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4D Seismic Monitoring of a CO_2-EOR Demonstration Project in a Desert Environment: Acquisition, Processing and Initial Results

Robert Smith, Andrey Bakulin, Mike Jervis, Emad Hemyari, Abdullah Alramadhan, Kevin Erickson
Geophysics Technology, EXPEC Advanced Research Center, Saudi Aramco

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Abstract

Saudi Aramco recently started the company's first CO_2-EOR demonstration project in an onshore carbonate reservoir. Time-lapse (4D) seismic has proven to be a valuable reservoir management tool for monitoring the areal expansion of CO_2 plumes in many similar projects around the world. However, the complex and dynamic nature of the near surface encountered in the desert environments of the Middle East results in high levels of 4D noise. This noise, coupled with the weak 4D signal expected from injection into a stiff carbonate reservoir, makes mapping the time lapse signal very challenging. The objective of this project was to develop a highly repeatable system capable of detecting small reservoir changes related to CO_2 injection to enable the plume expansion to be tracked over time.

Achieving highly repeatable seismic data requires specialized seismic acquisition and dedicated processing. A novel acquisition system using buried receivers was adopted to reduce 4D noise resulting from near-surface variations. To minimize the non-repeatability inherent in using surface sources, a differential GPS guidance system was implemented to ensure high positioning accuracy. Even with these acquisition efforts, a fit-for-purpose 4D processing workflow was necessary to further reduce differences between surveys.

Despite the challenges faced, outstanding data repeatability has been achieved, with mean NRMS values of less than 5% for data acquired during the same season. This level of repeatability is comparable to data acquired in marine 4D surveys and has resulted in the detection of the small 4D signal caused by CO_2 injection. Frequent monitor surveys, with one full survey acquired every four weeks, shows the CO_2 plume growing over time with increasing injection volume. While the observed CO_2 plume largely correlates to available engineering data, discrepancies have been identified when compared with the predicted seismic response based on the reservoir simulation model. This indicates that 4D seismic can be used to constrain the reservoir model, yielding a better history match and improved predictions to enable more informed engineering decisions to be made.

This is the first successful application of seismic monitoring of a carbonate reservoir in an area renowned for poor seismic data quality. To overcome the challenges, a novel hybrid acquisition system using buried sensors and surface sources was developed. Advances in the seismic processing workflow were also required to bring the 4D noise down to a level that enabled detection of the CO_2 injection.

Introduction

The first CO_2-EOR demonstration project in Saudi Arabia has been implemented by Saudi Aramco in an onshore carbonate reservoir (Kokal et al., 2016). While Saudi Aramco does not require EOR oil for decades to come, this project is being pursued primariliy to demonstrate the feasibility of sequestering CO_2 through EOR in the Kingdom and using it as grounds to test new monitoring and surveillance techniques. Figure 1 shows a schematic overview of the project, which includes four injectors (shown in red) and four producers (green) separated by approximately 500-700 meters. A major component of any project of this nature is understanding the volumetric distribution of CO_2, both to enable more informed engineering decisions and to verify that the injected CO_2 remains within the target reservoir. While the vertical distribution of CO_2 may be available from repeat logging, this only provides point measurements of the CO_2 cloud. Currently, the use of time-lapse seismic is the industry standard for obtaining information about CO_2 in the inter-well region.

Time-lapse (often referred to as 4D) seismic, which has the capacity to improve reservoir management through better understanding of fluid movements, pressure changes and the identification of bypassed hydrocarbon zones, has been successfully applied on other projects around the world such as Sleipner (Chadwick et al., 2010), Otway (Pevzner et al., 2017) and Aquistore (Roach et al., 2015). However, most of these accomplishments have been for offshore and/or clastic reservoirs, due to the favorable conditions for 4D seismic. Until now, there have been very few published results of this technology used for onshore carbonate reservoirs, which dominate in Saudi Arabia. This is largely a result of the high complexity and variability of the near surface, which causes higher levels of noise and non-repeatability. Therefore, the goal of this study was to design a monitoring scheme to overcome these challenges and make a useable time-lapse seismic system available for the first time in the harsh desert environments of Saudi Arabia.

Background

Time-lapse seismic is a relatively straightforward concept, where the seismic experiment is repeated to obtain snapshots of the subsurface at different points in time. If the data is acquired under exactly the same reservoir conditions (i.e. no injection/production between two seismic surveys), the difference when the baseline and monitor surveys are subtracted would ideally be zero (Figure 2a). Clearly such a survey would be of little value to engineers, but can give important insight into the repeatability of the seismic system.

To first order, seismic waves are sensitive to changes in acoustic impedance (the product of P-wave velocity and density). When a new fluid is injected into a reservoir, it can change the acoustic properties of the saturated rock, modifying the seismic response. 4D signal is defined as those changes in the seismic data that are caused by engineering activities (Figure 2b). For this project, the variations in seismic response resulting from the injection of CO_2 into a hydrocarbon reservoir are of interest. These differences may appear as changes in seismic amplitude and/or events that are delayed in time. Since seismic is a volumetric measurement, changes in the overburden can also be monitored, so 4D seismic can also be used as a tool to verify that the injected CO_2 remains in the target reservoir.

However, the dynamic nature of desert environments make conducting multiple surveys under exactly the same near surface conditions impractical. Since the seismic wavefield propagates from the surface to the reservoir, any change in the near surface will be imprinted on the reflected signal from the reservoir (Figure 2c). In this example, the 4D seismic response of the reservoir is entirely caused by near surface variations. These changes in the seismic response, that are unrelated to engineering activities, are termed 4D noise. Note that the level of 4D noise can be of the same order or larger than the response due to changes in the reservoir. Therefore, sources of non-repeatability need to be minimized in order to successfully monitor small reservoir changes.

Surface conditions in the Middle East are constantly evolving, with sand dune migration (Figure 3) being one example that results in significant topography changes over time (Lisitsa et al., 2015). There are also very large difference during wet and dry seasons, with significant rainfall occurring over short periods of time that can raise water content in the sub-surface during several months. The potential for high levels of 4D noise, coupled with the small 4D signal expected from CO_2 injection into a stiff carbonate reservoir (acoustic impedance change of 3-6 %), makes seismic monitoring in a desert environment one of the toughest geophysical challenges (Smith et al., 2017). Although numerous successful applications of time-lapse seismic exist in the literature, there are few cases for land carbonates. One example is the Weyburn project (Li, 2003) in Canada, but this was performed in an area with less challenging near-surface conditions than encountered in Saudi Arabia.

