Effective processing of nonrepeatable 4-D seismic data to monitor heavy oil SAGD steam flood at East Senlac, Saskatchewan, Canada

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The concept of time-lapse (or 4-D) seismic monitoring is straightforward: A baseline 3-D survey describing initial reservoir conditions and a subsequent monitor survey (or surveys) recorded after conditions have changed are calibrated, compared, and the intersurvey differences analyzed and interpreted in terms of net variations in pore fluid saturation, pressure, or temperature inside a hydrocarbon reservoir.

Seismic monitoring thus depends largely upon whether "repeatability" of surveys is achievable. Ideally, the difference between surveys should contain nothing but the changes in reservoir properties. However, it is almost impossible to obtain perfectly repeatable (or identical) time-lapse seismic surveys in the real world. Ross and Altan (1997) report that even a "zero-time repeatability test" (in which two offshore 3-D surveys were shot only one day apart by the same crew using identical equipment and survey geometry in an area of no production-related dynamic influences) could yield visually coherent energy on difference sections, if the processing sequence was not optimal.

Therefore, uniform processing of time-lapse surveys is crucial for successful 4-D reservoir interpretation, especially when there are large differences in acquisition or in ambient recording conditions. An important component of uniform 4-D data processing is cross-equalization to remove artificial effects caused by nonreservoir factors, such as changes in acquisition and/or processing parameters, so that time-lapse 3-D data will be identical everywhere except within the reservoir zone (where dynamic changes should be expected).

This article presents a case study of effective 4-D seismic data processing. Time-lapse seismic surveys monitoring a heavy oil thermal EOR site in west Saskatchewan, Canada, were uniformly processed by a sequence including: spatial realignment, amplitude balancing, and cross-equalization. This case involved three 3-D seismic surveys with significantly different parameters—different types of source (Vibroseis, weight-drop, and dynamite), varying orientations in geometry, and varied spatial parameters such as line spacing and bin size. We found that carefully designed processing based on cross-equalization is crucial for legacy data and would help minimize major differences and nonrepeatability in data acquisition, thus making it possible to extract reliable information about a reservoir's dynamic changes from time-lapse seismic data.

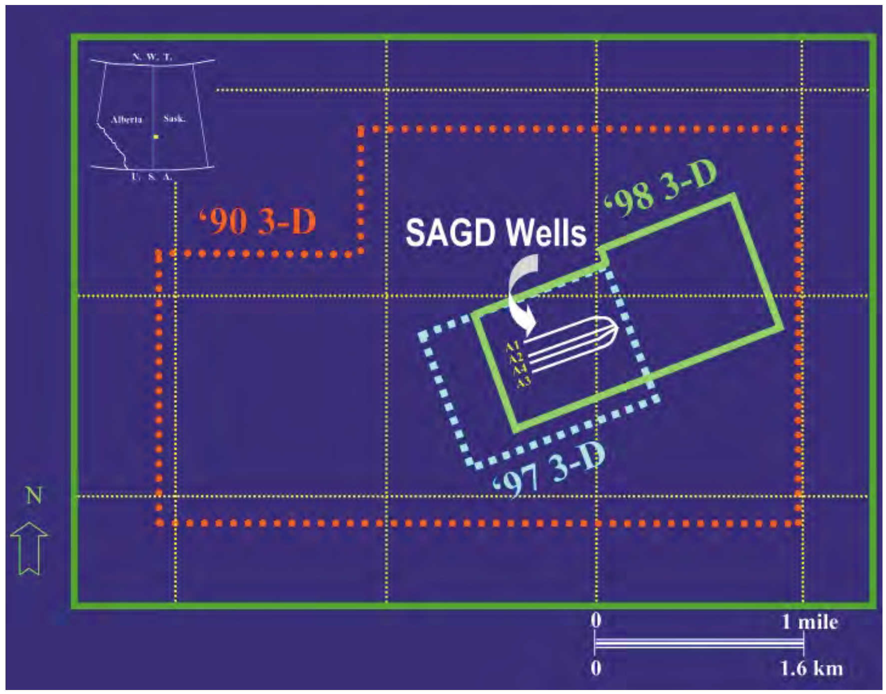

Figure 1. East Senlac study area and cover of the time-lapse seismic surveys.

Data acquisition. East Senlac is close to the Alberta-Saskatchewan border (Figure 1). The producing reservoir is unconsolidated fluvial channel sand of the Lower Cretaceous Dina Formation, which directly overlies the erosional surface of Paleozoic carbonate rocks. The 15-m thick sand has average porosity of 33% and permeability of 5-10 Darcy. At about 730 m, this shallow reservoir is highly saturated with a viscous heavy oil. To make this oil mobile and producible, steam-assisted gravity drainage (SAGD) technology has been used, and high-temperature steam is continuously injected into the reservoir. Three pairs of horizontal wells, A1-A3, were first drilled (Figure 1). The upper well injects steam, and the lower well, a few meters below and parallel to the injector, produces oil and condensate from the heated zone (referred to as the steam chamber). A fourth infill horizontal well pair, A4, was drilled later to boost production. Three time-lapse 3-D surveys were collected at various times to monitor steam chamber growth, determine steam sweep efficiency, and examine the effects of reservoir heterogeneity on the distribution of the heated reservoir zones.

