

Seismic time-lapse surprise at Teal South: That little neighbor reservoir is leaking!

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Why perform time-lapse seismic monitoring? Is it to verify the reservoir model? No! We should conduct time-lapse seismic surveys in order to find out what is incorrect in the reservoir model, in a way similar to the production history matching familiar to reservoir engineers as they look for improvements to the model. This being the case, it is difficult to determine in advance of monitoring just what it is we should be monitoring. Thus, surveys designed specifically to test one feature of a reservoir model may be missing other important features. In this paper, we present a set of very surprising results from the Teal South time-lapse multicomponent (4-D/4-C) study, in Eugene Island Block 354 in the Gulf of Mexico. We will show that time-lapse seismic observations have revealed that an undrilled reservoir near a producing reservoir is exhibiting time-lapse changes consistent with expansion of a free gas phase, and that this implies that oil is being lost through the spill point, never to be recovered, even if that reservoir is eventually drilled for production.

The Teal South 4-D/4-C study has provided seismic data sets covering three different times: one time prior to production ("legacy" streamer data), and at two times during production (phase I and phase II, each using four-component ocean-bottom cables). The project, initiated by Texaco, has been continued through a consortium organized by the Energy Research Clearing House. Some results of this project have been described in previous articles in *TLE* (Ebrom et al., 2000; Entralgo and Spitz, 2001). Although this project was originally designed specifically as a test of seismic technologies, it has evolved into a test of petrophysics and reservoir models as well.

The field of most interest to the study is the so-called "4500-ft" reservoir labeled "A" on Figure 1; it quickly generated free gas under production, having been near bubble point at discovery, and appears to have developed a zone of encroached water as well as a gas cap. Reservoirs with an initial liquid expansion drive mechanism undergo an initial very rapid decrease in pore pressure, followed by a less rapid, but nonetheless steady, continued decline in pressure during the solution-gas-drive phase of production (with moderate water drive in this case). The production history of the 4500-ft reservoir is summarized in Figure 2. Conventional wisdom had predicted that the seismic response of the 4500-ft reservoir would consist of continued "brightening" of this class III AVO reservoir with production as the gas saturation continuously increased. A prediction was made (Pennington, SEG 2000 *Expanded Abstracts*) that the situation would actually be quite a bit more complicated. Due to the fluid-substitution effects alone, there should be continued brightening at all offsets; but because there is also an increase in effective confining pressure as a result of pore-pressure decline during production, this bright spot should dim at near offsets after the initial brightening from the exsolution of free gas. This type of petrophysical behavior has also been proposed by Landro (GEOPHYSICS, 2001) and Bentley et al. (SEG 2000 *Expanded Abstracts*).

In order to test and calibrate the model used in time-

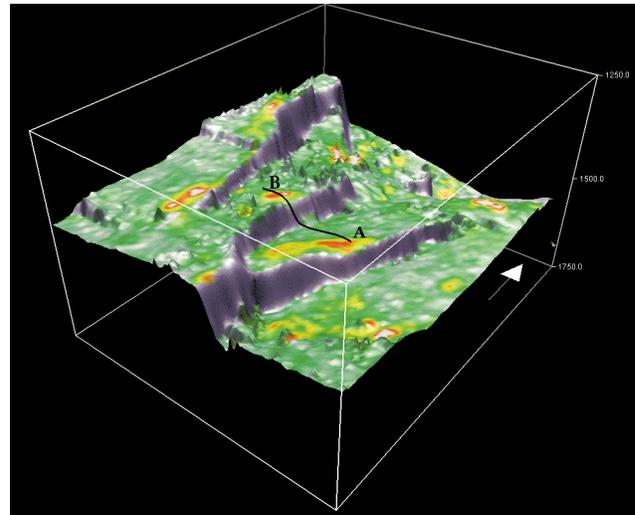


Figure 1. 3-D perspective view of the sand structure containing the currently producing 4500-ft reservoir (A) and nearby undrilled potential reservoirs, including Little Neighbor (B). The arrow points north; the box outlining the volume extends from 1250 ms to 1750 ms in two-way travelt ime, and is roughly 8000 ft (2500 m) on each side. Hotter colors indicate larger negative amplitudes on the migrated legacy (preproduction) seismic data. Data provided by Diamond Geophysical.

