A broadband full azimuth land seismic case study from Saudi Arabia using a 100,000 channel recording system at 6 terabytes per day: acquisition and processing lessons learned

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Summary

In 2010, a 100,000 channel point receiver acquisition system was mobilized together with 24 80,000 lb vibrators to improve the characterization of both conventional and unconventional reservoir properties. Using a low frequency sweep design with productivity rates exceeding 8,000 vibration points (VPs) per 24 hours significantly increased the seismic data volume and data rate. Over 6 Tb of seismic data were routinely acquired with critical quality control decision points to maintain the integrity and manage the significant increase in seismic data volume. To ensure that full azimuth signal amplitudes were preserved for all offsets and azimuths, carefully selected true amplitude processing parameters were applied. We present this case history and lessons learned, from this Saudi Arabia project, as part of an ongoing fully integrated broadband acquisition-to-rock mechanics interpretation project.

Introduction

There is an emerging consensus in the seismic industry that broadband full azimuth symmetrically sampled (Vermeer, 2002) onshore seismic acquisition and imaging is now within reach, enabled by acquisition developments and enhanced true amplitude processing workflows.

This broadband full azimuth case history presents the acquisition and processing over a challenging data area characterized by a complex near surface and significant loss of high frequencies. The objective is to improve the imaging of the primary and secondary targets at approximately 3,000 m (1.7 s TWT) and 4,500 m (2.3 s TWT), respectively. This is solved with uniform full azimuth symmetric sampling and a broader bandwidth vibroseis source, as compared to the narrow azimuth legacy data acquired with an 8 to 80 Hz linear sweep.

To meet the near surface challenges – intermediate and deep target objectives without compromising full azimuth sampling – a high-capacity rule-based continuous recording system was used, along with point accelerometer sensors and vibrators using a low frequency sweep design to achieve high production rates with broadband signals. Acquisition productivity planning was a key criterion to manage crosstalk interference and maintain high-productivity levels. Additional critical factors included self-testing and real-time QC for sources and receiver spread integrity, “stakeless” survey operations, deployment of significant infield data processing capacity, and expertise.

Field implementation of quality control procedures for continuous, high-capacity, high-productivity and near-simultaneous vibroseis acquisition raises new challenges when the signal-to-noise ratio of raw traces is low. A key aspect of this integrated project was that all point receiver data are available for the full data processing sequence with no digital group forming performed prior to imaging (Ongkiehong and Askin, 1988).

We present the uncommitted acquisition and processing lessons learned in this integrated broadband full azimuth project.

2D field test

To evaluate the minimum group interval needed to record unaliased noise and signal wavefields, a twin 2D receiver test line with 5.00 m and 6.25 m source and receiver group intervals was acquired over the 3D program area. This 2D test demonstrated good to poor data quality. From source record analysis, it was determined that a 12.5 m group interval was sufficient to record unaliased coherent noise generated by a complex near surface, characterized by rapid lateral velocity variations (Figure 1).

Figure 1. Surface wave inversion results showing the complexity of the near surface.

The final 2D processing result using current advanced technology was surpassed by the initial 3D full azimuth brute stack followed by poststack migration (Figure 2). This result confirmed that a dense full azimuth design illuminates multiple targets from different azimuths and undershoots near surface anomalies. We concluded that 2D
field tests should always be used with caution when used to design 3D surveys and processing workflows.

3D survey design

An orthogonal, full azimuth, symmetric sampling design template was selected with 48 receiver lines (1,680 channels per receiver line), 125 m source and receiver line intervals, 12.5 m source and receiver point intervals, and a maximum inline and crossline offset of 6,000 m. To maintain an aspect ratio of one, a super-spread design was used with vibroseis fleets oriented outside the receiver spread to the north and south (Hastings-James and Al-Yahya, 1996). As the spread rolls from south to north, VPs are reoccupied, and when combined produce an equivalent source record with 96 receiver lines (161,280 channels). The point receiver and VP density are both 640/km² with 1,280 recorded VPs/km² (repeated VPs). This geometry resulted in 46,080 traces per source record and a nominal 9,216 fold for 12.5 m x 12.5 m common midpoint bins.

