First dual-vessel high-repeat GoM 4D survey shows development options at Holstein Field

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In the Gulf of Mexico (GoM), loop and eddy currents can cause large errors in 4D shot and receiver locations between baseline and repeat streamer surveys, which invariably lead to poor data quality. In a recent 4D acquisition, a dual-vessel 3D acquisition method addressed the repeatability problem and showed reliable time-lapse measurements over Holstein Field. The time-lapse seismic data show time shifts up to 6 ms over depleting sands and amplitude changes over swept and compacted sands. This 4D information has improved understanding of the field and can support optimal placement of injection and production wells.

Holstein, in the deepwater GoM (4300 ft water depth), is operated by BP and jointly owned by Shell (50%). The field produces from stacked Pliocene turbidite sands at depths of 11 000–14 000ft. Production started in December 2004. Since the majority of resources are as yet unproduced, understanding reservoir compartmentalization is a key issue for future development decisions.

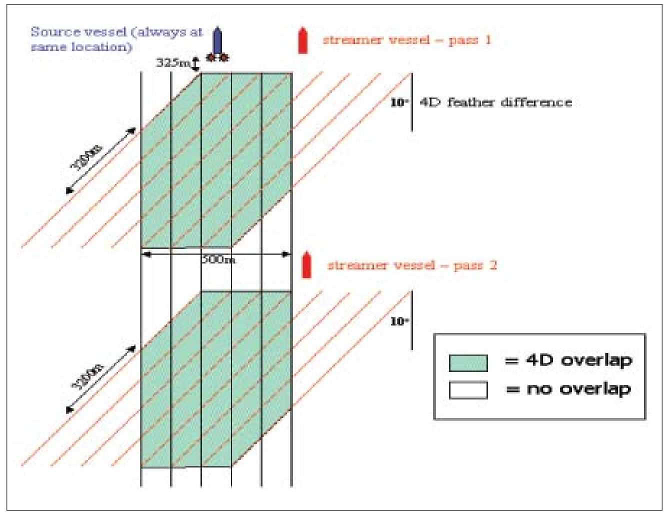

Figure 1. *Illustration of two-boat, multipass acquisition.*

4D acquisition

The preproduction 2001 baseline survey for Holstein is a high-resolution survey with excellent image quality. A 4D seismic modeling study concluded that the best timing for a monitor survey would be just prior to water injection to separate depletion from water-injection changes and that high-repeat far offsets would be important to allow 4D AVO inversion for separating pressure changes from water-saturation changes.

In late 2005, two high-repeat 2D lines using a dual-vessel configuration and short cables were acquired. The data showed small amplitude changes and timeshifts consistent with the limited production to date. At the end of the study, calibrated 4D seismic modeling and the 2D lines helped build the case for 4D acquisition over Holstein.

Figure 1 illustrates the two-boat multipass concept for 3D streamer acquisition. The six-cable baseline survey, 6 km in length, is in black. The eight short-cable monitor survey in two-pass mode is in red. A 10° feather difference between baseline and monitor survey is assumed for illustration. The 4D overlap area of offsets for each pass is indicated in green. In practice the near offsets may be acquired with a conventional single-boat operation or in "reverse push" mode with the source vessel trailing the cable boat. However, even for near offsets, the 4D overlap for the two-boat method will be better than single-boat acquisition.

A high-repeat 4D survey combining single-vessel (for near offsets) and dual-vessel (for mid and far offsets) was acquired at Holstein in August–September 2006. The second boat was ready for operation in dual-vessel mode from the start of the survey, and high repeatability would not have been achieved without the two-boat acquisition. Errors in shot and receiver location between baseline and monitor acquisition ($\Delta s+\Delta r$) of less than 100 m for over 90% of the survey were obtained for offsets up to 4500 m. The whole survey has an average nrms (normalized root-mean-square difference) value of 0.23 (Figure 2), a level of repeatability not seen before in the GoM. Furthermore, for the first time, both the nrms and the $\Delta s+\Delta r$ values are consistent with repeatability values achieved in the