To detect very small levels of 4D signal, all sources of non-repeatability have to be minimized as far as possible. To optimize data repeatability, the ideal solution is to bury both sources and sensors below the complex and changing near surface. This would have two main benefits. First, the wavefield does not pass through the shallow near surface (Figure 2c), so much of the near surface non-repeatability problem is avoided. Second, conventional seismic noise including ground roll and scattering that are normally recorded on gathers is significantly reduced, enhancing the signal-to-noise ratio (SNR) of the primary reflection events. In reflection seismology, we wish to record primary wave energy that has propagated through the earth and reflected back to the surface from an impedance boundary (red line, Figure 4a). Unfortunately, when energy is sent through the earth from the surface, a whole range of different waves are generated, including surface waves and refracted arrivals (Figure 4). As shown by the synthetic example in Figure 4a, when source and receivers are located on the surface, the recorded data is dominated by noise, which is considered here as anything other than P-wave reflections (red line). Note that this definition of noise is distinct from 4D noise, which was defined earlier in the paper and relates to changes in the primary reflection events over time that are unrelated to reservoir changes. When the sources and receivers are placed below the complex near surface, surface wave noise is reduced and the reflection events of interest are visible on the gather (Figure 4b).

Project objectives

The primary goal of this project was to develop a highly repeatable system capable of detecting small reservoir changes related to CO_2 injection. To achieve this goal the following was required:

- Design a seismic monitoring system to minimize non-repeatable noise
- Evaluate different setups to find the most suitable configuration for time-lapse seismic in a desert environment
- Adapt conventional processing technology to handle the new acquisition geometry in a 4D compliant manner
- Use time-lapse seismic to track the areal extent of CO_2 injection over time

Field tests

A number of smaller scale field trials were first performed to determine the best survey design to maximize data repeatability. Although the use of buried sources and receivers is the ultimate goal to avoid near-surface changes and optimize data repeatability, tests conducted with buried piezoelectric sources proved to be inadequate to sufficiently image the deep reservoir of interest (Berron et al., 2012). Development of a stronger source is required before this can be considered a viable option in complex desert environments.

The next best alternative is to use a hybrid system consisting of surface sources and buried receivers. Vibroseis trucks were used as seismic sources for this project. Although a significant portion of the energy will still be lost to surface waves (also known as ground-roll), far less will appear on the recorded data due to the use of buried receivers. While surface waves are very high amplitude and dominate records when recorded at the surface, their amplitude (which can be thought of as the amount of displacement of the rock caused by the passing surface wave) decays exponentially with depth. In addition to recording less surface wave noise, the reflection events of interest only pass through the very near surface once, rather than twice as with conventional surface acquisition. This should reduce the amount of non-repeatable noise imprinted on reflection events by changes in the near surface.

A 2D seismic survey (i.e. imaging a 2D cross-section of the subsurface) was acquired using geophones (seismic sensors) installed at three depth levels (10, 20 and 30 m), as shown in Figure 5. The goal was to observe the effect of receiver depth on the seismic image quality and data repeatability. A total of 80 receiver holes were drilled over a 2.4 km line. Surface sensors were also installed as a reference for the buried data. Note that while the buried surveys used a single geophone at each depth level, a group of 12 bunched geophones were used at each surface station to enhance the SNR. A cross-section of the site in Figure 5 shows some of the near-surface complexities, with variable surface sand thickness ranging from 2 to 3 meters on the left side of the line up to 20 m on the right. A dense source grid (9 lines of 300 sources each with 7.5 m x 7.5 m spacing) was used for this test. The seismic experiment was repeated a total of six times over a period of four months to assess the repeatability of the seismic system.

Repeating the source

Avoiding changes in the near surface is just one component of achieving highly repeatable data. In addition, the acquisition geometry between surveys should be identical. On the receiver side, this is easily achieved with buried sensors since their position and coupling should not change over time. However, the need to use surface sources introduces an additional component of non-repeatability. The source energy is generated by a Vibroseis truck using a piston that drives a baseplate coupled to the ground (red arrow in Figure 6a). Preferably, the center of this baseplate would be located in exactly the same position for each survey. However, small geometry errors between surveys are inevitable when trying to reposition a 10 m long truck while maintaining high acquisition productivity.

To determine the impact of source position change on data repeatability, a simple test was conducted where the first arrivals for the repeated seismic surveys were compared. Figure 6b shows the early arrivals recorded on one of the 30 m buried receivers from multiple surface sources (with small source-receiver offset). The traces in black and red show the data recorded during surveys one and two respectively. A 75 ms time window is taken around these early arrivals (green box) and a metric known as the normalized root-mean-square (NRMS) is calculated. The NRMS is a measure of the similarity between two datasets, which effectively quantifies the normalized difference energy between two traces. For traces that are perfectly repeatable, the measured NRMS would be 0%. Increasing values of NRMS indicate that the traces are becoming less similar (Kragh and Christie, 2001). The NRMS is computed for the difference between the baseline (survey one) and five subsequent repeat surveys (two - six).

NRMS is plotted against the change in horizontal source position in Figure 6c and shows a clear trend of decreasing data repeatability with increasing source position error. Interestingly, even if the position error is very close to zero, we do not obtain identical data (NRMS = 0 %). This is a result of a number of factors including: variable near-surface conditions, presence of random noise, different coupling between the baseplate and earth surface and small changes in the performance of the Vibroseis source. Due to the complex nature of the near surface, it is believed that even very small geometry changes can significantly affect the propagation of the wavefield. For instance, shallow karsts (voids caused by dissolution of carbonates) cause scattering of the seismic wavefield. Small differences in the location of the source can significantly change how this energy is scattered, degrading overall repeatability. Note that in this discussion we have only focused on the baseplate position, but changes in direction of the Vibroseis base plate (i.e. azimuth) may also have an impact on repeatability.

Image and repeatability

The final seismic image obtained from sensors placed at the surface and 30 meters depth are shown in Figures 7a and 7b, respectively. A seismic image shows reflections generated by boundaries in the subsurface having significant impedance contrasts (i.e. change in acoustic properties). Comparing the two images (produced using identical seismic processing workflows), we see substantial improvements with the buried receiver data, particularly in the region of thick sand dunes on the right side of the line (blue arrows). The event is almost completely lost with the surface sensors, likely due to the primary signal being completely buried beneath surface generated noise (e.g. Figure 4a). On the buried receiver image, a clear reflection event is obtained across the full section. At the level of the horizon of interest (indicated by red arrows), event continuity is markedly improved compared to the equivalent surface image. In general, we observed improving image quality with increasing depth of receiver burial. The best stack section was produced from the 30 m receivers due to being located beneath the sand layer and some of the near surface karsts.

