Making time-lapse seismic work in a complex desert environment for CO_2 EOR monitoring — Design and acquisition

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Abstract

Onshore seismic monitoring for CO_2 injection in carbonate reservoirs in the Middle East is a major challenge for many reasons. The 4D signal is generally much smaller than that of clastic or chalk reservoirs due to the high bulk moduli of the rocks and the relatively small fluid effect. In addition, seismic data are characterized by low signal-to-noise ratio (S/N) due to poor signal penetration below high-contrast near-surface layers, poorly consolidated materials at the surface, conversion of source energy into surface waves and trapped modes, and scattering from near-surface complexities. Seasonal variations in surface conditions combined with low S/N make acquisition and processing of 4D seismic data some of the greatest challenges in geophysics today. We show results from feasibility and field pilot seismic programs for enhanced oil recovery (EOR) monitoring that resulted in successful imaging of CO_2 injection in such a challenging onshore environment and achieved 4D metrics comparable with offshore seismic monitoring. The final acquisition choice included a hybrid surface source/buried receiver system with point sensors and sources based on cost and effectiveness of the various technologies tested. Acquisition included continuous monitoring with a full 3D survey acquired once every four weeks for a period of several years. Burying sparser receivers with dense source coverage minimized 4D noise to acceptable levels (< 5% normalized root mean square) and allowed fluid saturation changes from CO_2 EOR to be observed.

Introduction

Time-lapse (4D) seismic, in which seismic surveys are repeated to obtain snapshots of the subsurface at different points in time, can be a powerful reservoir management tool. Valuable insight into reservoir fluid flow behavior, provided by seismic monitoring, enables improved reservoir simulation history matching and management, which can ultimately lead to increased oil recovery. The success of time-lapse seismic depends on the level of 4D signal (i.e., the magnitude of the reservoir rock property change due to fluid saturation or pressure changes) relative to nonrepeatable or 4D noise (i.e., differences that are not the result of reservoir activity, such as near-surface changes and processing artifacts).

In Saudi Arabia, the region's first carbon capture for an enhanced oil recovery (EOR) demonstration project is taking place in an onshore carbonate reservoir (Kokal et al., 2016). It was decided to use 4D seismic, in addition to well data, to track the lateral expansion of injected CO_2 over time. The complex nature of the near surface in the area results in major challenges for even conventional 3D imaging. In addition, the constantly changing nature of the near surface, with migrating sand dunes and seasonal weather effects, leads to high levels of 4D noise. The problem is further compounded by the low levels of expected 4D signal (predicted change in acoustic impedance of about 3%–6%) due to injection into a stiff carbonate reservoir. Consequently, a highly repeatable acquisition system is required to observe these small reservoir changes. This article covers the design and acquisition aspects of the project to overcome these challenges and enable small seismic signals related to CO_2 injection in carbonates to be observed.

Land time-lapse seismic challenge

Until now, the majority of 4D seismic data has been acquired in marine environments. This is largely due to the more demanding conditions that are encountered in land time lapse, although economic factors also play a role. Johnston (2013) highlights some of these issues, which include strong source-generated noise that can obscure reflection events, result in weak signal penetration, and cause higher levels of ambient and scattered noise. Most challenging of all is the more complex nature of the near surface onshore compared to typical marine settings, with large variations of near-surface velocity in addition to variations in source and receiver coupling. Exposure to ambient temperature variations, rain, and wind results in a constantly evolving weathered layer and a high 4D noise environment.

In recent years, more and more land 4D seismic has been acquired, with CO_2 monitoring projects reported at Otway (Pevzner et al., 2011), Ketzin (Lüth et al., 2015), Acquistore (Roach et al., 2015), and Quest CCS (Bacci et al., 2017). These tend to focus on the more favorable geologic conditions encountered in clastic reservoirs, which are more sensitive to fluid changes than carbonates. The Weyburn Carbon Capture and Sequestration Project in Canada (Li, 2003) is a rare example of onshore monitoring in a carbonate field.

The near surface at the CO_2 sequestration and EOR demonstration site in Saudi Arabia is characterized by karsted limestone overlain by sand dunes of variable thickness, ranging from just a few meters to more than 20 m. Prestack data quality under these conditions is typically poor, with strong lateral velocity heterogeneity and high levels of surface wave and back-scattered noise resulting in extremely challenging data sets for imaging (Figure 1a). Under ideal circumstances, differences between baseline and monitor surveys would only be due to elastic property changes in the reservoir. The constantly changing nature of the near surface in this area means that this will never be the case (Figure 1b). Along with seasonal weather variations, dune migration can have a significant impact on data repeatability, with vertical shifts of more than 1 m being recorded over a two-year period (Figure 1c).

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Figure 1. The main challenges faced by time-lapse seismic in a desert environment include (a) low S/N levels on recorded data and (b) constantly shifting sand dunes resulting in (c) changes in topography shown over a two-year period.

