Improved imaging by adopting wide azimuth processing in Padra area of Cambay Basin, India

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Abstract

Wide Azimuth (WAZ) data acquisition offers better sampling of the seismic wavefield compared to narrow azimuth acquisition. Improvement in spatial sampling helps in better attenuation of the ground roll as well as other coherent noises and results in improved data regularization. Azimuth dependent velocity estimation provides insight for the study of anisotropy in the subsurface formations. The difficulty often faced while processing the WAZ seismic data is the inadequacy in the processing using 2D workflows. As the signal and different types of noise are recorded in a 3D sense, the methods used for signal-to-noise enhancement should also be volume-based. The offset vector tile (OVT) approach is better suited for the wide azimuth acquisition.

The tile refers to a small cell which is in the shape of a rectangle for orthogonal geometry and a parallelogram for non-orthogonal geometry. The OVT cell is composed of several common midpoints (CMPs) with a limited source and receiver range, and thus the offset and azimuth range. 3D seismic data acquisition using an orthogonal geometry was carried out in the Padra area of Cambay Basin situated in the western state of Gujarat, India. While processing the data, coherent noise attenuation was carried out forming cross-spreads. For orthogonal geometry, each intersection of a source line and a receiver line forms a center of a cross-spread, and a dense sampling of sources along the source line and receivers along the receiver line yields a dense areal coverage. 5D data regularization was performed to improve the azimuthal coverage and reduce migration artifacts. The OVTs formed after 5D seismic data regularization carry an even distribution of offset and azimuth information and the benefit of doing this was seen both in the gathers as well as the stacked seismic data. The migrated OVT gathers when sorted as snail gathers (where for every offset there are sub-traces, one for every azimuthal sector), exhibit a wavy behaviour on the seismic reflection amplitudes for the mid- to far-offsets, which is attributed to azimuthal variations of the amplitudes. Significant improvements were observed on the stacked sections after incorporating azimuthal velocity variations.

Keywords: NAZ, WAZ, OVT, cross-spread, regularization, VVAz, anisotropy, snail plot

Introduction

Wide azimuth (WAZ) seismic data acquisition and processing are used where the conventional narrow-azimuth (NAZ) seismic data are unable to address the azimuth-dependent velocity effects, either because of lateral velocity gradients or because of azimuthal anisotropic effects. During WAZ processing, first order of improvement in data quality will arise because of noise attenuation done in the cross-spread domain. Second order of improvement can be realized by incorporating azimuthal velocity variations present in the area. In addition, after the seismic data are regularized in five dimensions (inline, crossline, offset, azimuth and time) through 5D interpolation, better target illumination is obtained after migration.

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Tectonically, the Padra area falls in the northeastern part of the Jambusar-Broach tectonic block of South Cambay Basin and lies on the northeastern rising flank of Broach syncline. Figure 1 shows the area of study on the enlarged map of Cambay Basin. The study area falls in the eastern part of the block. The Dadhar, and Olpad formations are present in the area of operation. Cambay Shale and Hazad members are seen in the area; however the field is currently producing from fractured and weathered trap, Olpad and Ankleshwar formations. The main geological targets in the area are Dadhar and Hazad sands above basalt and the identifiable features below basalt which supposed to be portion of weathered or fractured trap. On seismo-geological sections of Cambay Basin, basalt is found from 500ms to 1100ms northeast to southwest dip direction in Padra area. A representative seismo-geologic section of Cambay basin with study area highlighted inside a box is indicated in Figure 2. 3D seismic data were acquired in Padra area using orthogonal geometry and with fair distribution of offset and azimuth. WAZ processing workflow including 5D regularization and azimuth-based velocity analysis or Offset Vector Tile (OVT) processing was carried out to better assess the hydrocarbon potential of the target zones.
Figure 2: Representative seismo-geologic section of Cambay Basin.

**Input data**

The seismic data were acquired under three different seismic investigations A, B, and C (Figure 3), using the same set of geophones, and the recording instrument. The seismic data so acquired for the three investigations had a common bin size of 10 x 10 m and a fold of 110, 110 and 80. Before 5D regularization, the data were re-gridded into a bin size of 20 x 20 m to increase the foldage up to 400. The combined fold map for the 3D seismic data volume is shown in Figure 3. Out of the total area, a major portion with fold around 400 (final foldage after re-gridding and 5D regularization) and fairly good wide azimuths (refer to Figure 3) was selected (black polygon) for further processing. One swath of the data was extended to connect the well location as indicated in Figure 3.

