meet this need, 4-D software must provide a seismic inversion method to invert time-lapse, 4-D seismic volumes that provides the capability of normalizing overall seismic volume with-

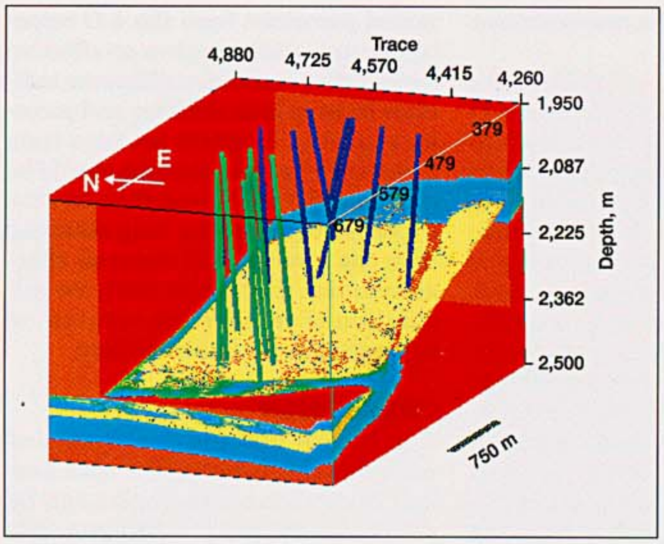

Fig. 21. Shale-volume fraction of LF reservoir estimated using stochastic simulation technique. Regions colored in gold or red have low shale content. Well data used to constrain the simulation are also illustrated.

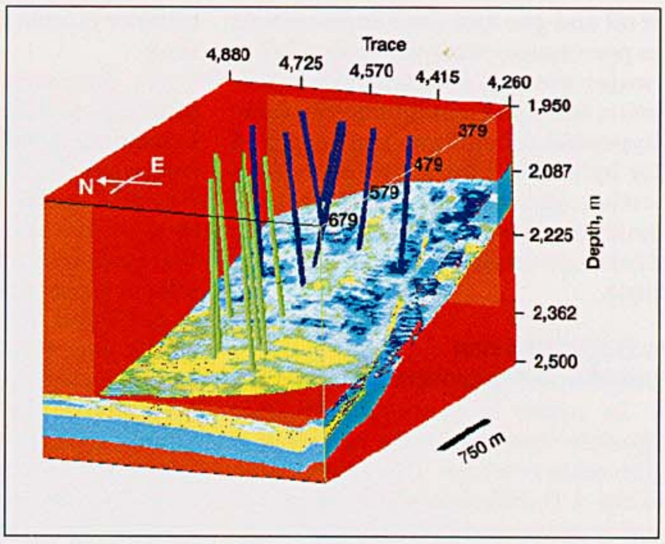

Fig. 22. Effective oil saturation (inside cube) of LF reservoir plotted with shale-volume fraction cube (on the sides of the cube). Regions colored in gold and red have high oil saturation, and blue indicates low oil saturation.

out affecting real, fluid-derived changes within the reservoirs themselves.

The starting model is the long-wavelength component of the impedance-vs.-depth function for a field, measured by density and velocity logs in wells. The inversion first estimates a wavelet approximation for each individual input trace, and uses a convolution model to predict each seismic trace. Many inversion algorithms exist for this step. The same set of parameters, especially the constraints, are then applied to the next time-lapse survey; and the resulting impedance volumes are output into the same region growing and differencing modules previously used in the rapid analysis workflow (see 4-D—Part 3).

Steps unique to 4-D inversion. The elimination of changes caused by seismic data acquisition and processing differences between 3-D surveys is the real key to successful 4-D investigation of drainage changes in reservoirs. Frequency and phase matching within the inversion of multiple 3-D seismic datasets does not involve cross correlation and filtering (as described in 4-D rapid analysis in Part 3) and it is not interactive. Instead, the 4-D inversion quantitatively matches the surveys through use of a dynamically-extracted seismic source function unique to each trace of each survey.

However, since seismic amplitudes are relative, amplitude normalization must be performed before starting the inversion. Then, synthetic seismograms generated from sonic and density logs from wells in the field are used to determine the scaling factors for normalizing seismic volumes.

An important advantage that 4-D has over 3-D is that wells have produced known volumes of oil, gas, and water over a known time from known reservoirs. This production history is linked to the 4-D seismic through well log petrophysical properties.