Vibrator groups operated in fleets of two vibrators with one 12 s broadband maximum displacement sweep (Bagaini, 2008) per location. Nominal sweep band was 3.5 to 90 Hz at -3 dB, with a maximum target fundamental force envelope of 56,000 lbf per vibrator (Figure 3).

Rule-based productivity and infield QC

With a targeted production rate of 8,000 VPs/day, approximately 6 Tb of uncorrelated seismic data was generated per day. To daily manage this huge data volume and significant increase in data rate, a mobile processing system was configured with 520 nodes, 170 Tb of disk storage and 10 tape drives (1 Tb) to perform daily QC and infield processing.

The high-density symmetric sampling geometry provides excellent trace distributions in the common shot, common receiver, cross spread, and offset vector tile domains. This results in optimum sampling for infield suppression of random noise, vibrator engine noise, air wave, surface and guided waves, and crosstalk interference (Figure 4).

Acquisition systems with the capability of continuously recording very wide receiver super-spreads with a choice of nonaggressive or aggressive time-distance rules will always depend on the ability of processing technology to suppress harmonic and crosstalk interference. All these methods can be used in combination to achieve the greatest source density in a minimum amount of time. When the source density is increased as compared to vintage surveys, the roll-rate (number of sensors moved per VP) will be maintained or reduced, having little or no impact on the productivity of the line crew.

For a high-productivity rule-based acquisition system operating with approximately 100,000 active and continuously recording sensors, it is critical to enable real-time QC monitoring of receiver spread availability to maintain data integrity, avoid lost production time and for the observer to assist in spread management.

Eight fleets of vibrators operating with multiple time-distance rules (distance separated simultaneous slip-sweep, slip-sweep or flip-flop) were distributed over the active super-spread with the objective of achieving maximum daily productivity. As the vibrator operators became more efficient, the slip-time and simultaneous percentages increased to 400 VPs per hour. Another advantage of point receivers and fewer vibrators per pattern is the reduction in total size of the seismic crew. With advanced positioning-with-deployment techniques, the survey crew of two people plus the “front crew” of 20 to 22 persons required for...
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receiver layout, on conventional production crews in Saudi Arabia, was replaced by a team of eight individuals responsible for surveying, layout, and crossing points (Figure 5).

Figure 4. QC time slice used in noise characterization and infield processing parameterization.

Figure 5. Layout and survey team.

Seismic data processing

Point receiver data in this area have very specific challenges, such as relatively low signal-to-noise ratio, coherent and random noise, and near surface effects. None of these are easily solved, but must be addressed prior to the interpretation. Near surface complexity and absorption effects may cause significant traveltime and wavelet distortion along with loss of high frequencies, adversely affecting the imaging step. Special attention was given to ensure that low frequencies are properly processed and enhanced through the sequence as a preparation to inversion. Field processing included vibroseis correlations, preliminary noise attenuation, surface wave dispersion analysis and geometry update, followed by residual noise attenuation, statics, signal processing, and imaging.

A key benefit of point receiver acquisition is access to 12.5 m spatially sampled field data to support reliable coherent noise attenuation processes. Coherent noise attenuation is applied on 3D cross spreads through noise modeling utilizing an F-x domain fan filter (Hildebrand, 1982). Additional QC parameter selection steps are performed to preserve low frequencies and mimicize the artifacts from multi-channel filtering across different source and receiver azimuths. Given the history of near surface challenges on the Arabian Peninsula (Pecholcs, 2008), a significant amount of testing was performed using refraction statics, diving-wave tomography, surface-wave inversion (Figure 1), and simultaneous joint inversion of first breaks and dispersions. The legacy near surface model based on an intercept-time method proved to provide the most stable medium to long wavelength solution, followed by iterative residual statics. The controlled amplitude and phase processing workflow included model based wavelet processing (MBWP) (Hart, Hootman, and Jackson, 2001), inverse Q filtering, and robust surface consistent deconvolution (Hootman, 2011) that utilized an advanced simultaneous Jacobi decomposition with an over-relaxation algorithm. This technique combines robust surface-consistent deconvolution, surface-consistent amplitude correction, and noise attenuation in one pass to provide relative amplitude preserved data. Application of MBWP allowed derivation and analysis of the surface consistent maps of signal-to-noise ratio and effective Q, as well as compensation for each convolution component in the surface-consistent model. A phase only residual operator was then applied to bring the wavelet close to zero-phase. Well data were frequently utilized for calibration throughout the processing sequence to verify the selection of appropriate processing parameters.