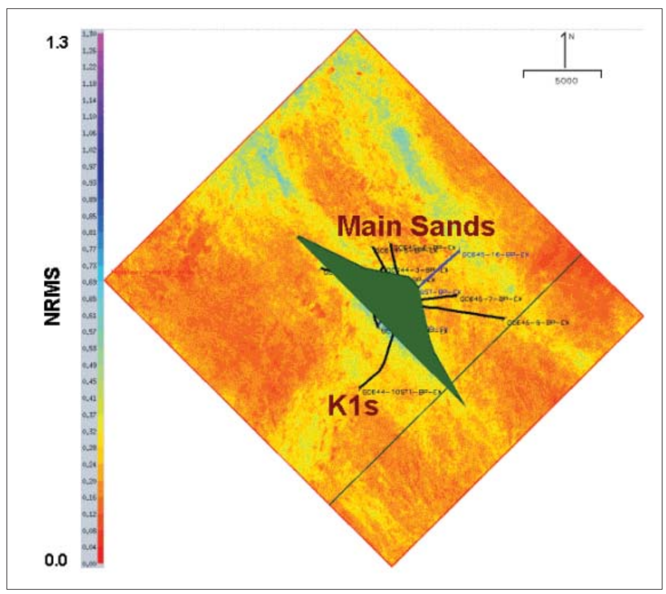

Figure 2. *The nrms values from the high-repeat acquisition over Holstein Field (undershoot polygon in green). The nrms is estimated in a 1-s window centered at 2.5 s. An average nrms value of 0.23 on final migrated data and an average shot+receiver repeat error of 75 m was achieved.*

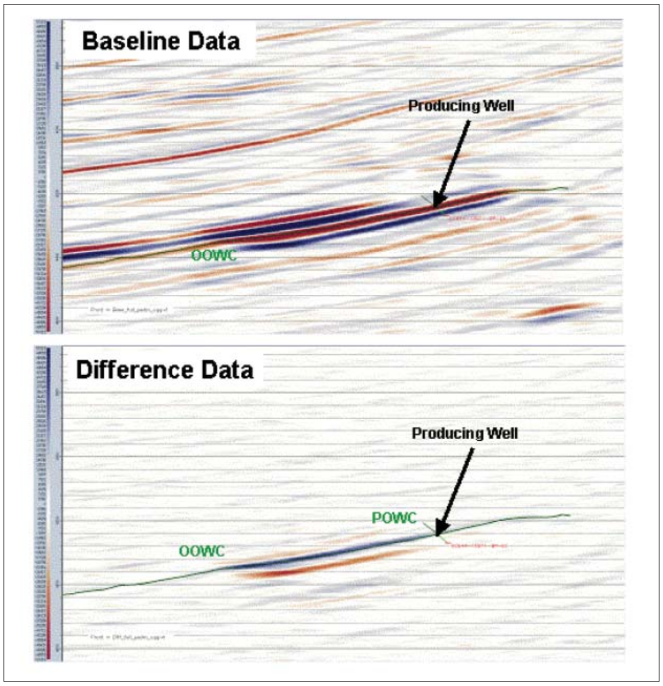

Figure 3. Baseline and difference data through K1s producing well. The difference data show exceptional time-lapse data quality and clearly show updip water movement. The original oil-water contact (OOWC) has moved updip to the present oil-water contact (POWC) approaching the producing well. As of December 2007, water cut at this well has reached 80%.

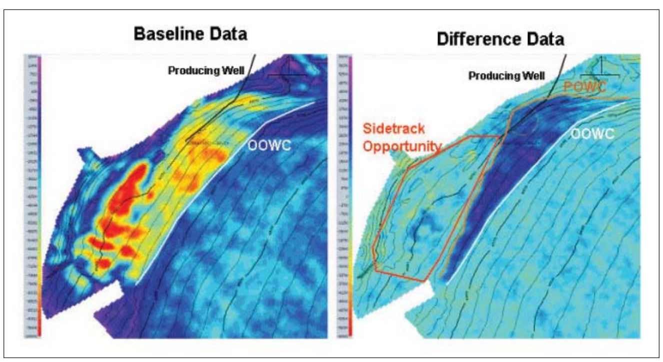

Figure 4. Map view of baseline and difference top-sand amplitude at K1s. The original OWC (white line) and present OWC (brown line) based on 4D are indicated as well as the location of the producing well. The red polygon shows an area of by-passed hydrocarbons.