The surveys were acquired with quite different field parameters. The first (baseline) survey was shot in the winter of 1990 for static reservoir

Table 1. Detailed acquisition information for all surveys

Field parameters	Survey 1	Survey 2	Survey 3
Date	Winter 1990	Fall 1997	Spring 1998
Source type	Vibroseis	Weight-drop	Dynamite
	1 vibrator center on flag	Truckmount	1 Kg, single hole
	8 sweeps, 6 seconds	16 pops per shot	6-m burial depth
	18-144 Hz linear		
	6 dB/oct boost		
Geophones	Geospace 14 Hz	SM-24 10 Hz	OYO 10 Hz
	12 over 2 m inline	6 over 20 m inline	6 over 20 m inline
Recording equipment	I/O system I	I/O system II	I/O system II
	360 channels max	728 channels max	532 channels max
	SEG-D format, FP gain	SEG-D format, FP gain	SEG-D format, FP gain
	3(12)-180(75) Hz (dB/oct)	3(12)-207(298) Hz (dB/oct)	3(12)-411(275) Hz (dB/oct)
	notch out	3/4 Nyquist min phase	3/4 Nyquist linear phase
	9.0 s listen	notch out	notch out
Record length	3.0 s @ 2ms	3.0 s @ 2 ms	3.0 s @ 1 ms
Source line spacing	180 m EW	160 m NE-SW	80 m NW-SE
Receiver line spacing	180 m NS	120 m NW-SE	80 m NW-SE
Source interval	60 m	40 m	80 m
Receiver interval	30m	20 m	40 m
Typical patch	8 lines × 45 stations	13 lines × 56 stations	19 lines × 28 stations
	1260 m × 1320 m	1440 m × 1100 m	1440 m × 1080 m
Natural bin size	15 m × 30 m	10 m × 20 m	20 m × 40 m

characterization. Vibrators were the source. An I/O System I did the recording. A standard orthogonal 3-D acquisition geometry, oriented E-W, was used. Source and receiver lines were separated by 180 m; 60-m source intervals and 30-m receiver intervals yielded a natural bin size of 15 × 30 m.

The second 3-D, a monitoring survey, was recorded in September 1997 after 18 months of continuous steam injection. A truck-mounted weight-drop source was used to avoid damage to surface facilities surrounding the steam plant and wells. The survey used an orthogonal geometry in a NE-SW orientation. Finer line spacing and station intervals resulted in a smaller CDP bin size (10 × 20 m). The recording system was I/O System II.

Our third 3-D survey was acquired in the spring of 1998, when steam had been continuously injected for almost two years and the maximum reservoir temperature had achieved 260°C. Its purpose was to monitor movement of the steam front and prepare for new SAGD locations in the eastern portion of the area. We applied a new proprietary 3-D acquisition technique, MegaBin, to record wider-band seismic signals containing higher S/N ratio, and better offset and azimuth distributions. Dynamite charges, shot from 6-m drill holes, did not damage the surrounding surface facilities and wells. An I/O System II was again used. Parallel source lines and receiver lines were spaced at 80 m. Source locations were staggered relative to receiver locations. Station intervals were 80 m for sources and 40 m for receivers, producing CDP bins of 20 × 40 m with a nominal fold of over 80 at offsets equivalent to reservoir depth. This was much higher fold than in the two previous surveys. Table 1 details acquisition information for the surveys.

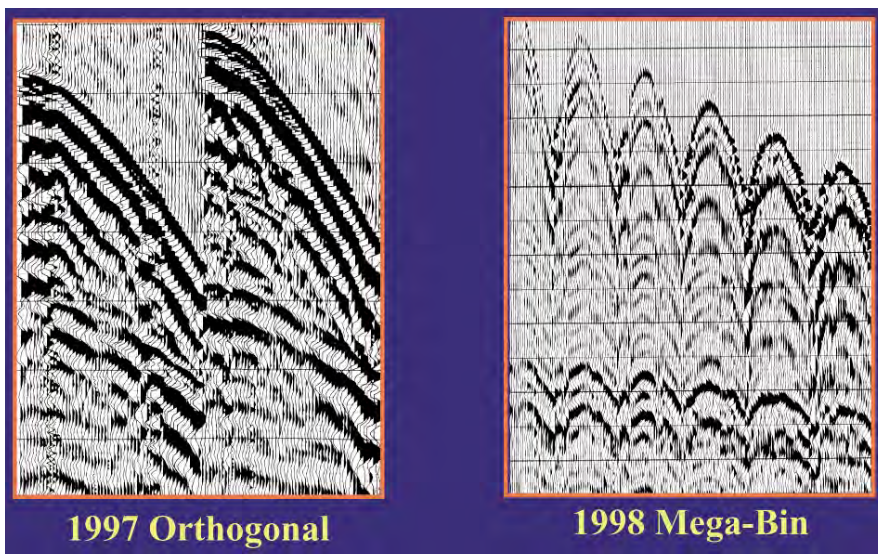

Figure 2. Raw shot records from 1997 (left) and 1998 monitoring surveys.

Obviously, these 3-D surveys were not optimally designed for time-lapse monitoring and certainly did not meet generally accepted requirements for repeatability. Therefore it is not surprising to observe big differences in the data. Figure 2 shows typical shot records from the 1997 and the 1998 surveys. As can be seen

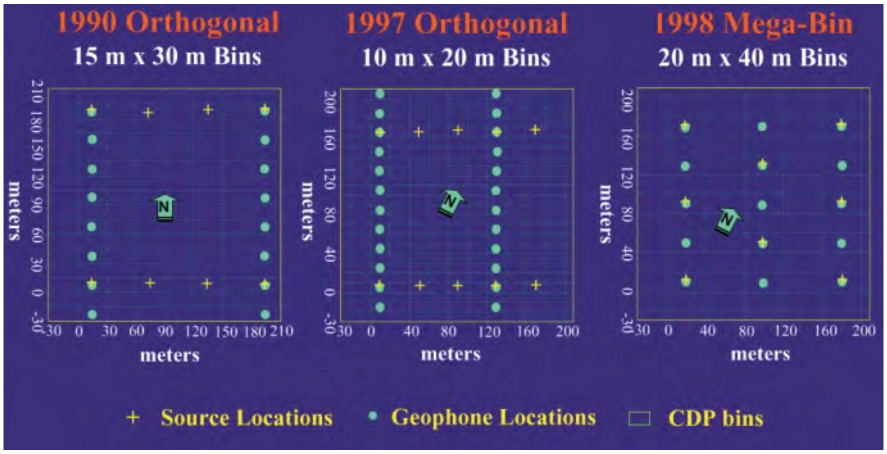

Figure 3. Differences in CDP bin geometries.

