Effects of complex near surface on 4D acquisition with buried source and receiver

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Summary

A seismic field acquisition test was conducted in an onshore field in Saudi Arabia. The effects of near-surface complexity (in the form of sand, karsts, topography), environmental noise as well as large surface temperature variations are illustrated and quantified by 4D attribute analysis using permanent seismic sources and buried geophones. We show that burying receivers dramatically improves the wavelet amplitude stability as well as naturally reduces the effect of man-made surface noise.

The near-surface layers comprise sand from 3 m to more than 20 m thick in this area overlying layered limestones and marls with karsting of limited lateral extent from 20 m to at least 50 m deep. Data quality from the permanent sources at this depth was inadequate for imaging using such low-fold acquisition, but the best data seems to come from the deepest buried sensors at 50 m. In addition, more sensitive sensors may be used to properly record weak high-frequency signal in this buried quiet environment.

Introduction

To evaluate technologies for 4D seismic reservoir monitoring on Middle East carbonate reservoirs, a seismic field acquisition test was conducted over an onshore field in Saudi Arabia (Bakulin et al., 2012). One of the goals of this experiment was to analyze the influence of near-surface conditions on seismic data repeatability and quality. To do so, we analyze seismic data recorded with seismic sources and geophones at various depths. The use of permanent sources allows a precise analysis of the signal stability in a 4D context. In this study, the near-surface was characterized by a variable thickness sand layer from 3 m to 17 m, overlying layered limestones and marls with thin karsts (generally less than 1 m thick) of limited lateral extent. Signal quality on legacy seismic data is poor on pre-stack records where the sand thickness exceeds 5 m, but can result in good stacked volumes given adequate fold and offset and azimuthal coverage. Observations lead us to confirm that the best signal repeatability is obtained for the deepest buried sensors and sources.

The second part of this data analysis concerns the sensitivity of the sensors. We show that, when buried in a quiet environment, the sensitivity of the sensors has to be increased to properly record signals, especially at higher frequencies.

Acquisition geometry and data quality

A comprehensive 4D pilot survey took place in an onshore carbonate field in Saudi Arabia. Only tests related to permanent sources are described in this paper. Figure 1 shows part of the line of receivers that were deployed. Eighty receiver locations were spaced at 30 m intervals, with four depth levels deployed at each station. At surface, strings of 12 bunched SM4 geophones in series were deployed below shallow sand cover to limit wind noise and other surface related effects such as direct sunlight. At 10, 20 and 30 m, we deployed SM4 geophones each comprising four elements in series. At 30 m depth, an additional single SM4 geophone was also deployed to evaluate the effect of sensitivity on the signal and noise recorded.

Records from two piezoelectric sources are presented here. Both sources vibrated continuously over a 4 to 148 Hz frequency range: one located at the surface and one cemented at a depth of 65 m. The buried source vibrated for 132 days, and the surface source, which was bolted to a reinforced concrete pad, vibrated for 64 days. Automated and real time processing provided a reconstructed shot record equivalent to a three-hour sweep eight times per day. Additional signal-to-noise enhancement was obtained by summing data over longer periods of time. Stacking of eight days of buried source data produced the gather shown in Figure 2. Pre-stack single-fold data from the permanent sources showed little sign of reflections, particularly at large two-way times. While this is normal for surface seismic data in this area, it suggests that either signal penetration from a permanent source is limited in these types of environments, or the depth of source-receiver burial is insufficient to reduce dominant noise to a level where reflections can become visible, or both.

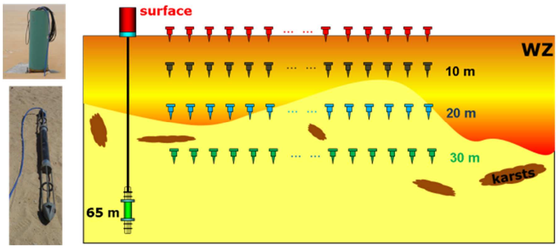

Figure 1: The field experiment acquisition geometry. Geophones are deployed at four different depths and piezoelectric sources are placed at the surface and at 65 m below surface. The near surface (weathering layer noted WZ) is complex because of cavities (karsts) and an unconsolidated sand layer.