**General processing flow**

The general processing flow adopted for the 3D seismic data volume is shown in Figure 4, which broadly includes signal enhancement processes especially in the cross-spread domain, deconvolution, multiple passes of residual statics estimation and application, 5D regularization, RMS velocity analysis, OVT domain prestack time migration.
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(PSTM), azimuthal velocity corrections and finally random noise attenuation on PSTM stack. The crucial steps for the wide-azimuth flow are shaded in yellow.

Figure 3: (a) Map showing the study area covering major portion of the Padra Field. (b) The combined foldage map for the 3D seismic volume with the area selected for WAZ processing. (c) Representative azimuthal distribution in the area.
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Figure 4: The general processing workflow. The yellow shaded boxes show the crucial steps for WAZ processing.

Figure 5: The cross-spread contains one shot line and one receiver line orthogonal to each other and corresponding CMP coverage in square/rectangular form.
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Figure 6: A perspective 3D view showing an inline, crossline and a time slice (a) before, and (b) after ground roll attenuation. Notice the cleaner look of the sections in (b).

Figure 7: Time slice at 2000 ms, (a) before, and (b) after ground roll attenuation.
Figure 8: A stacked section shown (a) before, and (b) after noise removal. Notice the better definition and continuity of the reflection events in (b) especially in the upper half of the section.
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Noise analysis and attenuation was judiciously done with the combination of different approaches. Noise strips, spikes, random and frequency-dependent noise were suppressed using single and multichannel based methods. Ground roll attenuation was done in cross-spread domain. The data acquired with orthogonal geometry can be considered as a collection of cross-spreads (Vermeer, 2002). Each intersection of a source line and a receiver line forms the center of a cross-spread. The dense sampling of the sources along the source line and of the receivers along the receiver line creates a dense single-fold areal coverage. A sample cross-spread along with its coverage is displayed in Figure 5.

The midpoints of traces with the same absolute offset are located on a circle with diameter equal to that offset. Therefore, the first arrivals of the ground roll are lying on the surface of a circular cone. Hence, the ground roll in a cross-spread behaves as a truly three-dimensional event and can best be attenuated in a 3D sense. Figures 6 and 7 show ground roll attenuation in the cross-spread domain. A comparison of representative stack sections before and after noise attenuation is shown in Figure 8.

Based on the test results related to improvement in frequency above basalt (~ basalt at 1 sec indicated in Figure 8) and event identifications particularly below basalt, a two window (one above basalt and other below) deconvolution was applied on the data. Two passes of residual statics application were also performed. After deconvolution and residual statics application, 5D regularization was performed on the data, and is discussed next.

5D regularization

Various obstacles at the surface will alter the regularly sampled acquisition survey geometry (orthogonal) and introduce some randomness in source and receiver spacing and source line and receiver line spacing. These perturbations will clearly affect the uniformity of the coverage. Midpoint, offset, and azimuth variations in the recorded data result in non-optimal interference of seismic energy during migration. Thus, there is need for regularizing inadequately sampled seismic data is to minimize migration artifacts. 5D regularization (interpolation) offers a potential way of improving the spatial sampling so that prestack time migration (PSTM) could be used to provide a higher resolution image.

5D regularization can perform simultaneous regularization of several prestack dimensions through a forward-reverse Fourier transform (FT). Forward irregular Fourier transform is done in all five data dimensions simultaneously to build a representation of the data in the frequency domain. Reverse transform is run to output the data on a regular grid (e.g., regular midpoint, offset, and azimuth).

It is known that FT of regularly sampled data too may exhibit aliasing depending on the sampling rate. Likewise, FT of irregularly sampled data in any domain also leads to aliasing popularly termed as “leakage”. 5D interpolation uses an Anti-leakage Fourier Transform. (Xu et al., 2004), which yields a clearer image. Gathers with residual statics applied were taken as input for data regularization. Data regularization for azimuths was carried out for 8 azimuth classes of 45° aperture (Figure 15). As the data were acquired with a nominal foldage of 100, after re-gridding into 20 x 20 m bin size it became 400. To maintain a sufficient foldage in each offset-azimuth sector (i.e., OVT), the offset sectors as well as azimuth sectors were taken as 60 m and 45° respectively. By making
azimuth sector as 45°, the nominal OVT foldage became 50, which was sufficient for azimuthal velocity analysis and further processing. Consequently, the size of OVT was not conventional (RLi x SLi in Cartesian coordinates) but rather defined in polar coordinates with offset class increment of 60 m and azimuth class increment of 45°. Representation of OVT in Cartesian as well as in polar coordinates is shown in Figure 9.