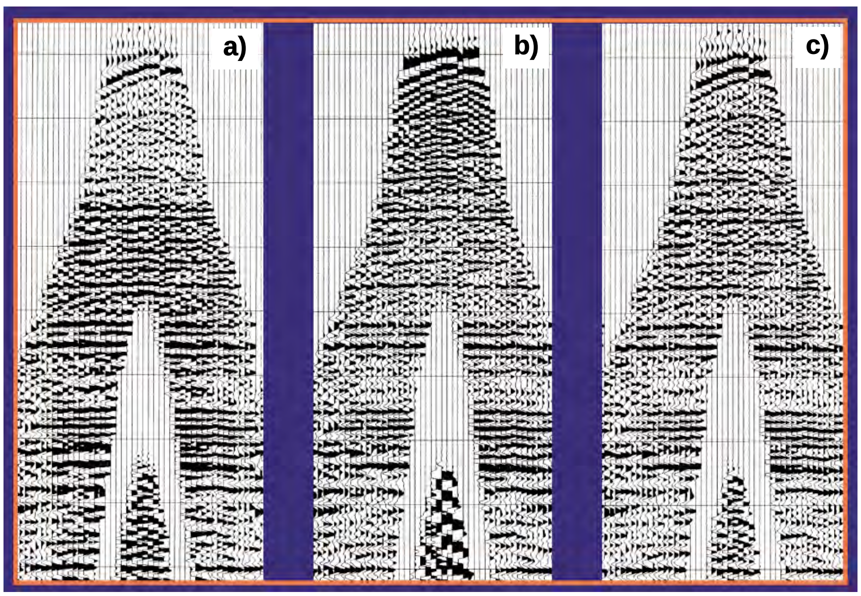

Figure 4. Prestack amplitude balancing. Shot record (a) after surface-consistent deconvolution and single-trace zero-phase spiking deconvolution; (b) after adding amplitude rescaling to (a); and (c) after adding a global scale correction to (c).

clearly, data quality varies remarkably. The weight-drop source tends to yield lower-frequency signals (left) than the dynamite source. The latter apparently has, as planned, recorded an improved S/N ratio within a wider frequency band. It is extremely important to remove these acquisition-related differences from the data sets during processing before attempting to infer reliable information about reservoir changes from them.

Data processing. Because of severe nonrepeatability with the time-lapse surveys, a special data processing sequence, aiming at preserving relative amplitudes and intersurvey balancing, had to be designed, tested, and applied. The sequence included spatial realignment (regridding), preprocessing, surface-consistent deconvolution, single-trace zero-phase deconvolution, surface consistent amplitude recovery, various static corrections, detailed velocity analysis, NMO and CDP stack, poststack *f-xy* deconvolution, trace interpolation, migration, and cross-equalization. During each step, effort was made to ensure consistency from one survey to another in the selection of processing parameters. This article focuses only on regridding, amplitude balancing, and cross-equalization.

1) Spatial realignment. The considerable variations in acquisition geometry for the 4-D surveys have two important consequences: varying bin sizes and different orientational directions. Figure 3, a close up of the initial CDP bin grids of the surveys, reveals the nonrepeatability problem.

Regridding was done at the very beginning of prestack processing to realign the 4-D surveys onto a common grid. This new grid aligned the surveys in the NE-SW direction, which is nearly the azimuthal direction of the 1997 and 1998 surveys. The new bin size is 20 × 40 m. Every trace from prestack gathers of each survey was reassigned according to the new bin locations and dimensions. Traces were reorganized according to their new bin positions to form new CDP gathers. After regridding, processing continued from prestack through poststack. Once the data were stacked, trace interpolation produced smaller bins (20 × 20 m).

2) Amplitude balancing. To facilitate time-lapse analysis and the possibility of subsequent AVO analysis, data processing was required to preserve relative amplitudes. Bad and excessively noisy traces were eliminated early in the processing sequence, and 60-Hz power line noise was subtracted from contaminated traces. Offset-dependent spherical divergence gain corrections and an inelastic attenuation correction were applied to the cleaned-up data. A pass of surface-consistent deconvolution followed (source, receiver, and offset waveform components were resolved, but only source and receiver components were removed). Surface-consistent amplitude scalars adjusted the relative amplitude contributions of sources and receivers before traces were CDP stacked. Note that these scalars were derived from band-limited data, using only frequencies with the best signal to noise characteristics, but were applied to unfiltered traces.

Two complicating factors caused us to modify the basic amplitude-preserving processing. One was the observation that data output from surface-consistent deconvolution lacked the temporal resolution desired. This led us to insert a single-trace zero-phase spiking deconvolution step immediately after the initial surface-consistent deconvolution pass. This did increase the effective bandwidth of the data, but unfortunately single-trace deconvolution does not maintain amplitude relationships, especially in the presence of noise. Consequently, after this additional deconvolution step, we saw, for example, that amplitudes on near-offset traces that were overlain by ground roll increased relative to

