# Performance of a hybrid seismic monitoring system with buried receivers for an onshore carbonate reservoir – current status and way forward

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## Summary

Seismic monitoring of carbonate reservoirs in a desert environment has remained one of the final time-lapse frontiers due to the low 4D signal produced by carbonates combined with potentially high 4D noise resulting from complex and changing near-surface geology. Here we show how a hybrid acquisition system utilizing buried receivers, combined with time-lapse processing, can achieve highly repeatable data capable of detecting weak 4D signal. For surveys acquired under similar climatic conditions, average NRMS values of 2-5% have been observed, enabling detection of small reservoir signal related to fluid injection in a carbonate reservoir. Small increases in 4D noise when comparing surveys acquired during different seasons masks the 4D signal and remains a challenge. The use of multiple baseline surveys can help overcome this issue. Monitoring larger areas will require bigger receiver spacing than the 50 m grid used here, but receiver decimation tests show that unacceptable increases in 4D noise result from sparser grids. Novel designs using DAS technology may be the key to more efficient acquisition systems.

## Introduction

By 2030, the International Energy Agency (IEA) estimates that more than 60% of daily oil production will come from onshore fields, which are dominated by carbonate reservoirs (Johnston, 2013). The inherent complexity of carbonates practically demands 4D seismic for revealing fluid flow patterns, but their stiff rock frame means they are less sensitive to changes in reservoir conditions than clastics. This results in relatively small changes in the seismic response that has subsequently led to the underutilization of seismic monitoring for carbonates. In arid environments, the problem of weak 4D signal is compounded by the complex and changing nature of the near-surface, which can generate large non-repeatable noise between surveys.

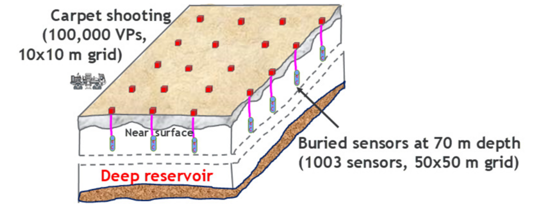

Figure 1: 3D permanent installation with buried single sensors.

Bakulin et al. (2013) describe the key acquisition elements that contribute to 4D success in desert environments. These findings led to the implementation of a hybrid design for monitoring of a fluid injection program into a carbonate reservoir. Here permanent buried receivers (50-80 m deep on 50x50 m grid) and dense carpet vibroseis shooting covering a circular area of 4 km diameter, were used to reduce 4D noise (Figure 1). 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. Continuous data acquisition produced one complete survey approximately every four weeks. In this paper we utilize this frequent monitoring data to outline the short- and long-term repeatability trends observed in both pre-stack and final processed data and discuss the implications this has on 4D interpretation. We also highlight some of the important lessons learned that will need to be addressed to scale the technology for monitoring over larger areas.

## Repeatability trends and impact on 4D interpretation

Unprocessed early arrivals

The buried sensor system enables a straightforward, real-time assessment of repeatability using direct arrivals from

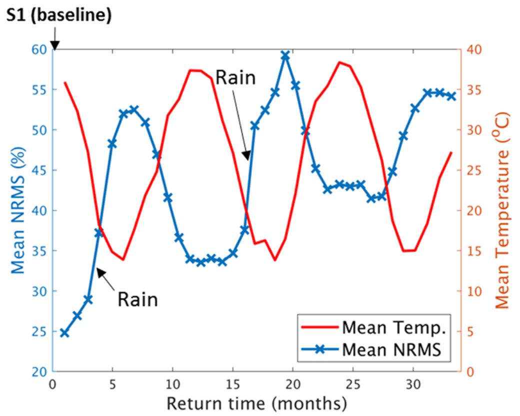

Figure 2: Mean early arrival NRMS return curve (baseline S1) and average monitor survey temperature. Each ‘x’ represents a monitor survey.