It is best to exclude some wells from the initial model building. Such excluded wells may subsequently be used to estimate the level of uncertainty in the inverted 4-D drainage results. In the example in Fig. 19, the inversion yields a cube of acquisition and processing differences between traces within each dataset derived from the extraction of a source wavelet at each trace from migrated, previously deconvolved, 3-D post-stack datasets. As can be seen, there are differences between volumes that can be quantified and corrected for by the inversion to seismic impedance *before* region-growing and differencing.

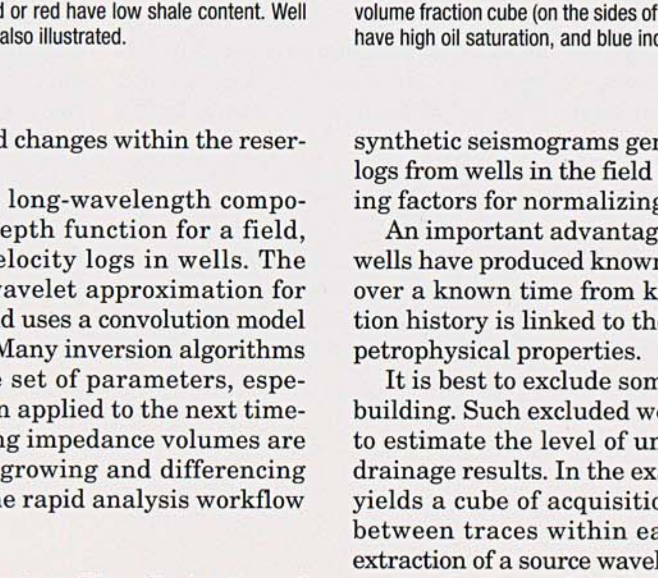

Fig. 23. Effective oil saturation is the product of porosity and oil saturation. The average effective oil saturation map of the LF reservoir shows remarkable similarities to bypassed hydrocarbons obtained from the 4-D acoustic impedance analysis.

4-D impedance differences. "Most-likely" impedance cubes are then output from the inversion, fed into the region grower and differences between the time-lapse images are computed, Fig. 20. In soft-rock environments, these changes might be from increases in the concentration of natural gas in pore spaces of the reservoir rock as with the formation of a secondary gas cap. Alternatively, increases in impedance over time might be caused by the drainage of oil and gas and their replacement in pore spaces with water and brine (water sweep). In hard-rock reservoirs, the reverse might be the case. Bypassed oil and gas are searched for by looking for sustained areas within grown regions that have maintained *low* impedances despite drainage from known wells over time.

4-D RESERVOIR CHARACTERIZATION

In order to quantify seismic changes observed by the inversion, a fine-scale reservoir characterization of the 4-D differences is needed. For many years, reservoir characterization has played an essential role in the initial stages of production planning. Reservoir simulations used by developmental geologists and reservoir engineers to optimize hydrocarbon production, require these reservoir characterizations.

Traditionally, only 3-D seismic, wireline logging data and pressure/production histories have been used in reservoir characterization. However, such static reservoir descriptions cannot easily predict the 4-D, dynamic behavior of hydrocarbon reservoirs over time.

As an example, consider the drainage pattern derived from 4-D impedance differences converted into components of lithology, then porosity and finally, fluid saturation. We first derive the lithology distribution because it is the dominant factor affecting acoustic impedance, and it is assumed not to change significantly over time within a reservoir. Lithology interpreted from well logs is treated as the most reliable determinant in reservoir characterization (the hard data). Lithology derived from inverted acoustic impedance is treated as imprecise data (the soft data), and a most-likely shale volume fraction is derived from both acoustic impedance volumes, Fig. 21. Wellbores were plotted in green and blue to cross-validate the simulation results.

The porosity volume for each time-lapse seismic impedance volume is then calculated by correcting the impedance to eliminate effects of variations in shale volume fractions assuming water is the only fluid present, Fig. 22. Subsequent differencing of estimated porosities from the 4-D reservoir characterization gives an effective hydrocarbon saturation difference indicator because both lithology and porosity should be constant between time steps. Only fluid saturations should be changing, Fig. 23. We can then derive a bypassed hydrocarbon map obtained from the inverted 4-D reservoir characterization that is now ready for calculation of recoverable volumes of bypassed pay for future drilling.

CONCLUSION

It is clear that the combination of reservoir characterization with new 4-D inversion technologies can be used to achieve much higher economic recovery rates because reservoir petrophysical properties, such as lithology, porosity, pore pressure and permeability, rather than seismic response, are the dominant factors that control hydrocarbon production. 4-D seismic data, when integrated with well logs, pressures and production histories, gives a quantitative estimate of remaining reserves. The next step is to integrate all this with reservoir simulation, the topic of Part 5 of this series. ***WO***