



An integrated approach of fracture characterization using seismic azimuthal anisotropy analysis and diffraction imaging: A case study from Padra field, Cambay Basin, India

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Keywords

Fracture system, Local angle domain (LAD) migration, Diffraction imaging, Seismic azimuthal anisotropy, VVAz & AVAz, AFE, Borehole image logs

Abstract

This work presents fracture characterization at the Deccan trap top of Padra field, Cambay Basin. The applied methodology utilizes high-resolution diffraction imaging and azimuthal anisotropy analysis (VVAz and AVAz) of seismic data in migrated local angle domain (LAD). VTI anisotropic sub-surface modelling and LAD depth migration were performed for in-situ angle domain wavefield decomposition. Fracture induced HTI anisotropic effects were then characterized in LAD reflection angle-azimuth gather by means of travel-time and amplitude variation with azimuth to estimate fracture intensity and orientation. Directivity driven diffracting imaging is then combined with fracture intensity & orientation maps at trap top, which efficiently delineated different fracture sets, their vertical extent and inter-zonal connectivity. The results exhibited promising agreement with existing borehole image logs, adequately justified well production pattern, helped in planning new wells and providing newer insight.

Introduction

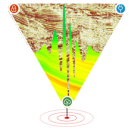
Reservoir fracture characterization is one of the significant hydrocarbon exploration challenges for well planning and production enhancement. In this study, we employed an integrated approach combining diffraction imaging and azimuthal anisotropy analysis of seismic data to characterize fracture sets and their interzonal connectivity. Fractures mainly represent horizontal transverse isotropic (HTI) media and produce azimuthal anisotropy during wide azimuth acquisition (Al-khalifa et al., 1995). Fractures exhibit two primary directions: the "fast direction," parallel to the fracture, and the "slow direction," perpendicular to it. Due to the continuous material, seismic waves travel faster with minimal amplitude decay along the fast

direction. Conversely, due to periodic openings, seismic waves slow down and experience rapid amplitude decay along the slow direction. These phenomenon resulted in azimuth-dependent moveout and amplitude variations (Anat Canning et al., 2009).

In Padra field hydrocarbon production primarily occurs from the fractured trap top. These fractures are interconnected through a transverse fault system. Understanding these fault systems and fracture architecture is crucial for effective hydrocarbon exploitation. To achieve this, we utilized anisotropic VTI local angle domain (LAD) depth migration techniques for subsurface imaging and azimuthal gather generation. LAD migration allowed us to decompose the recorded data into in-situ directional angle-azimuth gathers (DG) and reflection angle-azimuth (RG) gathers (Koren and Ravve, 2011). By employing directivity driven wavefield separation and diffraction imaging on the DG, we successfully delineated the major/minor fault networks within the subsurface. Simultaneously, 3D LAD RG captured the azimuthal anisotropy effect induced by fractures. For fracture characterization, we then performed kinematic velocity vs azimuth (VVAz) analysis to evaluate azimuthal moveout variation, and dynamic amplitude vs azimuth inversion (AVAz) to analyse azimuthal amplitude variation. Both VVAz and AVAz estimated the fracture intensity and orientation at trap top. These intensity maps were then combined with the diffraction image to generate high-resolution fracture model depicting connectivity.

Underlying Geology

The Cambay tertiary basin is an intra cratonic rift between Satpura uplift and Aravalli ranges, extending in N-S alignment. It has been active since Proterozoic up to Late Cretaceous. The rifting along the western continental margin of India along with sea floor



An integrated approach of fracture characterization using seismic azimuthal anisotropy analysis and diffraction imaging: A case study from Padra field, Cambay Basin, India

spreading created the major tectonic blocks with wide spread Deccan volcanism during Late Cretaceous.

Padra field is situated in the North-Eastern part of the Jambusar-Broach tectonic block of South Cambay Basin and lies on the north eastern rising flank of Broach syncline. The weathered and fractured Traps are the unconventional reservoirs where the occurrence of oil has been observed (M. A. Haseeb et al., 2017). The main source rock, Cambay Shale is absent here. Juxtaposition of weathered/fractured Deccan Trap, Olpad Formation and other younger sediments against Cambay Shale in the adjacent western part of Cambay Basin is considered as primary factor responsible for hydrocarbon migration into fractured Deccan Trap in Padra field. The overlying shales within Olpad and tight Trap layers act as the cap rock. The different fault blocks are having different oil habitats and understanding the orientation of these faults and fracture patterns is essential to exploit the hydrocarbons.

