

Minimizing structural uncertainties below the complex configurations of sub-sea canyons using anisotropic depth imaging of ultra-deep-water Cauvery Basin, India

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Keywords

Ultra-deep-water exploration, sub-sea canyon & buried channels, time-depth structural anomaly, VTI anisotropy, LAD techniques

Abstract

Improper estimation of depth interval velocity may give rise to several imaging related issues like structural-pull ups/sags, improper positioning and poor focusing of reflectors. These imaging issues accentuated in case of ultra-deep-water areas because of fast varying bathymetry, presence of deep canyons and buried channels. If the above complexities are not encountered properly, the inaccurate depth interval velocity model may result in poor sub-surface imaging and can generate pseudo- structural anomalies which can mislead in interpretation and in turn the exploration drive in the area.

This study presents the implementation of an advanced strategy to build geologically viable depth-interval velocity & anisotropic (epsilon & delta) modelling for an ultra-deep-water block of Cauvery Basin exhibiting highly complex bathymetry. We have utilized well-based VTI anisotropic estimation and tomographic upgradation followed by local angle domain wavefield decomposition & imaging. The study successfully resolved the structural anomalies, and resulted in conspicuous improvement over the legacy dataset in terms of sub-surface imaging and better amplitude preservation for inversion studies.

Introduction

In the backdrop of a rapidly changing energy landscape and growing domestic energy demand, sustaining production from mature fields is becoming increasingly challenging. This necessitates venturing into geologically and technologically demanding frontier plays, such as ultra-deep-water exploration. In our study area, the ultra-deep-water block Cauvery Basin, presence of gas reservoirs has been explored.

Hydrocarbons have been discovered in the Syn-rift and Cretaceous formations in the eastern part of the area. The drilled reservoir is characterized by a high impedance gas sand of AVO class-1 [ongc internal reports]. However, there are significant imaging obstacles that need to be overcome in this region, including structural anomalies, the accurate imaging of the basement configuration, the deeper Syn-rift and Cretaceous sequences, and the preservation of amplitude responses for hydrocarbon characterization through inversion studies. The study area exhibits steep and highly complex bathymetry, ranging from 300m to 2800m of water depth. The complexity additionally pronounced by deep channel incisions (fig 1). These water-filled canyons introduce travel time variations that result in structural distortions of the underlying reflectors in earlier processed time-migrated images. Additionally, the shallower sedimentary columns are heavily influenced by the presence of low velocity buried channels. The combination of these low-velocity buried channels and complex bathymetry leads to the creation of pseudo structures and spurious fault planes in the earlier processed time-migrated images (fig 2).

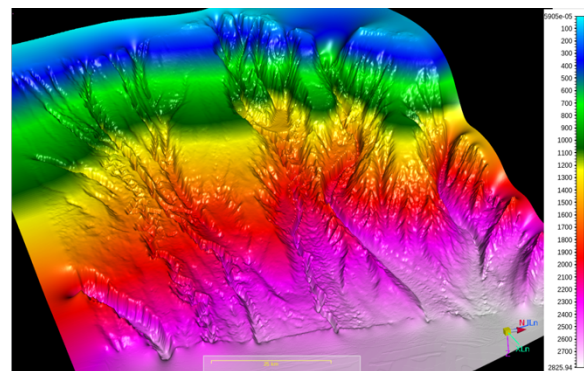


Figure 1: Bathymetry map showing canyon and complex drainage pattern

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In this study, to address these challenges and to achieve high-quality subsurface imaging for reservoir delineation, a comprehensive depth imaging strategy has been implemented. This strategy incorporates high-fidelity water bottom-controlled depth interval velocity modelling, well-based anisotropic parameter estimation followed by tomographic upgradation, local angle domain multi-dimensional wavefield decomposition, in-situ reflection angle gathers generation and diffraction imaging. Through the application of these advanced methods, the study has successfully built geologically viable sub-surface models, resolved the pseudo structures, improved the continuity of subsurface reflectors, preserved AVO responses, and also delineated major-minor fault networks. Notably, a significant enhancement has been observed compared to the legacy dataset.

