

# Cross-equalization in Time-lapse Seismic Data Processing

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## Summary

A unique series of repeated seismic reflection profiles were acquired over an active steam injection site since late 1999. Despite efforts to retain nearly exact acquisition conditions between most of the surveys, there remain discrepancies in the characteristics of the seismic traces from survey to survey. Cross-equalization procedures, based on conventional Wiener minimization methods, were employed to improve the temporal similarities between the sections of the profiles that should not have experienced any change in geological conditions and hence no change in seismic reflectivity. Sections calculated as the difference between the temporally cross-equalized sections suggest this method adequately corrects variations in the seismic character not resulting from changes in the reservoir. A new quality control technique that relies on the determination of the similitude between sections of the seismic frames using a standard statistical correlation test reinforces this view. This correlation method may additionally diagnose and highlight those areas within the reservoir zone that have undergone seismically detectable changes.

## Introduction

The elastic behaviour of rock changes due to fluid movement and variations in saturation state, stress, temperature, and pore pressure. This change in the rock properties serves as the basis for reservoir monitoring by time-lapse seismic surveys. In such surveys, seismic data is collected at two different calendar dates. The comparable section is calculated from two calibrated seismic images in order to observe fluid property changes. Due to possible coherent energy existing on comparable sections, uniform processing between time-lapse seismic data is the key for successful time-lapse interpretation. An important part of uniform data processing is cross-equalization. In essence, a wavelet operator is extracted from monitoring survey to shape and match the reference survey (Ross et al., 1996). Theoretically, operators are designed over static time window where little or no dynamic change is expected. In cross-equalization, an operator can be computed trace by trace from the monitor survey that is then transformed to match the reference survey. Operators are designed in horizon-specific windows that exclude the reservoir zones. Here, we present the latest results of an ongoing time-lapse monitoring study. A cross-equalization methodology is developed on five time-lapse seismic 2-D frames. Additionally, a simple correlation calculation provides a quantitative basis of confidence in the quality of the time-lapse comparison.

## Case Study

Our target is located in East Senlac area in the vicinity of Alberta-Saskatchewan border. At around 730m (about 710ms) there is highly viscous heavy oil in the producing reservoir. High-temperature steam is injected to enhance the oil recovery. Details on the reservoir and geology may be found in Li et al. (2001). This study is motivated by trying to find visible change in repeated 2-D seismic surveys.

To date, five different surveys have been acquired at the site since 1999 through October 2001; more surveys are anticipated. Only the results obtained from a 2D survey that crosses obliquely one of the steam injection zones will be presented here. The surveys are unique in that they employ high spatial sampling of geophone singles at a 3-m spacing: this results in a close 1.5-m trace spacing in the final CMP stack. The seismic source employed is a high frequency 6000-lb seismic vibrator operating from 12-Hz to 150-Hz with a 15 second linear sweep. A close source spacing of 6-m along the 700-m profile allows for high fold. Further, a great

deal of care has been taken to make the repeated surveys nearly identical. The geophone placement does not vary by more than a few centimetres (as measured via repeated differential GPS surveying). Cultural changes did result in shifts of the source positions, but most of the surveys were carried out with a general source spacing of 9-m with variations in positioning usually better than 20-cm. In the latter four surveys, the data was acquired using the same 240-channel distributed system and geophones. The data were acquired at a 1-ms sampling rate.

Despite the care taken to repeat the geometry of the experiment from frame to frame as consistently as possible, there remain variations in the character of the waveforms with time. Part of this is likely due to the high cultural noise levels near such industrial sites. Most of the difference is probably attributable to seasonal changes in the near surface conditions, especially as they influence the coupling of the seismic vibrator.

## Data Processing

A shift-stack procedure, developed for severe static and near surface Athabasca reservoirs (Schmitt, 1999), was first attempted. However, a more conventional approach was found to be adequate for the deeper reservoir studied here. In order to preserve relative amplitudes, a uniform processing sequence is used that includes de-bias, bandpass filter, refraction static correction, detailed velocity analysis, NMO, CDP stack, surface consistent correction, and finally cross-equalization. Cross-equalization is an important component in time-lapse seismic processing that transforms one seismic section to be comparable with the other (Ross et al., 1996). In cross-equalization, an operator is computed trace by trace in order to make the, presumably, unchanged portions of the seismic profile match in amplitude and character from the monitor survey that is then transformed to match the reference survey. Operators are designed in horizon-specific windows that exclude the reservoir zones. Figure 1 shows time-lapse traces that have the same location before and after cross-equalization. The traces in figure 1 are cross-equalized using an operator with a long-window that includes the reservoir zone. By comparing later data to the reference (November 1999), one can see that phase and amplitude match well.