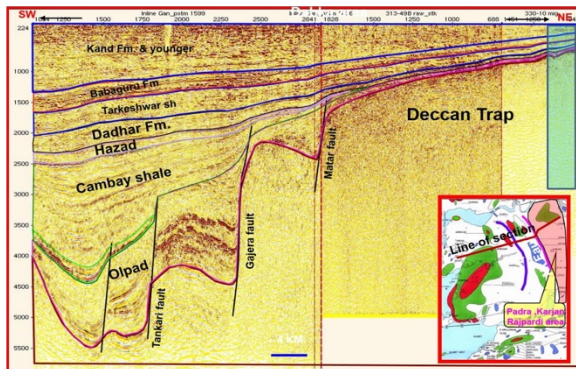


Figure 1: Regional interpreted section describing basin configuration, major formations and location of the Padra field (light green box)

Details of Wide-Azimuth Seismic Acquisition

In order to characterize fracture, ONGC conducted high-density onland 3D wide-azimuth seismic data acquisition (parameters in table 1). An orthogonal shooting pattern with an asymmetric split spread (ASS) and an aspect ratio of 0.7 were carefully designed to maximize the azimuthal illumination of sub-surface. The rose diagram (fig.1) describes the adequacy of required offset and azimuth distribution. The target zone, mainly the top of the trap, is situated

within a two-way time range of 600-900 ms, corresponding to a depth range of 500-800 m covering an extent of 75 sq km full-fold area.

Parameter	Value
Source	Explosive
Bin size	10mX10m
Nominal fold	110
Maximum offset (IL/XL)	2150m /1800m
Receivers Line	20
SLI/RLI	140m/140m
SI/RI	20m/20m
No. of Channels	3080 (20x154)

Table 1: Wide-azimuth (WAZ) seismic acquisition parameters

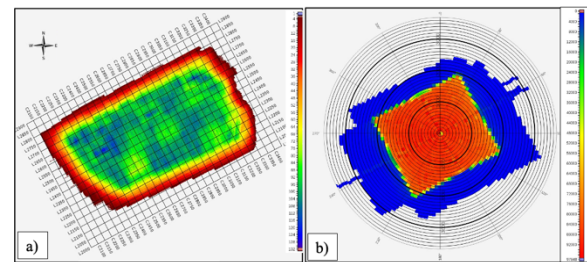


Figure 2: a) Foldmap and b) rose diagram of wide-azimuth (WAZ) seismic survey

Methodology

Seismic azimuthal anisotropy analysis requires reliable sub-surface model (velocity, epsilon & delta) and a robust migration algorithm that can accurately position recorded energy in proper vertical and lateral position. In our study, we have performed well based VTI anisotropic modelling followed by tomographic upgradation of sub-surface models and advanced LAD migration. The LAD approach ensured the direct preservation of azimuthal information in the in-situ angle configuration (Alexander et al., 2017). Generated 3D LAD gather has dense spiral sampling in angle-azimuth space, making it suitable for azimuthal anisotropy analysis. Moreover, we meticulously preserved azimuthal information and amplitude response throughout the pre-migration time processing steps. In this paper, our focus is primarily on after migration diffraction imaging and fracture characterization. The key processes involved in our analysis are as follows:

1. Time series analysis with careful preservation of amplitude, frequency/phase and waveform

An integrated approach of fracture characterization using seismic azimuthal anisotropy analysis and diffraction imaging: A case study from Padra field, Cambay Basin, India