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near zero-offset shots (Bakulin et al., 2015a). Figure 2 compares mean early arrival NRMS (average of all shots) and the average temperature during acquisition of the monitor dataset. Here return time represents the elapsed time between the baseline and monitor surveys. Using a baseline acquired during the hot and dry season (S1), we observe a sharp increase in NRMS with the first rainfall in survey five. Repeatability continues to degrade during this cooler and wetter period of the year, but improves once we return to similar climatic conditions the following year. During the second year we see similar patterns, again with a jump in NRMS after 16 months caused by rain. Increases in 4D noise cannot be explained completely by rain however, since no precipitation was recorded during the final cool period (months 27-33). Here a gradual increase in NRMS is observed rather than the sharp increase that typically accompanies rainfall. This indicates that these seasonal repeatability trends are a combination of moisture and temperature variations in the very shallow near surface that likely affect baseplate-ground coupling. Similar trends to those reported here have been observed in the early arrival predictability, indicating that the seasonal variations represent complex waveform changes rather than simple amplitude scaling or time shifts (Bakulin et al., 2018a). Note that although repeatability improves during the summer months, it does not reach the levels observed during the first few surveys. This general decay of repeatability over time is likely related to sand dune migration which leads to topography changes over time.

Processed data

Despite these acquisition efforts, specialized processing is necessary to achieve the required levels of repeatability. Synthetic seismic studies using reservoir simulation outputs and fluid modelling predict maximum 4D signal of 5-8% in terms of NRMS change. Our background NRMS needed to better this to enable the detection of changes related to the reservoir. Figure 3 summarizes the effect of processing on the mean stack NRMS (reservoir level) after each stage in the workflow. Two survey combinations are compared; one with both surveys acquired in the dry summer months (S1 and S2) and the second compares S1 to S7 acquired after the first rain. We can see that the processing flow reduces the gap between these pairs, but the 4D noise remains higher for the dry-wet pair even after migration. The most significant steps for reducing 4D noise were found to be noise attenuation, surface consistent amplitude balancing and supergrouping (Bakulin et al., 2017) which all enhance reflection signal-to-noise ratio (SNR).

The final migrated data repeatability is shown in Figure 4. Here a window at the reservoir level (but excluding zones where 4D signal is expected) is used to measure the background NRMS. Survey one is used as the baseline in Figure 4a, which shows mean NRMS values of around 3% for surveys separated by more than one year and acquired around the same time of year, a remarkable result for onshore 4D data. This level of repeatability has enabled clear 4D anomalies to be mapped that are consistent with the fluid injection schedule (Jervis et al., 2018). A seasonal imprint remains in the final repeatability however, suggesting that time-lapse processing only partially corrects for climatic effects. Although the maximum NRMS is still only 8% when comparing surveys from different seasons, this level of 4D noise was still large enough to mask our time-lapse signal. Rather than waste the extensive data acquired during the cooler months of the year, we use a second baseline (survey seven) for these surveys which results in qualitatively similar conclusions (Figure 4b). The best repeatability is obtained when comparing surveys acquired under similar climatic conditions which enables the detection of small reservoir related changes.

## Receiver decimation tests

The current system uses buried receivers on a 50x50 m grid. Here we perform receiver decimation tests to determine the effect of increasing this spacing on the image quality and resulting repeatability. Ideally a larger spacing would be used since it's more efficient, but only if 4D signal can still be detected. Figure 5 shows the results of these tests, where the current geometry is compared to 100x100 m, 200x200 m and 300x300 m receiver grids. Here the source geometry (red area) remains constant. We see that doubling the spacing has little effect on the image quality, but the mean NRMS (taken between the first two surveys) increases from 3% to 5.9%. For most projects this would not be a problem,

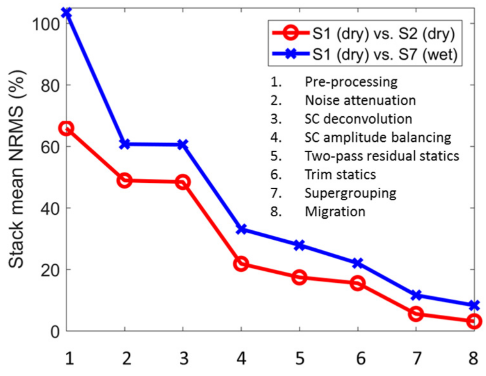

Figure 3. Processing repeatability progression for two survey pairs; S1 vs S2 (red line) where both surveys were acquired in hot, dry conditions and S1 vs S7 (blue line) where S7 was acquired in cooler conditions after rain (Modified from. R. Smith, personal communication, 2019).

