Introduction

Inherent complexity of carbonate reservoirs practically demands 4D seismic for revealing fluid flow patterns (Johnson, 2013), although seismic monitoring in desert environments remains the most challenging 4D frontier. We have taken this extremely ambitious challenge as a necessary step toward greater recovery. In this study, we report the first successful application of monitoring of CO2 injection in an onshore carbonate reservoir with complex near-surface conditions.

Bakulin et al. (2013) describe key acquisition elements that contribute to 4D success in a desert environment. Permanent buried receivers and dense carpet shooting using Vibroseis are required to achieve highly repeatable data for the detection of small 4D signals (Figure 1a). Although buried sensors reduce surface-related noise and boost repeatability, such a configuration is essentially a point-source, point-receiver acquisition system with challenging pre-stack data quality (Bakulin et al., 2016). A novel multi-survey 4D processing flow was applied to fully leverage all acquisition benefits and to reduce remaining non-repeatability caused by variable source coupling and changing near surface conditions (Bakulin et al., 2016, Al Ramadhan et al., 2017). We outline short- and long-term repeatability trends obtained using this system and demonstrate the successful application to monitoring the plume in the CO2 EOR demonstration project.

Long-term vs. short-term repeatability

The buried sensor system offers a straightforward, real-time assessment of repeatability using direct arrivals from near zero-offset shots (Bakulin et al., 2015). Figures 2b and 2c show average repeatability metrics for early arrivals averaged over all shots as a function of return time (elapsed time between baseline and monitor surveys). Normalized root-mean-square (NRMS) and predictability are two common metrics used for 4D seismic (Johnston, 2013). For a baseline acquired during the dry season, NRMS increases and predictability decreases when we enter the wet season. Repeatability improves upon returning to the same season as the baseline survey, although it usually does not reach identical levels, likely due to sand dune migration (Figure 2e). Such changes of NRMS and predictability demonstrate that seasonal variations represent complex waveform changes (Figure 2d) instead of simple amplitude scaling or time shifts (Bakulin et al., 2014). Despite being rather subtle (Figure 2d), their effect is significant because the expected 4D response is of a similar order of magnitude. Figure 3 shows NRMS of the imaged and stacked data after the multi-survey 4D

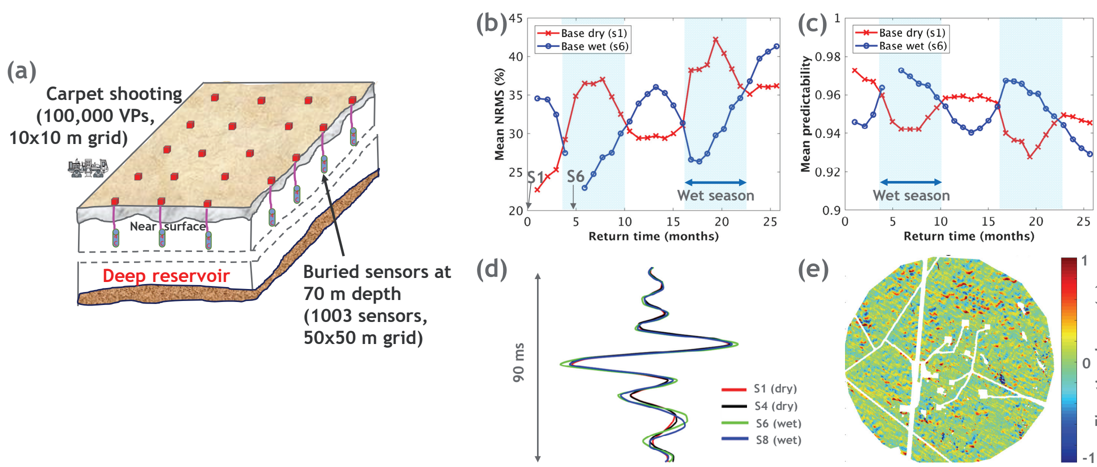

Figure 1 *(a) 3D permanent installation with buried sensors. Repeatability (b) and predictability (c) of early arrivals over the course of two years. Subtle waveform changes occur with the onset of wet season (d). Overall deterioration of repeatability over time may be caused by shifting sand topography shown over the period of two years (e).*