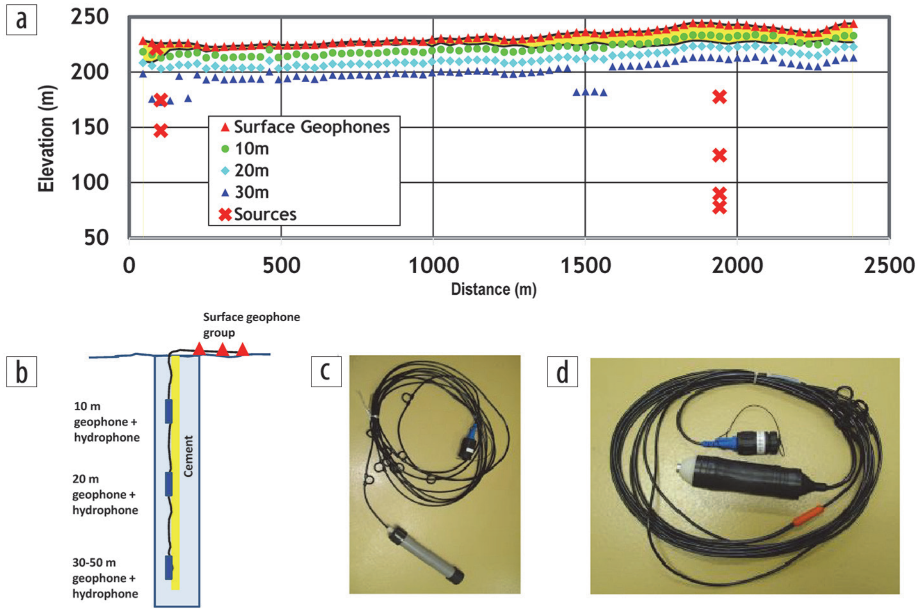


Figure 2. Time-lapse 2D feasibility test showing (a) field layout (surface sand highlighted in yellow), (b) receiver hole design, (c) geophone, and (d) hydrophone examples. Photos are courtesy of CGG/ARGAS.

The best way to mitigate the challenges posed by the shallow near surface is to use a fully buried acquisition system to minimize 4D noise (e.g., Schissele et al., 2009). Buried sources are rarely deployed at present due to cost and performance issues, but it has become increasingly common to utilize a permanent buried receiver system. The progressive move toward buried acquisition for time lapse started in marine environments with the development of permanent ocean-bottom systems at Valhall in the North Sea (Calvert, 2005), resulting in significant improvements in data repeatability. On land, monitoring projects at Otway and Acquistore have also used buried receiver systems to reduce levels of 4D noise (Pevzner et al., 2011; Roach et al., 2015).

2D feasibility test in a desert environment

Test setup. As the first step, a 2D feasibility study was conducted to test different time-lapse seismic technologies for use in the challenging onshore environments typical of Saudi Arabia and the Middle East. These tests were performed at the site of the CO_2 sequestration and EOR project (prior to injection) with the objective of better understanding some of the key design, installation, acquisition, and processing requirements to obtain highly repeatable seismic data with adequate signal-to-noise ratio (S/N). These requirements included the evaluation of different source and receiver configurations (both surface and buried systems), near-surface influence on image quality and data repeatability, 4D noise characteristics, and installation methodologies (Bakulin et al., 2012).

A cross section through the site is shown in Figure 2a. Here, the sand dunes range in thickness from a few meters on the left side of the line up to 17 m on the right. The target carbonate reservoir is at a depth of approximately 2 km. To examine the effect of burying sensors on repeatability, a line of 80 shallow receiver holes were drilled at 30 m intervals, each with collocated geophone and hydrophone sensors cemented at three depth levels (10, 20, and 30 m; Figures 2b–2d). A cluster of 12 geophones was installed at the surface for comparison purposes. On the source side, both permanent and conventional surface vibroseis sources were tested. Six piezoelectric sources (Schissele et al., 2009) were deployed at varying depths to evaluate their response, power output, signal quality, and repeatability over time. For the surface sources, conventional Mertz 26 hydraulic vibrators were used and achieved better than 50 cm repeatability in positional accuracy using modern surveying technology and guidance systems.

Buried source, buried receivers. The fully buried acquisition system concept was evaluated using the piezoelectric sources and receivers cemented at depth. While this permanent reservoir monitoring system has been successfully applied in simpler near-surface environments (Schissele et al., 2009; Lopez et al., 2015), this was the first application of the technology in the Middle East. Permanent sources were installed at the surface and cemented in shallow boreholes at depths ranging from 62 to 162 m.

Data were acquired using the same receiver array as described earlier. However, significant challenges for both imaging and repeatability were found, with little sign of prestack reflections on buried source records. This is probably due to a combination of weak source strength and poor signal penetration because of scattering from near-surface complexities below 30 m depth as well as the generation of trapped modes in near-surface layers. These modes were evident as linear events on the buried source records, despite being largely below surface wave propagation depths. Even after stacking records for more than 124 days, we concluded that it was impossible to obtain an adequate reservoir image due to low fold and poor S/N with this source-receiver technology. In terms of repeatability, we have analyzed amplitude and timing variations of early arrivals using multiple excitations of permanent sources stacked over different periods of time. We found that while burial improved signal stability (Table 1), variations in arid desert environments can be substantially higher than in humid parts of the world such as North America or Europe (Berron et al., 2012). This is possibly due to the relatively poor S/N. We suspect that signal strength of the piezoelectric source was insufficient to illuminate deeper targets of interest. The development of stronger buried sources and establishing optimal placement depth of sources and receivers will be required for this permanent monitoring system to be viable in the challenging conditions of the Middle East.

Table 1. Statistical estimate of time and amplitude variability obtained with multiple excitations of permanent piezoelectric sources at the surface and at a depth of 65 m. The last column represents similar quantities from a humid environment reported by Schissele et al. (2009).

