Interval velocity modelling and anisotropic full angle azimuth wavefield decomposition for enhanced seismic imaging in depth domain – A case study from KG Basin, India

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Keywords

Local angle domain (LAD) imaging, constraint velocity inversion (CVI), residual moveouts (RMO), full angle azimuth reflection grid tomography, vertical transverse isotropy (VTI)

Abstract

The improvement in seismic imaging depends on many factors like signal-to-noise (S/N) ratio, complexity of the subsurface geology, quality of velocity analysis, migration algorithm, and domain of imaging such as time or depth etc. In this paper, preparation of better interval velocity and full angle azimuth wavefield decomposition or local angle domain depth imaging is explained in detail. The methodology was applied to an onland seismic data set from Krishna Godavari (KG) Basin and encouraging results were obtained in terms of enhanced resolution, better reflection continuity showing subtle stratigraphic features. The processed outputs are expected to help in prospect evaluation, basin modelling, and reservoir characterization which will help in identifying hydrocarbon prospects and formulating exploration strategies.

Introduction

The study area Malleswaram–Bantumilli of Krishna Godavari (KG) basin falls in the onland part of west Godavari district of Andhra Pradesh, India (Figure 1). This area is geologically complex comprising steep structures, and the objective of the present study is to provide better imaging of the broad interval of interest, which extends from the Raghavapuram formation to the basement, as explained in the next section. During 2007-08, 3D seismic data (totaling up to 1600 km2) were acquired in six different investigation campaigns in the study area. The acquisition parameters included a maximum offset of 5,500 m, 2 ms sample interval, 6 s record length, and a bin size of 20 × 20 m. The seismic data comprised moderate azimuths as shown in Figure 2, where the azimuth in degrees is shown along the x- axis and the number of traces along the y-axis. These data were processed with Kirchhoff prestack time migration (KPSTM) individually, but they were not able to fulfil the interpreter's needs in terms of reflector continuity and structural interpretation. Consequently, these data were reprocessed and prestack depth migration (PSDM) was carried out using full azimuth wavefield decomposition or the Local Angle Domain (LAD) imaging.

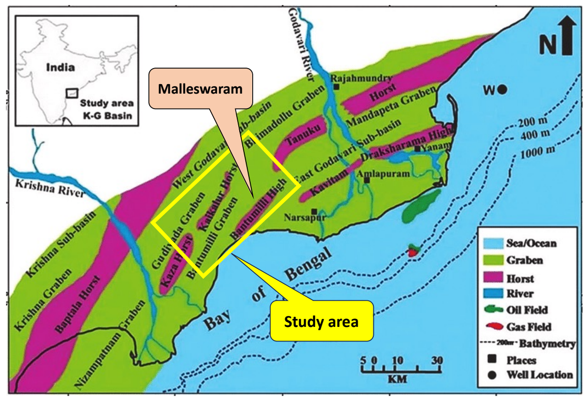

Figure 1: Location map of KG Basin and the study area. (After Das and Chatterjee, 2016)

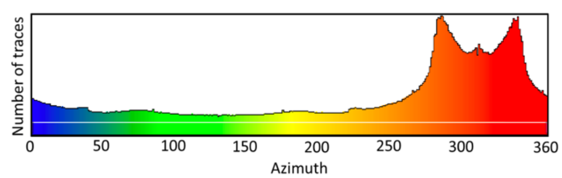

Figure 2: Azimuth histogram of the study area.

Signal processing is done as per standard operating procedures to increase signal to noise ratio. In this paper, the proper usage of azimuth and angle in the interval velocity modelling using Local Angle Domain (LAD) full angle azimuth depth migrated gathers is discussed. Initial interval velocity volume is generated from RMS velocity through constrained velocity inversion (CVI). This interval velocity model is then updated iteratively using full angle azimuth grid tomography for improved interval velocity. Local angle domain (LAD) imaging is then performed on the full volume with updated interval velocity. In this type of depth imaging, the migrated

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energy is decomposed to reflection and diffraction energy there by generation of specular stack and diffraction stack respectively. Newly processed data shows enhanced frequency and improved continuity of the deeper reflector with better fault delineation.