Figures 7c and 7d compare data repeatability when going from surface to buried sensors. Here the difference between the first two surveys is shown. Since no CO_2 is injected during this time, the perfect response would show white (i.e. the traces are identical meaning the data is perfectly repeatable, as in Figure 2a). Comparing the two sections, it is immediately clear that the level of 4D noise is far higher in the surface data (figures are shown with the same color scale). Using the NRMS repeatability metric to measure the level of 4D noise quantifies this improvement. Based on a time window about the target, NRMS values of 53 % and 16 % are obtained for the surface and buried receiver data, respectively. The level of 4D noise in the surface data is too high to enable small 4D signal to be detected, suggesting the use of buried receivers is an essential component of time-lapse seismic in desert environments.

A summary of these field tests for the different experiment configurations is provided in Table 1. While a buried source-buried receiver system is the ultimate goal and provides the best repeatability, buried source technology was unable to sufficiently image the deep reservoir of interest. For the detection of small reservoir signals, it was concluded that surface source-surface receiver acquisition is unsuitable due to high levels of 4D noise. A hybrid system using surface sources and buried receivers was found to be the best compromise, with buried sensors crucial for improving data repeatability. Minimizing the majority of source position errors to values below 1 m was another key finding of this study.

Final survey design and acquisition

Based on the findings of the 2D field tests, a surface source-buried receiver system was selected for the final 3D survey design (Figure 8a). This system comprises 1003 buried sensors at a depth of 50-80 meters (Figure 8b) on a 50 by 50 m grid. The depth was selected so that the receivers were deployed just below the water table in the same geological horizon (Bakulin et al., 2013). Additional tests based on a small number of receivers indicate that installation below the water table provides better sensor coupling which may enhance data repeatability (Burnstad et al., 2013). The field trials also showed that image quality generally improves with depth, but even at 30 m below the surface the geophones were still located within the complex near surface (due to noise observed on raw gathers and information available from shallow drilling logs). Deeper installation places receivers below more of this complex near-surface layer.

The installation of the more than 1000 geophones (Figure 9a) was a major component of this project. Vertical holes were drilled to the water table using mobile drilling rigs (Figure 9b). The highly variable nature of the near surface in this region resulted in challenging drilling conditions. Loose sand, overlying limestone consisting of soft and hard layers in addition to karsts all pose different problems for safe and efficient drilling (Bakulin et al., 2013). Air drilling with foam injection was preferred to the use of drilling mud, since foam fills any lost circulation zone rather than creating wash outs (which would make conditions even worse). Selection of foam also reduces the environmental impact of drilling, since it does not contaminate subsurface aquifers and results in more efficient use of water supplies.

Once drilling was completed, the sensor was lowered to the bottom of the hole and backfilled with sand (Figure 8b). The sensors are connected through surface trenches that ultimately feed back to the recording truck shown in Figure 9c. This serves as the control center during seismic acquisition, including tracking and guidance of the Vibroseis trucks, data recording and data QC (Figure 9d).

A dense Vibroseis source grid (10 x 10 meters), using approximately 100,000 unique source positions, was implemented for this project (pink shaded area in Figure 8a). The small source spacing serves two purposes. First, it provides sufficient unaliased sampling of remaining conventional noise to enable adequate removal during seismic processing in the common receiver domain. Second, it results in high fold data (the number of times each location in the subsurface is sampled by the seismic wavefield), which enhances the SNR of primary reflection events. Data repeatability is known to be a function of SNR (Pevzner et al., 2011), yielding more reliable results. Data is acquired 24 hours a day at a rate of approximately 4000 shots per day. This results in one full survey being acquired every four weeks. Once a survey has been completed, the crew immediately start the next. Frequently acquired surveys are particularly valuable when small 4D signal is expected and where rapid changes in saturation will take place during injection (over the course of months, rather than years) since it reduces uncertainty in the final interpretation.

As demonstrated by the field trials, source position changes between surveys have a significant impact on the repeatability of the data. To minimize the non-repeatability introduced by source position variations, a differential GPS (DGPS) based guidance system was used to direct the Vibroseis drivers. Upon completion of a source point, the screen directs the driver to the next source location, which is based on the position acquired during the baseline (first survey). If the center of the vibrator baseplate is not within a one meter radius of the target point, the driver is unable to initiate the source sweep. Using this system, excellent source position accuracy has been achieved, with mean error of 0.34 m (Figure 10), comfortably exceeding the target accuracy of 0.75 m. This was attained while maintaining high productivity of around 4000 source points per day. Note that the same path is followed for each survey to avoid major changes in the direction (azimuth) of the Vibroseis truck during acquisition.

4D Processing

Despite deep receiver burial, the raw data is still contaminated by events other than the P-wave reflections of interest. This means the receivers are likely still located in the complex near surface. The use of a strong buried source would reduce conventional noise recorded in the gathers. Deeper burial may also improve things, but would come at additional expense. While the surface-generated noise, which is particularly susceptible to changes in near-surface elastic properties, has been significantly reduced by the final design, the remaining conventional and 4D-related noise still needs to be addressed.

A fit-for-purpose 4D processing workflow was developed for this task. Figure 11a shows a general overview of the workflow applied to this dataset, while Figure 11b shows the effect of each stage of the flow on the average stack repeatability. The objective here is for the stack repeatability to improve after each stage of processing, although care must be taken to avoid destroying the changes we are interested in (i.e. the 4D signal). Details of the processing steps can be found in Al Ramadhan et al. (2017), but it is clear from Figure 11b that some components have a larger impact on the mean NRMS than others. Those processing steps yielding the biggest improvement in stack repeatability are linear noise attenuation and supergrouping. Both steps significantly increase the reflection SNR, which is thought to be the reason for their substantial role in enhancing repeatability. The role of supergrouping (Bakulin et al., 2018), where adjacent shots are stacked together to boost reflection events and suppress random noise, is particularly important for this type of data since we record with a single source and receiver (at each location). This is unlike conventional surface seismic acquisition which has the option to use source and receiver arrays to attenuate noise.

Final mean NRMS values of less than 5% have been achieved for surveys acquired during the same season, an outstanding achievement given the challenging conditions (Bakulin et al. 2016). To put the accomplishment into perspective, this level of repeatability is more typical of permanent reservoir monitoring (PRM) surveys recorded in marine environments. For example, PRM installations at Ekofisk and the deep water Jubarte field have reported background NRMS values of 5% and 6% respectively (Bertrand et al., 2014; Thedy et al., 2015) where the near-surface conditions are less complex (water overburden) and not as susceptible to changes over time, making it generally more suitable for conducting time-lapse seismic experiments.