4D variation (max)	Desert		Humid
	Surface	Buried	Buried
Time	0.5 ms	0.4 ms	0.01 ms
Amplitude	40%	20%	1%

Surface versus buried sensors. The next best alternative is to adopt a hybrid system of buried sensors and surface vibroseis sources. For this test, a narrow 3D swath configuration (nine source lines) was acquired using about 3000 shots on a dense 7.5 m (inline and crossline) source grid. Six surveys were acquired over a four-month period to assess the repeatability of the system using a single vibrator per shotpoint. Each survey took about two days to acquire.

Geophone data from each of the four depth levels were processed using a time-processing flow for land data. This included crossline diversity stacking of the nine source lines, spherical divergence correction, linear *f-k* filtering, normal moveout correction, field statics, time-variant scaling, common depth point stacking, and *f-x* deconvolution. The resulting vertical geophone stacks from the first survey are shown in Figure 3. It

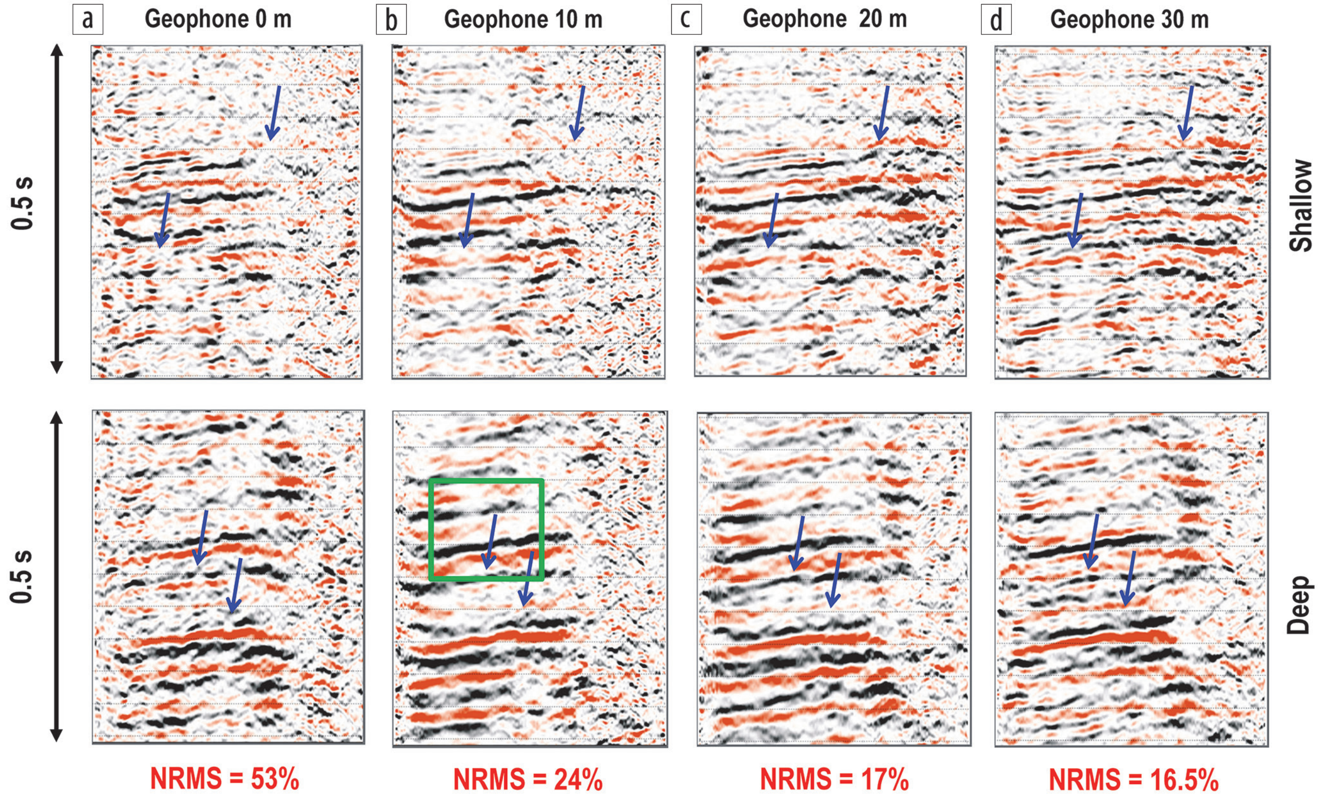


Figure 3. Stack and repeatability metrics from 2D surveys obtained with sensors at different depth levels including (a) permanently placed surface geophones (group of 12) and geophones buried at (b) 10 m, (c) 20 m, and (d) 30 m, respectively. Top row shows the shallow part of the section and bottom row shows the deeper part, including the target zone. NRMS is estimated over the target window shown by the green rectangle.

is clear that the buried receiver stacks (Figures 3b–3d) show significant improvement over the surface geophone data (Figure 3a), particularly on the right side of the line where thicker sand dunes are present. The best stack quality is produced by the deepest geophones, which display improved event continuity and broader bandwidth (Bakulin et al., 2012). This is likely due to recording less surface wave noise (although strong linear noise is still evident) and being below some of the karsted near-surface limestones and resulting scattered energy.

The buried sensor data also showed large improvements in data repeatability. The normalized root mean square (NRMS) was used as a measure of the nonrepeatability between the data sets (Kragh and Christie, 2002) where the RMS of the difference in a specified window is normalized by the average RMS energy as follows:

$$NMRS = \frac{200 * RMS(B - M)}{RMS(B) + RMS(M)}, \qquad (1)$$

where B is a window of data from the baseline and M is the same window from the monitor survey. The NRMS is zero in the ideal case where two data sets are perfectly repeatable. Larger values represent higher levels of 4D noise, with 144% indicating two random traces while 200% signifies traces of opposite polarity. This metric is sensitive to any change in waveform, including statics, amplitude and phase variations, and random noise.