Geology of the study area

Krishna Godavari Basin is a peri-cratonic passive margin basin on the east coast of India. Tectonically, the Basin can be divided into three sub basins, namely the Krishna, West Godavari, and East Godavari Sub Basins, which are separated by the Bapatla and Tanuku Horsts respectively. The West Godavari Subbasin is further separated by Kaza – Kaikalur Horst into the Bantumilli Graben and Gudivada Graben. Bantumilli Graben is flanked in the southeast by Bantumilli High and in the northwest by Kaza-Kaikalur Horst. The study area Malleswaram–Bantumilli falls along the rising flanks of Bantumilli High and parts of Bantumilli graben which is a proven petroliferous area. Bantumilli graben is filled with coarser to finer clastic rocks of fluvial to marginal marine environment of Nandigama/Kanukollu formation (Late Jurassic to early Cretaceous) overlying Achaean basement. The Kanukollu sandstone (rift fill sediments) is the oldest sedimentary rock in the area, which is unconformably underlain by weathered metamorphic basement. The sedimentation in the area is more or less continuous up to Paleocene. With further breaking up of continents, marine transgression had taken place by the deposition of Aptian- Albian sediments of High Gamma High Resistivity (HG-HR) shale unit of Raghavapuram formation. This HG-HR sequence of Lower Cretaceous (Aptian-Albian) age is bounded by regional unconformities at top and bottom. Above HG-HR, the upper Raghavapuram shale is a thick, dominantly argillaceous sequence deposited during rift to drift transition that caused a south-easterly tilt of the basin leading to widespread marine transgression during Cretaceous. Following this, continental and transitional sands of Tirupati Formation were deposited in a regressive depositional system. The Paleocene times saw a vast volcanic activity that led to the deposition of the Deccan Traps or the Razole formation, which is overlaid by thick Tertiary sequences. The generalized stratigraphy of the KG Basin is shown in Figure 3.

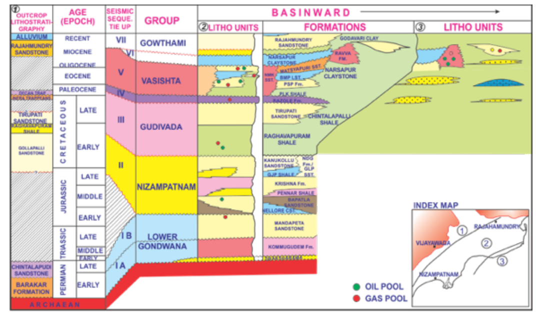

Figure 3: Generalized stratigraphy of Krishna Godavari Basin. (Adapted from Gupta, 2006)

Methodology

The processing workflow comprised the application of steps such as geometry merging, noise removal, signal enhancement, deconvolution, velocity analysis, regularization, and residual statics application etc., to the seismic data. Meticulous quality checks were performed after each processing step. As stated earlier, this paper describes the depth interval velocity modelling through full azimuth wavefield decomposition LAD imaging. The processing workflow for anisotropic (VTI) LAD imaging is shown in Figure 4.

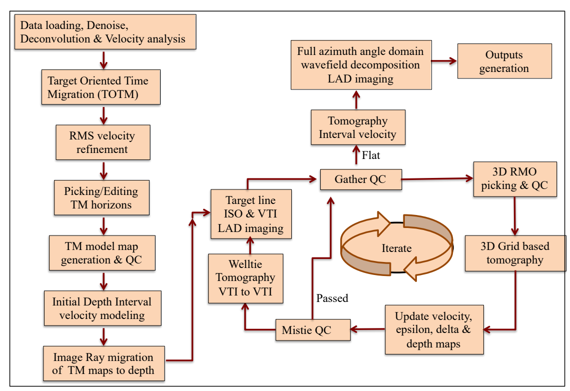

Figure 4: Processing workflow for anisotropic (VTI) Local Angle Domain (LAD) imaging.