Initial qualitative interpretation

Excellent data repeatability has enabled small 4D signal related to the injection of CO_2 to be detected. Figure 12 shows the seismic anomalies recorded after 14 and 24 months of injection for two injector-producer pairs. Here the NRMS is used as a simple metric to display where the largest changes in the reservoir have occurred. After 14 months of injection, we clearly see 4D signal in the inter-well region that stands above the level of background 4D noise (Figure 12b). The anomaly appears to move between injectors I1 and I2 towards producer P2. This is consistent with existing engineering data. Ten months later, after a much larger volume of CO_2 had been injected (Figure 12c), we observe a significantly stronger 4D anomaly in the seismic data (Figure 12d). The map indicates a greater volume of CO_2 now moving towards producer P1, which is again supported by injection and production as well as interwell tracer data.

The predicted seismic response to reservoir changes can be obtained by generating synthetic data based on the reservoir simulation model, using a process known as simulation-to-seismic. Differences observed between the predicted and field 4D seismic represents an opportunity to constrain the history match process using seismic data to obtain a better reservoir model.

Summary

Seismic monitoring of CO_2 injection in a carbonate reservoir has been achieved in the harsh desert environment of Saudi Arabia for the first time. Clear 4D signal, which grows with increasing injection volume and is consistent with engineering data, has been identified in the reservoir of interest. In addition to providing information on the areal extent of CO_2, differences between the predicted results and those observed in the field represent an opportunity for seismic to improve the reservoir simulation model.

This success is the result of developing a highly repeatable seismic system. The use of buried sensors was determined to be an essential component to achieve the level of repeatability required for detection of the weak 4D signal. Ideally, a fully buried acquisition system would be used to completely avoid the non-repeatability introduced by changes in the shallow near surface. However, a stronger buried source needs to be developed before this can be considered to be a viable option. Despite this, using a hybrid system of surface sources and buried receivers resulted in excellent data repeatability, with mean NRMS values of less than 5% for surveys acquired in the same season, comparable with the best marine 4D surveys. Since surface sources are required, minimizing source position errors was also found to be an important consideration when using Vibroseis sources. This was achieved by implementing a DGPS guidance system to ensure close positioning to the baseline survey geometry.

The development of a novel acquisition scheme and specialized 4D processing workflow has enabled seismic monitoring of a stiff carbonate reservoir in an area known for poor seismic data quality. This achievement marks a significant advancement in geophysical monitoring and paves the way for geophysics to have a more direct influence on reservoir management in the future.

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Tables

Configuration	**Redundancy**	**Image quality**	**Repeatability**	**Cost**	**Suitability**
Surface source-surface receiver	Medium	OK	Poor	Low	Not viable
Surface source-buried receiver	Medium	Good	Good	Medium	Viable
Buried source-buried receiver	Low	No reservoir image	Excellent	High	Currently not viable

Table 1 – Qualitative evaluation of different acquisition schemes for time-lapse seismic in a desert environment

Figures

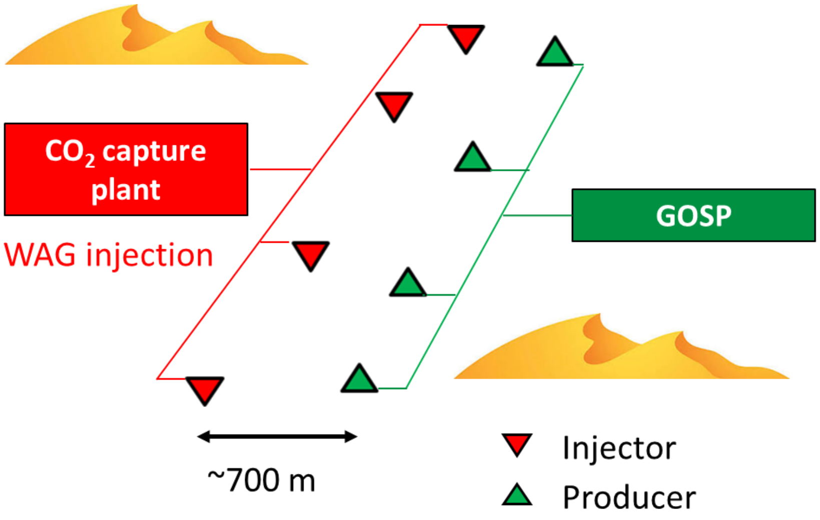

Figure 1 – Overview of the Saudi Aramco CO_2-EOR demonstration project (after Kokal et al., 2016)

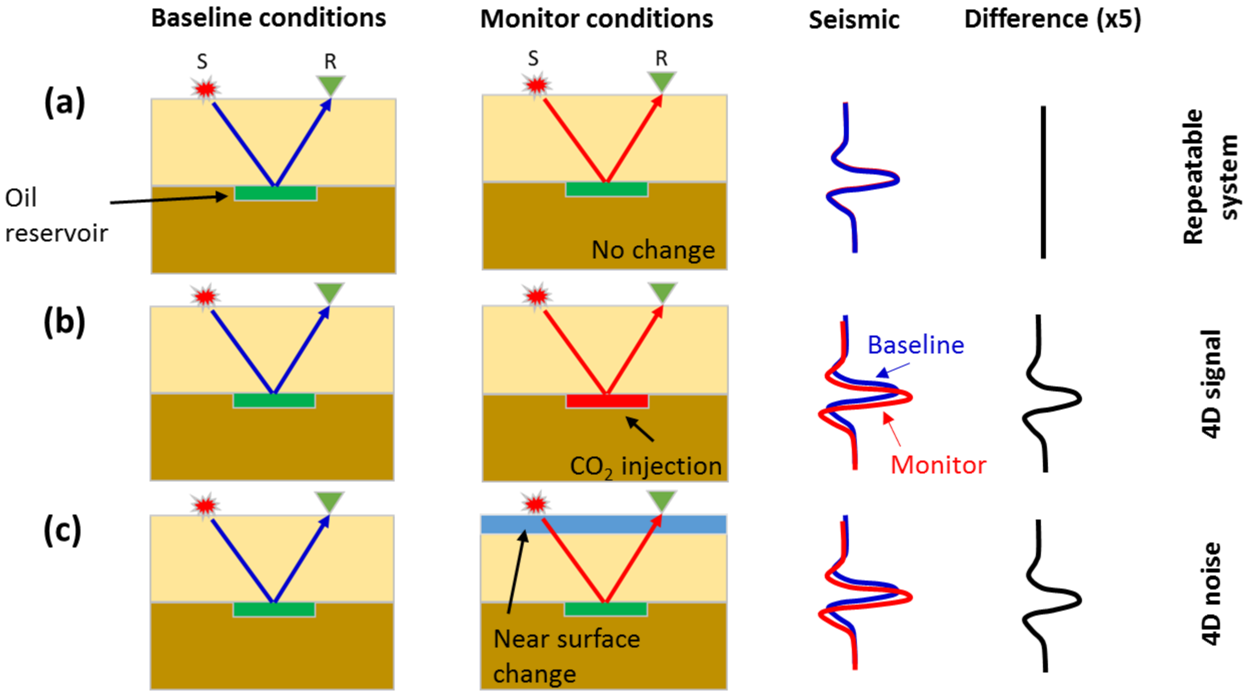

Figure 2 – Time-lapse seismic terminology demonstrated by a one source (S), one receiver (R) acquisition system, showing (a) a perfectly repeatable system, (b) seismic changes caused by engineering activity in the reservoir (known as 4D signal) and (c) the difference in seismic data resulting from changes in the shallow near surface (4D noise)

Figure 3 – Migrating sand dunes result in different near-surface conditions for each seismic survey. This introduces 4D noise to the seismic data.

