Imaging Intrusive Body below the Basaltic Trap in Tomography model building: Study from Kutch Offshore

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Abstract

The exploration strategy in the volcanic regime in the worldwide basins is becoming gradually challenging due to criticality of the sub-surface geology. The challenge takes more critical mode in Kutch and Kutch Saurashtra basin of western offshore India. The reasons being the presence of the basalt, thickness of basalt, the morphology of basalt, presence of intrusive below basalt that not only puzzle the geoscientists but also limits the seismic methods to receive echoes from below. The very limited number of wells, exact identification of Horizons, its continuity and S/N ratio of data within and below thick basalt limits velocity model building through reflection Tomography.

The present paper outlines new methodology of anisotropic reflection tomography for velocity model building of the basalt as well as below basalt. Again, the model building workflow also image the high velocity intrusive within Mesozoic. The present study area is structurally complex associated with 1000 meters of thick basalt, highly rugged topography, multifaceted faulting of trap bottom, highly tectonically disturbed Mesozoic, presence of high velocity intrusive within Mesozoic. The aforementioned geology produces strong reverberations/multiples of multi orders, dispersion, scattering, mode conversions, attenuation.

All these above seismic phenomena not only distort the wave propagation but also produce a composite wave filed in the recording domain. The presence of water bottom, trap top and trap bottom create complex multiple reflections creating strong reverberations in the data. The multiples reduce the coherent nature of reflections and produce coda waves alongside of central lobe. All the aforementioned phenpmena resulted in poor S/N ratio, reduced resolution and detectability of reflected events. The reflection tomography brought up very nicely the image of high velocity intrusive below basalt within Mesozoic sequences. The potential of tomography in the current case of complex and multifaceted geology is augmented by the following inputs.

1. Smoothing methodology of PSTM velocity. Incorporation of Geostatistical model building from sonic logs
3. Common reflection angle migration (CRAM) gathers for RMO picking
4. Interlayers

There has been a shift from isotropic to predominantly anisotropic models such as vertical transverse isotropy (VTI) and tilted transverse isotropy (TTI).

Introduction

The study area falls under Kutch offshore basin of Western offshore India. The geology of the area constitutes tertiary sediments at top mostly clastics in nature. The basalt trap is separated from clastic sediments by Paleocene carbonate. The basalt is composed of multi-layered extrusive flows that suggest at least 40 periodic pulses of lava forming intra-trap deposits. The sediments below trap are Mesozoic which is separated from tertiary sediments by basalt trap of thickness more than 1000m. High velocity and changing dips of intrusive are present within Mesozoic.

The imaging challenges below basalt has been a debate across all volcanic basins of the globe since decades.

The seismic response from such geology is accompanied by the following phenomena.

1. Strong multiples generated from strong boundaries of water bottom, trap top, trap bottom.
2. High velocity intrusive within Mesozoic also produce strong reverberations within the layer.
3. Energy scattering from basalt top and absorption within trap reduces energy propagation below basalt.

4. P to S mode conversion occurs at trap top, trap bottom and water bottom with different modes such as PS, PSPP, and PSSP.
5. Linear noise cone due to trap and random noises as scattering energies, diffracted energies contaminate the wavefield.
6. Diffractions from rugged trap top, faulted trap bottom and half graben of Mesozoic reduces the signal strength.

Any imaging algorithm requires an accurate velocity model of subsurface to register its efficacy. The velocity model in depth is very crucial in deciphering the subsurface due to the following reasons.

1. Flattening the gather
2. Improving coherency of evets
3. Positioning of the events
4. Enhancing stacking response and hence image

The model building in depth can be carried out through many techniques such as travel time tomography and full wave from inversion. The current discussion is about improving the velocity of thick basalt and imaging the high velocity intrusive within Mesozoic through travel time tomography. The basics of the method have remained unchanged since the late 1990s, but the problems of its solution have changed dramatically. This evolution has been driven by exploration demands and enabled by computer power. Over the decades, ray-based post migration grid tomography has become the standard model-building tool for seismic depth imaging. Standard model resolution has increased from a few thousand meters to a few hundred meters. This order of magnitude improvement may be attributed to both high-quality, complex residual-move out data picked. Reflection travel time tomography methodology is deployed to update the velocity model in the current complex geology of Deccan basalt. Multi inputs such as sonic log trend to the smooth initial model, interlayers below Deccan basalt where the horizons are limited and good S/N common reflection angle gathers for RMO picking are considered to prevail the tomography workflow so as to address the basalt as well as sub-basalt velocity structures. CRAM gathers with low frequency are very favorable for RMO picking as well as input in tomography to improve in estimating travel time errors. These multi-inputs to the tomography workflow will augment its perspective in imaging high velocity intrusive as well as intra-basaltic layers within thick basalt.