The mean poststack NRMS values shown in Figure 3 are computed on a 150 ms window about the target reservoir between the first two surveys. The surface receivers, with mean NRMS of 53%, are clearly not suitable for monitoring small reservoir changes. Considerable improvements are recorded for the buried data, with the most significant enhancement coming from burial beneath the first 10 m, which avoids most of the sand layer (NRMS reduced from 53% to 24%). This is likely due to avoiding changes in near-surface properties, which are suspected to be concentrated to the first few meters. Blue arrows (Figure 3) show shallow and deep reflectors that are increasingly better focused with improved continuity with increasing depth of burial (left to right).

The best repeatability is obtained using 30 m geophones, with a mean NRMS of 16.5%, a value similar to that obtained by marine time lapse acquired using towed streamers. Deeper receiver burial reduces surface wave and back-scattered energy contamination of the data, improving S/N of reflection events. Given that considerably higher fold and better illumination would be achieved with a full 3D survey, this gave us confidence to move forward with a buried receiver system, which was deemed essential for time-lapse recording in a desert environment. One observation was that repeatability degrades with increasing time between surveys (Bakulin et al., 2014), which indicates that more frequent surveys may be needed to better understand noise characteristics and how they change over time and to aid interpretation of 4D signal.

Land hydrophones. A major benefit of using buried receivers for seismic monitoring is that the recorded primary wavefield does not pass through the near-surface layer for a second time. This does not eliminate the problem entirely because the upgoing energy continues through the near surface and is partially reflected back toward the receiver, potentially interfering with the primary signal. Because the near surface is subject to diurnal and seasonal variations, these receiver-side ghosts will also be affected, which can reduce overall data repeatability (Cotton and Forgues, 2012).

A similar problem is encountered in ocean-bottom acquisition, where strong water column reverberations can occur. Barr and Sanders (1989) introduce the dual-sensor method as a way of attenuating these reverberations and get an estimate of the upgoing response at the receiver. This wave-separation technique takes advantage of the fact that geophones measure a vector quantity (velocity) while hydrophones measure a scalar (pressure). This means that geophones and hydrophones at the same location will record the same polarity for the desired upgoing reflections but will have the opposite polarity for the downgoing energy. By summing the response of the two sensors (after the application of a suitable scalar), the receiver-side ghosts can be attenuated.

The deepest hydrophones for this test (30–50 m deep) were above the water table (approximately 70 m deep), so the sensors were installed in a fluid-filled vessel to improve coupling. While it was not the first time hydrophones have been deployed on land, other reported results were for hydrophones buried beneath the water table and did not produce reflection images (Rebel and Forgues, 2010).

The resulting stacks for geophone and hydrophone data (at 30 m depth) are shown in Figures 4a and 4b, respectively. The combined stack following adaptive dual-sensor summation is displayed in Figure 4c. Due to the improved event continuity and bandwidth, it was concluded that P-Z summation of the dual-sensor data produced superior image quality compared to either data set on its own (Bakulin et al., 2012). The repeatability of the dual-sensor stack was found to be worse than the geophone data alone, which is thought to be the result of greater hydrophone coupling variability (Burnstad et al., 2012).

To overcome these issues, Burnstad et al. (2013) conduct a smaller scale test using deeper placement of the

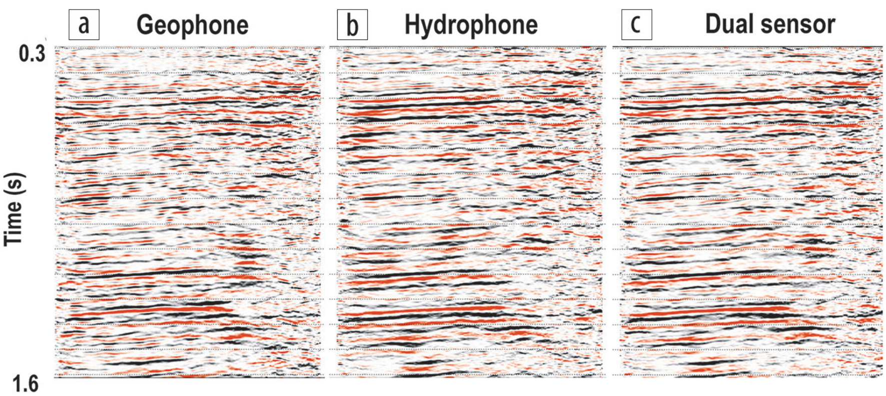


Figure 4. Comparison of stacks from (a) colocated vertical geophones, (b) hydrophones, and (c) results from dual-sensor summation.

hydrophones. Results showed that by deploying hydrophones beneath the water table, coupling and repeatability comparable to the geophones was achieved even when using gravel pack or cement for coupling. In addition to improved hydrophone coupling, the increased sensor depth should also improve geophone performance with less back-scattered energy being recorded.