LAD imaging is a depth migration algorithm that simultaneously uses the full recorded wave field within a controlled aperture to generate amplitude preserved, multi-dimensional, subsurface angle gathers. This entails bottom-up ray tracing which handles the multi-pathing unlike conventional ray-based imaging methods. LAD imaging uses a point-diffractor operator to shoot rays from subsurface grid points to the surface, forming an accurate system for

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mapping the recorded surface seismic data into the subsurface Local Angle Domain (LAD) for each image point. This procedure ensures maximum illumination of the image points from all subsurface directions and surface source-receiver locations; all arrivals are taken into account and amplitudes and phases are preserved.

Interval velocity modelling in depth and full azimuth wavefield decomposition LAD imaging:

The constrained velocity inversion (CVI) (Koren and Ravve, 2006) technique is used for generation of initial depth interval velocity volume from RMS seismic velocity volume. The crucial parameters like data, trend, and damper in CVI technique gives more confidence in the velocity unlike Dix inversion in the preparation of interval velocity. CVI also utilizes the geological time migrated domain horizons information to generate the interval velocity.

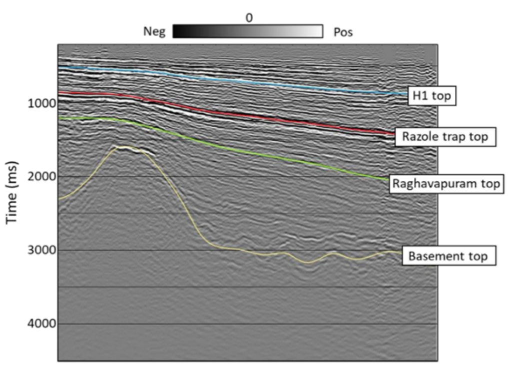

Figure 5: Prominent horizons displayed on an inline section from KPSTM vintage data.

Rajahmundry sandstone (Horizon1 or H1) top, Razole trap top, Raghavapuram top and Basement top are the prominent horizons sequence in the study area and are shown displayed on an inline section extracted from KPSTM vintage data in Figure 5. The high velocity Razole trap is also one of the challenges in depth interval velocity modelling. The initial interval velocity is further updated with the help of 3D reflection angle azimuth grid tomography that utilizes angle and azimuth gathers generated through LAD imaging.

Full azimuth wavefield decomposition Local Angle Domain (LAD) imaging uses the complete recorded wavefield to provide a highly accurate and detailed description of the subsurface (Ravve, and Koren, 2011). It also handles multi arrivals and provides rich information on the subsurface image points. The surface recorded seismic data are downward propagated using an advanced ray-based solution to the subsurface and binned into high resolution, multi-dimensional tables at each sub surface grid point. Each bin is characterized by the spatial location coordinates of a given subsurface image point and by a given central ray pair, arriving to the image point from a given source and scattered up to a given receiver forming local four- dimensional angle system, referred to as LAD. Two of four LAD angles indicate the apparent directivity (dip $\nu 1$ and azimuth $\nu 2$) of the given ray pair, while the other two indicate opening angle $\gamma 1$ and azimuth $\gamma 2$ between the ray pair. Hence the output consists of 5D LAD image gathers. The vertical axis of these image gathers indicates the fine grid depth locations, and the other four axes indicates directivity (directional dip and azimuth) and reflectivity (opening angle and azimuth) LAD angles. The outputs of LAD imaging are reflection angle azimuth gathers and directional angle azimuth gathers. Specular and diffraction stacks are generated from directional angle azimuth gathers with the filtration of specular and non-specular components. Specular stack comprises of specular energy which is mainly used to enhance subsurface image structure continuity while diffraction stack comprises of non-specular (diffraction) components that are used to enhance discontinuous objects such as faults, edges, and fine fracture systems. Figure 6 shows in detail the pictorial explanation of full azimuth wavefield decomposition Local Angle Domain imaging.