The RMS velocity from vintage PSTM is used to create initial velocity model in depth. The velocity field is smoothed in multi-domains to extract velocity field which is varying gently with depth. Then, log driven geostatistical velocity model is created from sonic logs to assign the initial log trend to the smooth initial model. The limited number of well tops, multiple dominance below basalt, poor S/N ratio restrict the confidence in horizon picking within Mesozoic. Therefore, interlayers are picked from stack section for estimating travel time which is used in tomography for velocity model update. RMO picking is effectively carried out on common reflection angle domain gathers that are cleaner and coherent than offset gathers.

Methodology

Reflection travel time tomography updates velocity model within grid defined by the resolution requirements restricted to low frequency update. To start the tomography the data is depth migrated with an initial model which is smooth with low frequency details.

Initial velocity model (IVM) building workflow is crucial due to the inherent limitations of solution of tomography. The solution converges to local minima when the initial model is too far from the actual model instead providing solutions for global minima. The local minima conversion produces layer parameters that are away from the true model parameters as there exists ‘N’ numbers of local minima. To overcome the local minima challenges, the initial model should represent the true model parameters in low frequency trend.

In the study IVM is carried out in two steps, first step is the smoothing methodologies (Figure-1) of RMS velocity, the results are shown in Figure-2 and second step is the geostatistical model building from well sonic logs. The workflow is presented in (Figure-3). The smooth model R-II zoomed at shallow produces the best smoothing in comparison to other two methods (Figure-2). The vertical stripes in the shallow are well averaged out by the second methodology (R-II). The smooth model back converted to RMS velocity which is transformed to depth by constrained velocity inversion (CVI)

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technique. The CVI technique produces interval velocity in depth from RMS velocity with weightages from data and the background trend. The background trend is geostatistical velocity extracted from well velocity in the area.

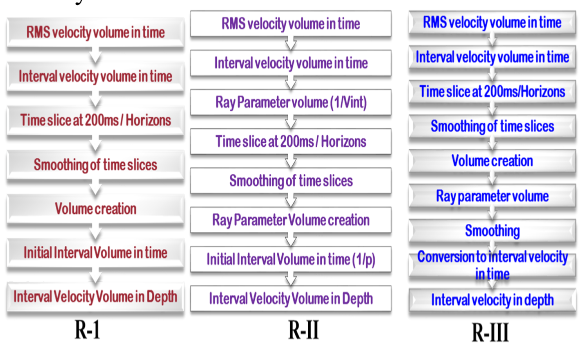

Figure-1: Three methods of smoothing of RMS velocity volume in different domains.

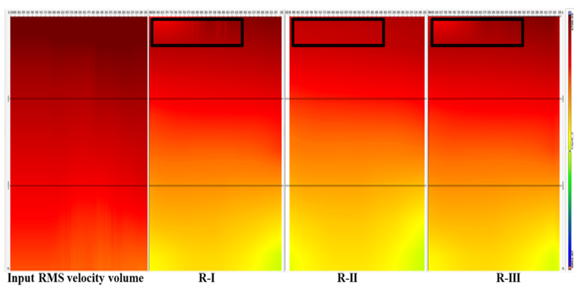

Figure-2: Results of three smoothing methodologies as mentioned in Figure-1. R-II method makes a smooth model than other two (as demarcated in black rectangle).