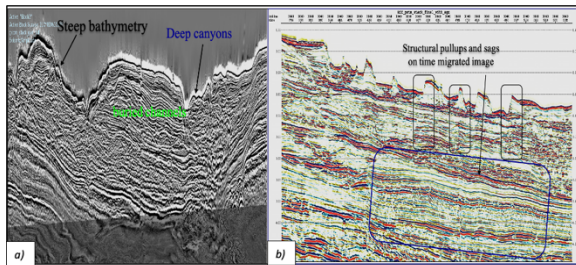


Figure 2: a) Steep bathymetry & deep canyon b) Structural pull-ups and sags on vintage time migrated image

Geology of the area

Cauvery basin is the largest among all the sedimentary basins on the east of India, came into existence during late Jurassic- early Cretaceous period due to rift-drift phenomena which gave rise to NE-SW trending host graven morphology in the form of broader depressions separated by narrow ridges. The basin is divided into five sub-basins and four ridges which are major tectonic elements of the basin. The basin is bounded by faults and was generally sloping towards east (towards the sea) during early rift phase as manifested in thickness behavior of units deposited during this phase. Faulting was contemporaneous with deposition, rapid in initial phase and with diminished intensity towards the end of cretaceous period. The maximum basin fill is of the order of 6.0 km. in the northern part and 4.0 to 5.0 km. in the southern part. The oldest sediments of

the Jurassic - early Cretaceous age were deposited as continental facies while late cretaceous to Paleocene sediments mostly represented marine deposition and were deposited as thick wedge of sediments over early Cretaceous sediments which provided uniform sloping surface. Thick cretaceous sediments have been found in all the depressions while these sediments are thin on ridges. Carbonate development at Miocene - Oligocene age is very limited in the basin and is present in few depressions only.

Our study area has numerous basement-related horst and tilted fault blocks which provide abundant trapping mechanisms within the rift & syn-rift mega sequence. Initially during rift phase, block faulting occurred and which were subsequently rotated during the spreading/wrenching phase. These rotated fault blocks are the dominant play type of fault associated or structural closures. Hydrocarbons are discovered in these syn-rift and Cretaceous play in the eastern part of the area.

Input Data Details

The 3D seismic data in ultra-deep-water block having steep bathymetry was acquired in two phases, one in 2005 and another in 2009. The acquisition parameters were designed ensuring optimized illumination at target levels. Regularized gathers were taken as the input for carrying out this study. The input data was free from the water-bottom multiples. Fig.3 shows the data acquisition parameters:

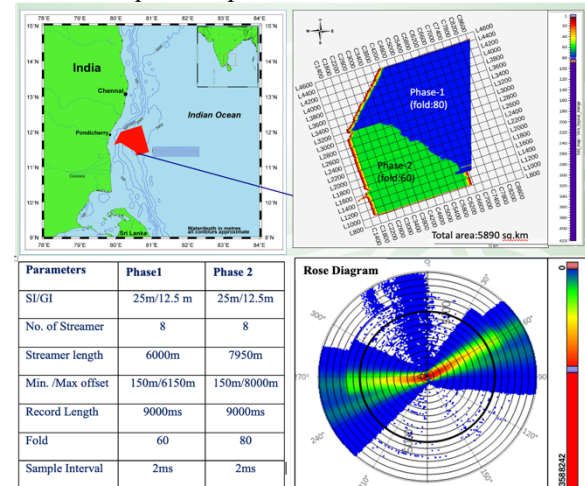


Figure 3: Location map & survey details of study area, Cauvery Offshore Basin

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Methodology

In order to perform precise anisotropic depth imaging, the primary focus is to have a reliable estimation of the depth interval velocity model, as well as anisotropic parameters (epsilon & delta). These sub-surface models are then utilized for conducting advanced VTI anisotropic local angle domain (LAD) wavefield decomposition (fig 4). High-fidelity industry standard time domain signal processing was carried out prior to depth domain imaging. In this paper, we will primarily focus on discussing subsurface modelling, depth imaging, and the generation of reliable reflection angle gathers.

