Maximizing the value of existing seismic data in the Bahrain Field with wide-azimuth processing technology

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Abstract
As seismic processing technology advances, it opens opportunities for further improvements of existing datasets. This is especially important in the case of survey areas that may no longer be accessible for new seismic acquisition. The onshore Bahrain Field is just such a case because massive urban development since the original acquisition of a 3D seismic dataset in 1998–99 precludes any large-scale reshoot effort. The application of new 3D wide-azimuth processing techniques to the Bahrain dataset has substantially improved imaging of both shallow and deep reservoirs. Furthermore, the subset of the data volume that is near-surface/near-offset, and therefore wide-azimuth, has provided better fracture characterization of key shallow oil reservoirs. Here we describe the main processing steps that resulted in these image improvements, and we provide an example of how the azimuthal data improved fracture characterization.

Introduction
The Bahrain Field, also known as the Awali Field, is one of the world’s giant oil and gas fields. It spans most of the island kingdom of Bahrain, and has been in production for over 75 years. The oil and gas come from multiple reservoirs, stacked on a large salt-cored anticline (Figure 1). There are gas reservoirs in the Palaeozoic Khuff and Pre-Khuff formations, oil and gas reservoirs in the Jurassic Arab and Fadhili formations, and several oil reservoirs in the Cretaceous formations. The structure is intensely faulted and fractured, and most of the reservoirs are very heterogeneous (Samahiji and Chaube, 1987). In such a complex setting the seismic data can play an important role in building more accurate geological and reservoir models, providing subsurface information for more efficient drilling, optimizing waterflood and steam injection projects, and finding under-developed areas containing bypassed oil.

The Bahrain 3D seismic survey was acquired and originally processed during 1998–1999 (Postel et al., 2002). It is a 68-fold Vibroseis survey, with cross-spread geometry (Figure 2). The shotpoint and receiver intervals are both 50 m, with shot lines aligned N–S and receiver lines E–W. Although the long-offset data are oriented around the E–W direction, there are data with offsets up to 800 m for all azimuths. The original processing was essentially a post-stack time migration flow. The data were reprocessed in 2003 through a pre-stack depth migration (PreSDM) flow, improving the image considerably for the main objective at that time, which was the deep gas reservoir, but it overlooked the shallower section where most of the oil reservoirs reside. Further, the vertical resolution from the depth migration was relatively low, and the depth-to-time conversion itself imparted some distortions in both travel-time and amplitude. These issues consequently prohibited any further inversion work.

Given the nature of the cross-spread acquisition geometry, with eight live receiver lines, there is wide-azimuth coverage in this survey for the shallow section highlighted in Figure 2d (Jones et al., 2001). This aspect was not utilized during the initial processing or the 2005 reprocessing: the data have full-azimuth coverage for offsets up to 800 m. Of course, the Bahrain 3D was designed as a narrow-azimuth survey and was originally processed as such. However, given the structurally complex nature of the shallow section, a new approach was deemed necessary to get the most out of the survey by taking advantage of the wide-azimuth nature of the shallow data.

Reprocessing strategy and goals
The main goal of the reprocessing was to resolve both shallow and deep reservoirs better by applying new technology. Further, the processing flow should preserve azimuthal travel-time and amplitude information so that the resultant azimuthal gathers and stacks could provide data necessary for fault illumination and fracture characterization in the shallow section beneath the crest.

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Figure 1 Bahrain Field location: (a) map of the Kingdom of Bahrain; (b) depth map of the top Mauddud horizon – one of the main reservoirs; and (c) W–E schematic geological section to approximately 4 km depth.