2. Well based VTI anisotropic subsurface modelling and upgradation using 3D full-azimuth reflection grid-tomography
3. VTI LAD Wavefield Decomposition to obtain directional (DG) and reflection (RG) angle-azimuth gather
4. Directivity-driven wavefield separation into specular & diffraction components on directional gather
5. Detection and visualization of azimuthal anisotropy in reflection angle-azimuth gather
6. Kinematic velocity vs. azimuth (VVAz) analysis on RG. VVAz result analysis: fracture intensity ($\Delta\alpha$), effective slow-azimuth (normal to fracture)
7. Gather flattening and preconditioning for dynamic AVAZ inversion
8. AVAZ inversion on flatten and preconditioned RG. AVAZ result analysis: anisotropic gradient and slow-azimuth
9. Generation of fracture intensity and orientation maps
10. Integration of the diffraction with the fracture intensity map followed by validation with high-tech well logs and production data

These processes collectively contributed to the comprehensive characterization of fractures and provided a reliable understanding of the subsurface properties.

Diffraction imaging

Small-scale subsurface features, such as natural fractures, act as scattering sources for seismic waves propagating through the subsurface that often suppressed by conventional processing and standard imaging algorithms (Ribet et al., 2017). However, 3D Directional angle-azimuth gather (DG) represents migrated scattered energy distribution with respect to subsurface dip and dip-azimuth. The direction reflecting maximum energy at a particular image point is known as ‘specular direction’, geologically it’s the true bed dip, and remaining scattered energy at that image point is known as ‘non-specular energy’ (Koren and Ravve, 2011). Fig. 3a represents the total wave field in DG for a single cdp location. The high energy central part is mostly reflection and based on the specular direction reflection energy is separated (fig. 3b) and stacked that resulted specular image

(fig. 3c). After separation of reflection, diffraction got enhanced (fig 3d). These remaining non-specular energy mostly include point diffractor, fault plane energy and corner waves which on stacking provides the discontinuity volume, diffraction image (fig 3e). The inset disk in the fig 3 illustrates the separation of energy into reflection and diffraction components from the total scattered wave field at the trap top. Along with strong reflection, trap top is generating significant amount of diffraction which indicates presence of faults and fractures.

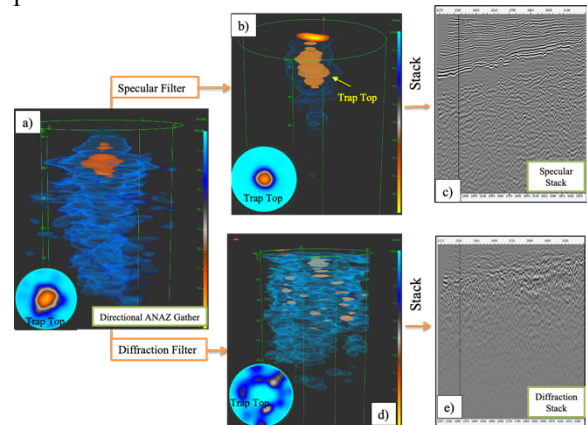


Figure 3: Energy separation from a) directional angle-azimuth gather into b) reflection and d) diffraction to generate c) specular and e) diffraction image

The diffraction image (fig. 4) clearly delineated the subsurface transverse fault network and small scale discontinuities at the trap top level which are hard to detect from reflection volumes. Intra-trapian extension of these fault blocks are also clearly revealed even 100m below trap top.

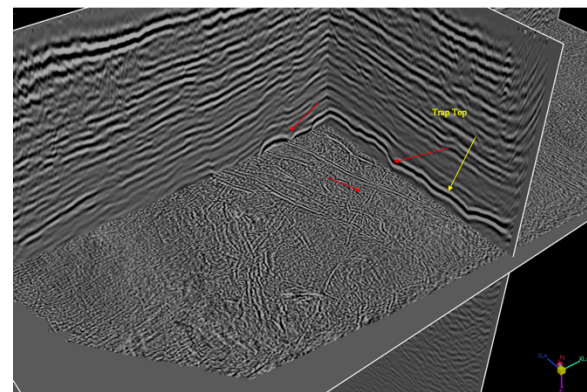


Figure 4: Diffraction on slice delineating different fault blocks and NE-SW trending transverse faults systems

An integrated approach of fracture characterization using seismic azimuthal anisotropy analysis and diffraction imaging: A case study from Padra field, Cambay Basin, India

Since, diffraction image itself is a discontinuity volume, automatic fault extraction (AFE) is performed to further enhance the major/minor fault networks. Different faults blocks and the NE-SW trending transverse faults of interest are identified in “AFE on diffraction” that was not seen using the conventional post stack coherency based attributes (fig. 5). These faults are providing newer insight for understanding migration and accumulation of hydrocarbon within the fractured zone.