North Sea, where time-lapse seismic is an established technology. In the undershoot area (green polygon Figure 2), the near offsets are missing in the monitor data. However, in the mid offsets, the baseline and monitor data start to match with Δs+Δr location errors less than 100 m. As a result, only the mid-offset stack is used, with caution, for interpretation in the undershoot area.

4D processing and interpretation

The 2001 baseline and 2006 monitor surveys were jointly processed in parallel through a 4D processing flow. Prior to merge, cold water and tidal statics, 3D SRME, and receiver motion correction were applied. The surveys were then merged and the following key steps were applied: global

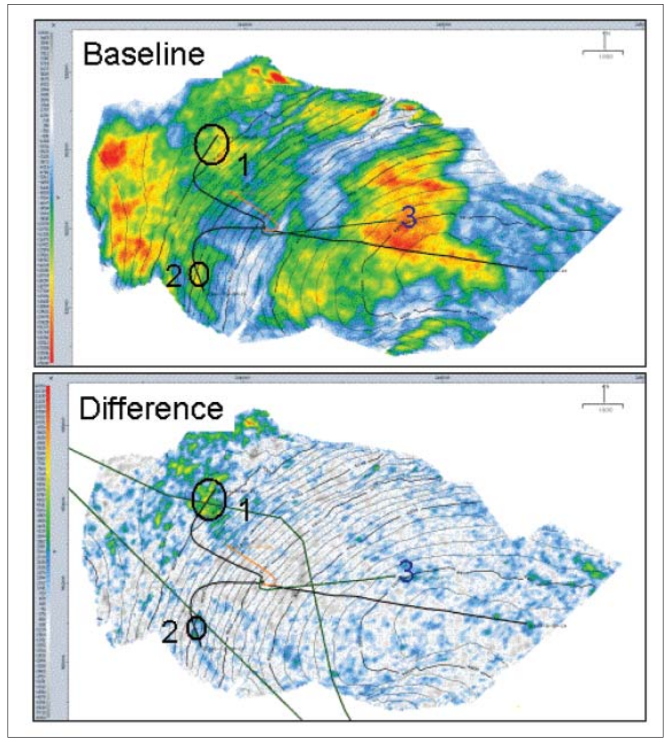

Figure 5. Baseline and difference amplitudes at K2. Black circles indicate amount of pressure drop up to the time of the monitor survey (4300 psi at well 1, 2500 psi at well 2). Green polygon indicates undershoot area. Difference data show compaction (impedance increase) around well 1 and compartmentalization around well 2. Well 3 is a post 4D well with good production.

matching, 4D binning based on a combined Δs+Δr and minimum nrms criteria, regularization, azimuthal moveout (AMO), high-frequency differential statics, Radon multiple attenuation, and acquisition footprint removal.

After these steps, PSTM and anisotropic PSDM were applied to baseline and monitor data using the same velocity models for both data sets. Final processing steps were RMO, stack (full, near, mid, far), and residual matching of stacked cubes. Each processing step was QCed in detail and parameters adjusted accordingly. 4D binning and regularization were seen as important steps.

A variety of 4D signals was expected at Holstein due to differences in production methods for the different reservoir sands. For J2 sands, we have a combination of depletion and water injection. For the K2 sands, we only have depletion. And for the K1 sands, we only have aquifer sweep. By using different attributes such as amplitudes and time shifts, we were able to separate these signals, relate them to the reservoir model, and recommend new well locations. The examples below illustrate the range of those different signals and development options.

Water sweep at K1s

The K1s reservoir is an isolated sand southwest of the platform (Figure 2). It is different from the "main sands" in that it has good aquifer pressure support. Figure 3 is a seismic section through the K1s producing sand. The difference data suggest an aquifer sweep. The original oil-water contact ap-