Vibroseis repeatability tests

Permanent buried receivers partially solve the repeatability challenge due to their fixed geometry and constant coupling. However, the need to use vibroseis sources requires a better understanding of their impact on data repeatability since variable surface conditions cannot be avoided. Faure and Spitz (2006) find that geometry differences, daily and seasonal near-surface variations, baseplate coupling, and vibroseis wear over time are all factors affecting source repeatability. To better comprehend the issues faced in a desert environment, tests were conducted to determine the impact of source-position error and time of acquisition on data repeatability.

Positioning error. To assess the impact of geometry errors, the near-offset traces from a single geophone (30 m depth) were extracted to compute NRMS between six repeat surveys (Figure 5a) using a 150 ms computation window about the early arrivals. The resulting repeatability values are plotted against source-position change in Figure 5b. As might be expected, a general trend of decreasing data repeatability with increasing geometry error is observed. This is often referred to as a 4D variogram (Calvert, 2005). Note that the geometry errors are small (0–4 m) when compared to marine surveys, which typically achieve repositioning accuracy of about 20 m. Unlike in marine surveys, where the media around the source is isotropic and homogeneous, small geometry changes on land can significantly change the propagating wavefield due to increased near-field complexity. In desert environments, it is thought that shallow karsts, surface dunes, and thin layers with large velocity contrasts result in a propagating wavefield that is highly sensitive to source positioning. This was confirmed by elastic modeling using a vertically varying model (Figures 5c and 5d).

Clearly, source errors of just a few meters may cause very high NRMS of early arrivals. Interestingly for field data, even when the geometry error is negligible the NRMS does not go to zero, reaching a minimum value of about 20%. This indicates that geometry is not the only factor to consider. With baseplate coupling, seasonal and daily near-surface variations and possibly source direction likely play a role. While perfect repeatability will never be attained using vibroseis sources, the test does indicate that minimizing geometry errors plays a key role in suppressing 4D noise.

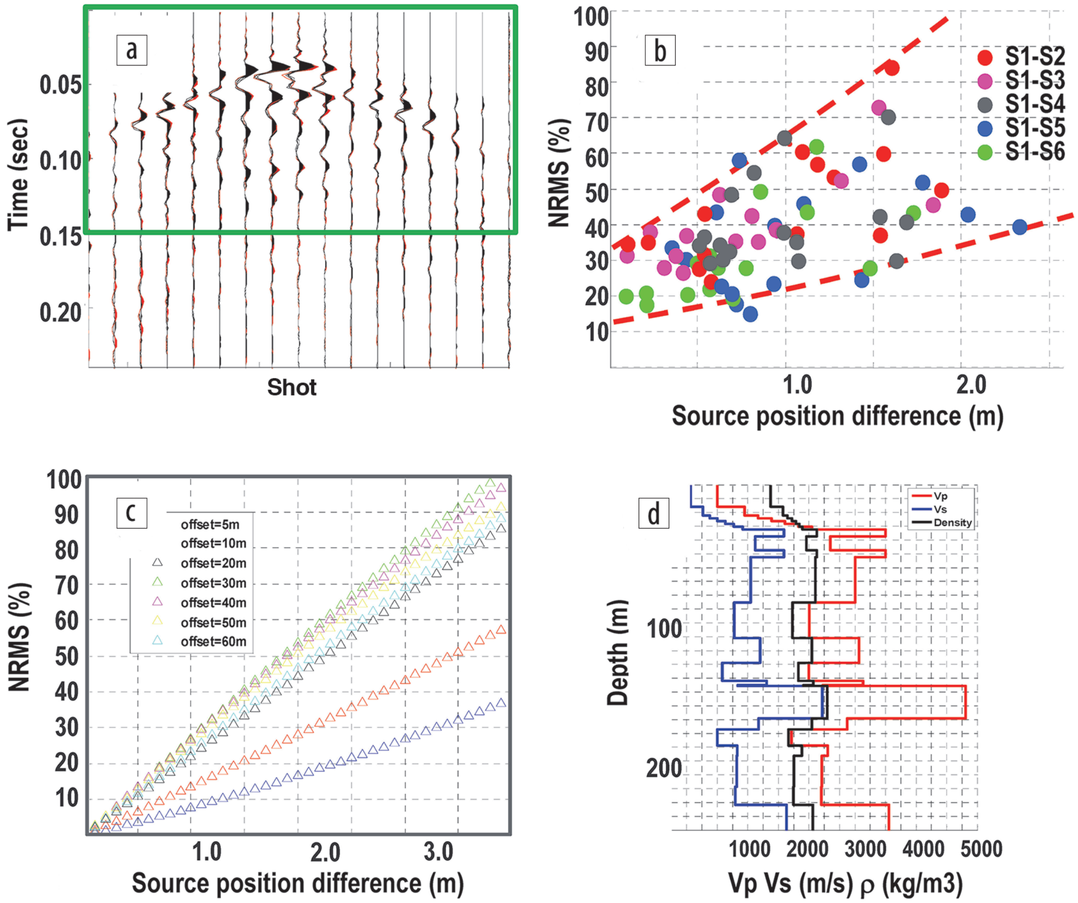


Figure 5. Results from vibroseis acquisition into a geophone cemented at 30 m depth showing (a) a common-receiver gather, (b) the corresponding composite variogram (trace-by-trace computation of NRMS versus source-position difference over five different surveys [S2 to S6] compared to a baseline [S1]), and (c) a synthetic variogram computed as for (b), using (d) a synthetic model based on field data. The analysis window is shown by the green box. Colored dots in (b) represent different survey pairs.

Time effects. To determine the impact of source coupling and temperature on data repeatability, daily and hourly source tests were acquired. For both cases, a stationary vibrator was used to avoid introducing geometry errors.