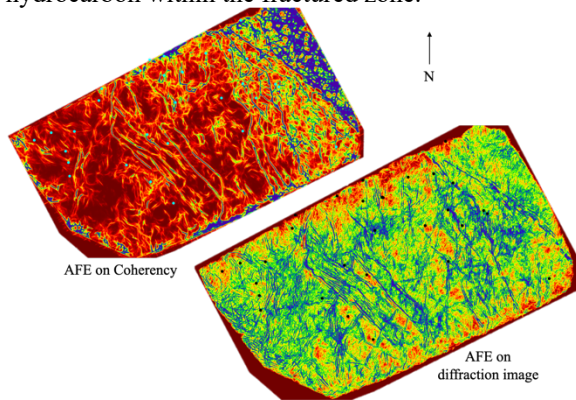


Figure 5: AFE on diffraction delineating NE-SW trending faults as compared to AFE on coherency. The coherency is first computed on specular image

Azimuthal Anisotropy Analysis (VVAz & AVAz)

LAD migrated 3D reflection angle-azimuth gather (RG) on the other hand captures the fracture induced HTI anisotropic effects. The sinusoidal oscillation of fig. 6b is a direct detection of fractured induced anisotropy. This oscillation exhibits periodicity with respect to azimuth (fig 6c), and the magnitude of oscillation increases as the angle/offset increases, since the waves travel a longer path. The variation in travel time manifests as azimuthal depth variation in the RG. The fast (red) and slow (yellow) direction of the fractures are clearly distinguished in RG (fig 6e).

Now the conventional approach for wide-azimuth velocity analysis and gather flattening involves independent velocity analysis for each azimuth sector. Here, we implemented automatic anisotropic residual velocity analysis and azimuthal amplitude analysis using LAD VVAz-AVAz method on 3D RG at a very dense lateral and vertical grid.

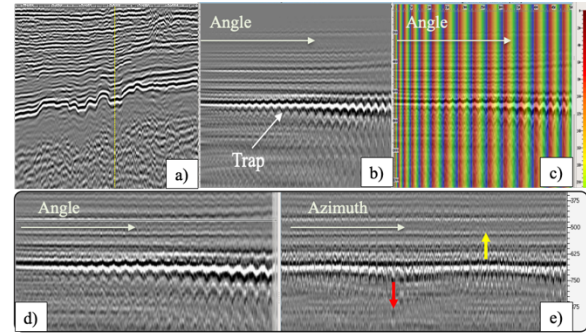


Figure 6: Fracture's HTI anisotropy detection on RG. A) specular image with cdp location, b) Oscillation at trap level on RG, c) periodicity of oscillation with azimuth overlaid, d) zoomed RG in angle increasing order and e) zoomed RG in azimuth increasing order

The 3D RG typically exhibit non-flatness, characterized by two components of residual moveout. One component is a global moveout error that depends on the reflection angle, while the other component describes moveout variations with azimuth. The objective in VVAz was to flatten the gathers and derive the azimuthal velocity field, revealing the fracture architecture. The outputs of VVAz characterized global velocity error (residual V_{nmo} , residual η), effective slow direction (normal to fracture), relative residual velocity (alpha slow) and fracture intensity (delta alpha: velocity difference between fast & slow direction). To visualize the fracture architecture, we generated vector displacement maps at the trap top using intensity and azimuth. The length of each vector is proportional to the intensity, while the direction of the vector represented the fracture azimuth.