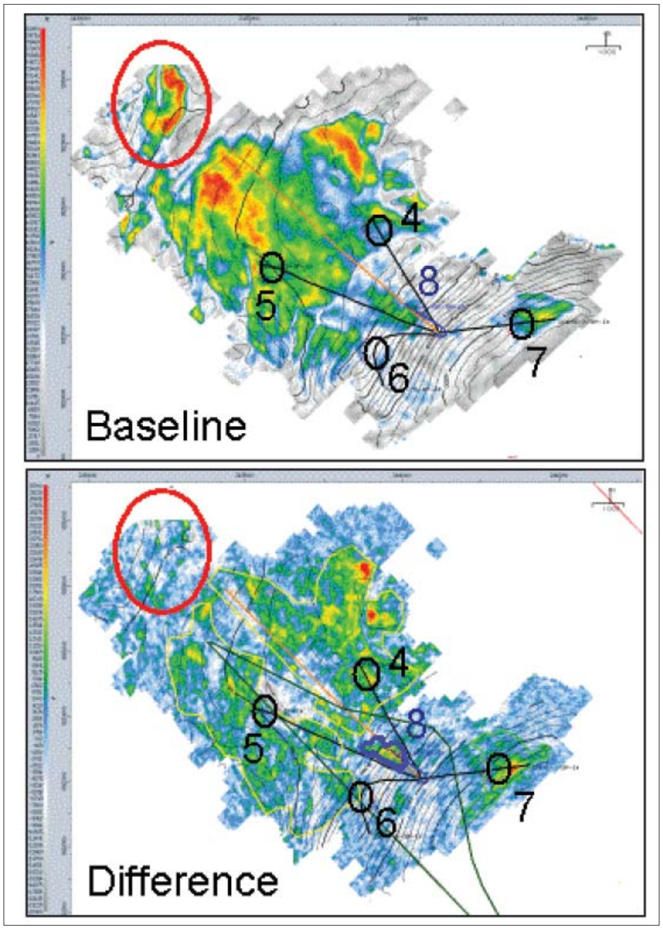

Figure 6. Baseline and difference amplitudes at J2. Black circles indicate amount of pressure drop up to the time of the monitor survey (around 2600 psi at wells 4–7). Green polygon indicates undershoot area. Difference data show impedance increase region around wells 4, 5, and 7. Well 8 is a water injector and injection-related impedance increase can be seen around this well (blue polygon).

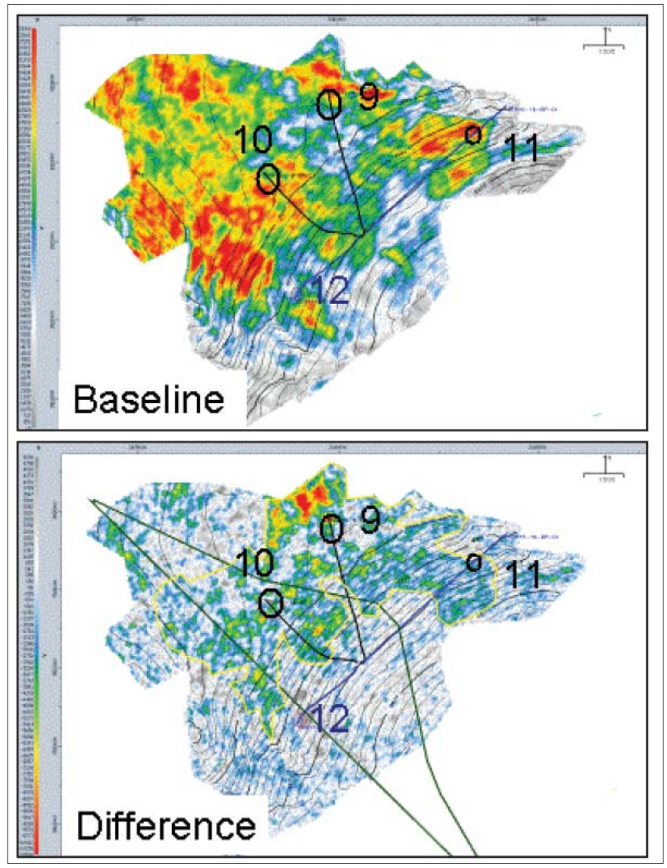

Figure 7. Baseline and difference amplitudes from base of J3 sand. Black circles indicate amount of pressure drop up to the time of the monitor survey (around 2700 psi at wells 9 and 10). Green polygon indicates undershoot area. Difference data show region of impedance increase around wells 9 and 10. Well 12 is a water injector in the undershoot area.

pears to have moved updip towards the producing well. A clear 4D signal, with minimum residuals from other seismic events, is observed.