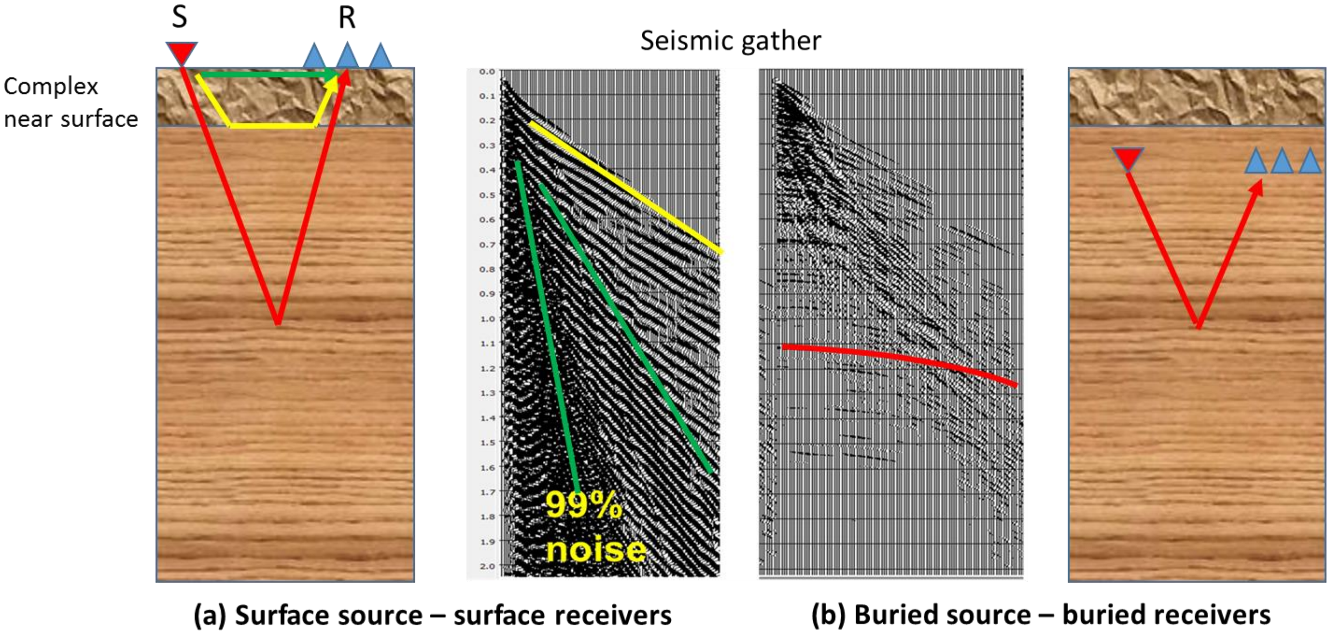

Figure 4 – The effect of burying source (S) and receivers (R) in reducing conventional recorded noise. Acquisition using surface sources and receivers (a) are dominated by surface wave (green) and refracted (yellow) arrivals. Burial of source and receivers (b) allows the primary reflection events (red) to be seen.

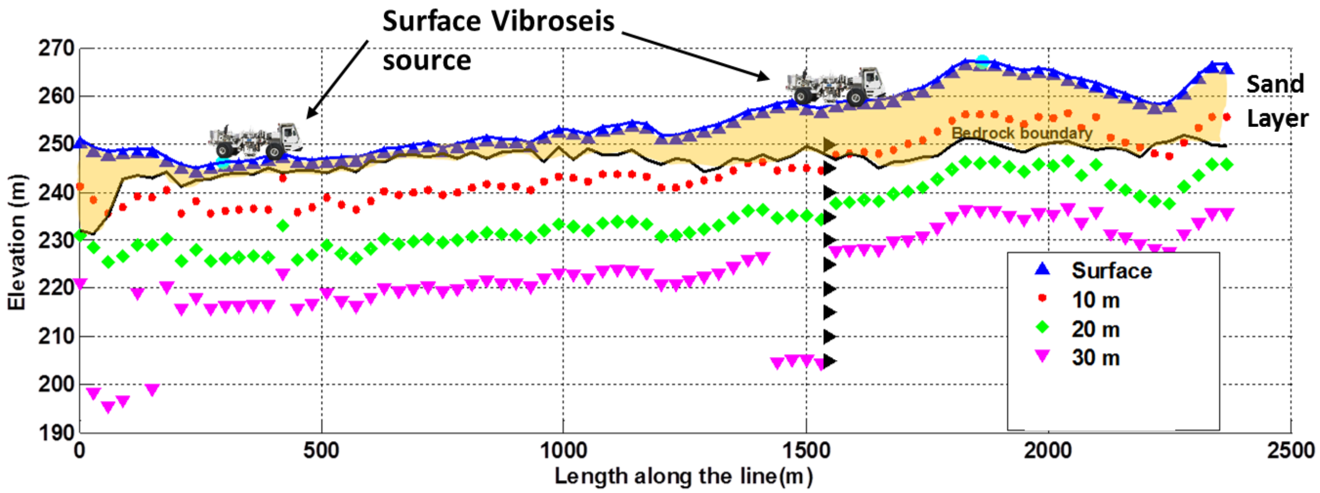

Figure 5 – Cross-section of the field test acquisition design, showing receivers placed at four depth levels.