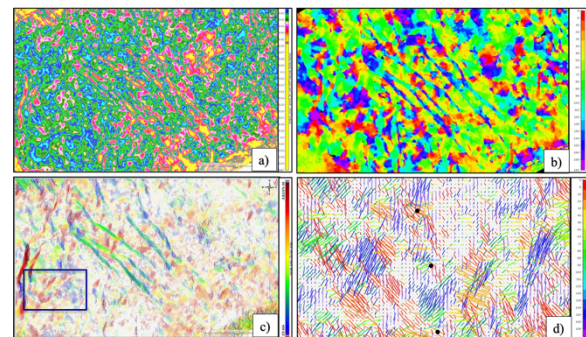
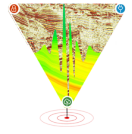


Figure 7: VVAz maps on trap top a) intensity (delta alpha), b) slow azimuth, c) displacement vectors and d) zoomed (box of c) displacement vector with producing wells



An integrated approach of fracture characterization using seismic azimuthal anisotropy analysis and diffraction imaging: A case study from Padra field, Cambay Basin, India

Figure 7a & 7b illustrates the fracture directions and intensity derived from VVAz analysis. The displacement vectors (fig 7c and 7d) highlighted the presence of fractures near the producing wells. Zones with higher relative residual velocity ($\Delta\alpha$) corresponded to densely fractured areas.

The next step involves dynamic AVAz inversion, which analyses the azimuthal variation of amplitude. Before performing AVAz, the azimuthal moveouts are flattened, and preconditioning of the flattened gathers are carried out. The VVAz velocity field is utilized for flattening, while preconditioning includes cross-offset gain equalization, stretch removal, muting, noise suppression, and wavelet-preserving trimming. Fig 8a and 8b demonstrate the impact of flattening and preconditioning on the amplitude responses of an azimuthally anisotropic zone at the trap top. These processes minimize scattering of amplitudes (fig 8d) and accentuate azimuthal amplitude variation (fig 8f).

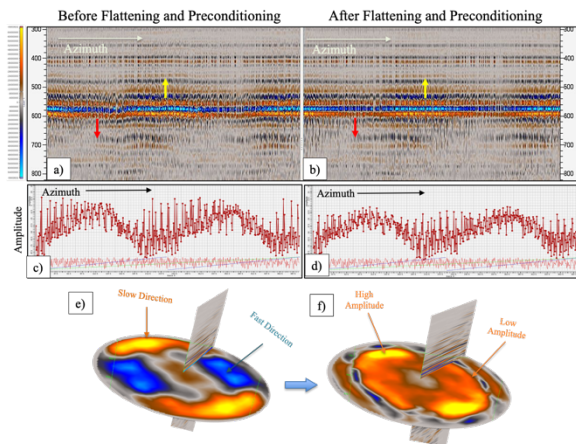


Figure 8: Effect of flattening and preconditioning on RG a) before & b) after, relative amplitude at trap top c) before & d) after and 3D view of amplitude at trap top e) before & f) after

AVAz inversions produced several key outputs, including normal incidence reflectivity, isotropic gradient (gradient with angle), anisotropic gradient (gradient with azimuth), and the slow direction (axis of symmetry). The anisotropic gradient (AG) and azimuth slow are used for generating displacement vector maps to identify fracture sets. Zones with higher AG indicate a higher degree of fracturing.

Figure 9 illustrates that the majority of producing wells are located within high-intensity fracture zones.

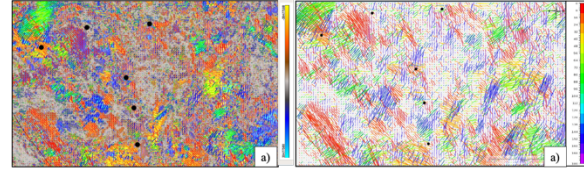


Figure 9: AVAz a) anisotropic gradient and b) displacement vector-maps on trap top with producing wells.

Result Analysis

Fracture maps were derived from both AVAz and VVAz analyses and they have similar outcomes. AVAz, being an amplitude-based layer property, provides enhance reliability and accuracy for assessing anisotropy (Anat Canning et al., 2009). So, we used the AVAz anisotropic gradient as a measure of fracture intensity in subsequent studies. By integrating the discontinuity map extracted from “AFE on diffraction” with the fracture intensity map, we generated a high-resolution fracture model for trap top. To validate the model, we incorporated well production data from the trap top. We categorized the wells as good, moderate (fair), or poor producers. Our analysis revealed that good producers predominantly fell within transversely connected zones having high fracture intensity (fig. 10), while poor producers were mainly located in low-intensity areas.