Figure 9: OVT formation geometry in (a) Cartesian, and (b) Polar coordinate systems.
Figure 10: CMP Gathers showing offset distribution (a) before, and (b) after 5D regularization. The offset variation is shown plotted above the gathers in both images. Notice the regularity in the offset population after regularization.
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Figure 11: CMP gather showing azimuth distribution (a) before, (b) after 5D regularization. The azimuth values are plotted above the gathers in both images. Notice the regularity in the azimuth population after regularization.
Figure 12: Segment of a near-offset stack section (a) before, and (b) after 5D regularization. Notice how the missing data in the input are now predicted and an enhanced continuity of the events is noticed.
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Figure 13: Segment of a full offset stack section (a) before, and (b) after 5D regularization. Notice how the missing data in the input are now predicted and an enhanced continuity of the events is noticed.

Figure 14: The fold maps (a) before, and (b) after 5D regularization. Notice the consistent spatial foldage seen on the map after 5D regularization.
Further processing was carried out with this dimension (60 m X 45°) of OVT. After 5D regularization, quality control (QC) was necessary to select interpolated data based on the minimum distance (between a trace and its original neighbours). Several other QC parameters can be estimated and saved into headers. Effects of 5D regularization on offsets, azimuths are shown in Figure 10 and 11 respectively. Near offset stacks before and after 5D regularization are shown in Figure 12. Figures 13 and 14 show the full stacks and fold map before and after 5D regularization respectively.

**OVT domain migration**

Wide azimuth seismic data sets offer the benefit of better illumination of the subsurface. The data were divided into 400 OVTs (50 offset classes x 8 azimuth classes). Figure 15 shows azimuthal sectoring as a result of 5D regularization which was used for migration. Considering the source-receiver reciprocity, diagonally opposite azimuths (e.g., 23° and -157°, 67° and -112° etc.) are exactly same; however, for demonstration purposes they are handled and displayed separately. Kirchhoff’s pre stack time migration was run for each OVT using RMS velocity. 400 OVTs were migrated rather than 200 OVTs to understand their uniqueness for study purpose.

![Figure 15: Azimuth classes after 5D regularization. Angle values displayed on arrows represents the median angle of each class.](image)

**Azimuthal velocity correction**

Velocity variation with azimuth (VVAz), examines variation in velocity (travel time) with azimuth to characterize the anisotropy. With the introduction of aligned fractures, the rock structure can no longer transmit P waves with equal velocity in all directions. Azimuthal NMO methods describe how P-wave velocity varies with the direction of travel. For short recording offsets – less than or equal to the reflector depth – the variation in NMO velocity with azimuth can be described by an ellipse. This velocity ellipse is a simplified model, characterized by the major axis, $V_{fast}$, the minor axis, $V_{slow}$, and the azimuthal orientation of $V_{fast}$. For most rocks, the fast velocity corresponds to the rock matrix, and so the orientation of $V_{fast}$ is parallel to the fracture strike. The ratio of the two velocities ($V_{fast}/V_{slow}$) provides an estimate of the magnitude of the anisotropy. The
anisotropy magnitude delivered by VVAz is directly related to Thomsen’s parameter $\delta (v)$. The analysis of effective anisotropy gives $V_{\text{fast}}$ and $V_{\text{slow}}$ averaged down to the target and is typically used to correct for azimuthal moveout in the data and to improve the imaging. The stack can be improved by azimuthal moveout correction; therefore, it was important to correctly model the azimuthal variation in wave propagation velocity. When traces are sorted into a “snail gather”, that is with respect to increasing azimuth within each offset range, any seismic event may exhibit a wavy behaviour as a consequence of azimuthal kinematic variations (Figure 16).

After the azimuthal residual move-out application, the event is flattened and can be stacked effectually. The CMP gather shown in Figure 17 demonstrates that azimuthal anisotropy is present. The traces in the gathers have been ordered as a snail gather. The effect of azimuthal velocity variation is not noticeable at near offsets, but it is very pronounced at larger offsets. This prevents us from obtaining a constructive stack image from different azimuths.

For azimuthal velocity corrections, CMP gathers were divided into separate 8 azimuth sectors. High density velocity and anisotropy picking were carried out on these common azimuth sectors. High density velocity and anisotropy picking was carried out so as to remove all 4th order velocity moveouts at far offsets. The workflow entails calculation of trim-statics for a set of CMP gathers and inverts them to derive an azimuthal velocity model using cross correlation. It is generally run post-migration on CMP gathers. It is a surface fitting technique honoring all azimuths that can invert for an HTI (Horizontal Transverse Isotropic) velocity model. It also provides a set of correlation values which give the degree of confidence in any given trim-statics workflow.
High density velocity and anisotropy picking workflow mainly consisted of 4 steps:

1. Generate a pilot stack from CMP gathers.
2. Use CMP gathers and pilot stack to predict the trim-statics.
3. Invert the trim-statics to derive the azimuthal velocity model.
4. Apply azimuthal NMO to flatten the CMP gathers.

