Introduction

Continuously acquiring time-lapsed (4D) seismic data for detecting dynamic changes (4D signal) in a desert environment over a land carbonate petroleum reservoir being injected with water-alternating-CO_2 poses many challenges for 4D seismic monitoring. First, the near-surface is highly complex due the existence of karsts and thick sand dunes which in turn generate strong coherent and scattered noise deteriorating the quality of seismic imaging and disguising 4D signals. Second, the changing nature of the near-surface over space and time induces significant amplitude and phase variations obscuring the dynamic changes within the reservoir. Third, the 4D signal is anticipated to be too weak to be detected due to the stiff nature of carbonate reservoirs.

To improve the detection of the dynamic changes, the noise level (4D noise) between the base survey and the monitor surveys must be suppressed significantly below the 4D signal level while preserving the 4D signal (Lumley et al., 2003; Bakulin et al., 2007; Schissele et al., 2009). Reducing the 4D noise can be achieved collectively during acquisition and processing stages (Rickett and Lumley, 2001; Bakulin et al., 2007; Ma et al., 2009).

To reduce the 4D noise during the acquisition phase, a dedicated hybrid acquisition system comprising of buried sensors and surface vibroseis points is deployed. The receivers are buried deep enough to avoid the noisy surface environment, the seasonal surface variability, and the effects of the strongly attenuating near-surface layers. This, in turn, leads to reduction in the noise level. In addition, burying the sensors guarantees perfect repeatability of receiver position but not response for the duration of the project life. Furthermore, vibroseis is used as seismic sources with a dense grid ensuring that the wavefield is sufficiently sampled within the common-receiver gather. In addition, vibroseis position and response repeatability can be maintained within a pre-specified tolerance.

Time-lapse critical seismic processing steps

Regardless of the field efforts, seismic data still suffers from numerous challenges. First, the 4D seismic data is dominated by significant high-amplitude coherent noise. Second, amplitude variations over space and time caused by source and receiver coupling and seasonal changes are common in time-lapse data acquired in a desert environment. Another problem is the presence of time and phase shift variations due to seasonal near-surface changes. Last, the time-lapse signal-to-noise ratio is low due to the use of single-source-single-receiver acquisition. Eliminating these challenges while preserving the 4D signal is optimized through the use of a novel processing workflow comprising five critical steps.

Time-lapse processing include many steps aimed to reduce 4D noise, preserve 4D signal and maintain the quality of seismic imaging. However, only five steps are identified as critical for successful time-lapse processing in a desert environment. First step is to eliminate the high-amplitude coherent noise from the time-lapse data. It is achieved by using FK-based techniques that preserve the reservoir dynamic changes. The method is implemented in the common-receiver domain as the wavefield is adequately sampled to avoid aliasing. This step is to ensure that all the subsequent derived operators are based on more signal and less noise.

The second step is to resolve the amplitude variations caused by near-surface variability among different surveys. This is attained by using four-term joint surface-consistent amplitude-scaling least-squared algorithm. The algorithm allows both source and receiver terms to have different scalars over space and time, but it restricts the offset and CDP terms to be time-invariant (survey-invariant). Unlike source scalars, receiver scalars maintain thin variability as predicted. Furthermore, the window of amplitude analysis involves merely the overburden so that the 4D signal is protected against the overburden changes. Consequently, the amplitude variations resulted from near-surface variability is removed by applying source and receiver scalars over space and time to all surveys, thus ensuring that the overburden has similar amplitude in spite of the survey. It also guarantees that the reservoir 4D signal is not scrambled by changes in the overburden.

The third step is to address the wavelet phase variations among different surveys (4D phase) caused by seasonal changes. This is accomplished by using a four-term joint surface-consistent spiking deconvolution algorithm that applies a similar principle as the scaling algorithm. But, it requires a longer analysis window for deriving the unwavering operators. This step may prove to be risky as the window of analysis includes the reservoir unless the phase variation caused by the dynamic changes is small compared to that of the seasonal variability. The phase variations resulted from near-surface seasonal variability is removed by applying the source and receiver phase only operators to all surveys over space and time, hence preserving the reservoir dynamic changes.

The fourth step is to determine the small variations in reflection times among different surveys (4D statics) caused by near-surface seasonal changes. 4D statics are resolved by an innovative approach, deploying two passes of a 3D surface-consistent statics algorithm. This step assumes that the common residual statics values caused by the near-surface layer and affects all survey have been applied. The algorithm, first, uses the 3D seismic data from the baseline together with its corresponding pilot trace to calculate the residual statics values. The statics are, then, applied to the baseline survey and a new pilot trace is re-generated. During the second pass, the statics algorithm uses the re-generated pilot trace from the baseline survey to compute static values for each survey independently. 4D statics are removed by applying the static values, computed during the second pass, to their corresponding surveys thus uncovering the 4D signal.