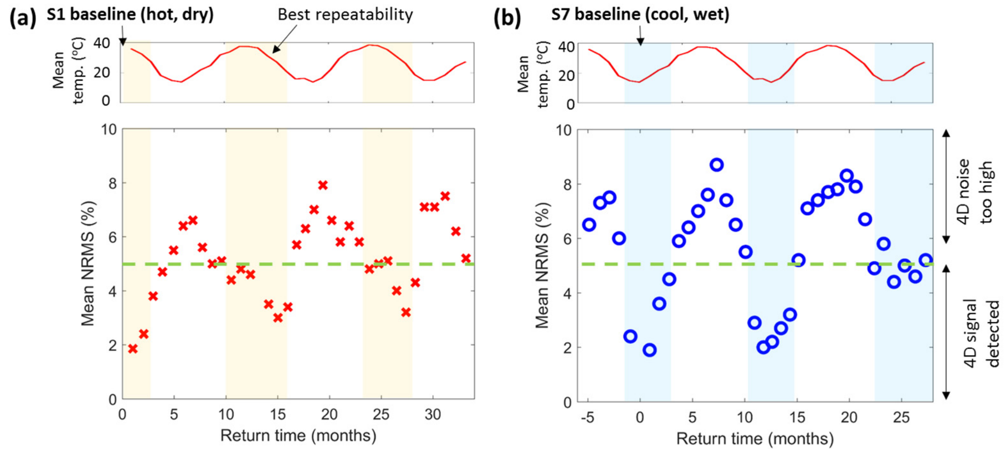

Figure 4: Seasonal repeatability trends in the final migrated stack data. (a) Mean NRMS return curve using survey 1 acquired in hot and dry conditions as the baseline. Shaded areas represent the best repeatability. (b) Repeatability using survey 7 (cool, wet) as the baseline.

but as discussed in the previous section, this would likely mask 4D signal in our pilot study. Clear degradation in image quality and resulting repeatability is evident for the two larger receiver arrays which would not be suitable for this monitoring program.

## Discussion

Despite showing that highly repeatable data can be acquired onshore in even the harshest conditions, further developments are required to enable this technology to be widely adopted. The use of surface sources means that the imprint of near-surface changes has not been completely eliminated from the data, with seasonal repeatability variations remaining even after full processing. Much better compensation can be achieved using the Virtual Source method (Silvestrov et al., 2017), however the acquisition geometry after redatuming lacks larger offsets necessary for mapping 4D signal in this case. Advanced techniques such as surface-consistent matching filters may also help improve repeatability (Almutlaq and Margrave, 2013). In the absence of further processing improvements, the development of a powerful buried source suitable for complex near-surface environments will be required. As demonstrated in this paper, the use of multiple baseline surveys acquired at different times during the year may be an alternative way to fully utilize frequent monitoring data.

The current design uses buried receivers installed on a 50 x 50 m grid, which may be too costly for monitoring over large areas. Receiver decimation tests showed that increasing the geophone spacing is not an option for weak signal detection since the background NRMS quickly exceeds 5%. Since repeatability and SNR of the data are tightly correlated (Pevzner et al., 2011), results of the pilot should be evaluated in this context. The pilot area is characterized as medium to complex in terms of seismic data quality. It may be possible that better repeatability can be achieved with less source/receiver density in areas with more favorable near surface and improved signal-to-noise ratio.

Novel acquisition designs are required to increase receiver spacing while maintaining image quality and repeatability. Recent advances in distributed acoustic sensing (DAS) technology for seismic acquisition may be the key to larger receiver well spacing. In place of the current setup, which uses a single geophone at the bottom of a shallow well, a fiber optic cable can be used as the seismic sensor, effectively turning the entire length of the well into a continuous sensor. The latter is referred to as smart DAS upholes (Bakulin et al., 2017), whereas a series connected together to create a vertical imaging array (Figure 6) was labeled a smart DAS uphole acquisition system (Bakulin et al., 2018). This system has proven capable of producing comparable images to surface geophone data, but has yet to be tested for monitoring purposes. If fold can be taken as first proxy for signal-to-noise ratio and repeatability, then smart DAS uphole acquisition with spacing and depth of 200 m (spacing=hole depth) delivers same fold and illumination as dense surface seismic with 10 m source and receiver sampling (Bakulin et al, 2018). For 4D seismic, the key is that every receiver below ~ 10 m produces 3-4 times better repeatability compared to surface sensors in desert environments (Bakulin et al., 2012).