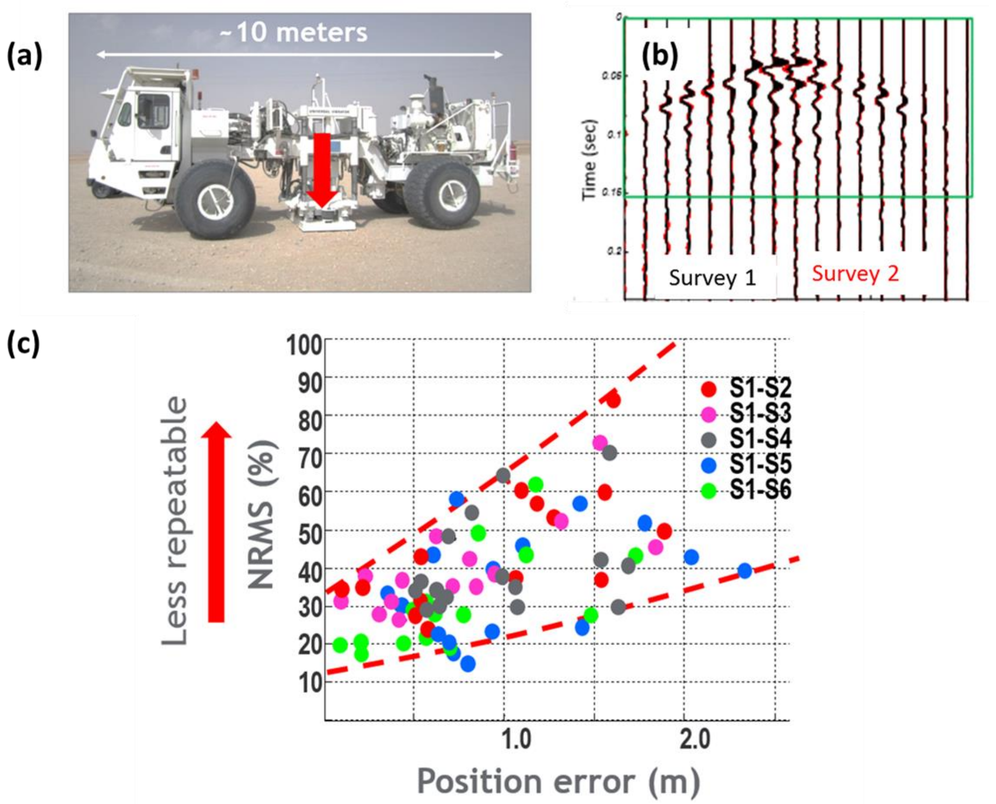

Figure 6 – Source position error impact on data repeatability including examples of (a) a Vibroseis truck used to generate energy that is transmitted through the earth, (b) early arrivals used to compute repeatability metric (green window) and (c) NRMS variations with source position error.

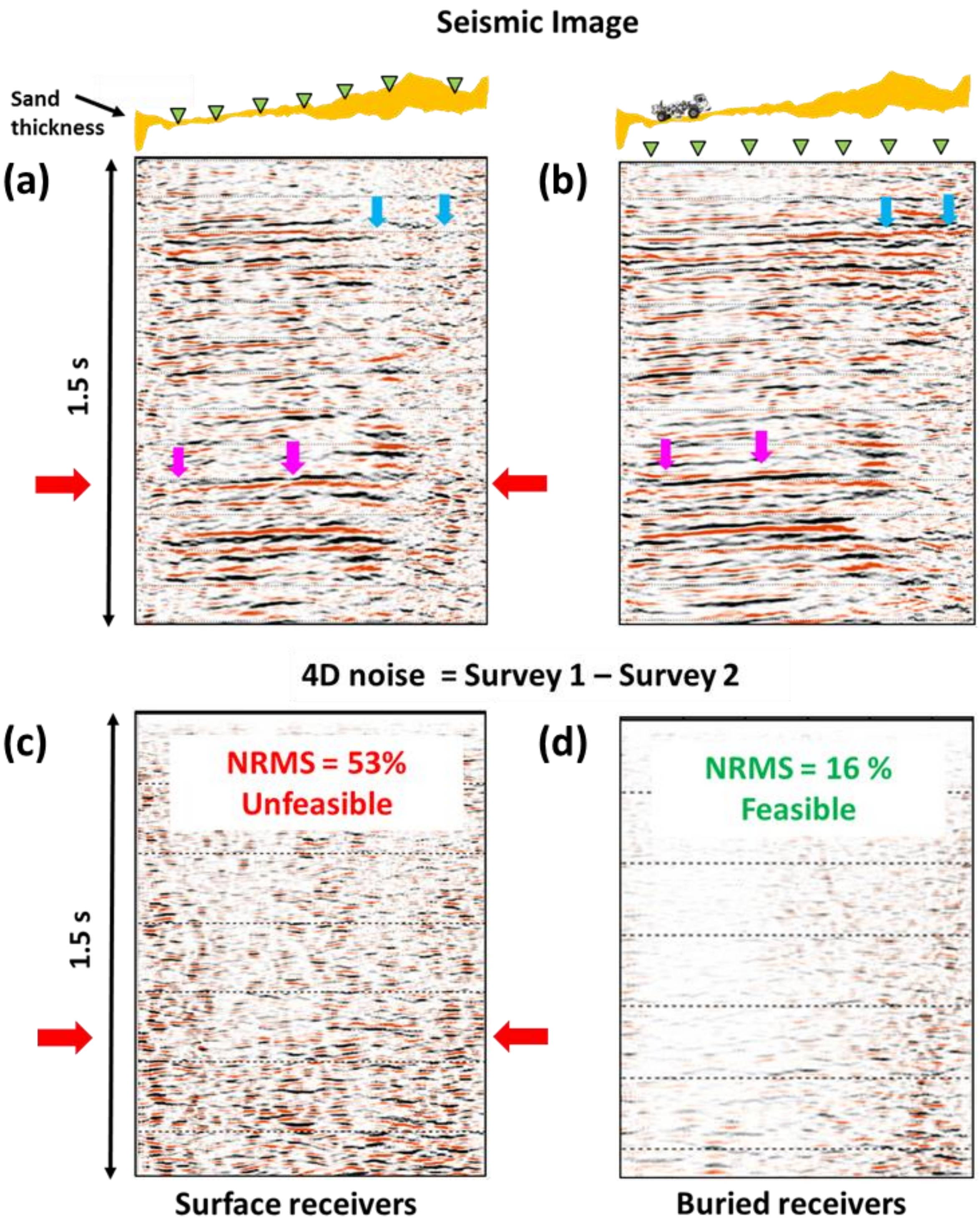

Figure 7 - Effect of burying receivers on seismic image quality and data repeatability. The final image produced by (a) surface sensors and (b) buried geophones (30 meters depth). The difference between the first two surveys (i.e. 4D noise) for the (c) surface and (d) buried geophones.