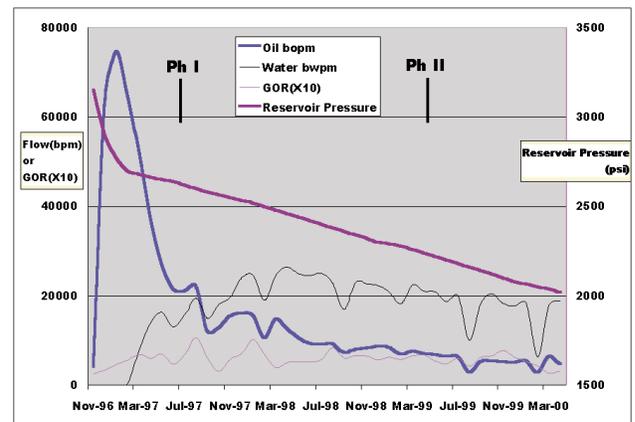


Figure 2. Smoothed production history of the 4500-ft reservoir. Oil flow rates (in bbls of oil per month), water flow rates (bbls of water per month), and gas-oil ratio (GOR multiplied by 10) are all read from the left axis. Reservoir pressure (in psi) is read from the right axis and is simplified from the results of a reservoir simulation conducted by personnel at Heriot-Watt University (presented at the Teal South Consortium meeting, June 2001, expected to be published in the D&P issue of *TLE*, March 2002). Times of the ocean-bottom time-lapse surveys phase I and phase II are indicated.

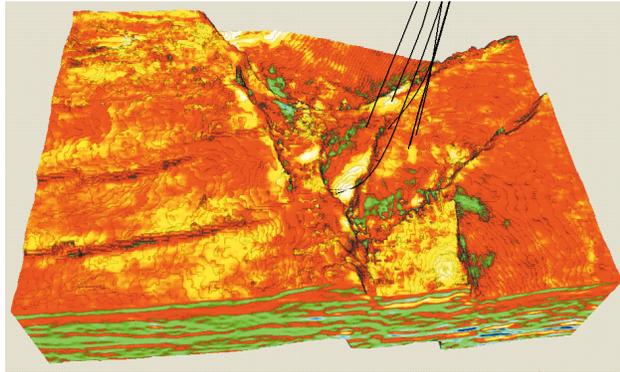
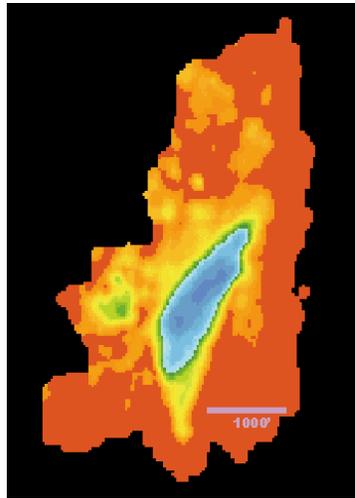


Figure 3. Inverted (legacy data) volume showing acoustic impedance 12 ms below the top of the tracked 4500-ft horizon, inside the reservoir intervals. Green indicates high impedances (shales). Red indicates intermediate impedances (water sands). Yellow indicates low impedances (oil sands).

Figure 4. Time-lapse difference mapped on the 4500-ft horizon, showing the change in amplitudes of the stacked seismic data between phase I and phase II, the two OBC time-lapse surveys. The 4500-ft reservoir and Little Neighbor reservoir both show significant changes indicated by the blue and green colors, although only the larger 4500-ft reservoir is under production. (Image provided by W. Haggard, C. Vuillermoz, S. Spitz, and P. Granger of CGG, presented to the ERCH consortium in August 2000.)



lapse seismic petrophysical predictions, we first needed to know the properties of the rocks in situ. Log data were inconclusive, and it was necessary to establish confidence in our petrophysical model through inversion of the legacy seismic data for acoustic impedance (Figure 3). The final result was a model in which fluid-substitution, using Gassmann theory, was consistent between the oil and water legs of the 4500-ft sand—that is, when we used the values obtained for acoustic impedance in the water sand, and made some simple assumptions for dry-frame Poisson's ratio (which, in this case, were not critical), we were able to predict the values for acoustic impedance observed in the oil sands. Thus, we had a set of rock properties on which to base our predictions for seismic response during production, at least to the degree of accuracy required here.