The amplitude peak from the K1s sand top is shown in map view in Figure 4. The bright colors in the baseline data indicate gas and oil whereas the dim colors downdip of the original OWC indicate water. The white line represents the original oil-water contact. In the difference section, the oil-water contact has moved updip toward the producing well. At the time of the monitor survey, this well had 70% water cut (80% as of December 2007). A map view shows that a large portion of the hydrocarbons, outlined by the red polygon, has apparently not been produced and might be accessed through sidetrack of the existing well.

The main sands: J2, J3, and K2

The main pay sands are a stacked vertical sequence in which the progressively deeper units (J2, J3, and K2) are currently producing. Water injection was initiated in May 2006 to offset pressure decline and provide pressure support to the J2 and J3 reservoirs. 4D interpretation of the main sands is complex due to poor repeatability in the undershoot area and time-lapse changes of several stacked reservoirs.

The K2 sand, thickness of 150 ft, lies below the J sands. Figure 5 shows the top-sand amplitude picks from the mid-offset stack (preferred in the undershoot area). Difference data suggest compaction-related impedance increases in a region around well 1, the largest producer (4300 psi pressure drop). Limited production and a rapid (2500 psi) pressure drop suggest that well 2 is either in a relatively small compartment or has completion problems. Difference data show a local 4D impedance increase at this location, possibly supporting the limited production results. Well 3 was drilled after the 4D acquisition in a region with good amplitude support (as seen from the baseline data) and no 4D signal (as seen on the difference data). Well results are consistent with the lack of 4D signal indicating no depletion.

The J2 sand has a thickness of 70 ft. Figure 6 shows wells 4 and 5, the best producers in this sand (approximately 2600 psi depletion in each). The difference data suggest that a large area (yellow polygons in Figure 6) has compacted around these wells, and the two areas could be connected which is consistent with production data. 4D data show that the area highlighted by the red circle is a compartment that is not being depleted by wells 4 or 5 and could be a future drilling target. Well 7 is in a compartment with limited production

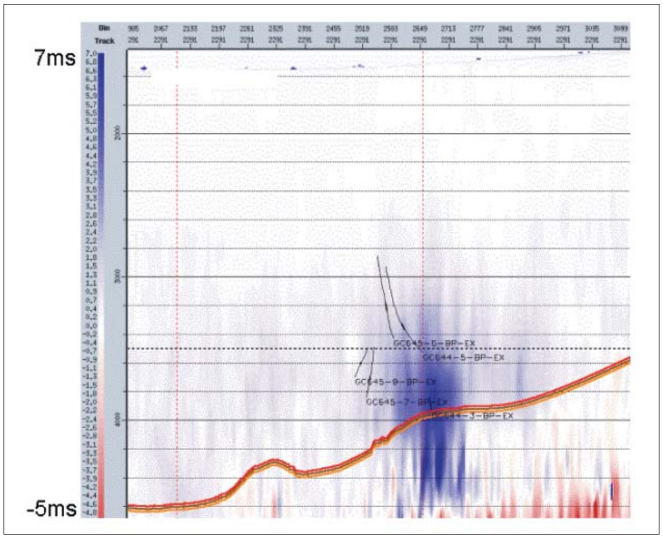

Figure 8. *Cross-section of time shifts over central part of depleting J and K sands.*

and a 2700 psi pressure drop. The difference data suggest that well 7 is not connected to the main reservoir. Well 8 (blue in Figure 6) is a water injector. 4D data from the mid-offset stack show a region of increased impedance around this well (blue polygon in Figure 6).

The J3 sand, which has a thickness of 110 ft, is just below J2. Well 9 is the largest J3 producer and is followed by well 10 (Figure 7). Both show 2700 psi depletion. The 4D difference data are consistent with production data and spatially identify the potentially depleted area. Well 11 is an injector drilled during acquisition of the 4D survey. Well 12 is a water injector; however, it is in the most poorly repeated part of the survey where 4D interpretation is not reliable.