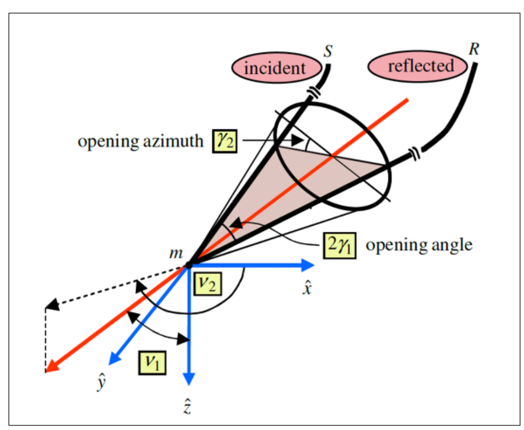

Figure 6: Pictorial explanation of LAD imaging (Duan et al., 2017).

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LAD imaging is performed on target lines (every 20 inlines in the study area) with the initial interval velocity volume. The output depth migrated gathers are reflection angle azimuth gathers and directional angle azimuth gathers. Specular stack and diffraction stacks are generated with the application of specular filter and diffraction filters respectively to direction angle azimuth gathers. The tomographic principle is used to convert depth errors in migrated CRP gathers to time errors along a CRP ray pair and thus enable use of conventional travel-time tomography (Kosloff et al., 1996). Reflection angle azimuth gathers are utilized in full angle azimuth reflection 3D grid tomography for interval velocity updation. This process is iterative, and in each iteration, both the reflection and direction angle azimuth gathers play a key role. The LAD imaging makes tomography extremely efficient, preserving high consistency between the imaging and tomographic update solutions. The substantial increase in information about the subsurface improves accuracy and reduces uncertainty, especially important when determining anisotropy model parameters. The H1 top, the Razole trap top, the Raghavapuram top and the Basement top were considered in the tomography. Seismic structural attributes like dip, azimuth, and continuity volumes are generated with directional angle azimuth gathers. The continuity volume is obtained by computing the normalized semblance and then comparing the similarity of dip and azimuth angles between the seismic traces within the computational window. Pencil database contains information about surface ID, depth, dip, azimuth, and continuity, as well as additional attributes such as velocity, residual moveouts and misties. In each iteration of tomography, horizons are updated with updated velocity. The 3D reflection angle azimuth grid tomography workflow is shown in Figure 7.

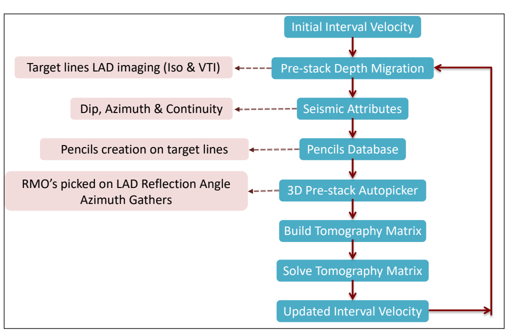

Figure 7: 3D angle azimuth reflection grid tomography workflow

3D RMOs (residual moveouts) picked on reflection angle azimuth gathers are utilized in tomography. In this study area, a total five iterations of full angle azimuth reflection grid tomography is performed at the cell dimensions of 400m x 400m x 300m. RMOs picked on reflection angle azimuth gather (red dot indicates the location of gather whereas green dots indicate RMO picks) are shown in Figure 8.

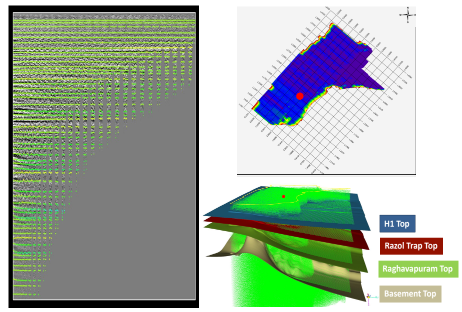

Figure 8: RMOs picked on LAD reflection angle azimuth gather (depth).

A total of 72 wells were considered for anisotropy (VTI) LAD imaging which are evenly distributed in the study area. Initially isotropic LAD imaging was performed in target lines for interval velocity update through 3D reflection grid tomography. Four prominent geological tops were matched with the well marker depths with the help of well-tie tomography. The basement markers in the wells match with the highly undulating basement top (after well-tie) as shown in Figure 9.