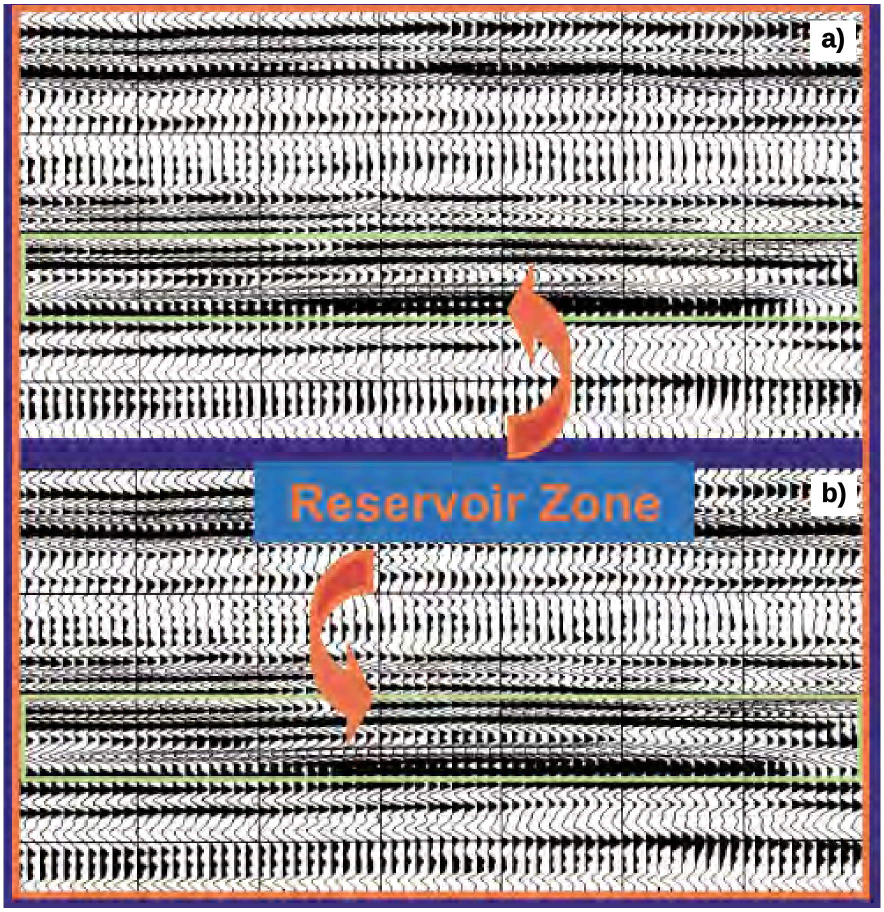

Figure 5. Effect of prestack amplitude balancing. Migrated stack sections (a) without and (b) with amplitude normalizations applied subsequent to prestack single-trace zero-phase spiking deconvolution following surface-consistent deconvolution.

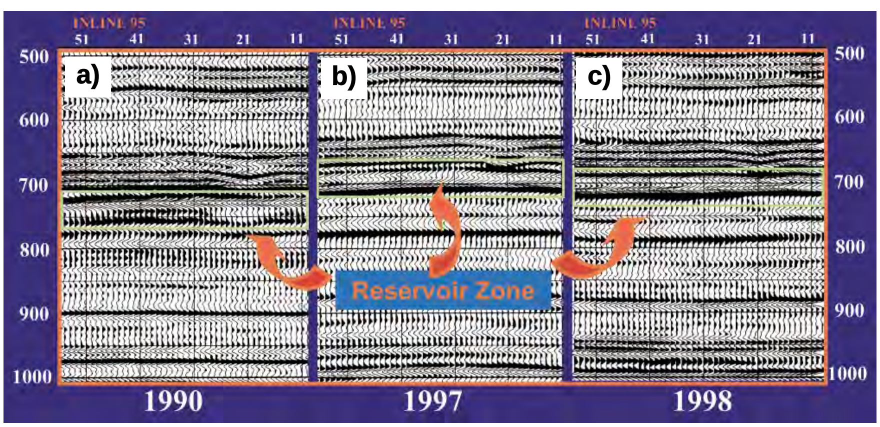

Figure 6. 4-D migrated stack sections before cross-equalization: (a) baseline in-line 95 from 1990 survey; (b) monitor in-line 95 from 1997 survey; and (c) monitoring in-line 95 from 1998 survey. Note phase variations, amplitude differences, and time shifts.

amplitudes on longer-offset traces free of ground roll (Figure 4a). To address this problem, a rescaling step (after the single-trace deconvolution) restored the rms amplitude values of individual traces to what they had been before the zero-phase deconvolution. Figure 4b shows a shot record after rescaling.

The other complication was the observation that the front ends of some traces output from the deconvolutions were abnormally high in amplitude. The temporal amplitude balancing first employed to address this problem naively failed to account for the fact that surface-consistent scalars derived from bandlimited traces were subsequently applied to wideband traces and therefore failed to produce the desired results. This was easily corrected by applying a global scale correction that compensated for applying scalars derived from filtered traces to unfiltered traces (Figure 4c).

Figure 5 shows traces from a migrated stack section (a) before and (b) after properly normalizing amplitudes in the manner discussed above. The green box highlights differences in waveform around the reservoir zone.

3) Cross-equalization. All data were processed in a consistent manner from prestack to poststack, but 00severe differences in phase, reflection strength and time shifts still existed. This is apparent in Figure 6, which shows three migrated stack sections along the same NW-SE line (in-line 95) before cross-equalization. The reservoir zone is highlighted for comparison. No doubt, it would be very difficult to reliably infer changes in fluid-flow patterns directly from such data without cross-equalization.

Cross-equalization requires a wavelet operator, estimated in a time window, to shape and match data from the monitor survey, A2, to the baseline survey.

Theoretically, the difference between A1 and A2 after cross-equalization should equal zero everywhere (inside and outside the design window) except in the reservoir zone where changes are expected. Ross et al. (1996) said the filter can contain up to four basic elements: time corrections, rms energy balancing, frequency bandwidth normalization, and phase matching. They suggested that the filter operator be designed over a range of static reflectors that excludes the reservoir zone where meaningful changes in pore fluid state or other reservoir properties may occur. We found that this is not necessarily the best approach.

We computed an operator from a fairly long time window (250-1350 ms) and used the baseline 1990 survey as the reference.

Figure 7 shows data after cross-equalization. By comparing data above and below the reservoir, one can see that time shifts, phase variations, and even amplitude differences (all evident in Figure 6), have been minimized, and that the sections in (b) and (c) now look almost identical to the baseline section in (a). Some subtle changes in terms of amplitude

