SEG SOCIETY OF EXPLORATION GEOPHYSICISTS

EAGE

We CO2 01

Case Study of a Time-lapse Seismic System Using Buried Receivers for CO2 EOR Monitoring in a Desert Environment

R. Smith* (Saudi Aramco), A. Bakulin (Saudi Aramco), M. Jervis (Saudi Aramco)

Summary

Time-lapse seismic in a desert environment is a major geophysical challenge due to the complex and changing nature of the near surface that inhibits both imaging and data repeatability. In this study, the problem is further compounded by the injection of CO2 into a stiff carbonate reservoir which results in small changes in reservoir acoustic impedance. Therefore, a highly repeatable acquisition system was required to detect these weak 4D signals. A hybrid system using deep buried receivers and surface vibroseis sources was found to provide the optimum solution. Along with careful survey design and acquisition, a specialized data processing workflow was developed to overcome the challenges faced by single source, single receiver data. In particular, the stacking of neighboring shots in a process known as supergrouping is essential for the reduction of 4D noise. Using this system, highly repeatable data has been achieved with mean NRMS of 6% between dry season surveys separated by more than one year. This level of repeatability allows small variations that may be related to CO2 injection to be observed.

Introduction

In 2015, Saudi Aramco started the company's first carbon capture and enhanced oil recovery pilot project in an onshore carbonate reservoir. Time-lapse seismic was selected as the best tool to track the lateral expansion of the injected CO_2 and ensure containment within the reservoir. Onshore time-lapse seismic remains a major industry challenge despite the many successful examples of monitoring in marine environments. This is particularly true in the desert conditions encountered in Saudi Arabia, where a highly complex and changing near surface inhibits both imaging and data repeatability. The problem is further compounded by the low levels of 4D signal expected due to injection of CO_2 into a stiff carbonate reservoir, where a change in acoustic impedance of around 5-6% is predicted. Subsequently, a highly repeatable acquisition system is required to enable observations of small reservoir changes to be made. In this case study of an onshore time-lapse seismic project, it is shown that through careful acquisition design and processing a highly repeatable system can be achieved in even the most challenging of environments.

Method

To detect low levels of 4D signal, sources of non-repeatability (4D noise) must be minimized as far as possible. This requires careful attention to all stages of the seismic workflow, from survey design and acquisition all the way through to data processing and interpretation.

Survey design and acquisition

Many of the challenges facing conventional land seismic in the Middle East are caused by the complex nature of the near surface. Strong surface waves generated by thick sand dunes and back-scattered energy from underlying karsted limestone severely inhibits seismic imaging in the area. Time-lapse seismic poses the additional requirement of achieving good repeatability between surveys, yet dune migration and seasonal variations cause the near surface to change over time. The ideal solution would bury both the sources and receivers to avoid much of the near-surface heterogeneities and minimize 4D noise generated by changing near-surface conditions.

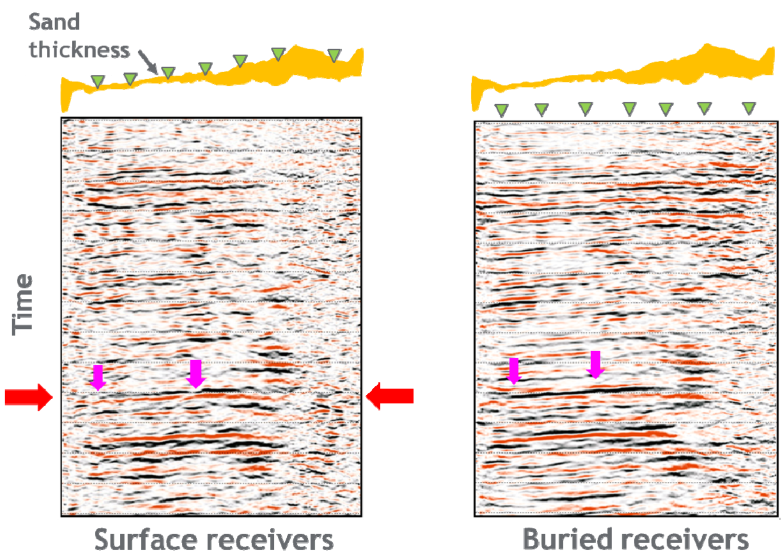

Figure 1 *2D seismic tests comparing image quality of conventional surface receivers (left) and buried receivers at a depth of 30-50 meters (right). A clear improvement can be seen in the buried receiver data, particularly in areas of thick sand where much better event continuity is observed. The red arrows highlight the zone of interest.*