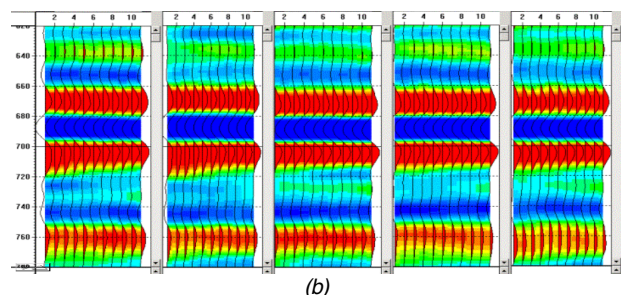
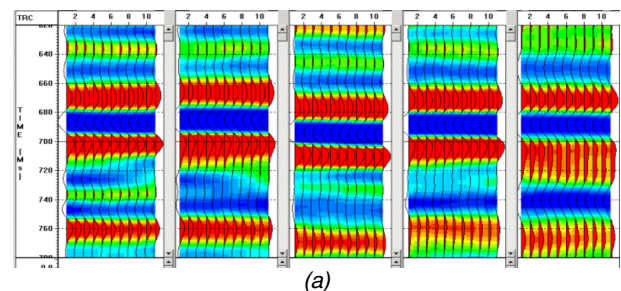
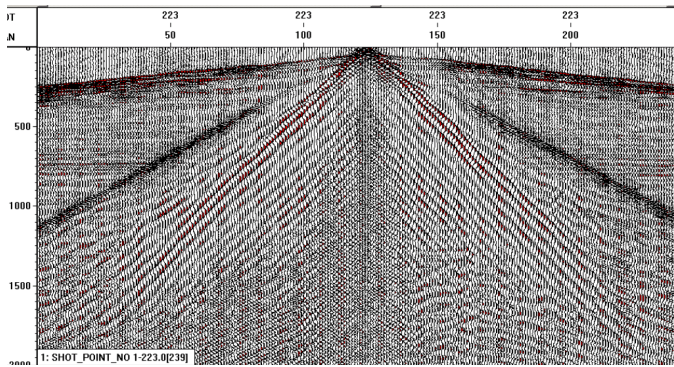


Figure 1. Time-lapse traces before and after cross-equalization. The earliest data(left) is chosen as the reference. From left to right are the data with time increase. (a) before cross-equalization; (b) after cross-equalization using an operator with a long window that include reservoir zone.



It is obvious that cross-equalization does minimize changes within the design windows so that the difference between two time-lapse data sets is near zero. However, sufficient residual reflector energy still exists outside the design window (Ross, et al., 1996). This makes fluid-state interpretation ambiguous. Also acquisition difference makes the problems inherent in time-lapse monitoring more complicated. In order to reduce this ambiguity and to indicate possible fluid movement to maximum degree, it is crucial to choose operators with proper design window to perform cross-equalization.

### Seismic Attribute Differencing

We suppose that fluid movement exists over calendar dates. The ultimate goal in time-lapse seismic monitoring is to see variations of inter-pore fluid movement between calendar dates. Usually this is obtained by subtracting a monitor survey from the base survey after calibrating the data through cross-equalization. Here we examine the effect of the choice of cross-equalization operator on the final seismic difference frames.

The reservoir is around 710ms. Two different cross-equalization operator windows were tested: a short 200-ms to 650-ms window above the reservoir and a long 200-ms to 1250-ms window that includes the reservoir reflections. The traces acquired in October 2000 were taken to be the reference. To characterize the effect of different operators on the final results, difference plots are given.

Difference frames were calculated by subtracting the November 1999 profile from each of the four subsequent sets. Figure 2 shows direct seismic difference between monitoring and reference surveys. Operators are extracted with time windows 200-ms to 650-ms and 200-ms to 1250-ms respectively. Corresponding frames between figure 2a and 2b have different characteristics; this difference makes unambiguous interpretation of the two different sets uncertain. One might expect the data in figure 2a to better highlight changes as the influence of the variation in the reservoir has not been included in the cross-equalization operator. But without additional information it is impossible to make this claim.