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Signal quality vs. sensor depth

Near-surface complexity strongly affects wave propagation (Bridle et al., 2006). Shallow reflections are hardly visible on a buried source gather stacked over eight days (Figure 2). Drilling operations conducted for buried sensor deployment confirm the presence of karsts down to a 45 m depth on 22 of the 80 sensor locations, with cavities of around 1 m or less (with one example 5 m in height). These cavities were generally not present on adjacent holes 30 m away, suggesting individual karsts are of limited lateral extent. Near-offset diffractions and strong surface noise contamination at far offsets complicate P-wave imaging of the subsurface. An unconsolidated surface sand layer varies in thickness from 3 m to 17 m and further complicates seismic wave propagation.

During this experiment (< 3 months), no 4D signals are expected to be observed. Figure 3 shows a wavelet over a 40 ms time window selected from the first break arrivals for offsets between 525 m and 825 m as represented by the yellow boxes in Figure 2.

Time and amplitude variations are calculated using the crosscorrelation of the daily wavelet with its median over calendar time. Figure 3 shows up to 1 ms time variations

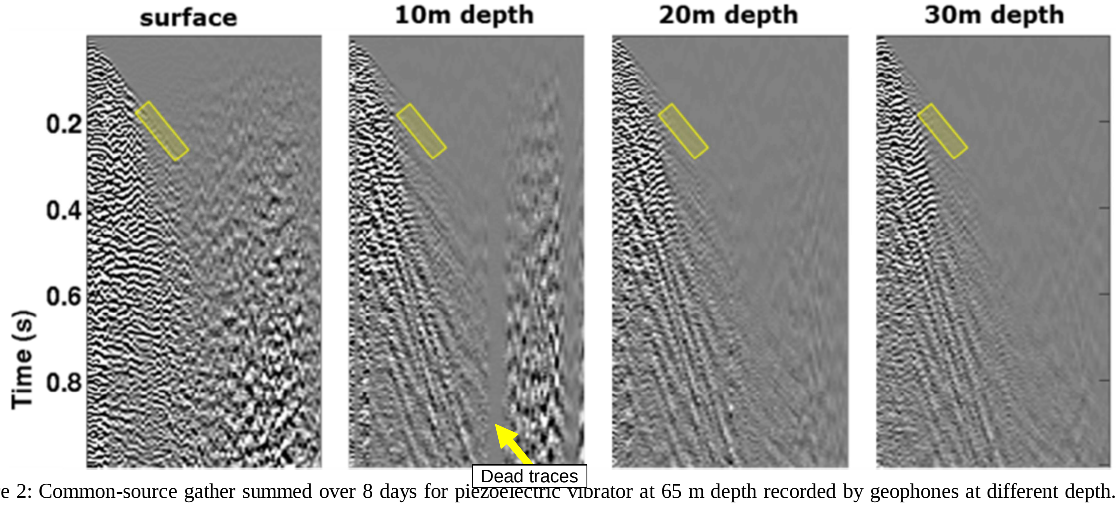

Figure 2: Common-source gather summed over 8 days for piezoelectric vibrator at 65 m depth recorded by geophones at different depth. Only spherical divergence is applied for display purposes. The window selected for first break wavelet stability analysis is shown in yellow. Environmental noise visible at far offsets is naturally attenuated by the burying of sensors.