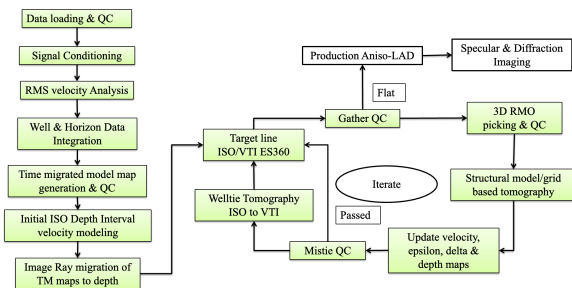


Figure 4: A-LAD (VTI) processing workflow

Anisotropic sub-surface modelling:

The final anisotropic depth interval velocity and anisotropic models were obtained through various passes of tomographic updates. The initial isotropic depth interval velocity model was generated from refined RMS velocity using constraint velocity inversion (CVI). Constrained Dix inversion (CVI) imposes geological boundary conditions using the formation volume in order to preserve the lateral consistency in the inverted depth interval velocity model [Koren, Zvi & Ravve, Igor. (2006)]. The formation volume was generated by providing adequate geological dominance of the regional horizons, water-bottom, KT, Turonian and basement. Fig. 5 shows the location of RMS velocity functions which are inverted and interpolated using the formation dependent velocity inversion and smoothing, prevents the sedimentary velocity to leak into the water canyon and vice-versa and thus maintain the velocity contrast along bathymetry. It provided a

stable initial depth interval-velocity model which is geologically conformable and structural consistent.

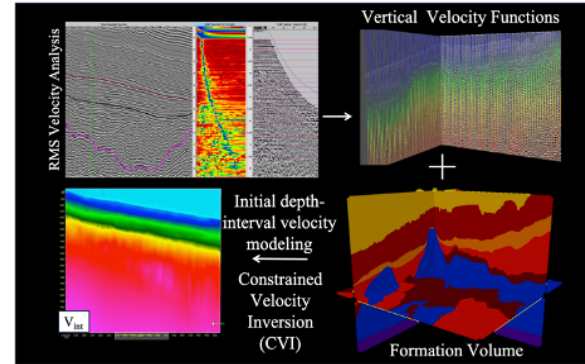


Figure 5: RMS velocity analysis and structural controlled initial depth interval velocity modelling

As the bathymetry is rapidly varying and highly complex, our first objective was to estimate the lateral velocity variation of water column. For that we performed model-based water bottom tomography taking move out control up to 200m below water bottom. It resulted into an adequate estimation of water velocity from shallow (~1535m/s) to deep (~1495 m/s) and provided flatten water bottom. Water bottom tomography helped to estimate the velocity within the canyons more precisely that further helped in resolving ambiguous structures.

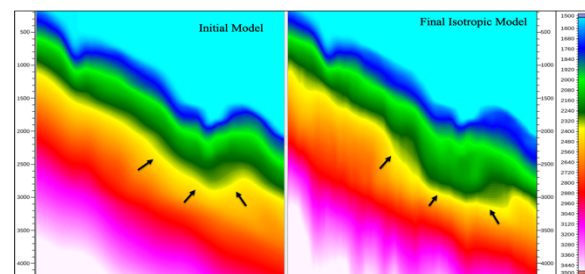


Figure 6: Final Isotropic $V_{interval}$ depicting low velocity buried channels as compared to initial model.