At the same time, additional nearby reservoirs were identified (such as the "Little Neighbor" labeled "B" in Figure 1), and were occasionally of interest to the investigators in the Teal South consortium. The production history from the producing fields was known, yet some effects were consistently showing up in the undrilled reservoirs. For example, Figure 4 shows a difference image obtained by subtracting the amplitudes on the 4500-ft horizon between phases I and II.

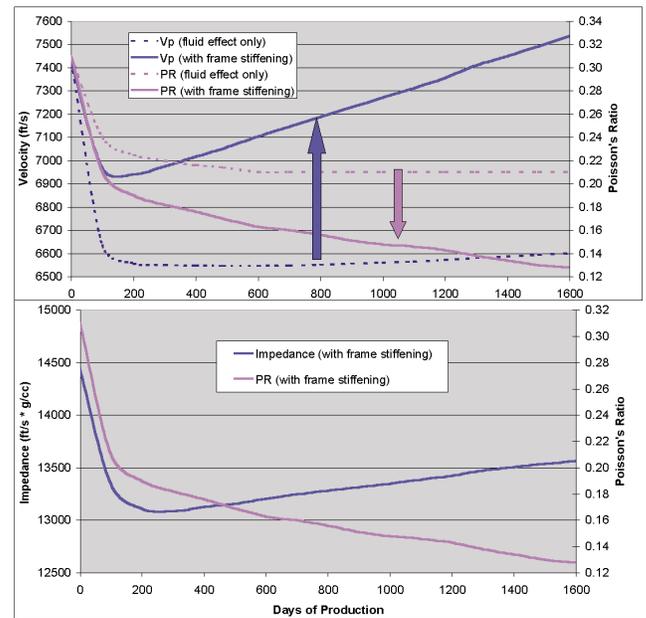


Figure 5. Changes in P -wave velocity (V_p), Poisson's ratio (PR), and acoustic impedance with time of production. Upper graph shows V_p and PR as a result of the fluid substitution calculations only (dotted lines) and with the inclusion of frame stiffening effects (solid lines). Notice that the frame stiffening effect eventually more than cancels the reduction in velocity due to the fluid substitution, while enhancing the Poisson's ratio effect. Inclusion of the density changes (oil to gas) decreases the impact of frame stiffening on the impedance results (lower graph), but following an initial dramatic decrease, the impedance increases with time during most of the life of the field.

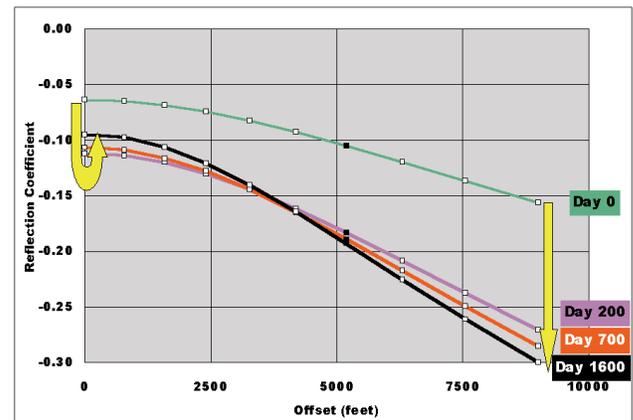


Figure 6. Predictions for AVO effect to be observed in time-lapse data for Teal South. Small squares indicate each additional 5° in angle of incidence. Black square indicates 30° . Notice that the far offsets are expected to continuously increase in amplitude as production continues, but that the near offsets will initially increase, then subsequently decrease in amplitude. Phase I seismic data were collected about 230 days after production began and phase II about 950 days.