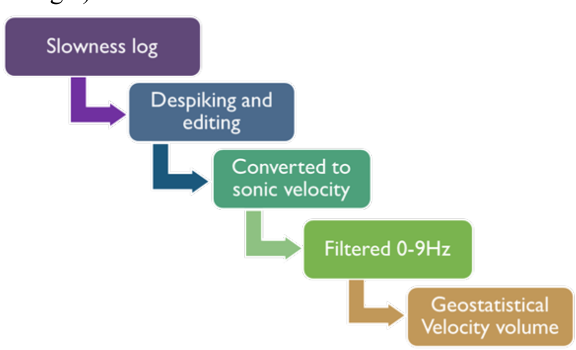

Figure-3: Geostatistical model building workflow

The workflow of deriving geostatistical velocity model is mentioned in Figure-3. The geostatistical velocity from sonic logs is displayed in Figure-4. The velocity model is a low frequency version of sonic velocity trend within the area. This is well depicted in the zoom view (right side of Figure-4). The initial velocity model (IVM) in depth modelling workflow (Figure-5) produces model which accommodates all the details of sub-surface velocity variation in low frequency trend as observed from geostatistical velocity model (Figure-4).

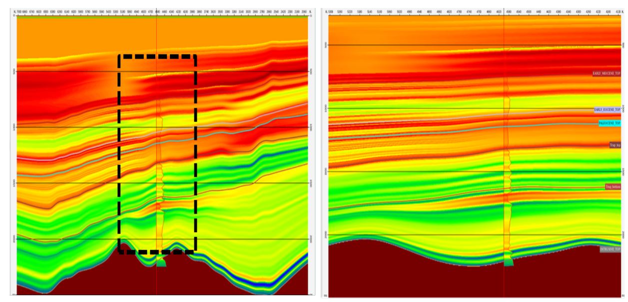

Figure-4: (left) geostatistical velocity model within the log length and (right) zoom view of the dotted black rectangle superimposed with sonic log.

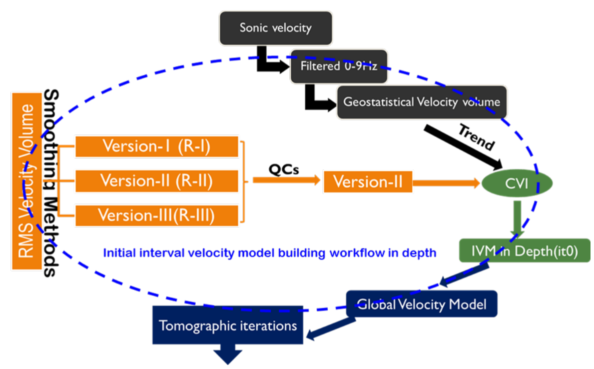

Figure-5: Initial interval velocity model building workflow in depth

The IVM in depth presented in Figure-6 will be updated in tomography workflow to further refine the model so as to approach actual model.

The common reflection angle domain migration outputs angle gathers which are very suitable for RMO picking due to the following reasons.

1. Good S/N content because of angle domain filtering

2. Least contamination of multiples
3. Improved coherency of events

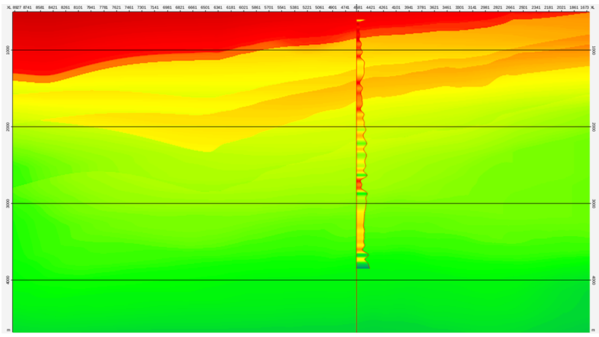

Figure-6: Initial velocity model overlay with sonic log. Low frequency variations are well captured in the initial model

In geologically complex regime of Deccan basalt with high velocity intrusive within Mesozoic, salt and high velocity chalk, velocity model update through tomography favors angle CIP angers than offset gathers. Hence, in the current study CRAM CIG gathers are produced to input for tomography to pick RMO in the computation of travel time residuals. We analyze RMO on common-angle image volumes sorted to common-image- point CIP gathers. Standard industry grid tomography generates and solves ray-traced residual-migration equations to produce earth models that flatten RMO on CIP gathers.
The travel time errors/depth errors are translated to update the layer parameters starting from top-to-bottom sequentially. The depth variation of reflection events across offset/angle is residual moveout RMO. When there is no RMO, the earth model has optimized the data focusing; when there is RMO, we can trace rays through the model to determine which parts of the model to change to flatten the moveout and improve the focusing. The picking of RMO is very dependent on the noise characteristics, multiples and signal coherency. Less the noise, least the multiple and more coherent is the event, better will be RMP picking.
Interlayers (figure-7) are picked within the layers where horizons are not available. These interlayers provide the picks from which travel times are modelled for tomography.