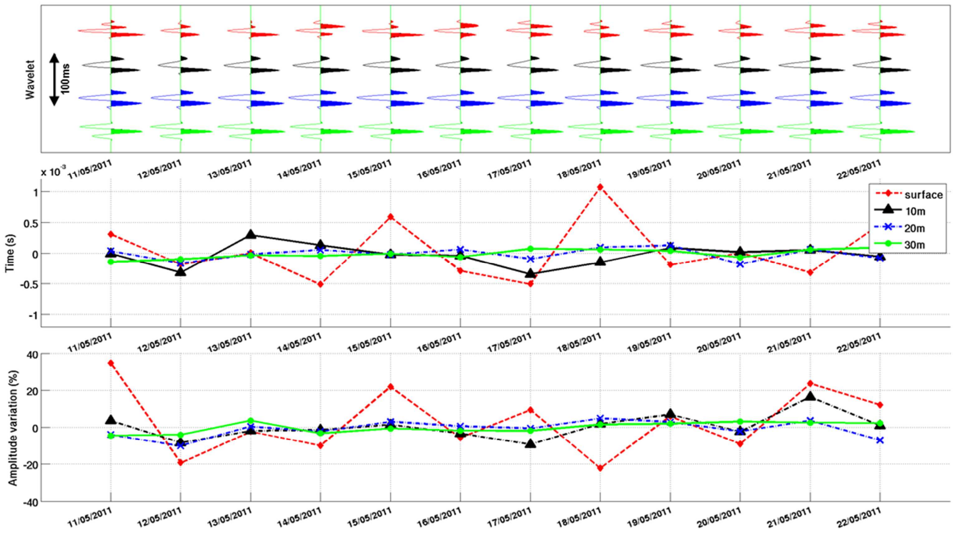

Figure 3: First break wavelet stability improvement according to the geophone depth of burial for 12 days analysis of the buried piezoelectric source. Stability is increased by a factor of 10 from surface to 30 m deep geophones.

for surface geophones and 10 times less variation (~0.14 ms) for 30 m buried geophones. In addition, a maximum 34% daily amplitude variation observed for the surface receivers is reduced to 4% for the deepest receivers. Man-made noise such as construction and drilling activities in the field appear to be largely attenuated by the shallow near surface when burying sensors. This noise attenuation is quantified in the second part of this article. A comparison of trace repeatability from buried vs. surface piezoelectric source data is shown in Figure 4. As expected diurnal variations, probably due to temperature and soil moisture changes, clearly appear stronger on the surface source data (Figure 4c) than for the buried source data (Figure 4b). Note that the surface source has up to 30 dB more power than the buried source at 60 Hz due to source design: reacting mass source versus dipole source. A quantitative wavelet analysis (Berron et al., 2012) shows that amplitude variations are around two times smaller when using the buried source vs. the surface source. Difficulties to identify similar noise patterns between surface and buried source data for the same receiver highlights the presence of strong heterogeneities and complex propagation in the study area.

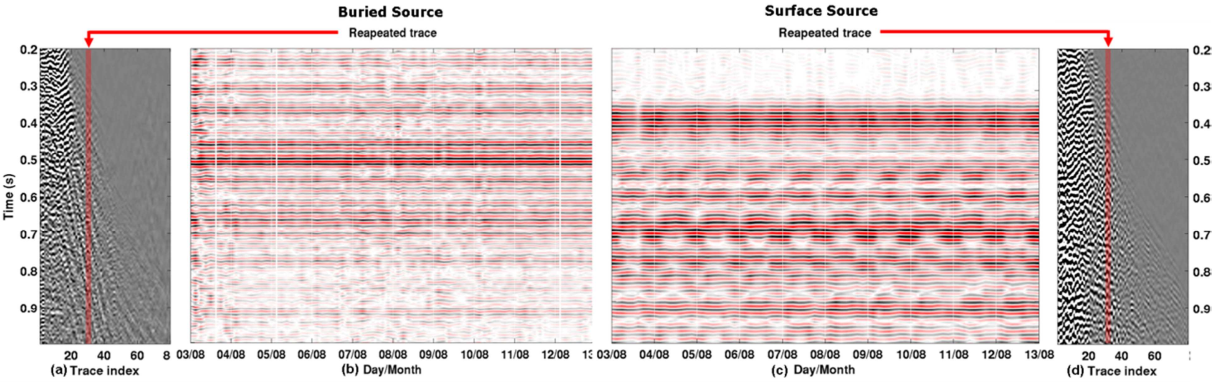

Figure 4: Shot gather for (a) 65 m buried source and (d) surface source recorded on geophones buried at 30 m depth after 64 days of record summation. Red line shows the trace at 645 m offset used in the analysis. On panel (b), over a 50 to 100 Hz bandwidth, the same selected trace is displayed every 3 hours over 10 days. On panel (c) is the same sensor but recording the signal from the surface source. Daily variations (nights and days) due to very near surface temperature and moisture changes are clearly observed through amplitude and phase modifications. The difficulties in linking panels (a-b) and (c-d) of the figure highlight the presence of surface noise on the surface source data, which is likely more affected by near-surface diurnal acoustic property changes.