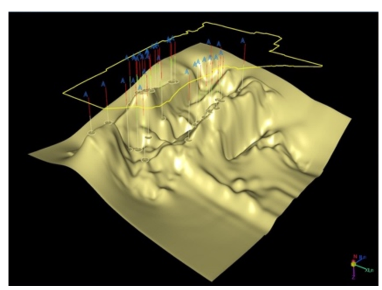

Figure 9: Basement marker of wells matches with basement top (after well-tie tomography).

After well-tie tomography, anisotropic (VTI) LAD imaging on target lines (every 20 inlines) was performed in the study area. Five iterations of full angle azimuth 3D reflection grid tomography were performed. In each iteration, anisotropic (VTI) LAD imaging on target lines are performed. After 5th iteration, the depth migrated gathers were flat. The updated anisotropy parameters (epsilon, delta) and depth interval velocities are the results of full angle azimuth 3D reflection grid tomography. Anisotropic (VTI) LAD imaging is performed on the full volume (1600 km^2) with the updated epsilon, delta, and interval velocity.

Structural consistency of geological sequences with final interval velocity has been seen. Figure 10a shows the study area comprises of 72 wells (shown as black dots) distributed evenly in the area. One well named well-A is shown in red circle. The initial interval velocity overlaid with P-velocity sonic log of well-A is shown in Figure 10b. Final angle - azimuth based tomography interval velocity overlaid with P-velocity sonic log of well-A is shown in Figure 10c. The high velocity kick shown in P-velocity sonic log at approximately 1500m is due to Razol trap. In Figure 10c, we can see that the final angle - azimuth based tomography interval velocity derived at well-A almost matches with the P-velocity sonic log. Similar type of match was seen in almost all wells in the area, which indicates the interval velocity generated with full azimuth reflection grid tomography is accurate.

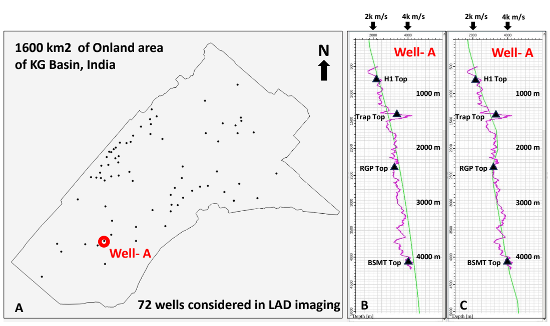

Figure 10: Interval velocity overlaid on sonic log.

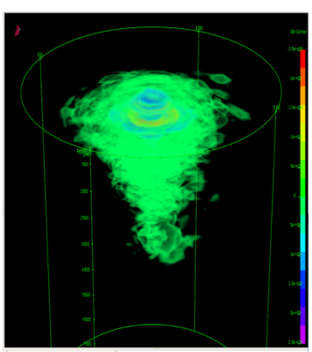

Figure 11: Directional angle azimuth gather at well-A location is shown in 3D gather viewer.

Figure 11 shows the 3D visualisation of a directional angle azimuth gather at location well-A generated by anisotropic (VTI) LAD imaging. In this figure, the directional angle azimuth gather is sorted in a spiral manner with increasing dip angle and periodic azimuth. The generated velocity was used for carrying out the pre-stack depth migration on the seismic data.

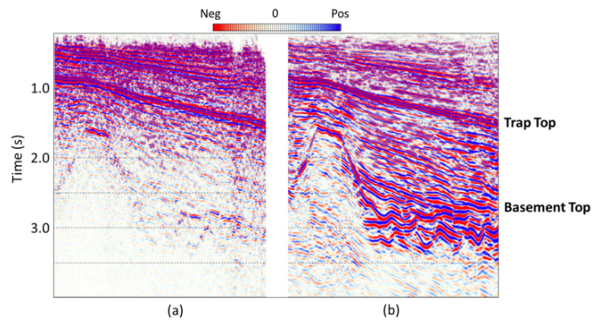

Figure 12: An inline section comparison from (a) vintage data (KPSTM), and (b) the present study. The depth data were scaled to time for both displays.

