



Seismic fracture characterization on a heterogeneous basement with limited azimuth data: A case study from on land Cauvery Basin, India

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Summary

Seismic fracture characterization utilizes the anisotropy induced by the preferential alignment of cracks in the subsurface. The azimuthal variations of traveltimes and amplitude observed in the seismic data allow us to understand the extent and orientation of fractures within the strata. It is often recommended to use high-quality, full azimuth seismic data for this study. However, with vintage seismic datasets, we often fall short of the desired azimuthal coverage. The present study tries to decipher the basement complexities using limited azimuth vintage data. We utilize the local angle domain (LAD) imaging to characterize the fracture intensity and orientation and validate the same with the available downhole observations. The inferences were also tallied with a “reliability” volume generated based on the limitations in the data and the complexity of the area/strata. The results also conform to the existing idea of basement heterogeneities and provide possible explanations for the anisotropic barriers due to closed fractures/infills.

Introduction

Basement fracture plays are developed due to the brittle failures of mainly non-sedimentary rocks, which provides the requisite permeability for fluid flow. Fractures enhance permeability, but if closed, they might prevent the economic viability of the play. Therefore delineating the fracture characteristics would provide an understanding of these unconventional reservoirs. In most proven fields, understanding fracture networks has mainly utilized down-hole instruments, well, and pressure tests for fluid flow. These provide precise information but are localized.

Conventional seismic-derived volumes like coherency cubes and discontinuity analysis are also used to infer the fracture systems. However, they mostly map fractures with length scales above seismic wavelengths.

Seismic characterization mostly targets fractures well below the seismic wavelengths, providing an idea of cluster-oriented fracture sets that would manifest seismic anisotropy due to the preferred orientation. For “proper” fracture characterization, full azimuth seismic data is required. However, very often, with vintage data, we do not see the rich azimuths required for this study.

The studies carried out so far mainly utilize the azimuthal sectoring of the migrated data to analyze the azimuthal variations of traveltimes and amplitude. In this study, we

have used a local domain imaging engine (Koren and Ravve, 2011), which maps acquired energies in time to a 5-dimensional hyper-plane at each depth point, preserving the angle and azimuth from which it “collects” the energy, as well as the in-situ “attitude” of the depth point where it “positions” the energy. This way, the imaging algorithm retains a non-sectored continuous angle azimuth variation of traveltimes and amplitude for analyzing the seismic anisotropy manifested by the preferentially oriented fracture sets.

In this study, we present a workflow for seismic characterization using local angle domain migration on limited azimuth vintage seismic data. The study is further validated with existing down-hole data and other geological insights. It is intended to comprehend the complexity of the basement play and derive meaningful inferences which might help us analyze the past exploration standouts, furthermore, generate and prioritize our future prospects.

Input Data

The input data was a multi-vintage asymmetric split spread data acquired around 2006-07. The parameters of the acquired data are tabulated below.

Field Geometry	Ort. Asymm. SS
No. of receiver lines	12
No. of channels per receiver lines	196
Active channels in a spread	2352 (192x12)
Receiver lines interval	400 m
Shot lines interval	560 m
Group Interval/Shot Interval	40m/80 m
Near offset/Far offset	21 m/5584 m
Fold	6x7
Bin size	20 mx40 m
Record length /Sampling interval	6 Sec. / 2 ms
Source of energy	Dynamite

Challenges

The input data was not acquired considering the future applicability of fracture characterization. This can be well understood from the attributes of the acquisition geometry. The narrow to moderate azimuth distribution (Figure 1) was used for analyzing the azimuthal variations of traveltimes and amplitudes.

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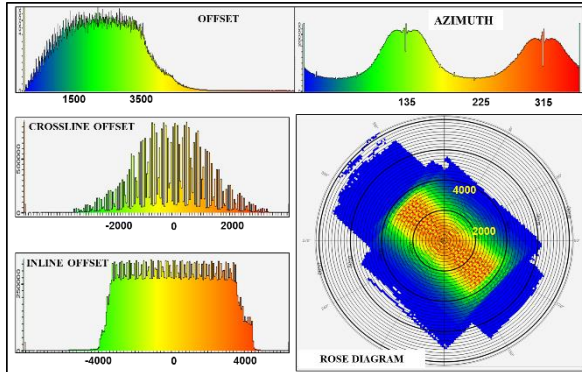


Figure 1. The attributes of the input data acquisition geometry, clearly showing a limited azimuthal coverage.