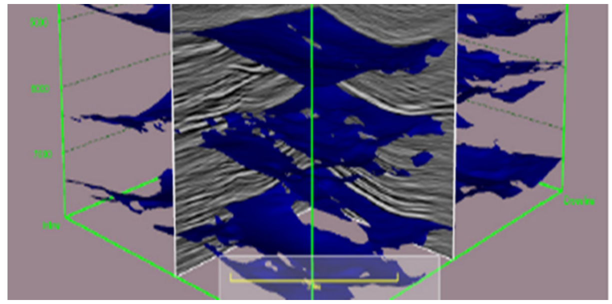

Figure 7: Interlayer picking for input to tomography

Reflection travel time tomography (Anisotropic VTI approach) aims to update model parameters (velocity, delta, and epsilon, structure) in order to flatten common image gathers. It is based on solving a large set of linear equations (equations-1 & 2). Tomography linear equations relate the desired (unknown) model update parameters with input data containing travel time errors (depth errors) along reflection rays traveling across the model. The grid-based tomography method updates the layer parameters on a regular spatial grid. The equation governing the tomography is as follows;

$$\mathbf{A\ \delta m = \delta t} \quad \text{------------------------- (1)}$$

A - Matrix built in the Tomography build stage
δm - Inversion solution vector – model perturbations output of the Tomography solve stage
δt -The travel time error input vector

Results:

The smoothing methodology R-II well compensates the stirpes in the velocity model. This smooth model creates an initial depth model driven by well velocity which is very close to the vertical velocity of subsurface. The initial velocity in depth, initial delta and initial epsilon in subsequent tomography iterations update the subsurface layer properties as close as to the actual values. The tomography solutions follow the global minima due to the closeness to initial model with the actual model of the earth.
The subsequent iterations of VTI reflection tomography update the model parameters close to the actual sub-surface layer properties. Well-tie tomography workflow (figure-8) uses mis-tie

perturbations to update velocity and delta for mild angles from the input information of mis-tie maps calculated from well markers and depth updated seismic horizons.
The solution minimizes the difference between seismic horizons and geological markers that stabilizes the mild angle variations of layer properties.

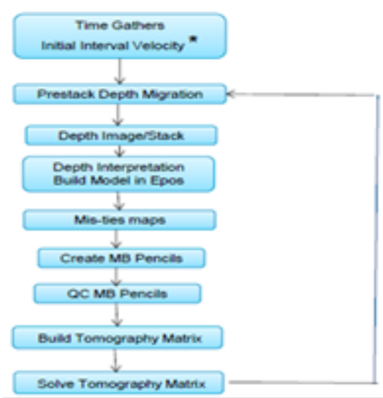

Figure-8: Well-tie tomography workflow

The velocity model in subsequent iterations of tomography is incorporating high frequency trend to the model as shown in Figure-9. Furthermore, final model better matches with the well velocity as presented in Figure-10.

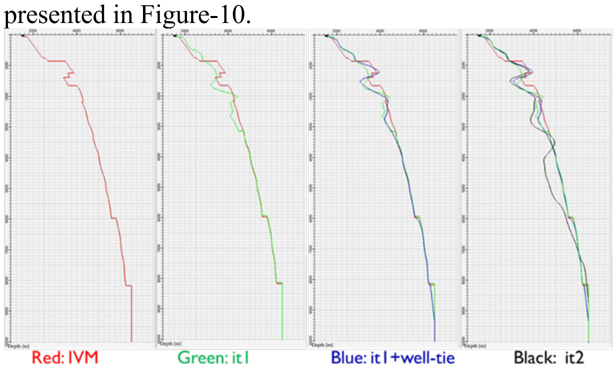

Figure-9: Velocity overlays at subsequent iterations as labelled

Most importantly, the image of high velocity intrusive as demarcated in black dotted ellipse in Figure-11 is better recognized in the model below thick basalt of this complex geology. Moreover, the structural characteristics such as steep dip, thickening at bottom and thinning towards top are immensely ascertained in the final model within sub-basalt geology. In addition to that the intrusive velocity and the variations in velocity away from well are also well accommodated in the final model.