The model for fluid substitutions due to changing gas saturation and for frame stiffening due to increased confining pressure indicated (Figure 5) that the P -wave velocity should initially decrease and then increase significantly during production, while Poisson's ratio should continu-

Figure 7. Amplitudes extracted from the partial-offset (unmigrated) stacked seismic *P*-wave data for the 4500-ft reservoir from phases I and II (data provided by CGG). Upper diagrams show the amplitudes of each partial-stacked trace, measured on the upper trough and the lower peak as shown on the lower diagrams. Measurements are made on both time-lapse data sets (different colors of lines in the upper graphs), and for three different offset ranges comprising the partial stacks. Near-offsets did not exhibit any noticeable change between phase I and phase II, but far offsets significantly increased in amplitude between phases. This is in rough, although not exact, agreement with the model prediction in Figure 6.

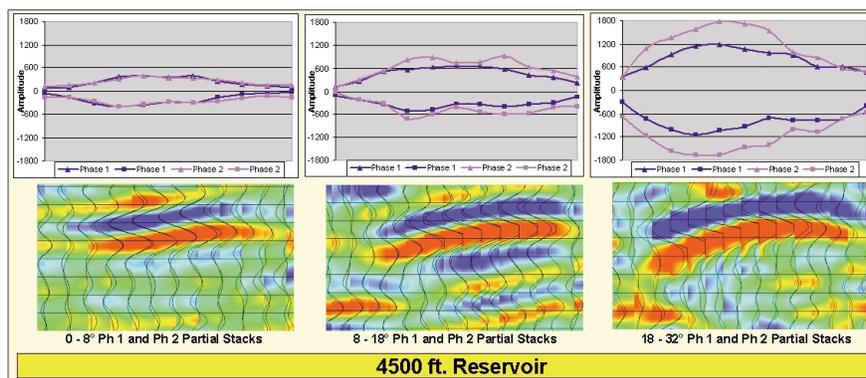
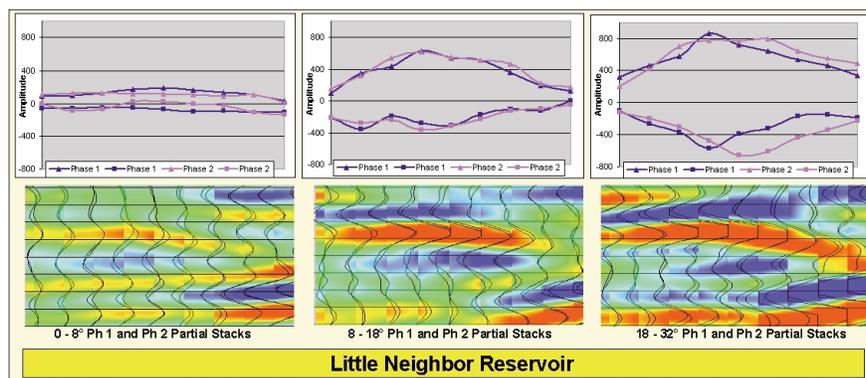


Figure 8. Amplitudes extracted from the partial-offset (unmigrated) stacked seismic *P*-wave data (phases I and II) over Little Neighbor (data provided by CGG). Compare with the observations for the 4500-ft reservoir in Figure 7. Note that the near-offsets have decreased in amplitude between phases I and II, and that the far offsets have increased in amplitude, in very good agreement with the model presented for the expansion of a free gas phase and a decrease in reservoir pressure, even though this reservoir is not being produced.



ally decrease. This scenario results in an AVO effect (Figure 6) that includes an initial brightening at all offsets, followed by a dimming at near offsets and a continued brightening at far offsets. The model used in calculating the frame stiffening is an extension of one presented by Pennington, Green, and Haataja at the 2001 AAPG Annual Meeting. It was developed by Aaron Green (master's thesis in progress at Michigan Tech); in this case, the results are very similar to those produced using the model cited earlier by Bentley et al.