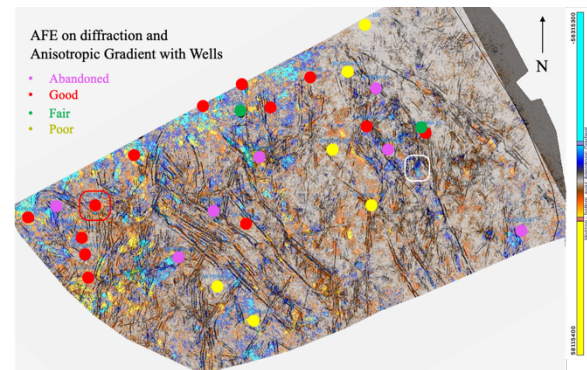


Figure 10: Integrated maps of AFE on diffraction and AVAz anisotropic gradient at trap top with classification of wells

For a good producer (marked by red box in fig. 10) presence of vertical fracture is detected in FMI log (fig 11c). We observed a high anisotropic gradient

An integrated approach of fracture characterization using seismic azimuthal anisotropy analysis and diffraction imaging: A case study from Padra field, Cambay Basin, India

near this well (fig 11b), and it coincides with a transversely connected zone (fig 11a). These findings from our study provide validation for the productive behaviour of the well. Similar validations were conducted for other wells, and the results consistently aligned with observed well production patterns.

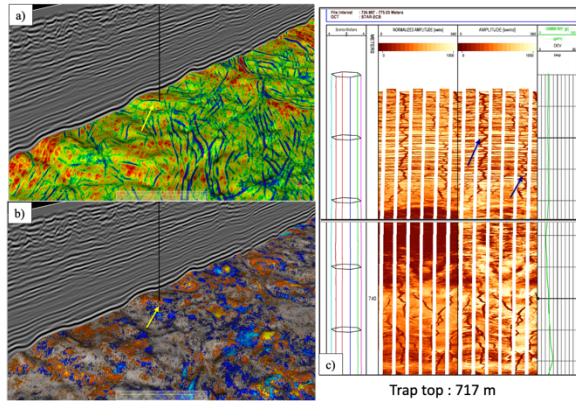


Figure 11: Validation of results: a) connecting faults from AFE on diffraction, b) anisotropic gradient and c) FMI logs

Based on these findings and with the incorporation of other interpretation data an exploratory well location is planned and drilled at the marked white box location of fig. 10. It was a success and the well is commercially producing hydrocarbon from fractured trap top. The fracture orientations identified by our study also corresponded favourably with recorded FMI image logs (Fig. 12), confirming the efficacy of our approach. Our study is currently contributing for the identification of new development locations.

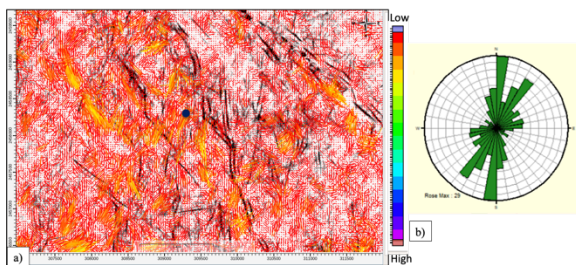


Figure 12: a) Integrated fracture map at trap top showing orientation & intensity (color map) of fractures and b) fracture orientation at trap top from FMI log at well location (black dot)

Conclusion

The successful outcome of the drilled location reaffirmed the efficiency and effectiveness of our

integrated approach. The combination of outputs obtained through our methodology offers new insights in understanding fracture architectures beyond traditional post-stack attribute-based studies. As our approach is entirely seismic-driven and independent of wells, it can be readily implemented in other unexplored basins with similar geological significance. Moreover, our method provides reliable predictions of fracture orientations, enabling better planning of horizontal wells to intersect multiple fracture sets and maximize production from a single well location.

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