To determine the optimum survey design, a series of 2D tests were conducted at the injection site. A fully buried system utilizing a piezoelectric source was found to be unsuitable for imaging the deep reservoir of interest (Berron *et al*., 2012), so the next best option was to employ a hybrid system consisting of 80 buried receivers and surface vibroseis sources. The study concluded that substantial improvements in stack quality and data repeatability resulted from receivers buried at a depth of 30-50 meters compared to conventional surface geophone arrays (Bakulin *et al*., 2012), particularly in areas of thick sand cover where energy penetration is typically an issue (Fig. 1). In the reservoir of interest, the mean NRMS was 53% and 17% for the surface and buried receivers respectively, showing that buried sensors are essential for 4D seismic in desert environments.

The final deployment (Fig. 2) consists of 1003 four component sensors buried 50-80 meters deep, placed just below the water table for optimum coupling. These are positioned at a grid spacing of 50 by 50 m, while a dense vibroseis source grid of 10 by 10 meters ensures adequate sampling for noise removal and high fold data to enhance repeatability. Surveys are acquired in flip-flop mode using two fleets of vibrators with a single vibrator for each shot point resulting in single-source and single-receiver data. Continuous 24/7 data acquisition results in one complete survey delivered every four weeks, with frequent surveys allowing better separation of 4D signal and noise.

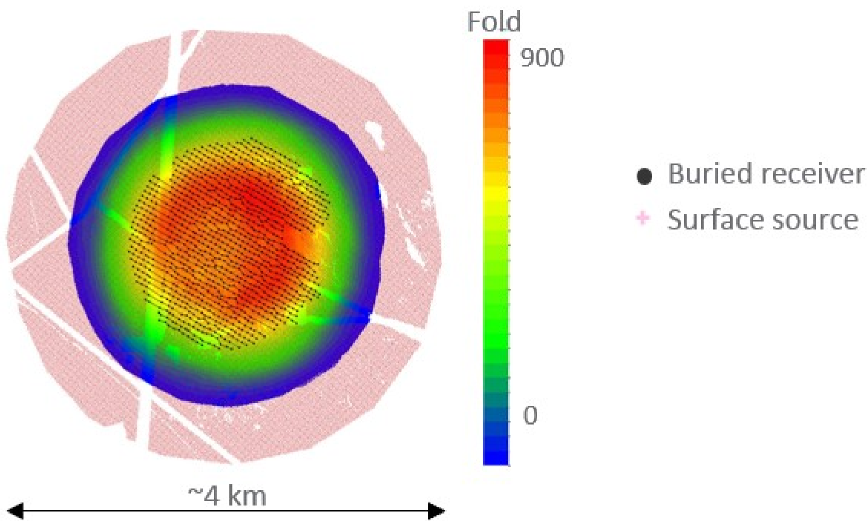

Figure 2 *Acquisition geometry consisting of 1003 buried receivers (black circles) and over 100,000 surface vibroseis shot positions (shaded pink). The design ensures high fold data (shown by the color bar) is acquired over the bulk of the target area to improve SNR, with maximum fold of over 900.*

Particular care has been paid to the positioning accuracy of the sources from survey to survey. Due to the highly heterogeneous nature of the near surface in the region, even small source positioning errors can introduce large differences between surveys (Jervis *et al*., 2012). Each vibroseis is equipped with a guidance system based on differential GPS which, coupled with careful field procedures, allows to acquire data with a mean horizontal positioning error of approximately 0.3 meters for each survey.