Figure 2 Geometry and acquisition parameters of the Bahrain 3D seismic survey: (a) shot and receiver map; (b) acquisition parameters; (c) spider diagram showing the azimuth distribution; and (d) seismic section from the 3D. The upper section that is covered by wide-azimuth data at all azimuths is indicated by the yellow box.
1. Refraction statics
The first step of the flow was to build a near-surface velocity–depth model from first break picks by refraction tomography (Taillandier et al., 2010). The near-surface velocities range from 1500 m s\(^{-1}\) to 3500 m s\(^{-1}\) (Figure 4a). A reference datum 200 m below the average ground surface elevation was chosen, and statics were calculated using a replacement velocity of 3000 m s\(^{-1}\). These primary statics, varying from –3 ms to –40 ms, improved the long/medium wavelength character of the structures in the stack (Figures 4b and c).

2. Coherent noise attenuation
In a wide-azimuth time processing sequence, the algorithms are 3D to protect azimuthal information. The first step in terms of signal enhancement was linear noise attenuation using a 3D

![Special Processing Steps Diagram](image)

**Figure 3** Wide-azimuth processing flow.

![Figure 4](image)

**Figure 4** In-line 2156: (a) model after tomographic inversion; (b) stack with 2005 statics solution; and (c) stack after new statics solution from tomographic inversion.
f-k, conical filter in the cross-spread domain. To better handle aliased linear noise, an interpolation of shots and receivers was performed along the shot and receiver lines within each cross-spread gather. The interpolated traces were dropped after filtering to retrieve the original shot and receiver sampling.

3. Surface-consistent corrections
The next step was signal enhancement in the form of surface-consistent waveform harmonization. 3D surface-consistent amplitude compensation was computed and applied. This process included careful editing of noisy traces, noise bursts, and spikes, with an additional pass of frequency-dependent noise attenuation. Further, a 3D surface-consistent deconvolution, with statistical pre-stack zero-phasing, was run. Finally, residual reflection statics were calculated and applied. The values ranged from −3 ms to +3 ms.

4. Regularization
Prior to migration and using 5D interpolation/regularization (Poole et al., 2010), the original data were mapped onto a regular base geometry to remove irregularities. As a result of the interpolation, the shot-line and receiver-line spacing were essentially halved, producing four times the number of traces input to migration. This interpolation not only reduced migration noise, by appropriate cancellation, but also better defined near-surface events at gather level. Keeping the acquisition pattern during the 5D interpolation allows the PreSTM to be run on COV tiles, such that the azimuths are preserved after Kirchhoff migration.

5. Pre-stack Kirchhoff time migration (PreSTM)
Migration velocity analysis was performed on stacked migrated data, using percentage scans of the initial field derived from the NMO velocities. The resultant migration velocity field was calculated in an azimuthally isotropic sense, with particular care being taken in the choice of the mutes when picking velocities in the shallow section. PreSTM of the original data is compared with PreSTM after 5D regularization in Figure 5. The PreSTM was run on COV tiles to keep the original azimuth distribution.

Figure 5 In-line 2292: (a) PreSTM of original data; and (b) PreSTM of 5D regularized data.

Figure 6 (a) Azimuthal sectors. (b) The all-azimuth stack. (c)–(f) Stacks from the four azimuthal sectors with PreSTM.
In this case, azimuth-limited seismic cubes, or attributes such as average amplitudes derived from these, are used as the multi-dimensional input. Geo-statistical decomposition/filtering (Angerer et al., 2003) was subsequently applied, using combinations of these azimuth-limited cubes to extract the noise-free isotropic/common component as well as the noise-free anisotropic components.

Reprocessing results

The new, all-azimuth PreSTM data are compared with the existing PreSDM data in Figure 7. Following PreSDM, the 2005 data were converted back into time for post-stack processing. The improvement in the newly reprocessed data is evident for all the reservoirs, especially for reservoirs in the mid-section such as Nahr-Umr and Kharaib, where the reflections are much stronger and more continuous (Figure 7). The reprocessed data are also free of artefacts, and the faults are better defined and easier to interpret.