In summary, we believe that receiver-side of the permanent system can be adequately addressed with DAS and upscaled for larger volumes. The requirement for dense and repeatable source grids appears not easily addressed however. Significant density is required to overcome near-

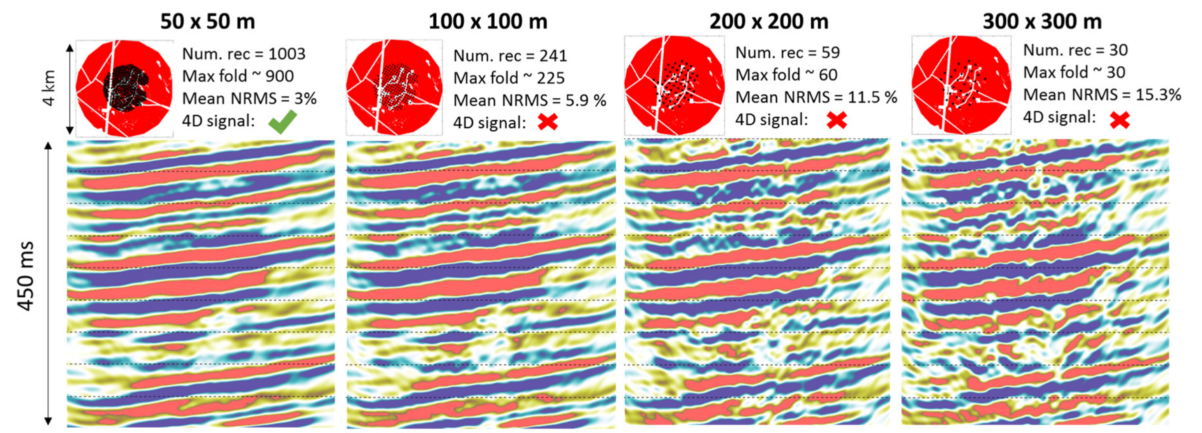

Figure 5: Effect of receiver decimation on image quality and repeatability (between S1 and S2) for four grid sizes starting with original geometry (left) to 300x300 m spacing (right). Red area of map indicates source geometry (fixed) while black dots correspond to buried receiver array.

surface scattering and uncover reservoir reflections from under the noise. A sparse grid of repeatable sources failed to deliver basic image (Berron et al., 2012) not to mention repeatability. Perhaps in-situ permanent seismic with distributed sources/receivers in shallow horizontal U-shaped wells (Figure 7) could be an alternative delivering enough source/receiver density to overcome near surface scattering while maintaining good repeatability for reservoir monitoring. Distributed omnidirectional receivers are reality today with DAS. Distributed source remains an unsolved challenge but may be achieved with segmented magnetostrictive materials pumped instead of cement or other novel materials.

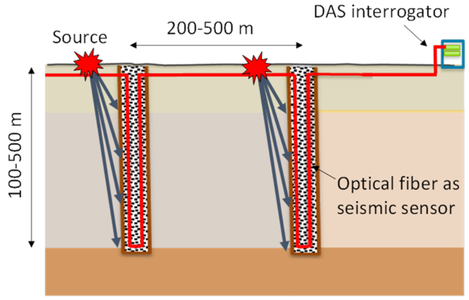

Figure 6: Vertical imaging array formed by connected smart DAS upholes enables greater receiver well spacing.

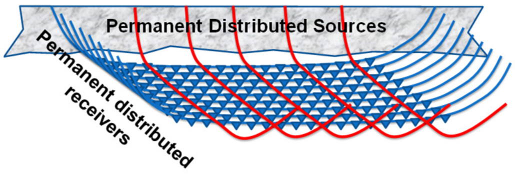

Figure 7: In-situ permanent seismic with distributed sources and receivers that may allow enough trace density for reliable imaging in complex desert environment whereas maintaining good repeatability for sensitive reservoir imaging.

## Conclusions

We have presented findings from the world's first successful areal seismic monitoring of a carbonate reservoir in a challenging desert environment. A hybrid point-source, point-receiver acquisition system, using permanently installed buried sensors and a dense vibroseis source grid, delivers mean NRMS on the order of 2-5% when measured from year to year between surveys acquired under similar climatic conditions. 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 fluid injection into a stiff carbonate reservoir. Increases in 4D noise caused by seasonal near-surface variations remain a challenge that prevent 4D signal detection when comparing surveys acquired in different seasons. Extension of the hybrid system to larger areas may benefit from using optical fiber and distributed acoustic sensing to enable densely instrumented vertical arrays that allow increased hole spacing.

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