The area is from the Cauvery Basin on the east-coast of India. The basement topography is highly fluctuating and varies from 1.5 km to 5 km in depth (Figure 2). The deeper part of the basin is envisaged as the source to charge the shallow basement reservoirs (Lal et al., 2009; Bastia and Radhakrishna, 2012.). Thus the analysis in the shallow part of the basement in this area is more important from the exploratory point of view.

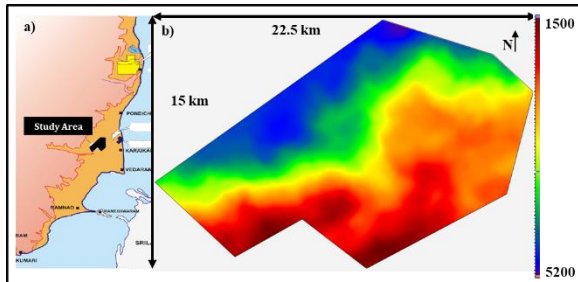


Figure 2. a) Location map and b) Basement topography in the area.

As per the current basement exploration status, almost all the wells have encountered fractures in the logs. The fracture is encountered not just on the interface but percolates deeper within the basement strata. This is well established from the FMI logs and other down-hole measurements. Again only a few wells have shown the presence of oil and gas, and that also from deeper basement sections (~200 m from the top of the basement). Thus there may be chances of some flow barriers owing to these heterogeneities in the fracture distributions along and within the basement.

Methodology

Considering the limitations in the input data and the complexity of the basement, we have designed a workflow to address the challenges in fracture characterization in this area.

Feasibility Test

The available seismic data was vintage, and the azimuthal trace distribution was not rich but moderate. So before migrating the entire area, a portion was selected near a well where the fractures were observed on the logs. The reflection angle gathers at the well location, and the vicinity was checked for the “jitters” in the reflection event at the basement level. The amplitude variations along the angle were also perceived on the event. Once ensured (Figure 2), we went ahead with the project. It may be a good exercise to carry out such feasibility before performing the actual project, especially while working with vintage data.

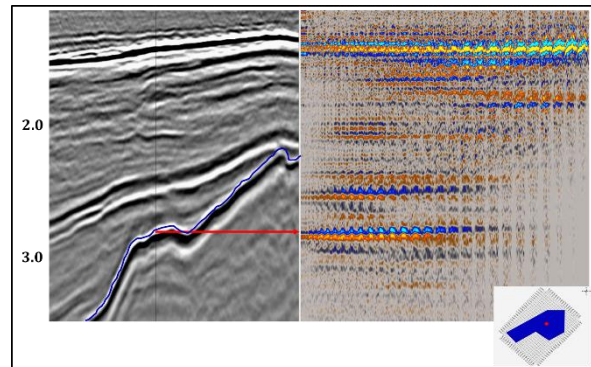


Figure 3. The azimuthal variations of traveltimes and amplitude at the well location which has indicated basement fractures in the well logs.

Pre-processing: Inputs for migration

The present input shot gathers were acquired over three vintages. So, a comprehensive pre-processing strategy was adopted to bring all the data to the same level. Prominent processing steps include surface-consistent amplitude preservation and surface-consistent residual statics applications. These processes ensure no surface or near-surface-related amplitude and traveltim irregularities that would contaminate subsurface amplitude analysis.

The isotropic velocity model was generated from a layer-constrained Dix Inversion of the RMS Velocity. The interval velocity model was updated through reflection tomography to arrive at the starting model for imaging.

Imaging Algorithm

The basic requirement for the desired imaging algorithm for studies related to fracture characterization is azimuthal information preservation. We have used Local Angle Domain (LAD) Full Wavefield separation and migration in this study. The migration maps the recorded surface energies (cmp-sorted time gathers) into a 5-D space preserving the original angle and azimuth (opening angle and azimuth) from which the energy was mapped. Additionally, the other two angles (dip angle and dip azimuth) characterize the attitude of the local subsurface depth point.



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The 5D LAD gathers are difficult to comprehend and analyze intuitively and computationally if treated in a 5D hyper-plane. So, the 5D gathers are summed across the dip angle and azimuth to generate the reflection gathers, along the opening angle and azimuth to generate the directional gathers.

The directional gathers are used for imaging the subsurface by separating the non-specular wavefield from the specular wavefield.

The reflection gathers inherently preserves the information of the acquisition space while mapping into the subsurface opening angles and azimuth. This gather, therefore, contains the reliable angle/azimuthal information of the residual velocity move-outs (RMO) variations manifested as a traveltim difference of the reflected ray pairs (Figure 3).