Noise content according to sensor type and depth

In the context of reservoir monitoring, 4D measurement is affected by noise content. What we call “noise” encompasses two main notions: ambient noise and instrument noise. Ambient noise is generated by human activities (oil production, traffic, construction works, generator, etc.) and by nature such as wind, natural seismicity and ocean waves. Ambient noise is most dominant at low frequencies (in our case, <25 Hz) and is much stronger at the surface compared to greater depths. A gain of more than 20 dB is usually observed when we bury the sensors at a few meters (Schisselé et al., 2009). Instrument noise is electronic noise, which depends on the sensitivity of the recording equipment itself (digitizer, recorder).

When burying a sensor, we place it in a naturally lower ambient noise environment compared to the surface and sensor sensitivity has to be taken into account. This is because as we can reach the instrument noise level, especially for high frequencies (> 100 Hz), the sensitivity of the acquisition system should be chosen so that we properly record ambient noise and not only the instrument noise over the bandwidth of interest. Figures 5 and 6 illustrate that burying the sensors can naturally mitigate the environmental noise and as a consequence when burying receivers one should make sure they are sufficiently sensitive to record noise and signal above the instrument noise level. Figure 5 qualitatively shows the noise amplitude decay with sensor burial depth. Figure 6 helps to quantitatively draw conclusions from the noise Power Spectra Density:

- The quietest environment is obtained with the deepest sensors at 30 m depth.
- Differential gain (~10 dB at 40 Hz) obtained by increasing the depth of burial from 10 m or 20 m to 30 m does not appear to be linear with depth and strongly depends on heterogeneities specific to this area.
- As per the sensitivity of the sensors situated at a 30 m depth, the recorder noise floor is quickly reached (above 30 Hz) when using a unitary geophone (with an open circuit sensitivity of 28.8 V/m/s). If a string of 4 geophones in series is used (with an open circuit sensitivity of 115.2 V/m/s), the noise or signal with the same order of magnitude is then properly recorded up to

80 Hz. To record on an enlarged bandwidth, we recommend 8Z or 12Z sensors.

We note that in this specific noisy survey environment, surface deployment of a highly sensitive string of 12 geophones provides a comfort zone of around 50 dB above the electrical noise floor at -208.7 dB.