We chose to investigate the prestack behavior of the reflections from the 4500-ft reservoir and from the Little Neighbor reservoir in the OBC data from phase I (shortly after the initial release of free gas) and phase II (after a couple years of continued production). Because the seismic traces are not equally distributed among the offset ranges and their distribution varies among CDP gathers, we grouped the offset traces into different ranges and constructed partial stacks within each range. Results are presented here for every fourth CDP gather along one east-west line intersecting both reservoirs, as indicated in Figure 1. Reflections from the 4500-ft reservoir (Figure 7) show that the far offsets increased in amplitude between phases I and II, while the small-amplitude near-offsets remained essentially constant. Reflections from Little Neighbor (Figure 8) show that the same situation occurred, except that the near-offsets actually decreased slightly in amplitude between the two phases. Both reservoirs show characteristics (within noise limits) of reservoirs that have released free gas, and which continue to increase gas saturation while decreasing reservoir pore pressure.

This behavior contains two surprises for the conventional viewpoint:

First, the amplitudes do not monotonically brighten as additional gas is released; instead, the near-offsets eventually decrease (from one time-lapse survey to another after an initial brightening), while the far-offsets increase in amplitude.

Second, Little Neighbor, originally thought to be separated by sealing faults, is responding to production in the 4500-ft reservoir in a manner that is remarkably similar to the seismic response exhibited by that reservoir. Our conclusion is that Little Neighbor is undergoing a decline in pressure due to production of the 4500-ft reservoir. It must be in pressure communication through some route within the formations for this to occur, and therefore not isolated by the faults which bound either reservoir. By examination of the inverted acoustic impedance volume along an arbitrary seismic path that links the down-dip ends of each reservoir, we find that there is indeed a path of continuous (water) sands that connect the two reservoirs, and perhaps others as well (Figure 9).

There are serious implications for reservoir management contained in this interpretation. The fact that the Little Neighbor appears in pressure communication and that it exhibits a seismic response appropriate for the creation of a free gas phase results in a volume accommodation problem. The free gas occupies more volume than the oil from which it was released; usually, this volume is more than accounted for by the production of the oil. But in the Little Neighbor's case, the oil contained within it is not being produced. It must be moving downstructure within the formation as the gas cap grows. But downstructure there is no trap to contain it—there is only the spill point (Figure 10). The displaced oil of the Little Neighbor reservoir can-

Figure 9. A seismic traverse through the inverted acoustic impedance volume from the legacy data set, connecting the downdip ends of the 4500-ft and Little Neighbor reservoirs. The ends of the section meet, providing a full circle starting (at the left edge) updip of Little Neighbor, with bends in the section at each vertical line, extending, clockwise, through the 4500-ft reservoir, finally returning to the starting point. White highlights the lowest-impedance sands (those likely containing light hydrocarbons); red indicates impedance corresponding to water sands; and green indicates impedance corresponding to shales. Note that the shales form traps, but each reservoir has its own spill point into water sands; the reservoirs are connected, and in pressure communication, through these spill points. Original data provided by Diamond Geophysical.