Prestack 3D Kirchhoff imaging is known to benefit from regular sampling in midpoint, offset and azimuth, and data conditioning prior to imaging. A regularization method based on compact Fourier interpolation (Moore and Ferber, 2008) was applied in the common offset vector tile (COVT) domain and prevented smearing across azimuths. This resulted in a reduction of noise, acquisition footprint, and migration artifacts, which ultimately improved the imaging.

Anisotropic VTI analysis was performed with manual picking on migrated gathers. Anisotropic imaging using COVTs was performed using VTI curved ray Kirchhoff time migration. A workflow was applied that derives true vertical interval moveout velocity and interval ETA. This was achieved by ensuring that ray tracing including curved ray effects was used during both the velocity analysis stage and subsequent imaging steps. This allowed for compensation of both turning wave (curved ray) and VTI effects (Fowler et al., 2004). Residual velocity analysis with an azimuthal term was run after the final migration exploiting the fact that every CMP had full offset and azimuth sampling. Traveltime variations on common image gathers were analyzed and corrected assuming elliptical anisotropy. The analysis returned the interval velocities in the fast and slow directions, the interval azimuth of the fast direction, and the RMS fitting error. Currently, use of these attributes as direct indicators of fracture geometry is under evaluation.

Prestack time migration acted as a powerful noise attenuation tool, which conditioned data and improved overall signal-to-noise ratio sufficiently for subsequent
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processing. Following the residual multiple attenuation using a high-resolution radon domain process, various noise attenuation and bandwidth extension techniques were tested in close collaboration with the interpreters. In the end, iterative 3D tau-p signal enhancement, followed by spectral whitening, proved to provide the best solution (Figures 6 and 7).

Figure 6. Broadband raw migration stack (left), post-image processing (middle), and 0-5Hz (right)

Figure 7. Signal (red) to noise (blue) ratio displays for the final broadband (left) and legacy (right) migrated stacks.

A pre-inversion spatially adaptive wavelet estimation and shaping process stabilized the seismic wavelet in the 3D seismic cube into a space-invariant zero-phase wavelet, while controlling the noise level in the data. This process assumes a spatially stable amplitude spectrum with arbitrary phase. The final volume was converted to zero-phase using deterministic wavelet extraction from multiple wells. A stable wavelet (Figure 8) with extended bandwidth led to improved inversion results (Figure 9).

While the geophysical challenges outlined here were significant, the seismic data volume scale was also a major challenge. Prestack seismic datasets had a size of 190 Tb. To meet this challenge, a purpose-built computer facility was designed to minimize I/O and storage issues. The upgraded network capacity managed weekly data shipments and the full anisotropic prestack time-migrated data volume was completed within eight months of acquiring the last VP.

Conclusion

We presented a case history in which a high-capacity multiple “rule-based” recording system enabled the acquisition of an optimally sampled seismic wavefield suitable for simultaneous imaging and inversion of shallow, intermediate, and deep targets. We achieved this objective by replacing receiver arrays with point accelerometer sensors, resulting in a reduction in labor in the field, and increasing the number of near-simultaneous sources with two vibroseis trucks per fleet.

Figure 8. Extracted and average (black) wavelets before (left) and after (right) spatially adaptive wavelet estimation and shaping processing.

Figure 9. Spliced well model based legacy (left) and new broadband colored inversion (right) images along a common traverse.

Results of this case history provide validation that broadband signals can be recovered from low signal-to-noise ratio raw data, and the addition of low frequencies from 2 to 8 Hz ensures that poststack inversion is less constrained by low frequency well data. This high-resolution impedance volume introduced a step change in interpretation, where high-resolution geobodies can be extracted, along with rock properties, for reservoir simulation models. This broadband result was not possible with conventional sweep designs using “low trace density” narrow azimuth legacy data with a linear sweep from 8 to 80 Hz.

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EDITED REFERENCES
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