Data processing

The unique nature of the survey design and challenging data required the development of a novel 4D processing workflow. Although deep sensor burial avoids recording the surface waves that usually contaminate seismic records in the region, the data is still dominated by low apparent velocity noise (Fig. 3a) likely related to guided waves or mode conversions in the near surface (Bakulin *et al*., 2016). Localized F-K filtering uncovers the reflection events (Figure 3b), but these are still relatively weak due to the single-source, single-receiver acquisition. To enhance the data, supershots are formed by stacking groups of 49 neighbouring shots over a 7 by 7 shot grid in a process known as supergrouping (Neklyudov *et al*., 2015). Here the shots are stacked after NMO removal in order to preserve high frequencies. After supergrouping, the reflection events are much clearer and the level of random noise has been significantly reduced (Fig. 3c). Each stage of the processing flow is analyzed for its effect on image quality and repeatability to determine the optimum flow and parameters. The processes yielding the largest improvement in data repeatability are noise removal, supergrouping and migration.

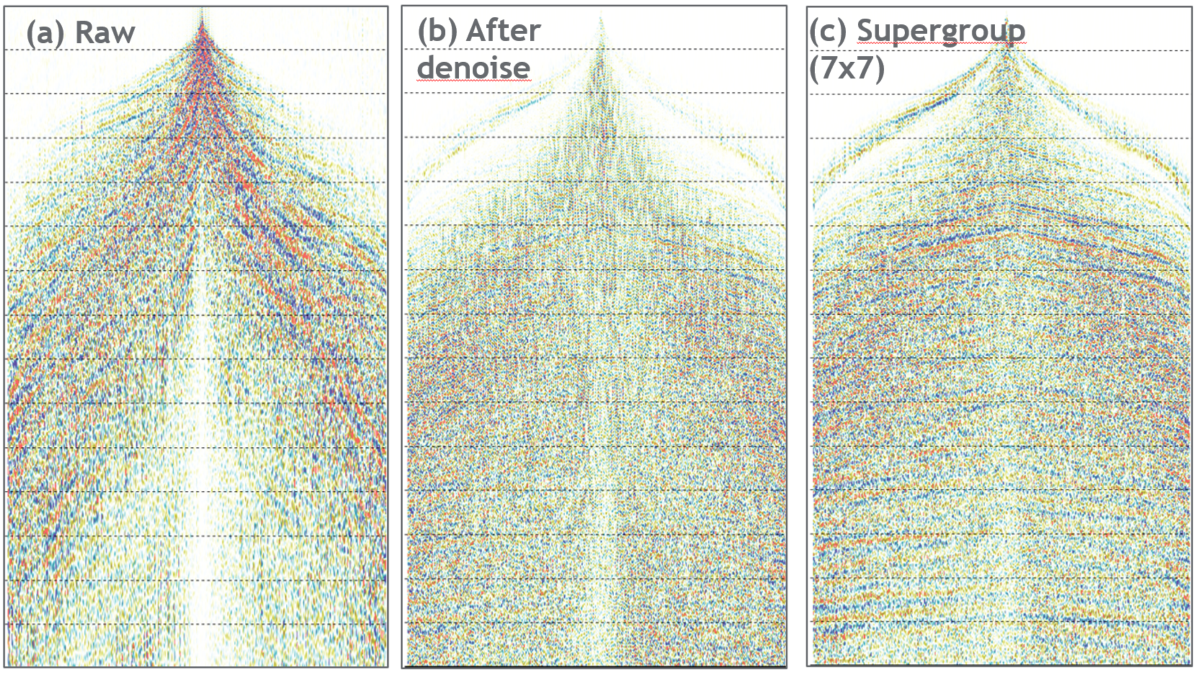

Figure 3 *A field gather showing high levels of noise (a) in its unprocessed state, (b) after localized F-K filtering to reduce linear noise and (c) after 7 by 7 shot supergrouping.*