The imaging algorithm collects the energies and preserves the angle and azimuth information while mapping the same into the subsurface. In the local angle domain, the energies are scaled/ weighed as per the specular direction from which it is arriving. This imaging algorithm, in a way, intrinsically performs a 5D regularization.

Illumination compensation scaling further reduces the effects of complex overburden, acquisition geometry, and the velocity model as a whole. This allows an increased fidelity of depth-mapped amplitude at the subsurface for any amplitude-related studies.

There are certain advantages that LAD imaging provides in comparison to other sectorized ray-based migration schemes. This imaging scheme addresses multi-pathing since the mapping is subsurface to the surface, i.e., different ray pairs may collect energy from the same trace/sample. Moreover, the rays are traced in all azimuths, collecting energy from the available patch acquired in the data. Thus, instead of analyzing in discrete sectors, we have covered the entire sphere in a spiral fashion. All these features ensure that the azimuthal traveltim and amplitude variations at the subsurface level are quite trustworthy for proper characterizations of the embedded fractures.

Workflow for Fracture Characterization

The input for the workflow (Figure) is the Reflection Angle Gathers from the isotropic specular scaled local angle domain imaging. A cross-offset equalization is performed to scale the far angle contribution for a better analysis of both the traveltim and the amplitude variations. The very far angles ($> 50^\circ$) were muted using an angle mute. The stretching effect observed at the far angles is reduced by wavelet processing.

The residual move-outs recorded in the reflection angle gathers at the subsurface are transformed into local 1D anisotropic parameters by a Dix-based inversion approach (Koren and Ravve, 2013). The orientation of the local 1D anisotropic model is, however, azimuthally varying at different spatial locations. The anisotropic parameters

derived above can be directly connected with the fracture intensity and orientation.

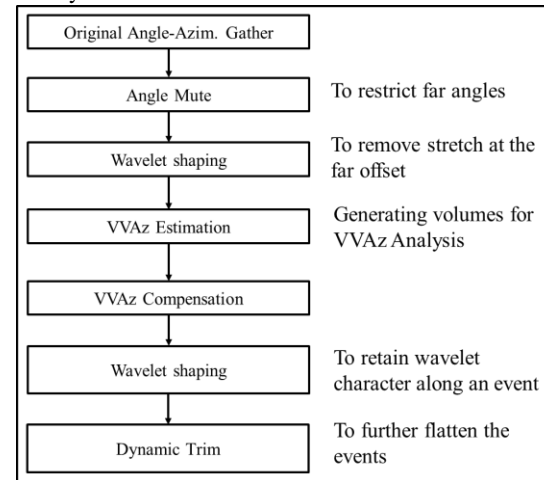


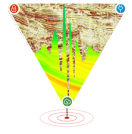
Figure 4. Workflow for Fracture Characterization from Angle Azimuth Reflection Gathers

The azimuthal amplitude analysis can only be performed after the jittery gathers are flattened out. The azimuthal traveltim variations computed above are applied to compensate for the move-outs making the gathers flat. Further, a wavelet preserved trim-statics is applied to correct for suppressing the residual move-out variations. Some amplitude-preserved pre-conditioning is also applied, like Q-compensation and geometrical spreading correction at this stage. A continuity mute was also applied to restrict the spurious amplitude in the estimation, but on testing, it was found that at the basement level, the gathers are quite clean. The relevant volumes for the anisotropic properties are generated after the inversions of azimuthal variations of amplitude. These volumes are then related to the fracture intensity and azimuths. The fracture intensity and orientation estimation obtained from the azimuthal amplitude variations are more reliable than the azimuthal traveltim variations. This is because the amplitude is a layer property, and traveltim is the effective-medium property and, therefore, can be influenced by overburden effects.

Workflow for Fracture Imaging

The scale of heterogeneities plays a crucial role in seismic fracture characterization. The length scale of the fractures, if small (\ll seismic wavelength) would manifest itself as anisotropy showing changes in azimuthal traveltim and amplitude variations. On the other hand, those fractures (~ 0.1 seismic wavelengths) manifested as discontinuities (heterogeneities) may be imaged through diffractions (Liu and Martinez, 2012).

Local angle domain imaging with wavefield separation can be a natural choice for image fractures. The diffractions are



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very weak compared to the reflections' energy, so they need to be separated from the directional gathers (Figure 5). The diffraction stack is generated by muting off the strong specular energies mostly concentrated on a specific angular aperture from the directional gathers and enhancing the weak diffractions. The diffraction stacks have enhanced spatially consistent geological discontinuities.