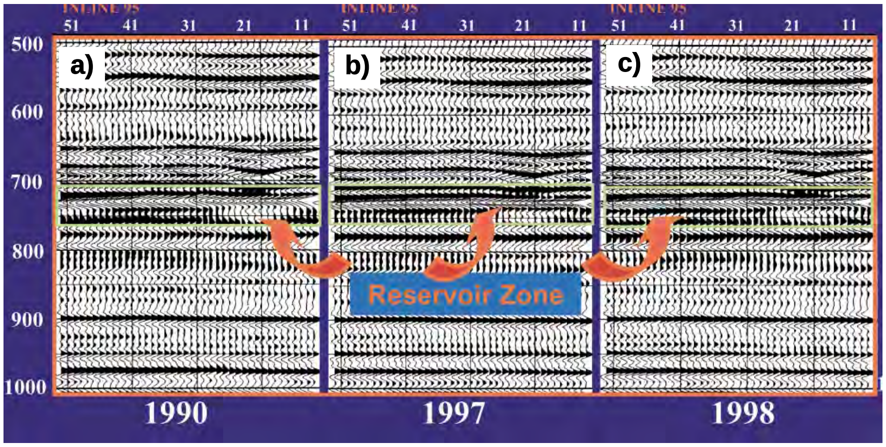

Figure 7. 4-D migrated stack sections after cross-equalization. The filter operator was designed from a time window of 250-2350 ms. Input data to filter are in Figure 6. (a) Baseline 1990 section as reference; (b) monitoring 1997 section; and (c) monitoring 1998 section. Filter contains bandwidth normalization, rms energy balancing, phase matching, and time correction.

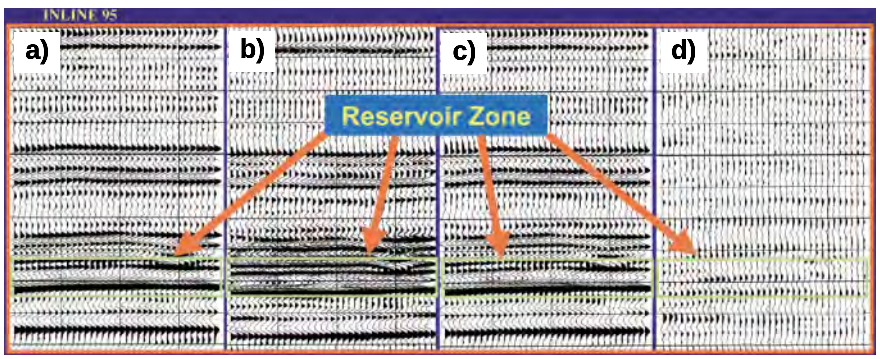

Figure 8. Cross-equalization results using a long design window (250-1350 ms). (a) In-line 95 of 1997 survey as reference; (b) in-line 95 of 1998 survey as input; (c) output of cross-equalization applied to (b); and (d) difference of (a) and (c). Filter contains bandwidth normalization, rms energy, phase matching, and time correction.

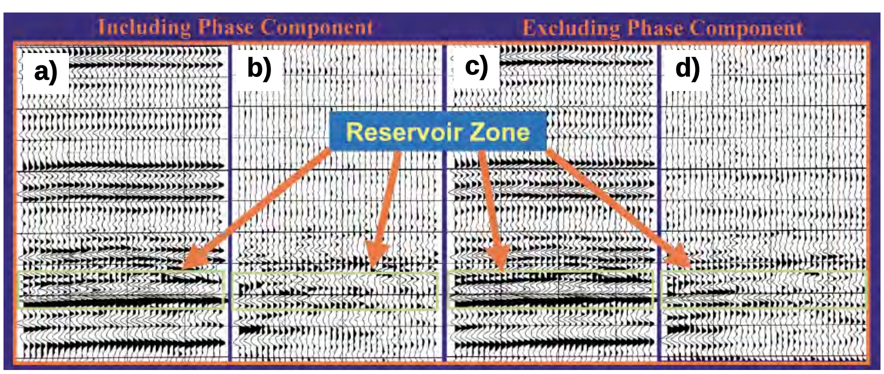

Figure 9. Cross-equalization results using a short design window (200-600 ms). (a) Filtered in-line 95 section; (b) Difference between (a) and Figure 8a; (c) Filtered section using an operator excluding the phase-matching component; and (d) difference between (c) and Figure 8a.

and waveform within the reservoir zone are evident in all panels in Figure 7. These subtle changes are indeed the expected consequence of the changing reservoir conditions (steam chamber effect), as explained in the next section.

Now let us consider the effect of design windows on cross-equalization. Ideally, one would prefer to exclude the reservoir zone (where dynamic change is anticipated) from the design window. Marine time-lapse studies use very large time windows (800 ms) that exclude the zone of interest. In another EOR monitoring study, Sun and Harrison (1998) also normalized time-lapse seismic data in a 600-ms time window that excluded the reservoir. However, when we tested the sensitivity of cross-equalization design windows on our data sets, we found that a long analysis window containing the reservoir zone tends to outperform shorter windows excluding the target.

Figures 8a and 8b show migrated sections from the monitoring surveys. The input to cross-equalization was from 1998 with 1997 as the reference. The cross-equalization filter contained frequency content balancing, rms energy equalization, time static corrections, and phase matching. The design window was 250-1350 ms. Note that our reservoir is around 710 ms. The output is given in panel (c) and the difference in panel (d). The cross-equalization operator worked very well.

We also tried a shorter cross-equalization operator on the same input section. It was designed from a window of 200-600 ms, with the reservoir zone excluded. Figures 9a and 9b show the new cross-equalized section and the difference.

By comparing Figure 9a (the output) with Figure 8a (the reference), one can see that continuity of reflections in the time zone immediately above the highlighted zone on the output is severely disrupted because of this short operator. The loss of reflection continuity is amplified on the difference section (Figure 9b) where much coherent energy has leaked into the nonreservoir zone.

Ross et al. (1997) concluded that phase correction is a major component of the total cross-equalization operation. It was also true in our case. Figure 9c shows the result of applying an operator designed from the same short window (200-600 ms) but excluding the phase-matching component. One can clearly observe the following consequences:

1) The cross-equalized data in a shallow window (300-600 ms) in Figure 9c look very similar to the baseline data in Figure 8a.
2) However, data below the design window (i.e., below 600 m) have different phase than the baseline data.
3) A large amount of reflection energy has leaked into the difference section (Figure 9d).