The last critical step is to improve the signal-to-noise ratio. This is accomplished through the application of super grouping method that uses 7 by 7 shot groups with NMO applied. This process enhances seismic data by boosting SNR, suppressing random and linear noise, and improving events continuity (Bakulin et al., 2016).

Field example

A processing workflow involving the five critical processing steps mentioned above is shown in Figure 1. It is applied to time-lapse seismic data comprising 32 surveys acquired in a desert environment over the CO2 EOR demonstration project in Saudi Arabia. On average, each 3D seismic survey takes one month to be acquired and consists of 100,000 vibroseis source points and nearly 1000 buried receivers. Figure 2 summarizes the repeatability between the baseline survey and a monitor survey by tracking the progression of mean NRMS (Normalized Root-Mean-Squared) throughout the processing workflow. After pre-processing, a mean NRMS value of nearly 40%, which is considered quite reasonable for land data. This is due to the permanent sensors are buried below the weathering layer to avoid 4D noise in conjunction with stacking high-fold CDP gather to improve signal-to-noise ratio. A mean NRMS value of approximately 29% is obtained after suppressing the high-amplitude coherent linear noise confirming that the coherent linear noise is quite unrepeatable. Removing the effects of amplitude variations caused by the near-surface variability has resulted in well-balanced pre-stack data with a mean NRMS value of around 28%. This is because the seismic data in the previous step is balanced using time-variant scaling whereas the current step is balanced by surface-consistent amplitude scalars. Therefore, changing the method of balancing the seismic data does not seem to reduce the 4D noise significantly. Still, the surface-consistent amplitude (SCA) scaling is crucial for preserving 4D-signal even if it has not reduced the 4D noise. The surface-consistent deconvolution (SCD) and the second pass of the surface-consistent amplitude scaling induce a minor reduction in 4D noise. Most of the phase shift variations, occurring during the rainy season, happens to be within the overburden. Resolving 4D statics has induced little or no change in NRMS suggesting that there is not much 4D statics to resolve as the two surveys are close in time. Still, the innovative approach used to compute the residual statics values is essential for uncovering the 4D signal. Application of trim statics values has reduced the 4D noise by another 3% on average, which is a comparatively large reduction. Application of supergrouping is another major step in reducing 4D noise and improving repeatability. It has remarkably reduced NRMS down to 10% by increasing signal-to-noise ratio, eliminating random and linear noise, and improving event continuity. Finally, the post-stack migration has further improved repeatability and brought NRMS down to 5.6%.