Time shifts from the main sands (J and K)

At Holstein, apparent 4D time shifts up to 6 ms are observed over the depleting sands (Figure 8). These time-shift values indicate reservoir compaction. In map view (Figure 9), the time shifts correlate well with the pressure decrease observed at wells over multiple depleting sands. The largest pressure decrease (largest black circle in Figure 9) corresponds to 4200 psi where the largest time shifts are observed. Modeled time shifts generated from dynamic reservoir simulation are consistent with the time shifts from field data after adjusting for pore compressibility. Further, the red circles in Figure 9 indicate areas of mismatch between the modeled time shifts and field data. Pressure data from wells drilled after the 4D in the northern mismatch regions (outside the green undershoot polygon) show depletion, supporting the accuracy of the field 4D time shifts.

Conclusions

Successful acquisition of 4D towed-streamer data with high repeatability at Holstein in the deepwater GoM has shown that high-quality 4D amplitudes and time shifts can be obtained and support development decisions. Time-lapse amplitudes show sweep and compaction of individual producing

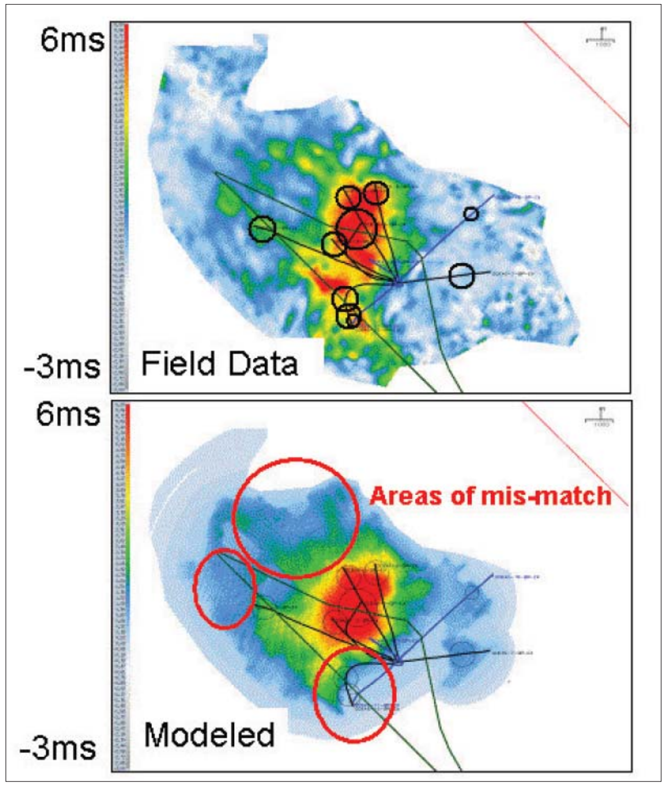

Figure 9. *Field data time shifts extracted above the J2 sands (top) and pressure depletion observed at wells in J and K sands (black circles). Modeled time shifts above the J2 sands (bottom) indicate areas of mismatch (red circles) with the dynamic model.*

sands and time-lapse time shifts suggest production-related effects of compaction of stacked sands. Seismic time shifts, in conjunction with 4D amplitudes, can support decisions to place production wells in virgin compartments and to place water injectors that will support existing producers. At Holstein, 4D is currently being used to place future production and injection wells. A second monitor survey is being planned for 2009.

Suggested reading. "4D repeatability using dual-vessel acquisition: Holstein Field, Gulf of Mexico" by Barousse et al. (SEG 2007 *Expanded Abstracts*). *Insights and Methods for 4D Reservoir Monitoring and Characterization* by Calvert (SEG, 2005). "Rocks under strain: Strain-induced time-lapse time shifts are observed for depleting reservoirs" by Hatchell and Bourne (*TLE*, 2005). "Discrimination between pressure and fluid saturation changes from time-lapse seismic data" by Landrø (Geophysics, 2001). "Estimating pressure and saturation changes from time-lapse AVO data" by Tura and Lumley (SEG 1999 *Expanded Abstracts*). "Monitoring primary depletion reservoirs using amplitudes and time shifts from high-repeat seismic surveys" by Tura et al. (*TLE*, 2005). TLE

Acknowledgments: The authors thank Shell and BP for permission to publish this work. Ali Tura is now employed by Chevron.

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