Iterative isotropic reflection grid tomography [Dan Kosloff et al, 1996] was then performed to update the velocity. The updated isotropic V_{int} clearly detected presence of buried channels (Fig.6), is structurally consistent and provides flat common image gather. A mis-match have been observed between the geological horizons and the well-markers as the isotropic approximation does not encounter the subsurface anisotropy. Mistie maps were generated

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using the key geological horizon. These mis-tie maps were then used for isotropic to VTI initial anisotropic modeling using well-tie tomography. To consider the near vertical anisotropy (δ), only 0 to 30 degree of reflection angles were used during ISO to VTI well-tie tomography. This initial VTI well-tie tomography provided the initial VTI interval velocity and initial δ . Epsilon were then calculated by performing eta analysis on migrated gathers. Six iterations of grid-based reflection tomography were performed that compensated the RMOs, flatten the gathers and provided updated VTI interval velocity, epsilon, δ (fig 7). Final updated VTI model is structurally consistent, water bottom controlled and clearly captured the buried channels and thus reduced well marker mis-tie.

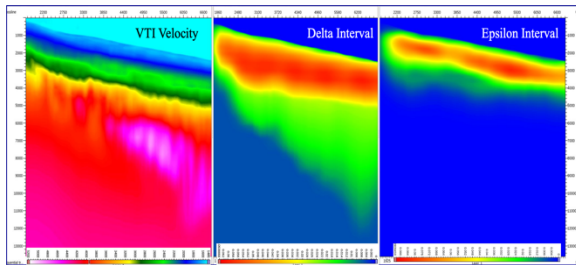


Figure 7: Final VTI velocity volume (left), estimated anisotropic velocity parameters, δ , (middle) and ϵ (right)

Anisotropic local angle domain (A-LAD) Depth Imaging

Local angle domain technique is bottom-up ray tracing approach which uses a point-diffractor operator to shoot rays from subsurface grid points to the surface, forming an accurate system for mapping the recorded surface seismic data into the subsurface Local Angle Domain (LAD) [Koren, Zvi & Ravve, Igor. (2011)]. LAD technique provides two complementary 3D full azimuth common image angle gathers: directional angle-azimuth and reflection angle-azimuth gathers. Directional angle-azimuth gathers has the energy distribution based on reflector dip & dip-azimuth. Figure 8 represents the total migrated wavefield in the directional angle-azimuth gather for the marked cdp location. The flat (blue) and dipping reflectors (yellow) can be easily identified by looking at the energy distribution in the directional gather.

Specular filter is then applied to separate out the reflection energy out of total scattered wavefield. On stacking it produced specular stack. The remaining scattered energy is mostly diffraction, generated by point diffractors, corner waves and small-scale discontinuities [de Ribet et al, 2017]. The stacking of this non-specular energy resulted into diffraction image.

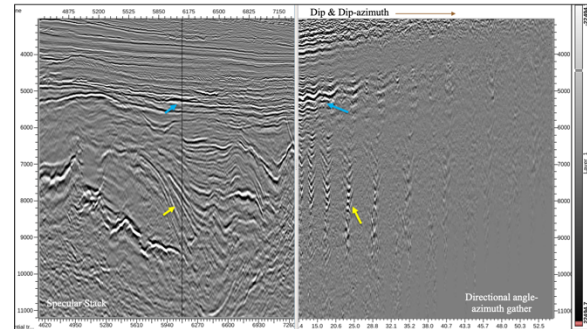


Figure 8: Energy distribution in directional angle-azimuth gather (Left: specular energy and right: directional angle-azimuth gathers)

Results

The tomographic approach successfully encountered the geological features within the velocity model. The final velocity model clearly brought out the buried channels at the shallower level. Fig. 9 shows the lowering of velocity within the buried channels and the CIGs are also sufficiently flat (fig 10)