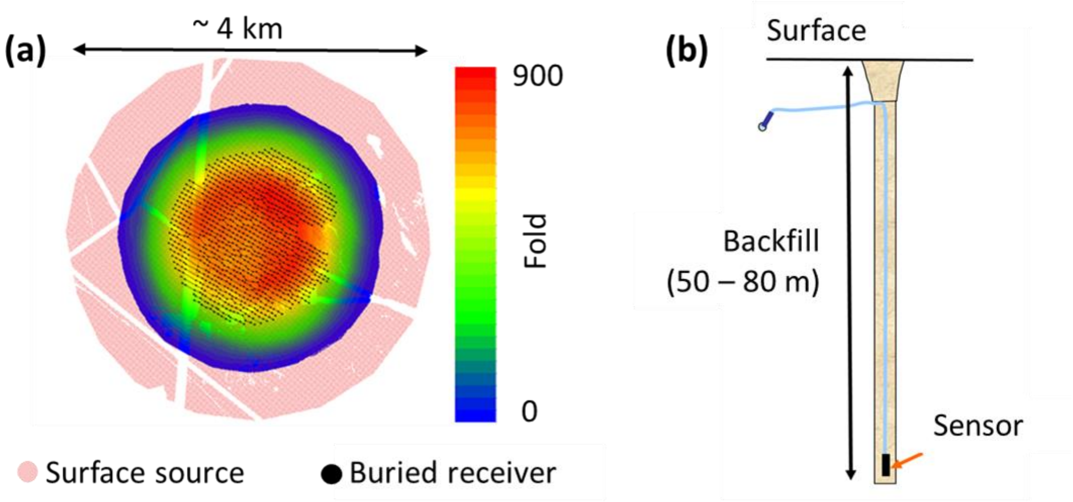

Figure 8 – Final 3D survey design showing (a) a map view of the site with buried geophones (black) and surface sources (pink), and (b) a cross section of a typical buried receiver hole back-filled with sand.

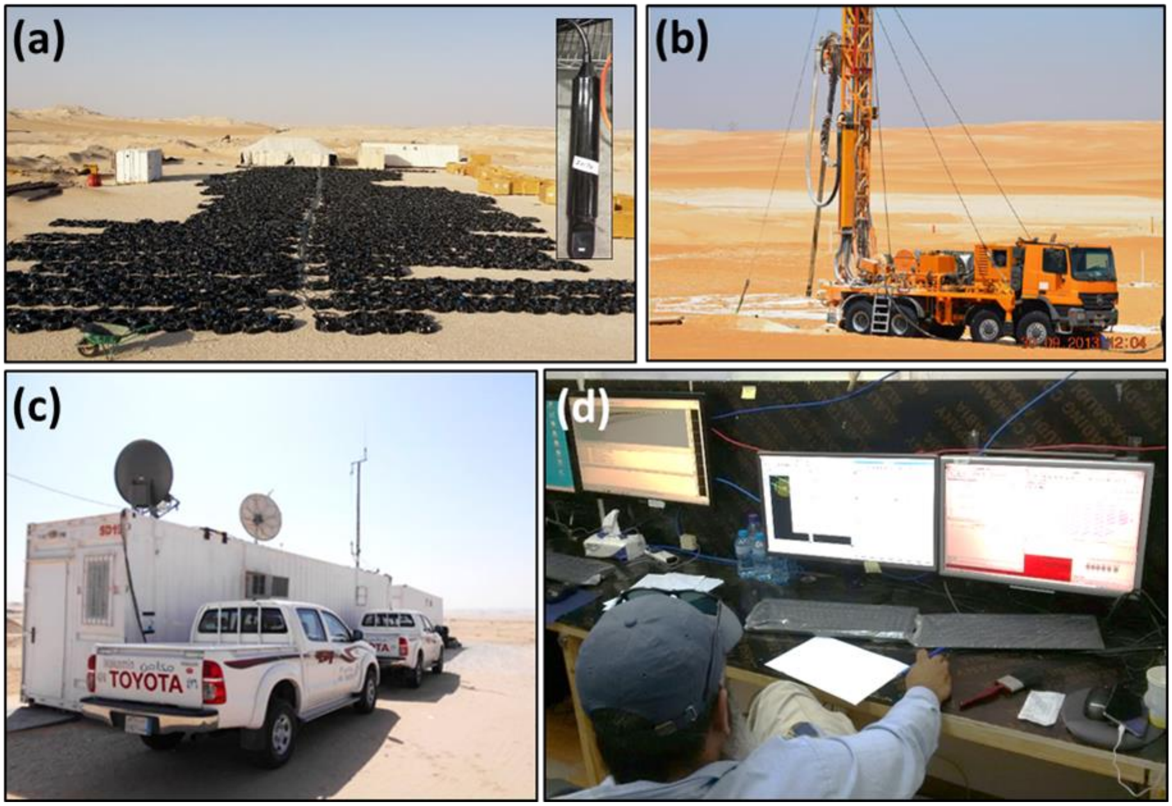

Figure 9 – Receiver installation showing (a) all 1003 sensors and cables laid out at the surface for quality control tests, (b) a mobile drilling rig used for shallow vertical holes, (c) the recording unit and (d) project management and data QC.

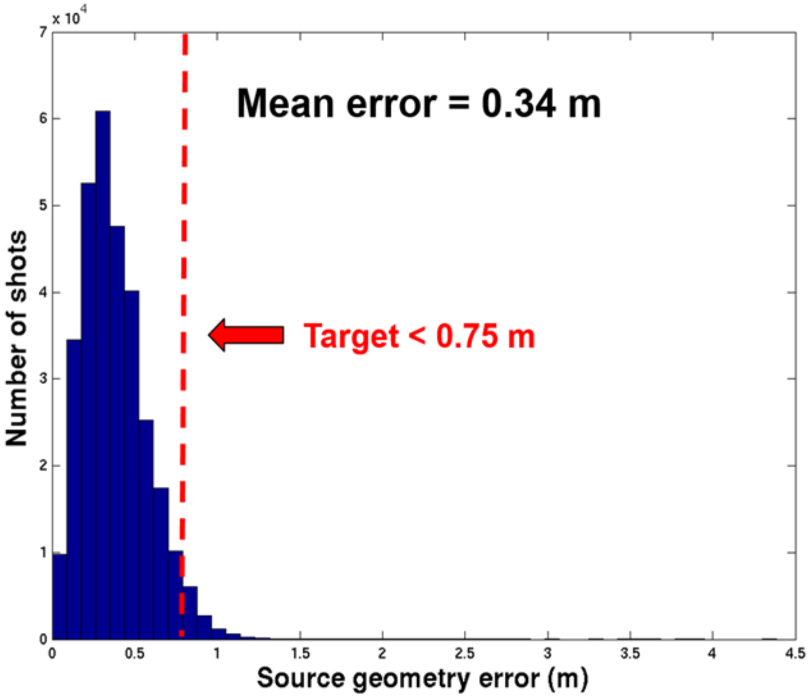

Figure 10 – Source position error histogram between the first two surveys.