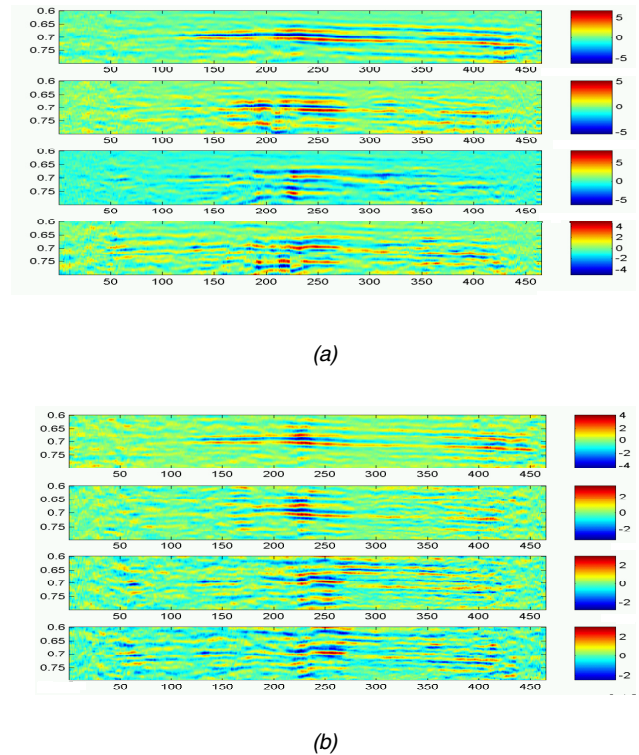
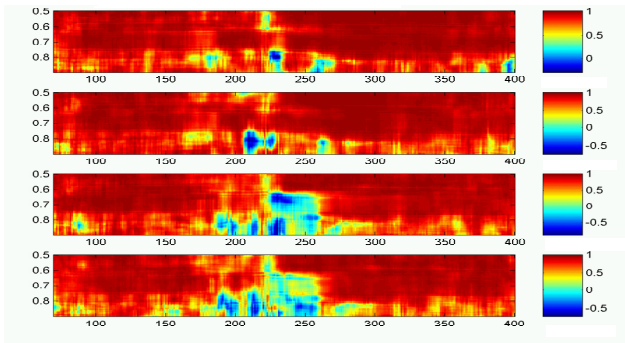


Figure 2. Time-lapse seismic attribute difference between reference survey and monitoring survey. Reference survey for cross-equalization is October 2000' data; reference survey for differencing is November 1999's survey; monitoring surveys are those collected in October 2000, May 2001, July 2001 and October 2001. (a) is computed when using operators with the design window 200-650m; (b) is sections cross-equalized with a design window 200-1250ms.

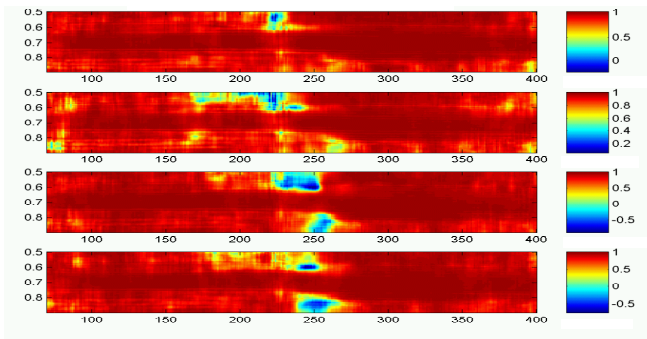
In order to overcome this difficulty and to allow for a more quantitative assessment of the time-lapse frames, a new methodology is developed that uses simple statistical concepts of correlation. The Pearson correlation coefficients between corresponding time windows of the amplitudes between a reference and a monitor survey are calculated. These coefficients are then mapped to make a comparison profile. Essentially, if there is no change in the seismic character (after cross-equalization), the linear correlation coefficient between the reference and monitor time window will have a value close to unity. If there is a change in the character, then the coefficient will be near zero or even negative. Mapping the correlation coefficient consequently provides:

- i) a measure of the quality of the time-lapse comparison (i.e. most of the image should be nearly unity and if not then there are potential problems with the cross-equalization), and,
- ii) a criteria for highlighting regions within the reservoir that have undergone changes (i.e. such areas within the profile will have a varied seismic character and a map with a low correlation coefficient).

Two different sets of Pearson correlation profiles are shown in figure 3; red indicates a good correlation near unity whereas blue shows poor correlation. It is interesting to note that the second set of panels of figure 3b, calculated using traces from the long cross-equalization frames, do not show substantive change near the expected reservoir reflection times. This suggests that the long cross-equalization operator may reduce the visibility of real potential changes in the seismic character.



(a)



(b)

Figure 3. Pearson correlation coefficient profiles highlight differences between reference and monitor surveys. In (a), the monitoring data are cross-equalized using operators with a designed window 200-ms to 650-ms with October 2000 as cross-equalization reference. In (b), the monitoring data are cross-equalized using operators with a designed window 200–12500ms with October 2000 as cross-equalization reference. In both sets of panels, the correlation profiles are calculated using November 1999 traces as the correlation reference. In each set of panels the correlation comparisons are with October 2000, and May, July, and October 2001.

## Conclusion

Using five time-lapse seismic data sets, we have presented the basic element involved in cross-equalization. With these examples, we have shown that effective cross-equalization is important to reduce residual variations in seismic character due to factors that cannot be controlled in even the most consistently repeated seismic surveys.

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