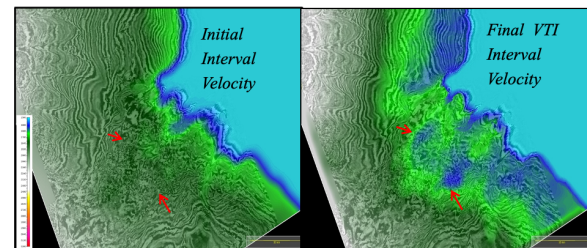
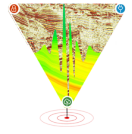


Figure 9: Final anisotropic depth-interval velocity model clearly brought the low velocity buried channels present at shallower level (slice 1400m)



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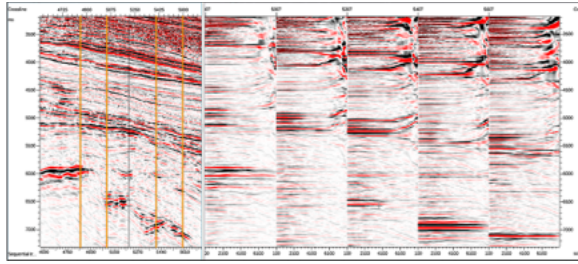


Figure 10: Flatness of gather ensures the adequate velocity model

The generated velocity model has close resemblance with well velocity which describes the confidence of modelling (fig 11). Focusing of the amplitude has improved. Adequate modelling of canyons and detection of buried channels has significantly resolved the time-depth structural anomalies (Figure-12) and minimized the depth mis-tie between horizon and well marker (fig 13).

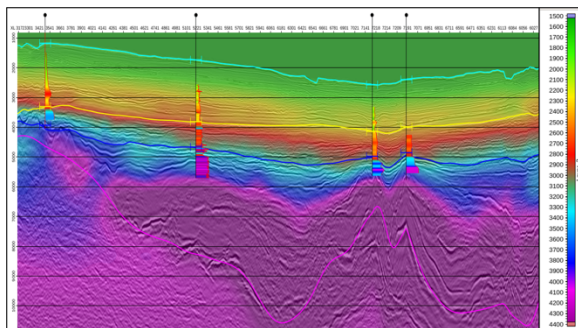


Figure 11: Final depth interval velocity profile along the key wells.

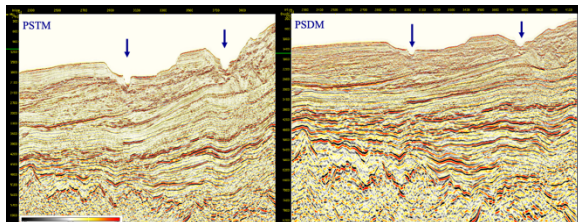


Figure 12: Depth image resolving the issues of structural sags and water column effects as compared to time domain image

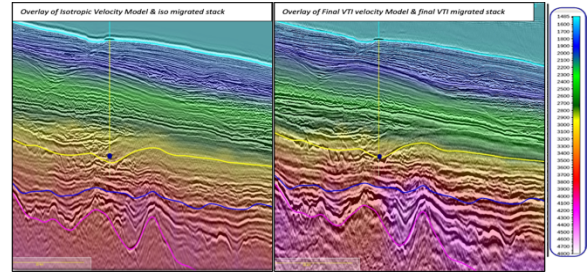


Figure 13: Mis-tie observed in isotropic interval velocity model has been minimized in the final VTI velocity model

Reflection and diffraction are separated from LAD (Legacy Angle-Depth) directional angle-azimuth gather. The generated specular stack shows enhanced reflector continuity at all level. The dipper syn-rift & Cretaceous sequences are clearly imaged as compared to the legacy data (fig 14). Amplitude reconstruction below the canyons are significantly improved in the reprocessed depth data as compared to legacy PSTM image (fig 15).