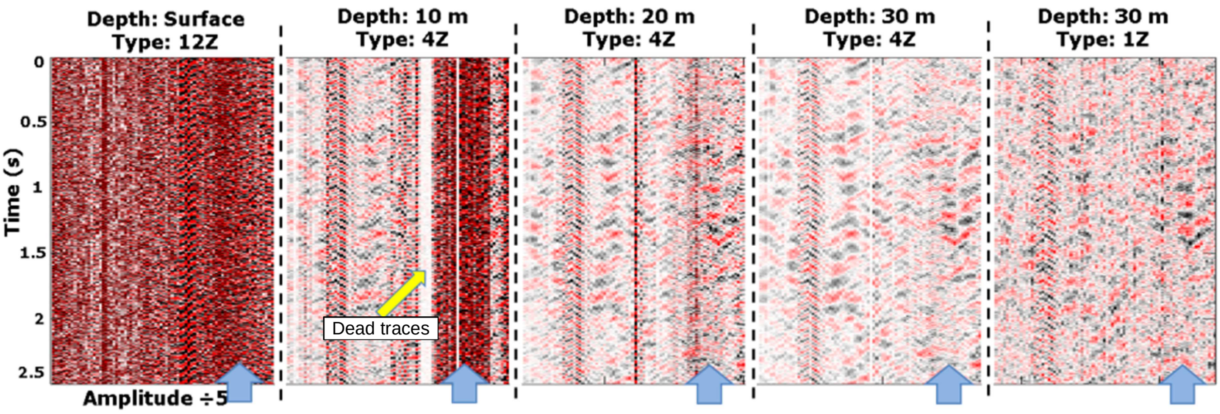

Figure 5: Five raw passive gathers of 80 geophones at various depths showing a one-day noise stack (no seismic signal recorded). A ‘*n*Z’ sensor is a series of *n* SM4 geophones in series recording the vertical Z-component of velocity. Sensor sensitivity has been taken into account to get units in $m.s^{-1}/\sqrt{Hz}$. Amplitudes can then be directly compared in a physical sense. Blue arrows indicate the same area of the spread contaminated by noise from a surface generator. It is naturally attenuated with depth bellow 10 m. Some dead sensors are pointed out with the yellow arrow. For the same 30 m depth, a single geophone noise record (Type: 1Z) shows a stronger amplitude as it reached the electronic noise, whereas a more sensitive four geophones string (Type: 4Z) correctly records lower seismic noise.

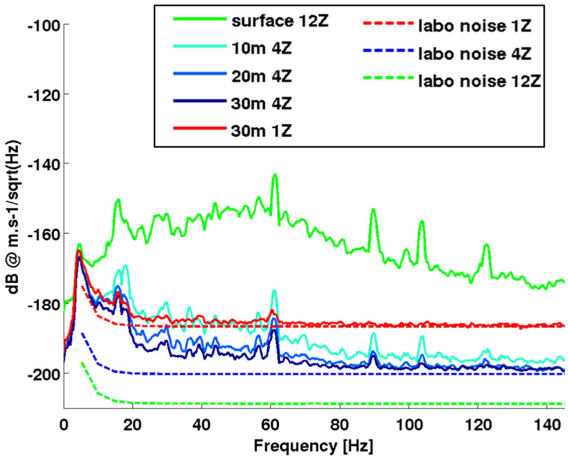

Figure 6: Median Power Spectrum Density corresponding to the various noise gathers from Figure 5. The theoretical electronic noise floor for each geophone string (noted labo noise in legend) is estimated from the manufacturer recorder specifications.

Discussion and conclusions

The effects of near-surface complexity and variability have been illustrated and quantified by 4D attribute analysis over an onshore carbonate field in Middle East. As observed in other environments, survey design with buried sources and receivers greatly reduces detrimental non-repeatability effects caused by temperature and seasonal changes in the near surface. Burying receivers helps avoiding complex karsted and surface scattering as well as large surface temperature variations and therefore improves the wavelet amplitude stability by a factor of 10. Selection of sufficiently sensitive sensors to be able to record weak signal variations and ambient noise reduction obtained by deep sensor burial enhances the signal-to-noise ratio and helps to improve 4D attribute quality.

Several key issues are identified to improve penetration and repeatability. An increase in source power is required for permanent sources to be useful. The recorded wavefield in this challenging, highly scattering and attenuating near-surface environment shows us clearly that the receivers are buried within the complex near surface. Therefore, for 4D seismic in this area, a deep installation and the use of more sensitive buried sensors have to be considered.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2012 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Bakulin, A., M. Jervis, R. Burnstad, and P. Kelamis, 2012, The feasibility of permanent land seismic monitoring with buried geophones and hydrophones in a desert environment: 74th Conference and Exhibition, EAGE, Extended Abstracts, X039.

Berron, C., E. Forgues, M. Jervis, A. Bakulin, and R. Burnstad, 2012, Buried sources and receivers in a karsted desert environment: 74th Conference and Exhibition, EAGE, Extended Abstracts, X040.

Bridle, R., N. Barsoukov, M. Al-Homaili, R. Ley, and A. Al-Mustafa, 2006, Comparing state-of-the-art near-surface models of a seismic test line from Saudi Arabia: Geophysical Prospecting, **54**, 667–680.

Schisselé, E., E. Forgues, J. Echappé, J. Meunier, O. de Pellegars, and C. Hubans, 2009, Seismic repeatability — Is there a limit?: 71st Conference and Exhibition, EAGE, Extended Abstracts, V021.