For the daily tests, sets of 20 sweeps were acquired twice a day, once at 4 a.m. and again at 11 a.m. (GMT). The vibrator baseplate remained down for the duration of the test, which lasted for 14 days. To observe the impact of burying receivers on waveform stability, data from a single surface and buried receiver station (30 m) were evaluated. Amplitude and event timing repeatability were analyzed using a 40 ms window of stacked far offset refractions (see the yellow box in Figure 6a). A pilot trace was formed by taking the median of all the stack traces, which was then crosscorrelated with the stack trace from each sweep. The maximum of the crosscorrelation captures amplitude changes, while the temporal variation of the data is expressed by the crosscorrelation time lag (Jervis et al., 2012). The timing and amplitude variations for both hourly and daily testing can be seen in Figures 6b and 6c. Although the surface and buried geophone results show a similar background trend, the scatter is significantly higher in the case of the surface sensors (red triangles). This is likely the result of surface sensors being more susceptible to near-surface variations (particularly temperature) and the higher noise environment. Note that after the first two to three sweeps, the amplitude and event timing of the buried data are very stable. The initial variation may be explained by rapid compaction of the sand layer by initial sweeps. It reaches saturation after two to three sweeps, and decompaction occurs in a matter of minutes to hours since the next daily cycle exhibits a similar "compaction trend" as if no compaction took place during the previous cycle.

During the daily test period, a series of hourly sweeps was acquired over a three-day period for the buried geophones (Figure 6c). While similar tests carried out with a surface piezoelectric source and the same buried receiver showed correlation of the amplitude and timing variations with ambient temperature (which can have large daily fluctuations of more than 20°C), this was not found to be the case with a vibroseis source. For a vibroseis-buried receiver acquisition system, coupling or some other inherent vibroseis nonrepeatability may control the repeatability of the system (Jervis et al., 2012). Baseplate coupling with the ground is known to be very sensitive to the exact configuration of the ground with the baseplate, particularly at higher frequencies (Wei et al., 2011). Early arrivals for this test data set show stable phase spectra in the range of 10–40 Hz, but deviate significantly outside this range (Jervis et al., 2012).

We conclude that vibrator repeatability in a desert environment remains the most uncontrolled factor of 4D acquisition, even when mitigating geometry errors. Therefore, we try to minimize all remaining causes of source nonrepeatability that could be controlled in acquisition.

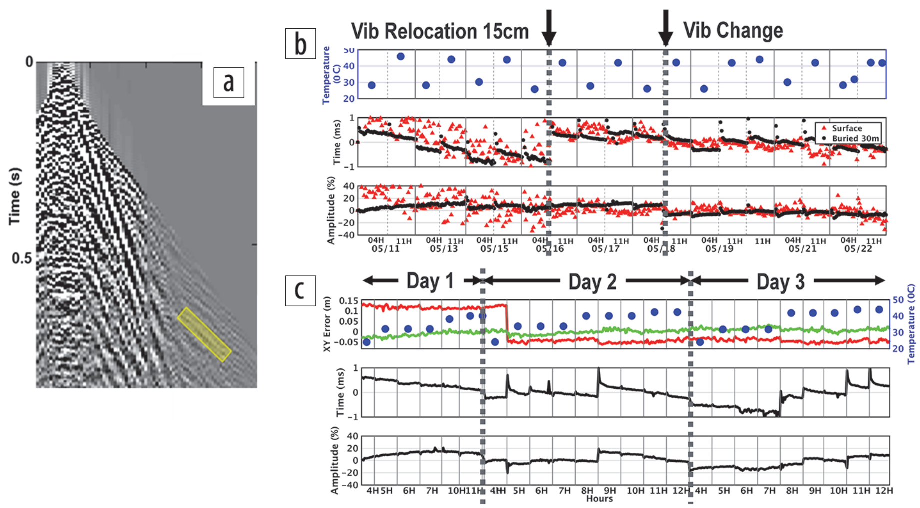


Figure 6. Daily vibrator repeatability tests showing (a) a raw shot gather (30 m buried receivers) with the window used for analysis overlain in yellow, (b) daily amplitude and timing variations over more than 10 days for both the surface (red) and buried (black) geophones, and (c) hourly variations recorded over three days compared to temperature variations (green and red lines are X and Y variations in baseplate location, respectively). Vibrator relocation (15 cm) occurred early in the second day of the hourly tests (c) where the red line shows a discontinuity.

Final 3D monitoring system

Survey design. The final survey design included 1003 4C sensors buried just below the water table (depth of 50–80 m) on a 50 × 50 m grid (Figure 7a). The 2D feasibility study showed that buried receivers are essential for repeatability, with lower noise levels and improved hydrophone coupling achieved below the water table. Vertical holes were drilled to depth using a mobile drilling rig (Figure 7b) and foam mix to flush cuttings and fill lost circulation zones that are common in the area (Bakulin et al., 2013).