To summarize, cross-equalization

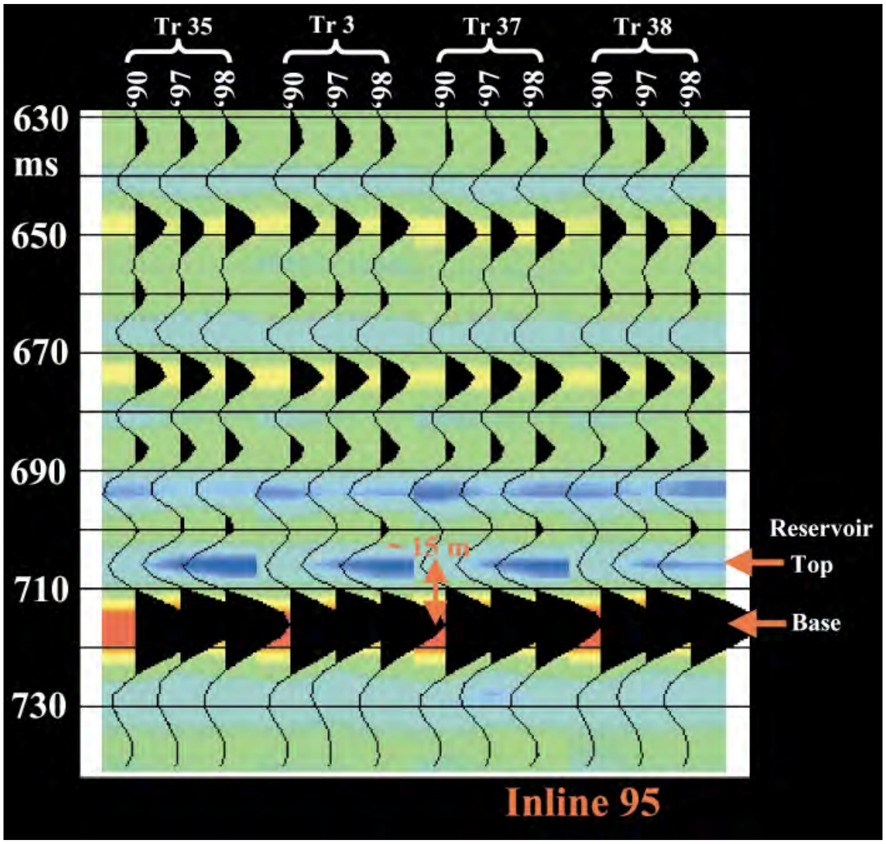

Figure 10. Time lapse trace-to-trace comparison, illustrating the effect of steam heating on seismic signatures.

is necessary to remove from time-lapse seismic data the differences not caused by the reservoir changes, an operator from a long design window (even including the dynamically changing reservoir zone) works better on our data sets, and phase correction is important for effective cross-equalization.

4-D seismic interpretation. Our 4-D seismic data have strong seismic amplitude anomalies around all the horizontal well pairs, A1-A4. These anomalous seismic signatures are characterized by a trough amplitude increase on the reflection at the top of the porous reservoir zone (Figure 10).

This 15-m thick reservoir is well defined by (at its top) a trough around 705 ms and (at its base) a peak about 715 ms. The base of the reservoir, a boundary between soft sands and an older hard carbonate rock, results in a significant impedance contrast in this area.

Within the lower horizontal producer of the infill SAGD well pair A4, in-situ temperature / pressure logs were recorded almost concurrently with acquisition of the 1998 monitoring survey. The in-situ measurements show that the pressure along the well bore within the reservoir more or less remains at the same level as the injection pressure while the reservoir temperature has increased beyond 240°C over the whole length of the horizontal leg. Engineering measurements and production history consistently confirm that a sizable steam chamber has been generated around the well.

This steam chamber effect is well reflected on the time-lapse seismic data. Figure 10 shows traces of four adjacent CDP bins, separated by 20 m, extracted around horizontal well pair A4. We have put the same CDP traces, from different surveys, side by side. One can clearly see that reflections on all three traces in each CDP group have the same characteristic patterns above the reservoir zone (705 ms), indicating that the overburden has not been affected by the steam flood. On the other hand, at the top of the reservoir (705 ms), one can identify increasingly stronger trough amplitudes, as indicated by the color changes. We interpret this anomalous amplitude variation as being caused largely by a significantly lower velocity and, to a lesser extent, by a decreasing bulk density as a direct result of steam flooding. The introduction of steam into the reservoir may have caused partial gas saturations that slow down wave propagation in the reservoir and decreased oil viscosity that softens the reservoir formation. Both weaken acoustic impedance. We also believe that, although started initially at the base of the reservoir, the steam chamber has actually grown upward and reached the top of the reservoir, at least in the vicinity of well A4. These observations and interpretation are strongly supported and validated by the in-situ downhole temperature / pressure logs collected in the A4 producer.

Figure 11 shows time-lapse profiles from the 1990 survey through the 1998 survey. These enlarged sections are cut along the same line across the toes of the four SAGD horizontal wells. The time-lapse effect of steam chamber migration on the seismic is evidenced again by an increasingly strong amplitude event at the reservoir top. After 24 months of steam injection, the reflection from the reservoir top is strong and thickening, compared to those on the 1990 survey (before steaming) and the 1997 survey (after 18 months of steaming).