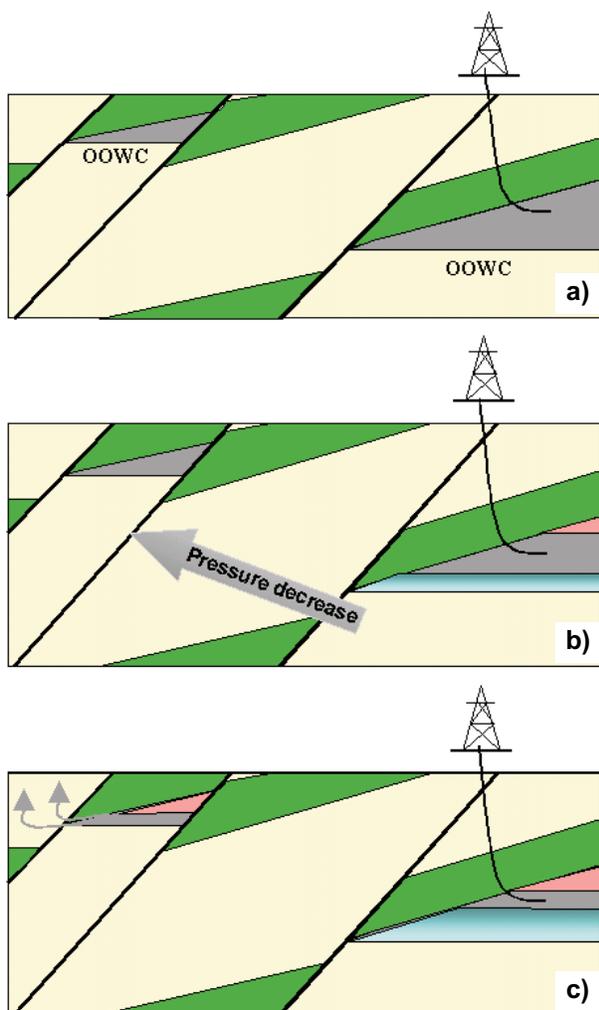
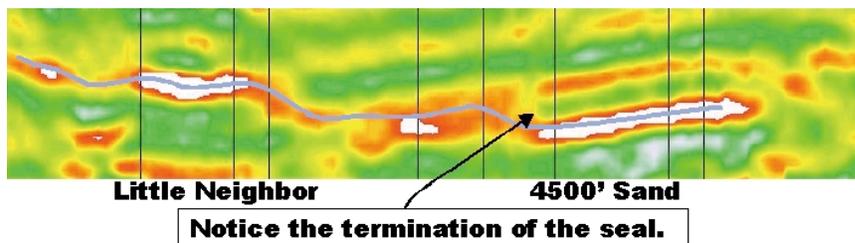


Figure 10. Schematic of the sequence of events resulting in the loss of hydrocarbons from Little Neighbor (left) due to production in the 4500-ft reservoir (right). Geometry is similar to that along the traverse line of Figure 9. OOWC is the original oil-water contact. (a) Production has just begun in the 4500-ft reservoir and no displacement has yet been observed. (b) Production from the 4500-ft reservoir has resulted in free gas and water encroachment in that reservoir, as well as a pressure decrease that is communicated through the water sands. (c) Pressure drop has resulted in creation of free gas in Little Neighbor and downward displacement of remaining oil. That oil eventually spills out of the reservoir, likely never to be recovered.

not migrate to the 4500-ft reservoir and be produced there; that is much too far downstructure, and there are many routes for the oil to escape prior to reaching it. Instead, the oil is likely escaping through the spill point and either pooling in some other local trap or escaping into the overlying sands. This oil is likely to be lost forever, inaccessible to future production, unless it happens to be trapped in some upper zone with economics favorable for recovery. If a well were to be drilled into the Little Neighbor reservoir at this time, the oil in place would be found to be much less than that estimated from the legacy data, obtained prior to production of the nearby 4500-ft reservoir.

The time-lapse survey of Teal South has yielded some completely unexpected results that could be of significant importance for reservoir management of the fields in this block. For this reason, it may not be advisable to design time-lapse surveys to test only one single aspect of production. We feel that our knowledge of the greater reservoir system is, in general, fairly incomplete, and seismic surveys for time-lapse purposes should be designed to allow for the observation of the unexpected. The Teal South experiment was designed in a manner that permitted us to draw the conclusions presented in this paper, which was fortunate. We do not presently know if the phenomenon observed here—that production in one reservoir is apparently resulting in the loss of hydrocarbons from another unproduced reservoir—is likely to be widespread in the Gulf of Mexico and elsewhere. But we do know that without the time-lapse seismic observations, we would not have recognized it in this instance. E

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Editor's note: H. Acevedo is also with Ecopetrol. J. Haataja is now at PGS Geophysical. A. Minaeva is now at Shell Exploration and Production Co.