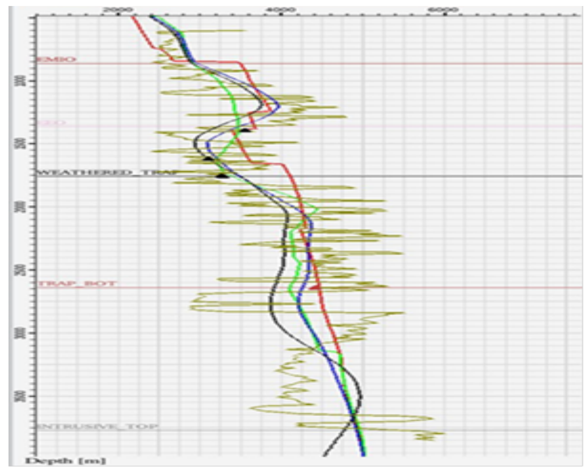

Figure-10: Interval velocity overlay with sonic log at well location. (red) initial velocity model, (green) after first iteration, (blue) first iteration with well-tie and (black) after iteration two.

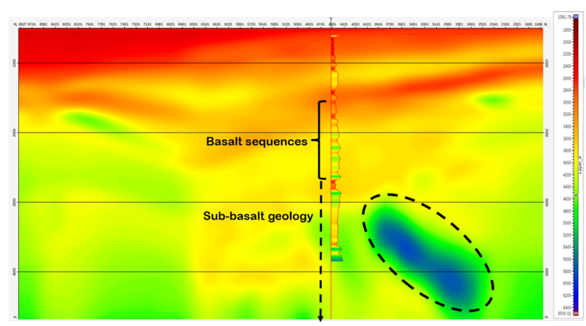

Figure-11: Final velocity model for migration. The high velocity intrusive image (black dotted ellipse) within Mesozoic very well captured by reflection tomography.

Conclusion:

The imaging of intrusive has come up nicely in the reflection tomography velocity model update (Figure-11). The linearized tomography solutions are dependent on the number of known variables that

stabilizes the solution and tending towards global minima. The good starting model as explained will inherently converge the solution of tomography toward the actual sub-surface velocity field. In addition, high quality RMO picks on CRAM gather and interlayers below Deccan basalt also help the tomography solutions to merge at global minima.
Therefore, along with the intrusive image, the lateral change in velocity is also captured in the final model. The final velocity model well delineates the intrusive as displayed in the overlay with final stack in Figure-12.

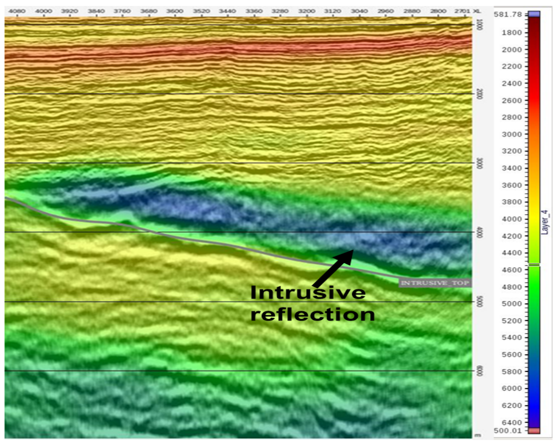

Figure-12: The velocity section overlaid with final stack. The high velocity corresponds to the intrusive signature in the seismic section.

Hence, more the number of known inputs, faster is the tomography linear equations and closer is the convergence of the to the global minima.
However, the fine details in the tomography model have not been captured due to inherent limitations of the ray-based methodology. Also, the abrupt change in the velocity of trap bottom and underlying sediments is another challenge in the tomography-based velocity update.
Therefore, full waveform inversion (FWI) is a solution to accurately and precisely define the velocity model in the complex regime of Deccan basalt. But, the offset requirement for FWI is always the biggest challenge in operations for low frequency update.

The efficient velocity model building like FWI also open up further space for Energy Transition towards “net zero”.

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