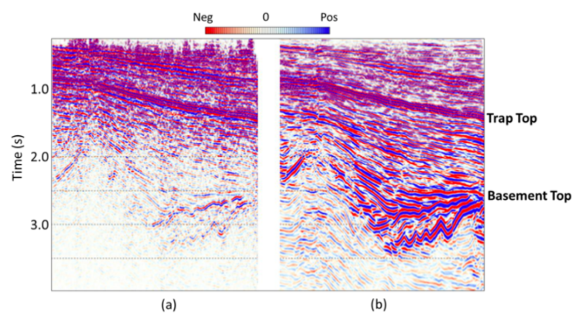

Figure 13: Another inline section comparison from (a) vintage data (KPSTM), and (b) the present study. The depth data were scaled to time for both displays.

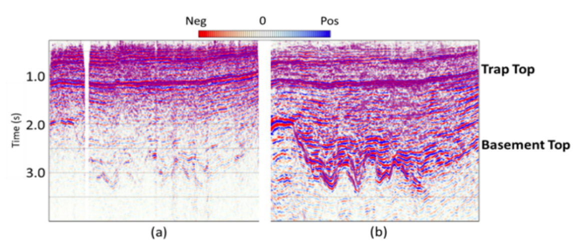

Figure 14: A crossline section comparison from (a) vintage data (KPSTM), and (b) the present study. The depth data were scaled to time for both displays.

In Figures 12 and 13 we show a comparison of two separate inlines drawn from the KPSTM vintage data

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and the PSDM data produced with LAD imaging. An equivalent comparison of a crossline drawn from the two volumes is shown in Figure 14. The depth data were scaled back to time for a fair comparison.

Incredible improvement is seen on the depth data with LAD imaging. Apart from the fact that the vintage data were time migrated and the reprocessed data are depth migrated, the full azimuth wavefield decomposition local angle domain depth imaging used in the latter has played a key role in the significant improvement noticed. Figure 15 shows Anisotropic (VTI) LAD imaging final depth outputs both specular stack and diffraction stack in chair- cut view. Diffraction stack details about the subsurface faults and fracture systems whereas specular stack gives the enhanced reflection continuity and better subsurface imaging. Red arrows shows the detail fault networks present in the sub surface at 4500m depth. The outputs of the recent study show enhanced frequency content and reflection continuity with better fault and fracture delineation throughout the volume.

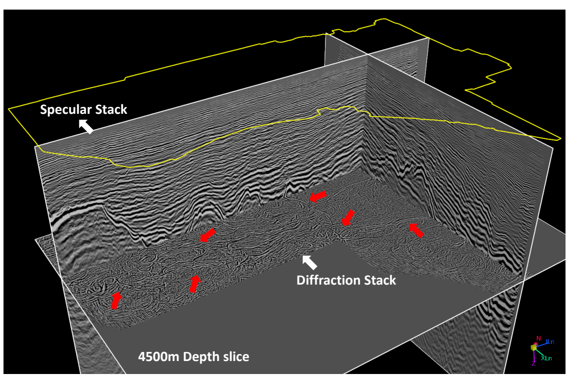

Figure 15: Depth stacks from LAD imaging exhibiting significantly more detail as seen on the vertical and horizontal displays.

Conclusions

The study demonstrates seismic depth interval velocity modelling and anisotropic (VTI) LAD imaging applied on a KG Basin dataset with complicated basement features involving discontinuities like faults and fractures. The final depth outputs were structurally consistent and have minimized the depth uncertainties between the well markers and geological horizons. The adapted subsurface imaging technique has significantly enhanced the geological configuration in the window from Razole trap to Basement and especially the deeper Basement trough fills of Mesozoics. The generated outputs have shown substantial improvement in terms of reflector continuity, discontinuity delineation and subtle stratigraphic features as compared to the earlier vintage data. The processed outputs can help in formulating the exploration strategies and will help in identifying hydrocarbon prospects in the study area.

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