Due to careful work during noise attenuation and in addressing azimuthal variations in travel-times and
Figure 9 Comparison between the results of the 2005 processing and the recent re-processing where there was an acquisition gap: (a) vertical cross-sections; and (b) time slices across the acquisition gap area.

Subtle Fault Picking Using Azimuthal Data

Figure 10 Using the azimuthal data to interpret subtle faults: (a) structure map for the top of a reservoir, where the yellow line is an arbitrary line normal to the fault; (b) the existing data; (c) the newly reprocessed full-azimuth data; (d) azimuthal sector data oriented NE–E; (e) azimuthal sector data oriented N–NE; (f) azimuthal sector data oriented NW–N; and (g) azimuthal sector data oriented W–NW.
amplitude, the bandwidth of the processed data has been broadened, and consequently the vertical resolution of the data was increased. The data have flattened amplitude spectra with high frequencies up to 70 Hz, compared with up to 50 Hz in the 2005 data volume (Figure 8).

Improvements in spatial continuity for both the shallow and deep section are evident in the newly reprocessed data. Specifically, the application of the 5D interpolation prior to migration brings significant uplift to the resultant image. Ordinarily, a survey over a mature field would be expected to have small acquisition gaps from obstacles related to facilities, but in the case of Bahrain Field, where large restricted areas exist, the acquisition gaps are even more severe. Figure 9 illustrates the effect of acquisition gaps in the 2005 processing, and how these were addressed in the new processing. The improvement in continuity is obvious, not only in the shallow section but also in terms of the reduction in migration artifacts in the deeper parts of the section.

**Field applications**

There is a great variety of reservoirs in Bahrain Field: carbonates and sandstones, high porosity/high permeability, high porosity/low permeability, low porosity/low permeability, thick, and thin (Zubari et al., 2005). Faults and fractures play a different role in each type of reservoir. In some reservoirs fractures should be avoided because they cause water breakthrough from the underlying layers or from the near injectors, and in others fractures provide the main conduits to the oil flow. So fault mapping and fracture characterization are crucial, especially in the enhanced oil recovery phase of field development.

The reprocessed wide-azimuth data have brought more insight into the interpretation of subtle faults, and enabled a more accurate structural framework model that is being used for reservoir modeling and well planning. An example of the application of the azimuthal data for fault detection and interpretation is shown in Figure 10, where a subtle fault striking NW (Figure 10 a) is crossed by the horizontal well (green line) and detected on a formation microimager (FMI) log. In Figure 10b and c, the results of the 2005 processing and the new all-azimuth processing are shown for an arbitrary vertical section normal to this fault, demonstrating that it is difficult to interpret the fault. The processed results for the individual azimuth sectors are shown in Figure 10d–g. As expected, the fault is visible in Figure 10e for the sector with azimuthal range N–NE, normal to the fault orientation.

The other application of the reprocessed data is in fracture characterization using seismic amplitude anisotropy. An example of the use of the azimuthal data and the anisotropy map to detect fractures is shown in Figure 11. The FMI data from the horizontal well A, drilled before the data were reprocessed, showed several fracture corridors oriented...
NW–SE. At the location of the well on the seismic sections, it is possible to see the effect of these fractures in the amplitude of the azimuth data normal to the fracture orientation. A fast-track amplitude-anisotropy map, calculated using the ellipse-fitting method on horizon amplitude maps from the four azimuth sector volumes, showed anomalies in the areas where fracture corridors were encountered. Based on this analysis, fracture corridors were predicted along the trajectory of well B before drilling, and were proved by the FMI log after drilling.

Conclusions
Reprocessing has achieved its main objectives, resulting in better seismic imaging for all reservoirs, improving the structure and fault definition. The azimuthal data can be used for subtle fault/fracture characterization and anisotropy calculations. Initial results show very good correlation with the fracture information from borehole image logs. Also, due to the improved bandwidth, the data show better vertical resolution. The newly reprocessed dataset opens possibilities for further seismic inversion work and reservoir property prediction.

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