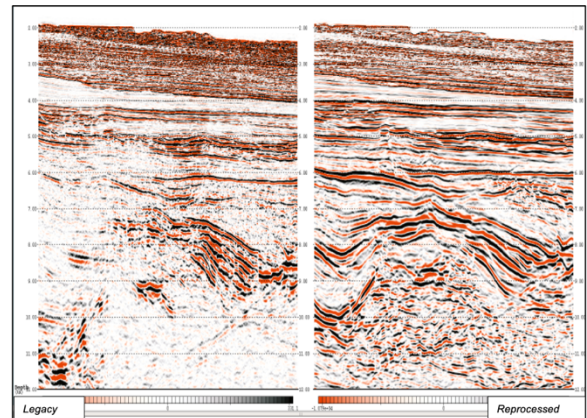


Figure 14: Comparison of legacy depth migrated data with the reprocessed A-Lad specular stack

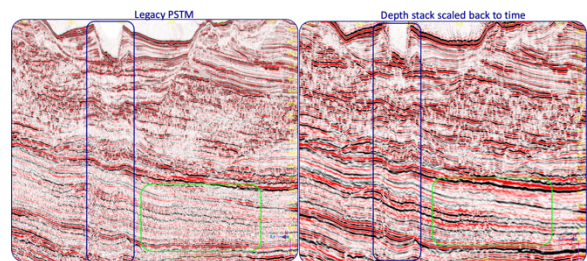


Figure 15: Comparison between legacy PSTM vs reprocessed depth stack scaled back to time

The diffraction stack on the other hand delineated the sub-surface major/minor faults networks which are

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hard to detect from the reflection data (fig 16).

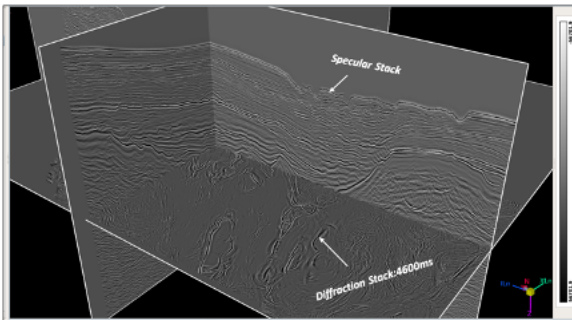


Figure 16: Diffraction volume delineating sub-surface discontinuities

We have also generated the synthetic AVO response from the well data. The reservoir is a high-impedance gas sand and shows class-I AVO response. AVO response observed in the reflection angle gathers at reservoir level are in adequate agreement with the well synthetic AVO responses (fig. 17). It ensured the amplitude fidelity of the migrated gathers.

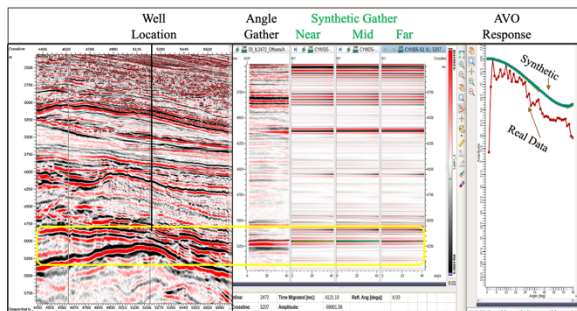


Figure 17: Amplitude preservation on reflection angle gather is validated with well-synthetic response

Conclusion

Anisotropic depth interval velocity, delta, and epsilon model produced using VTI reflection grid tomography adequately encountered the presence of buried channels at shallower level. Appropriate modeling of these low-velocity channels and water columns, helped in resolving the time-depth structural anomalies and consequently minimizing the structural uncertainties. Remarkable improvement has been observed in the imaging of Syn-rift and Cretaceous sequences as well as in basement configuration. The high-resolution diffraction stack is helping in delineating the major/minor fault networks

with better understanding. The reflection angle gathers adequately preserved the amplitude, phase and waveform. AVO signatures were validated with the well data and were highly amenable for inversion studies. The generated outputs are helping in identification of new hydrocarbon prospects and in turn, foster the exploration/development drive in the block.

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