Results

The survey design and processing has resulted in excellent data repeatability, even between surveys spaced more than a year apart. Figure 4 shows two NRMS histograms, one between surveys spaced 3 months apart and the other between surveys separated by 15 months. Repeatability of both sets of surveys shows a mean value of NRMS < 6%, suggesting that from year to year similar repeatability can be achieved. The histograms shown in Figure 4 are from data acquired during the dry season. Additional challenges are encountered when comparing surveys acquired during the wet and dry seasons (Fig. 4c), with seasonal near-surface variations leading to variations in the source wavelet over the course of a calendar year. Pre-stack repeatability of near-offset direct arrivals on buried receivers are a useful QC tool for data repeatability (Bakulin *et al*., 2015) and clearly show the deterioration of mean NRMS during the wet season. Importantly, the NRMS gradually reduces after the wet season and returns to conditions similar to the previous dry season.

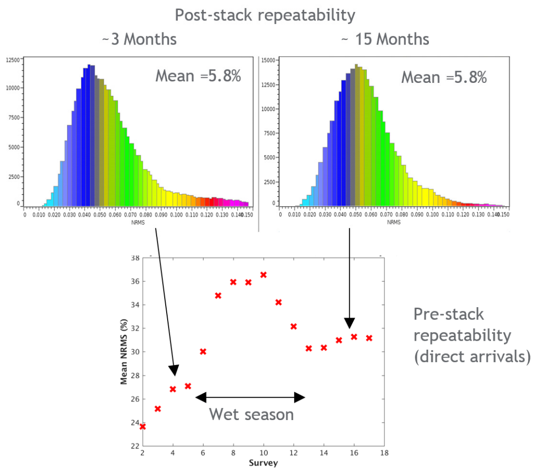

Figure 4 *Repeatability metrics comprising (a) histograms computed from post stack data computed between two surveys separated by 3 and 15 months and (b) pre-stack NRMS estimates computed using direct arrivals recorded on buried receivers.*

Conclusions

Careful survey design and acquisition, along with specialized data processing has produced highly repeatable data that has allowed small variations that may be related to CO_2 injection to be observed. Mean NRMS values of less than 6% have been reported on stacked data acquired during the dry season, which rivals data repeatability obtained in the more favourable marine surveys. This achievement would not have been possible without the use of deeply buried receivers, which are an essential component for time-lapse seismic in a desert environment. The wet season leads to a change in the seismic response that deteriorates the data repeatability, which has yet to be fully compensated for.

Acknowledgments

We would like to thank Saudi Aramco for allowing us to publish this work.

References

Bakulin, A., Burnstad, R., Jervis, M. and Kelamis P. [2012] Evaluating Permanent Seismic Monitoring with Shallow Buried Sensors in a Desert Environment. *SEG 82nd Annual Meeting*, Las Vegas. 1-5.

Bakulin, A., R. Smith, M. Jervis, and R. Burnstad [2015] Use of early arrivals for 4D analysis and processing of buried receiver data on land. *85th Annual International Meeting, SEG*, Expanded Abstracts, 5493-5497.

Bakulin, A., Smith, R., Jervis, M., Saragiotis, C., Al-Hemyari, E. and Alramadhan, A. [2016] Processing and Repeatability of 4D Buried Receiver Data in a Desert Environment. *SEG 86th Annual Meeting*, Dallas. 5405-5409.

Berron, C., E. Forgues, A. Bakulin, M. Jervis, and R. Burnstad [2012] Effects of complex near surface on 4D acquisition with buried source and receiver. *82nd Annual International Meeting, SEG*, Expanded Abstracts

Jervis, M., A. Bakulin, R. Burnstad, C. Berron, and E. Forgues [2012] Suitability of vibrators for time-lapse monitoring in the Middle East. *82nd Annual International Meeting, SEG*, Expanded Abstracts

Neklyudov, D., A. Bakulin, M. Dmitriev, and P. Golikov [2015] Enhancement 3D broadband land seismic data with smart super groups for processing and FWI. *77th Annual International Conference and Exhibition, EAGE*, P7 06.