A dense vibroseis source grid (10 × 10 m) of more than 100,000 shotpoints was employed to ensure adequate

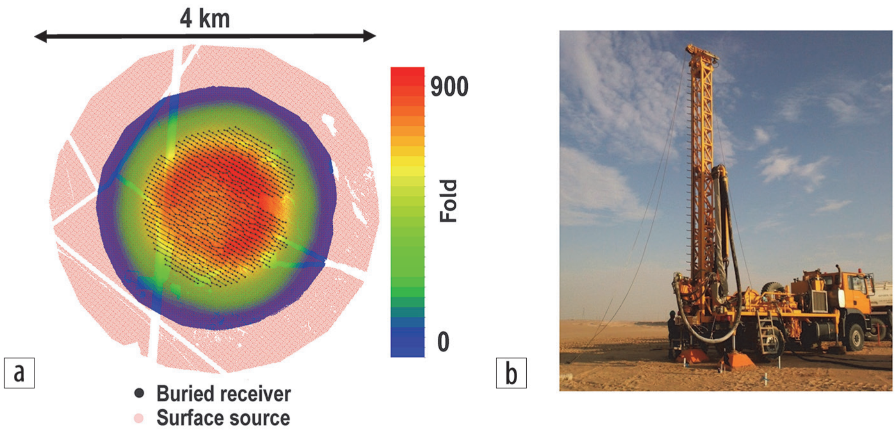


Figure 7. Final survey design showing (a) source (pink) and receiver (black) locations with fold in color, and (b) an installation picture with a portable drilling machine.

sampling for noise filtering. The resulting high-fold data (up to 900 for 5 × 5 m common-depth point bins) also enhance S/N, which is a key factor in driving down 4D noise. We stress that the final system represents a point-source, point-receiver acquisition, which is known to result in challenging data quality in desert environments. Wide-azimuth coverage better illuminates the target reservoir beneath the karsted near surface. About 4000 vibration points were acquired each day using two vibrators in flip-flop mode running a 12 s, 8–96 Hz sweep. A relatively broad sweep was used so final images would not be too band limited, despite having the best repeatability in the 10–40 Hz range (not shown here). This results in frequent surveys (one complete survey every four weeks), which enable better sampling of the seasonal 4D noise over time and more reliable interpretation of rapidly varying 4D signal caused by water-alternating-gas injection over a three-month cycle (water versus CO_2). The monthly seismic survey cycle is the fastest conventional 4D acquisition possible. It is designed to capture expected changes in the reservoir and is partially based on chemical tracer data that show breakthrough times between two and three months for most of the injector-producer pairs. Due to the relatively long survey time, there is a possibility of some smearing of the 4D signal.

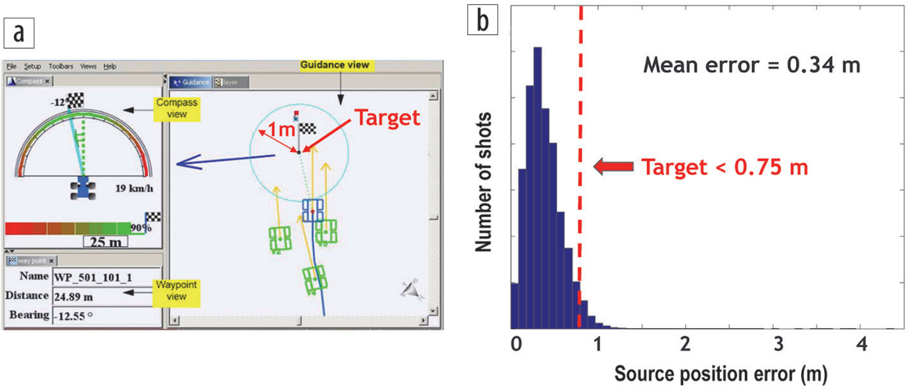
Source positioning. A key finding of the feasibility study was that source-position error between base and monitor surveys should be minimized. To achieve this, a real-time kinematic (RTK) GPS guidance system, accurate to 0.1 m horizontally and vertically, was used (Figure 8a). Sweep initiation was only possible if the center of the baseplate was within a 1 m radius of the baseline survey position. This has resulted in excellent source repositioning accuracy, with a mean error of 0.34 m between baseline and monitor surveys (Figure 8b), while maintaining high productivity. Shooting direction variations were controlled by ensuring that the vibrators follow the same path for each survey.

Early arrival repeatability and seasonal variations. Analysis of the near-offset early arrivals has proven to be a valuable quality control tool for data repeatability during acquisition. For each shot location, a 75 ms window about the first-break pick time is used to compute the NRMS between base and monitor surveys (using raw, unprocessed data). This allows early identification of acquisition issues that may affect repeatability, such as the regions of nonrepeatable shots shown in Figure 9a (red values), which were caused by system timing problems with the correlation pilot.

The early arrival prestack NRMS also provides a useful insight into overall data trends since it was found to be correlated to stack repeatability (Bakulin et al., 2015). By plotting the mean prestack NRMS for each survey against return time computed from the baseline survey (Figure 9b), significant seasonal variations in repeatability become apparent. The first three monitor surveys show a steady increase in 4D noise with time, but the onset of the first wet season brings a sharp rise in mean NRMS. Subsequent dry season surveys show similar NRMS values of about 30%. Prestack repeatability improves as we return to dry conditions, although the same levels obtained during the early surveys are not reached. There is also surface sand movement of about +/– 1 m elevation change per year (Figure 1c), but this is considered a minor effect. Dune elevation changes are generally random at any one point and occur over small spatial wavelengths when compared to near-surface changes due to rainfall.

Repeatability of reflection data and CO_2 detection. Outstanding data repeatability was obtained for the final migrated stacks of vertical geophone data. In high-fold areas outside the zone of expected production effects, mean NRMS of less than 5% was achieved at the target reservoir. This level of repeatability, which is comparable to that obtained by marine surveys using buried sensors, has been observed in surveys acquired during the dry season separated by a couple of months or more than one year. Although the hydrophone data were initially of very high quality, sensor issues cause performance to deteriorate over time, so they have not been included for analysis.