Figure 12 displays time-lapse seis-

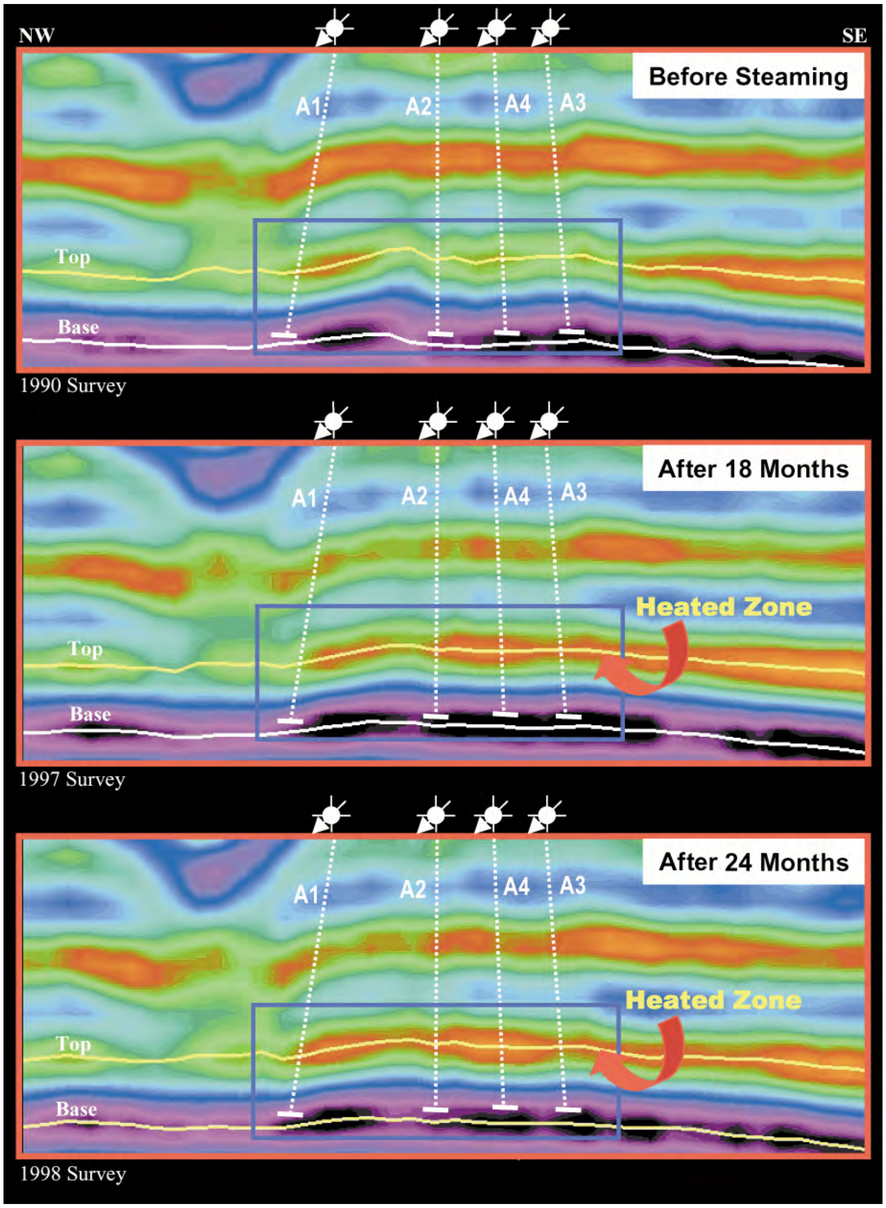

Figure 11. Steam chamber developing across the pattern of four SAGD horizontal wells.

mic sections along the horizontal trajectory of well pair A4. Obvious again is the significant influence of long-duration steam flooding (18-24 months). Note the remarkable variations in amplitudes before and after steaming. The steam chamber clearly has expanded around the well.

The difference sections provide more quantitative information about the net changes in a reservoir with time. In Figure 13, two difference sections, along horizontal well A4, effectively demonstrate the length of the steam chamber around the wellbore and its vicinity. Production logging in this well confirms our seismic interpretation that, during the 24 months of continuous steam injection, the reservoir rock in the neighborhood of the whole length of this horizontal well has been heated effectively and evenly.

Our 4-D interpretation also indicates that the steam chambers are not equally developed along all wellbores. At some locations, the steam flood patterns seem more spatially heterogeneous and unheated spots (namely, reflections without time-lapse changes) have been identified.

Discussion and conclusions. This case study shows that, when processing time-lapse seismic data, preserving relative amplitudes (in a manner similar to AVO processing) and cross-equalization are key components of the sequence. Even when major differences in acquisition parameters exist (resulting in significant nonrepeatability of the data), cross-