processing flow (Al Ramadhan et al., 2017, Bakulin et al., 2016). First, we note that 4D processing leads to a large reduction in NRMS as well as seasonal variations (compare Figures 2b and 3a). For instance, mean repeatability for surveys acquired after three and 15 months is almost identical, achieving 3% NRMS; a remarkable result for onshore 4D data. These monitoring surveys were acquired during the dry season. The seasonal variations revealed in Figure 3 suggest that current 4D processing only partially corrects for such changes. Much better compensation can be achieved using the Virtual Source method (Silvestrov et al., 2017), however acquisition geometry after redatuming lacks larger offsets necessary for mapping 4D signal in this case. Here, we utilize data from dry seasons that enable the most straightforward interpretation. Wet season data delivers qualitatively similar conclusions provided a baseline acquired under wet conditions is used.

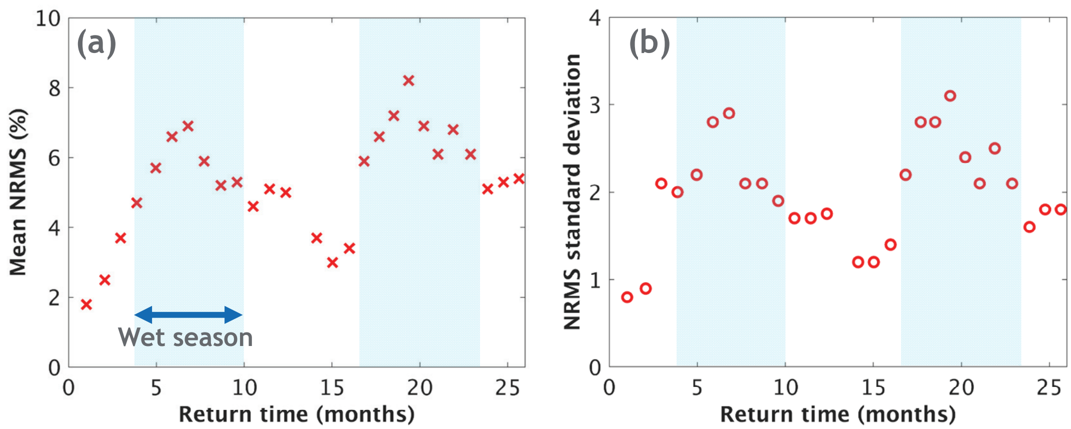

Figure 2 *Average NRMS repeatability along a horizon as a function of return time. For each pair of surveys, NRMS is represented by a Gaussian-type histogram with (a) mean value and (b) standard deviation.*

Monitoring results

Excellent data repeatability has enabled small 4D signal related to monitoring the CO2 EOR demonstration project to be identified. Here, we focus on initial qualitative results from two injector-producer pairs. Comparing data acquired in the dry season, we detect a plume that clearly stands above the background noise between the northern two injectors after a period of 14 months. As was observed in the early arrival analysis, comparing two surveys acquired during the wet season can also produces highly repeatable data. We see similar features as the dry season maps. We have analysed seismic snapshots using raw 4D differences as well as results of 4D facies analysis obtained with unsupervised classification. Volumetric seismic data provides invaluable insights into CO2 distribution in the subsurface, whereas full utilization of 4D seismic data requires careful integration with all other reservoir and engineering data available, accounting for proper connection between different scales. Additional insights can be achieved by training classification based on actual reservoir model scenarios that could further improve differentiation between signal and noise and enable interpretation of data between different seasons. Finally, adding an uncertainty estimation would be the next step to enable more quantitative interpretation in the presence of 4D noise.

Conclusions

We have presented results of the world's first successful areal seismic monitoring of a carbonate reservoir in a desert environment. A point-source, point-receiver acquisition system, using permanently installed buried sensors and a dense Vibroseis source grid, delivers mean NRMS on the order of 3-5% when measured from year to year between dry seasons. This represents a remarkable achievement considering the extremely challenging pre-stack data quality, seasonal variations and shifting sand dunes. Such repeatability allows reliable monitoring of the CO2 plume in the reservoir of interest.

References

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