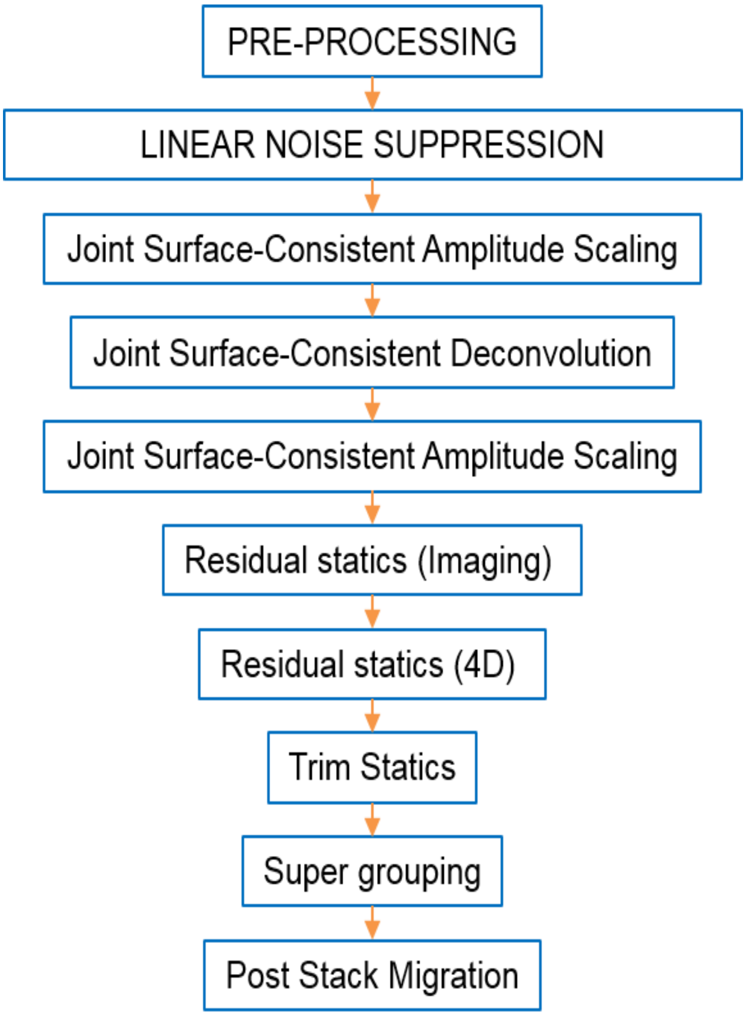

Figure 1 *Time-lapse processing workflow to reduce 4D noise, preserve 4D signal and maintain the quality of seismic imaging. The workflow contains five critical steps that are essential for 4D seismic data acquired in a desert environment over a carbonate reservoir.*

Conclusion

We presented a five critical steps in a 4D processing workflow for time-lapse seismic data that was continuously acquired to monitor the plume in the CO2 EOR demonstration project in Saudi Arabia. The success of 4D seismic processing relies on reducing the 4D noise below the 4D signal level in an arid environment with a challenging near-surface environment. Ultimately, the combination of buried receivers, carpet shooting, and novel processing delivered seismic repeatability of around 6% NRMS, which is exceptional. This is a first of its kind single-sensor permanent monitoring system combined with an innovative processing workflow. Multi-survey surface-consistent processing, supergrouping, and 4D-compliant statics were key steps to obtain repeatable images from these challenging data. This study confirms that land 4D noise can be effectively handled by buried receivers and innovative processing.

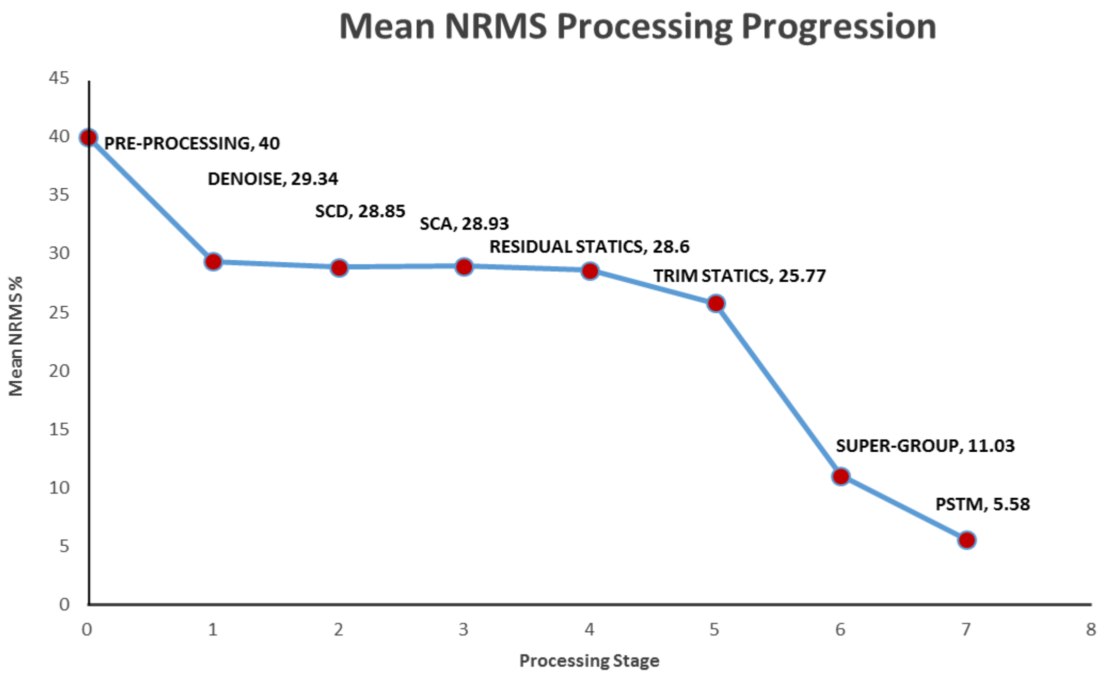

Figure 2 *The graph shows progression of mean NRMS of the stacked-data from pre-processing to post-stack time migration. Two processes that have remarkably reduced the mean NRMS value are coherent noise elimination and supergrouping. The surface-consistent processing including SCD, SCA and residual statics are essential for preserving 4D signal.*

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