Moveouts due to velocity ($V$) and anisotropy ($\eta$) fields were picked for each azimuth sector of a bin and corrections were applied. Figure 18 shows azimuth sectors corresponding to a single CMP.

Figure 19 shows the representation of a seismic event in snail gather earlier shown in Figure 17, after azimuthal residual move-out correction. A comparison of zoomed versions of select portion of snail gathers, before and after azimuthal moveout correction, is shown in both Figures 17 and 19.

Figure 17: Snail gather with offset and azimuth headers overlaid above. Azimuthal residual moveout is clearly observed on the far-offset traces.
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Figure 18: Single CMP divided into 8 common azimuth sectors with increasing offsets. Complimentary azimuths are shown with boxes of similar colour.

Results and analysis

Gathers at several locations were analyzed for $V_{\text{fast}}$ and $V_{\text{slow}}$. It was found that the direction for $V_{\text{fast}}$ is 145° while for the $V_{\text{slow}}$ is 235° which is perpendicular to the $V_{\text{fast}}$ direction (Figure 20). Improvements in the event continuity were noticed after azimuthal velocity corrections were made which can be seen by comparing the stack sections in Figure 21a and b. The portions marked by yellow boxes A and B are zoomed and shown in Figures 22 and 23 for clarity.
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Figure 19: Snail gather shown in Figure 17 after azimuthal residual moveout correction.

Figure 20: Observed fast and slow velocities in azimuthal anisotropic media.
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Figure 21: Segment of a PSTM stack section (a) before, and (b) after azimuthal moveout correction.

Figure 22: Zoom of yellow box A (in Figure 21) (a) before and (b) after azimuthal correction. Notice the improvement in event continuity as indicated by the cyan arrows.

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Conclusions

Padra area of Cambay basin does not possess severe azimuthal variations. However, a wide azimuth processing workflow has been adopted as a case study which majorly included standard signal conditioning in the cross-spread domain, 5D regularization, followed by data segregation into OVTs, migration in OVT domain, and azimuthal velocity corrections. Overall improvement in event continuity, particularly at shallower levels (500 ms to 700 ms) was observed as a result of 5D regularization. Due to regularization of offsets and azimuths improvement after migration is seen especially below 700 ms as indicated in Figures 22 and 23. Azimuthal velocity corrections after migration also showed improvements in event continuity. Although, Padra area is does not have major anisotropy variations; however, overall improvement in imaging is observed by adopting wide azimuth data processing flow over conventional processing workflow.

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Yogaxem Sharma joined ONGC in 2011 as Geophysicist (S), after completing his master’s in applied geophysics from IIT Bombay. Presently, he is posted as Superintending Geophysicist (S) at Directorate General of Hydrocarbons (DGH), Noida on deputation, where he is working on National Seismic Programme under Ministry of Petroleum and Natural Gas (MoPNG). Yogaxem has more than 12 years of experience related to seismic acquisition, seismic processing, VSP processing and seismic interpretation at different work centres of ONGC. He has also worked in production sharing contract (PSC) management of producing fields at DGH. In seismic processing, he has specifically worked on pre-stack 3D vintage merging (mega-merge), broadband processing and WAZ processing. He has been a national scholar in physics and has presented/published several papers mainly on seismic acquisition, 3D vintage merging, WAZ processing and rock physics.

Chandra Bhanu Yadava joined ONGC in 1988 as Geophysicist (S), after completing his M. Sc. Tech. (geophysics) from the prestigious Banaras Hindu University, Varanasi. Presently, he is an Executive Director and working as Basin Manager, Cauvery Basin at Chennai. Prior to taking over the charge of the basin, Mr. Yadava was Head of the seismic data processing division at GEOPIC, Dehradun. He has vast experience of over 33 years, primarily in the domain of seismic data acquisition and seismic data processing. Mr. Yadava has worked in seismic data acquisition in different basins of India like Frontier Basin, Upper Assam Shelf, Cachar and Cambay Basin. He ventured into seismic data processing in 1999. Since then, he has distinguished himself with the development of several innovative processing workflows and methodologies, which include in-house processing of multicomponent seismic data, and processing approach for long offset data in tau-p domain for sub-basalt imaging. Under his leadership his team has also developed an innovative workflow for sub-surface fracture characterization which is expected to help in exploration, especially reservoirs associated with basement fractures.

Mr. Yadava has coauthored more than 30 technical papers, presented/published in different national and international conferences. He has also been training geoscientists in seismic data processing for more than 15 years through the ONGC Academy programmes. He has been associated with SPG, India in different capacities since 2010. He led SPG technical committees at the last 4 conferences and served as SPG Vice-President also.