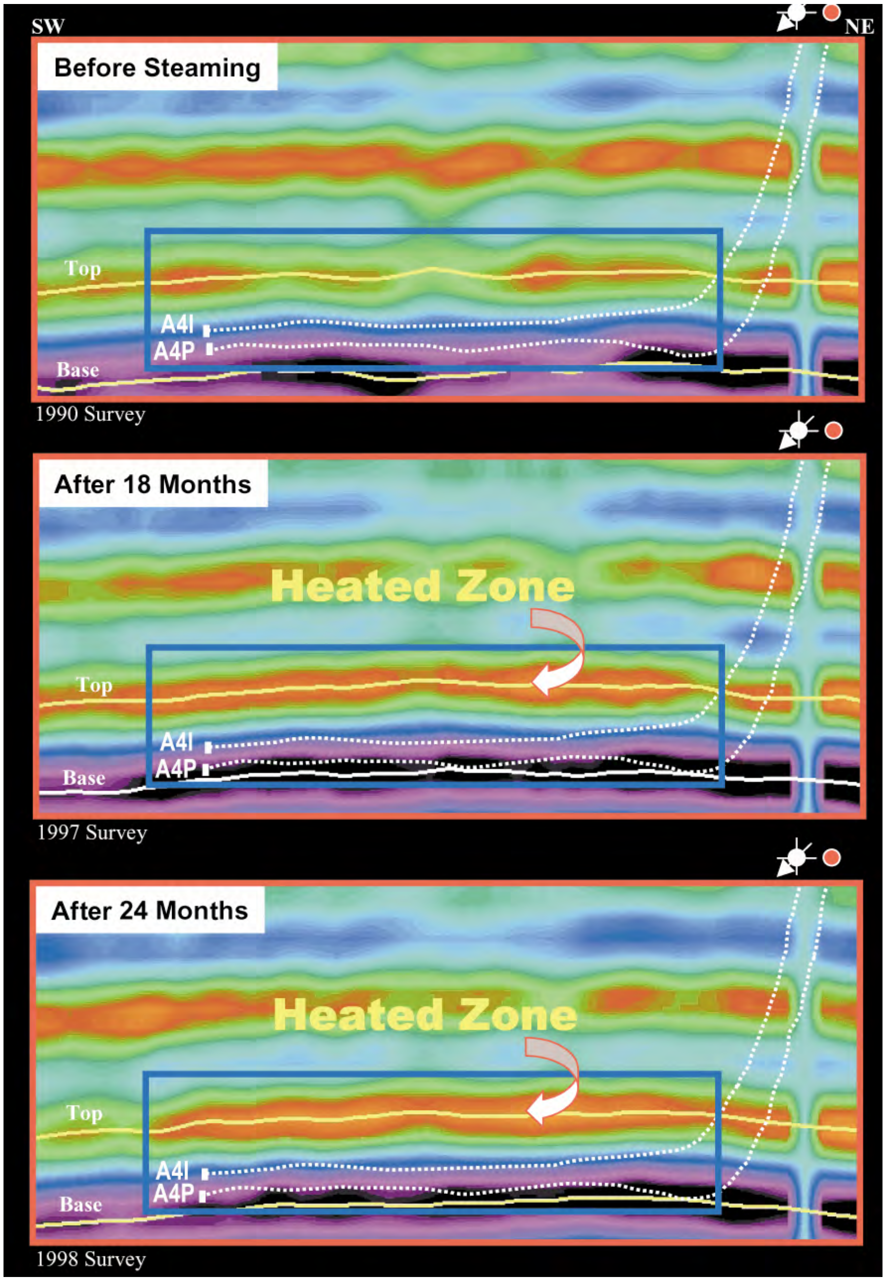

Figure 12. Steam chamber developing along horizontal well pair A4.

equalization can satisfactorily remove most of the nonreservoir differences (or artifacts) and permit reliable extraction of reservoir information.

Our study also shows that the cross-equalization design window is important. For time-lapse seismic data such as those described here, a longer window that includes the zone of interest is preferred. One possible explanation for this surprising situation is that a longer design window will have better statistical balancing characteristics on seismic signals than a short window. It holds true especially when the shallow parts of the seismic sections above the reservoir zone are inconsistent due to rapid geologic and near-surface changes. In particular, it is likely true for shallow reservoir targets.

Although repeatable acquisition in time-lapse seismic monitoring is always very desirable, strictly repeatable seismic data may not be obtainable. Actually, most often one has to deal with very different 4-D data sets for monitoring. Nevertheless, one should always pay attention to careful planning and implementation of time-lapse 4-D seismic data acquisition to minimize unnecessary nonrepeatability. When legacy data have to be used or when it is impossible to acquire repeatable time-lapse data, uniform processing becomes very important and sometimes essential.

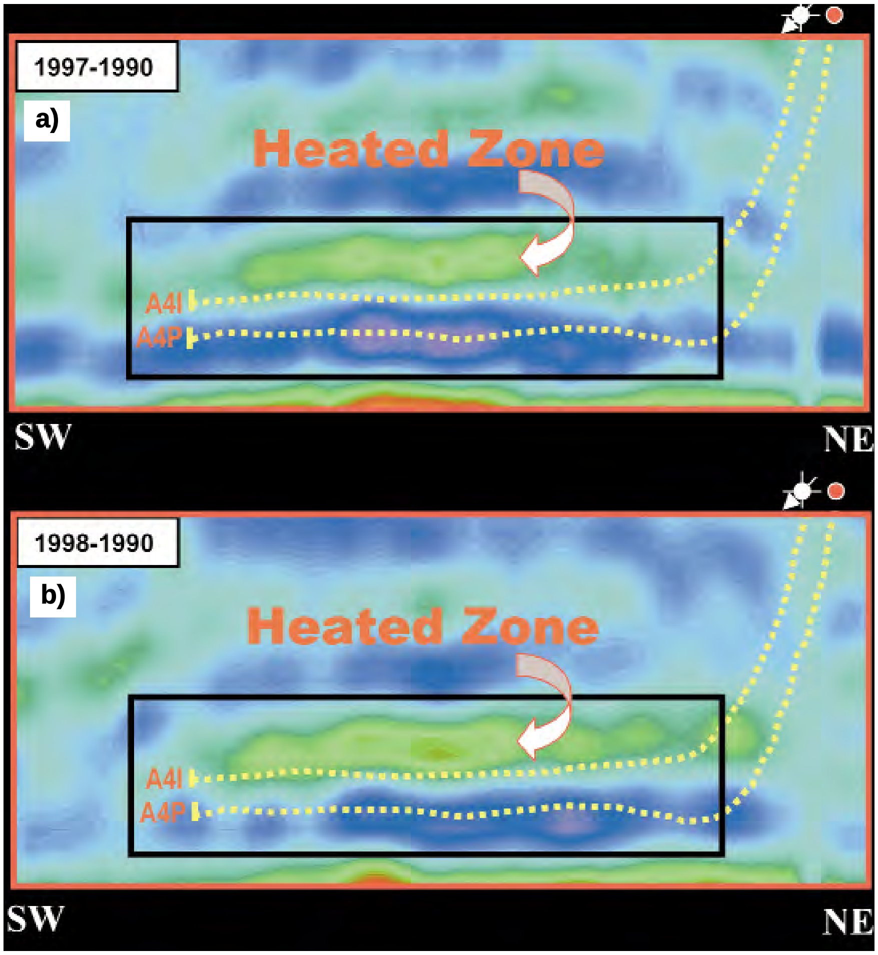

Figure 13. 4-D seismic difference section. Highlighted zone shows that the steam chamber is expanded along horizontal well pair A4. (a) Difference between 1997 and 1990 surveys and (b) difference between 1998 and 1990 surveys.

Suggested reading. "MegaBin land 3-D seismic: Toward a cost effective 'symmetric patch geometry' via regular spatial sampling in acquisition design and cooperative processing for significantly improved S/N and resolution" by Goodway and Ragan (CSEG Convention, 1996). "Time-lapse seismic monitoring: Some shortcomings in nonuniform processing" by Ross and Altan (*TLE*, 1997). "Inside the cross-equalization black box" by Ross et al. (*TLE*, 1996). "Time-lapse seismic data normalization and calibration" by Sun and Harrison (Joint CSEG/CSPG/CWLS Convention, 1998).

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