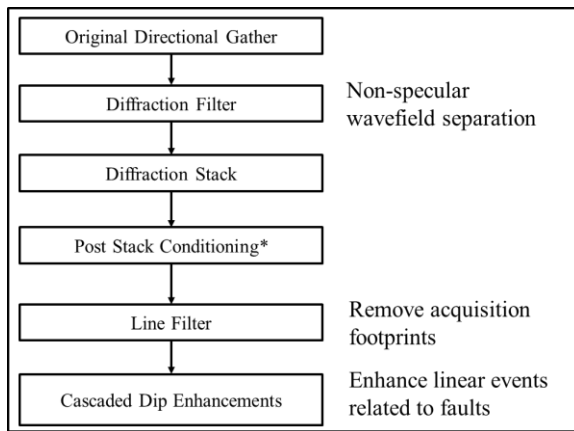


Figure 5. Workflow for Fracture Imaging from Directional Gathers

The diffraction stacks contain non-geological events like acquisition footprint, which are removed. Additionally, some linear dipping events related to faults are enhanced in stages. The images of the discontinuities related to faults and fractures are highly resolved after the filtering. This diffraction-derived fracture image is compared to the more conventional coherency cube generated from the specular stacks. The two images are conformal, rather, we are seeing more details in the diffraction volumes.

Results and Discussions

We have already observed the traveltime and amplitude variations at the well locations (Figure 3), which is an obvious indicator of the presence of fractures translated into seismic anisotropy.

The main aspect of fracture characterization is the understanding the intensity of subsurface fractures and their azimuth. The fracture characterization study provides us with similar deliverables using local angle domain imaging. The idea is to develop conformity between the volumes derived from different approaches. The fracture intensity derived from the dynamic changes (Amplitude Variation with Azimuth: AVAz) should be relatable to the traveltime-derived fracture intensity (Velocity Variation with Azimuth: VVAz).

However, the traveltime variations are effective properties, that is, the overburden anisotropy would influence the traveltime variations at the target interface (here the basement). The amplitude variations across the angle-

azimuth is the interface property and therefore would not be influenced by the overburden. Hence AVAz is a more reliable estimate of the fracture intensity and azimuth.

The problem with moderate amplitude is another issue. The availability of full azimuth coverage within a 2000 m radius (Figure 1) restricts the available angles required to construct the anisotropic gradient, G^{ani} from Ruger's Equation (Ruger, 2001). Therefore the estimate of the fracture intensity obtained from AVAz should be validated with that obtained from the VVAz and indicate similar variations irrespective of the scales which is what we see in Figure 6. Both the maps show higher fracture intensity values at the same places.

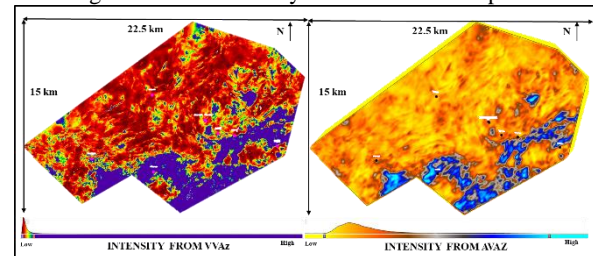


Figure 6. Fracture intensity calculated from VVAz and AVAz extracted on the basement horizon.

The fracture azimuths derived from traveltime changes should be similar to the fracture azimuths derived from amplitude variations with azimuth. The fracture azimuths derived from the AVAz is a more reliable estimate and may be compared with the well derived estimate for validation. Two wells from this area (Figure 7) shows agreement with the azimuth derived from AVAz. The FMI logs also indicates fractures with varying dips detected within the well column which are in agreement with the study.

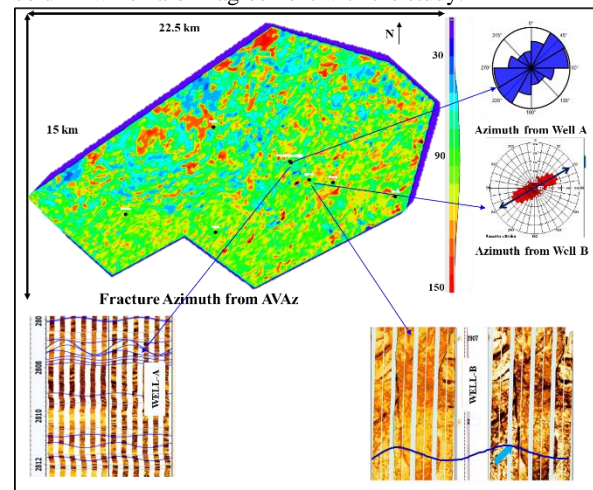


Figure 7. The fracture azimuths obtained from AVAz, extracted at the basement horizon, shows similar azimuth values at the well locations A and B as derived from the FMI logs. The FMI logs (shown below) also shows fractures with varying dip within the well column.