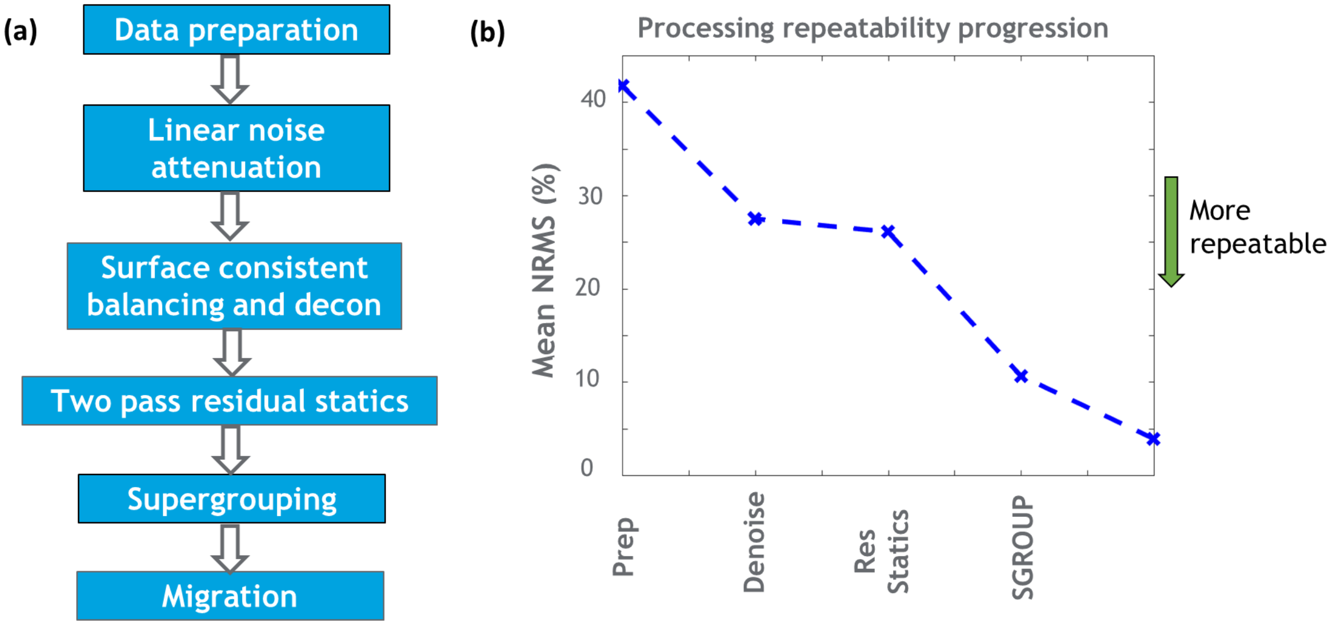

Figure 11 – Seismic processing summary showing (a) the basic workflow and (b) the processing repeatability progression curve.

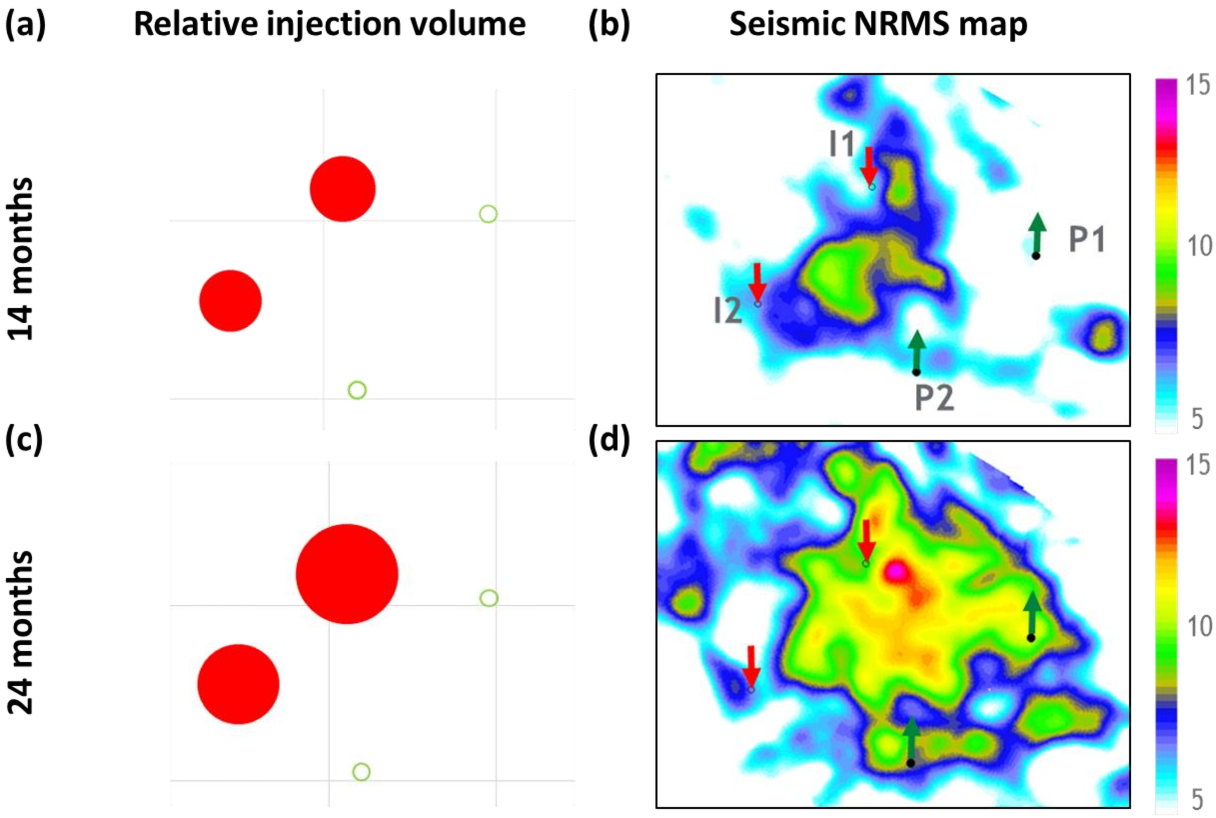

Figure 12 – 4D seismic detection of CO_2 for two injector (I) – producer (P) pairs showing (a) relative CO_2 injection volume after 14 months and (b) corresponding seismic difference map (using NRMS metric) and (c) CO_2 volume after after 24 months of injection and (d) corresponding seismic difference map.