Low levels of 4D noise have enabled small 4D signals related to CO_2 injection to be observed. Figure 10a shows an NRMS



Name WP_501_101_1
Distance 24.89 m
Bearing -12.55 °

Figure 8. Source-positioning metrics including (a) an RTK GPS guidance system and (b) a postacquisition histogram of positioning error between the first two surveys.

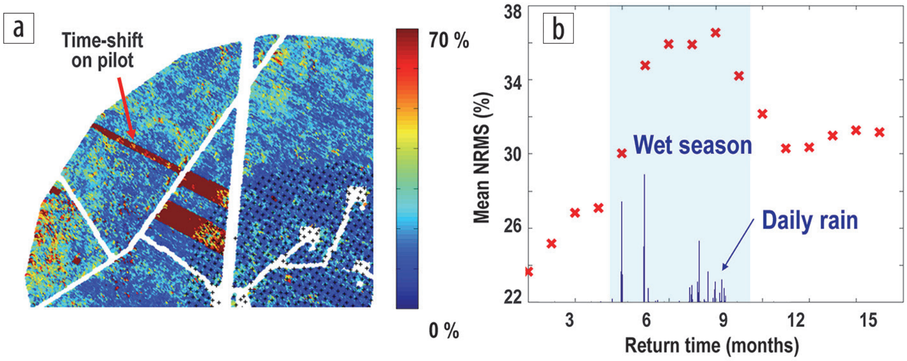


Figure 9. Daily acquisition repeatability metrics including (a) early arrival NRMS computed for each shotpoint to identify poorly repeatable shots during acquisition and (b) the mean early arrival repeatability return curve showing longer term seasonal variations.

map at the level of the reservoir after about 15 months. A clear anomaly is shown between the northern injector-producer pairs that are present between other survey combinations. A cross section through the difference volume shows a clear brightening of amplitudes and push down of the events below the reservoir in this region (Figure 10b).

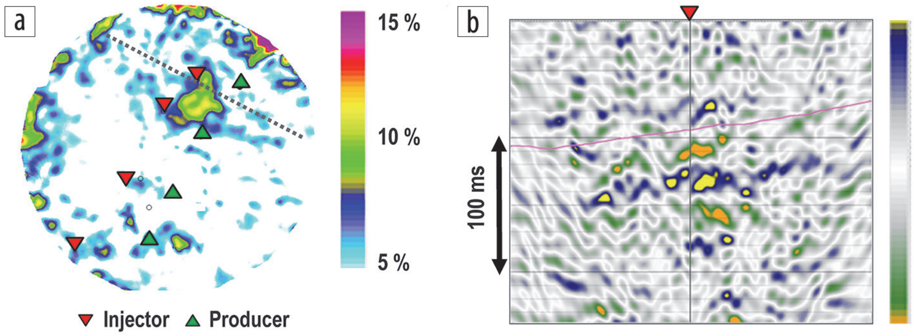


Figure 10. Detection of CO_2 using a buried receiver acquisition system including (a) an NRMS map over a 15-month interval showing the CO_2 plume between two northern injectors and (b) a seismic difference section through an injector well (dashed line in [a]) after the same time period.

These results were not achieved through design and acquisition alone. Despite deep receiver burial, prestack data are still dominated by strong linear noise generated by converted waves and trapped modes. Therefore, significant 4D compliant processing effort is still required to achieve highly repeatable images and will be covered in another article.

Summary and outlook

Onshore monitoring of carbonate reservoirs in a complex desert environment is an extreme geophysical challenge due to small 4D signal and a complex and changing near surface. Using a hybrid surface source/buried receiver acquisition system, it has been shown that small signals related to CO_2 injection can be observed even in this worst-case scenario. Outstanding data repeatability (mean NRMS < 5%) has been achieved between surveys acquired during the dry season, which is more typical of 4D marine surveys acquired with seafloor or permanent sensor networks. This was possible through careful design and acquisition to minimize 4D noise. Permanent buried sensors are an essential component of time-lapse seismic recording in a desert environment — they minimize nonrepeatability introduced by changes in the very near surface and significantly reduce groundroll and backscattered noise in the data. Ideally, buried sources would be used, but the current technology was found to be inadequate for imaging the target horizon. Source signature variations over time were minimized by careful control of source geometry errors using stakeless vibroseis acquisition with an RTK GPS guidance system, resulting in a small mean error of 0.35 m. Testing shows that using buried sources allows for acquisition on a continuous basis to better characterize the 4D noise over shorter time periods. If these can be made sufficiently powerful to illuminate the deeper targets, periodic acquisition can be programmed to identify different components of 4D noise as they occur.

Future developments will further improve land 4D seismic. As was discussed, hydrophones can be used in conjunction with geophone data to enhance repeatability. In this study, examples of stacks produced by land hydrophones and dual-sensor summation were provided, which is an industry first. However, more development is needed to understand sensor-coupling issues. Much of the remaining nonrepeatability in the system is likely due to the use of surface vibroseis sources. The design of a stronger buried source system might allow the deep target to be imaged and could greatly reduce 4D noise generated from the shallow near surface. In addition, instrumenting the shallow boreholes with distributed acoustic sensing fiber instead of a single-point geophone may be a more cost-effective approach that would significantly increase data fold and enable up-down wavefield separation. TLE

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