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The estimates of the fracture properties are dependent on various factors, like, data quality, available azimuth and angles, illumination, sampling of the angle-azimuthal plane, simplicity of the fracture model and background model, acquisition footprints, migration amplitude recovery, etc. These factors influence the estimates to a large estimate so it would intuitive to consider the same while interpreting the data. This is why a “reliability” volume is designed which takes into account all the above parameters in a statistical sense. The zones with low reliability should therefore not be considered or may be corroborated strongly with other available data (Figure 8). It is evident from the figure that the deeper part of the basement shows a very low reliability due to unavailability of rich angle azimuth in the input data. So the intensity volume would not show a reliable estimate of the fracture intensity on the deeper part of the basement.

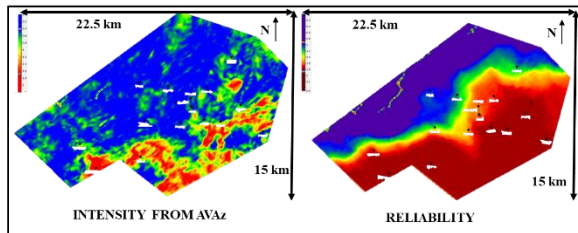


Figure 8. Fracture Intensity and Fracture Reliability derived from AVAz.

Basement heterogeneities and Infill

Most of the studies carried out so far in the basement fracture characterization is analyzed based on properties extracted along the top of the basement. But in many instances we might see weathering of basement due to long hiatus followed by periods of deposition. This phenomenon induce strong heterogeneities within the basement and properties extraction at the top might not give a reliable estimation of actual extent of fracture due to possibilities of infill within the fractures. These would reduce the fracture intensity at the top of the basement. The presence of fracture intensity should be investigated at deeper levels within the basement and integrated with studies from well-logs or other available information.

One possible indication may be that infill fractures may get imaged if the length scale is above the heterogeneity limit but would register a low intensity on characterization as the cracks have been filled. However, this is only an intuitive conjecture, which has to be inferred after consideration of other datasets.

Another way of investigating basement heterogeneities would be to observe the intensity along arbitrary traverses along wells. Figure 9 is an arbitrary traverse through Wells A, B, and C. We readily see a lower fracture intensity at the basement top than within the basement. Additionally, we see

a zone of lower fracture intensity indicated by the arrow between Well A and B, whereas the energy associated with discontinuities (shown in the “filtered and enhanced” diffraction stacks shows reasonably higher within the same zone. One of the explanations can be the possibility of infill cracks.

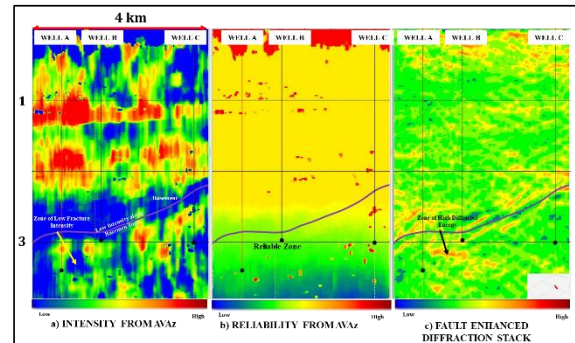


Figure 9. The sectional display of an arbitrary traverse showing a) Fracture Intensity, b) Reliability derived from AVAz and c) the filtered Diffraction Stack highlighting energies related to discontinuities.

However, the aspect of contamination of AVAz analysis due to the leakages of diffraction energy in the reflection gathers should also be considered, and therefore, the inferences should be weighted with other available datasets before drawing any conclusion. Nevertheless, the seismic characterization does indicate lot many nuances related to the basement fractures, which can possibly help derive some meaningful exploration insights.

Conclusions

The study was carried out on an inherently complicated fractured basement with very abrupt variations in the topography. The seismic data chosen for this particular study was not an ideal one due to the unavailability of adequate angle azimuth. However, in the shallower part of the basement, which is again important from an exploration point-of-view, we found our study reliable and meaningful. The seismic signatures of the presence of fractures were validated articulately at the well locations. Also, with this study, we found out that the fracture intensity within the basement is more compared to that at the top, which was also observed in the well logs. Additionally, through the sectional analysis, we could identify some “anisotropic barriers,” which may be inferred as some closures due to infill.

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