Advance Depth Imaging Workflow: Application of Q-Compensation in Local Angle Domain, Add Value to Imaging the Deeper Targets - A Case Study from Ahmedabad Carpet, Cambay Basin, Gujarat, INDIA

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Keywords

Velocity Modelling, Geostatistical Interpolation, Kriging, Tomography, Anisotropic parameters (epsilon and delta), Q-Migration, LAD (Local Angle Domain), Specular and Diffraction Imaging.

Abstract

Seismic imaging, particularly below coal and sub-basalt layers, is a major challenge in the Cambay basin. Accurately delineating deeper horizons on time-migrated sections is still a challenging task for interpretation, especially when prominent lateral variations in physical properties are present. The energy scattering near point diffractors and faults results in an increase in ambiguity. The high velocity gradient in complex overburden requires additional attention in velocity model building and refinement.

To tackle the imaging challenges, velocity refinement has been achieved through an iterative process involving traveltime and well-tie tomography. The application of Q-compensation in the local angle domain enhances the frequency content in seismic sections, resulting in improved imaging of deeper targets.

Introduction

Cambay basin is one of the most extensively explored sedimentary basins of India. The basinal limit in north starts from Sanchor and extends upto the coast line and the Deccan plateau in the south. The Gulf of Cambay and its south-west extension form the offshore part of the basin. Tectonically, the basin is divisible into five blocks from north to south – 1) Sanchor-Patan, 2) *Ahmedabad-Mehsana,* 3) Cambay-Tarapur, 4) Broach-Jambusar and 5) Narmada.

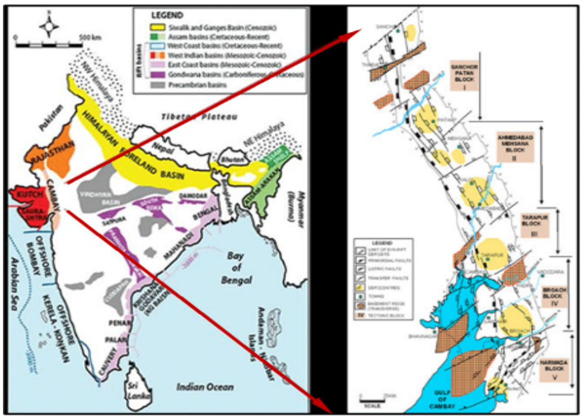


Fig. 01. Tectonic Map of Cambay Basin (*Bhowmik and Mishra, 2008*).

The current study focuses on the Ahmedabad carpet within the Ahmedabad-Mehsana tectonic block of the Cambay basin. This block extends from the Khari River in the north to the Vatrak River in the south, making it the largest block in the basin from an aerial perspective, extending from Dholka Nawagam to Unawa.

Theory and Methods

1. Initial Depth Interval Velocity Model Building

Interval velocity is defined as the thickness of an isotropic layer divided by the time, it takes to travel from the top of the layer to its base.

We used constrain velocity inversion (CVI) method to transform the RMS velocity to depth interval. The Dix transformation may produce unstable and highly oscillating, whereas the constrained velocity inversion converts seismic velocity functions to a regular instantaneous velocity, which is geologically plausible.

Initial velocity model has been created by splicing of well-velocity with seismic.

The well-velocity has been derived from conditioned sonic logs. The log data were re-sampled, and filtered to 8Hz and then transformed to p-wave velocity, the markers were calibrated from VSP curve. A velocity model has been created from wells, using Geostatistical interpolation method. Using *Paradigm software.*

The Geostatistical interpolation method uses Kriging method for interpolation, named after *Daniel G. Krige.* The primary data used by Ordinary kriging, in Geostatistical interpolation is conditioned and filtered sonic derived velocity logs. A seismic velocity volume has been used as the external drift (secondary data) for Collocated Cokriging.

Kriging is a geostatistical technique of spatial interpolation that is used to interpolate a surface from a scattered set of known points, which predicts a continuous surface between the known locations. It is based on the assumption that there is a spatial dependency between geological properties at separate points in an area and that this spatial dependency is a function of the distance between the points.

A semivariances is calculated for different distances between points and the results are plotted on a semivariogram, which is then used to calculate the weighting coefficients for kriging interpolation.

The semivariogram modeling is estimated from input data points, by finding the best fit among two theoretical models i.e. *exponential* or *spherical*, and the best fit model is used for kriging.

2. Travel-time Tomography

Traveltime tomography aims to update model parameters in order to flatten common image gathers. The degree of non-flatness of gathers is a measurement of the residual error in the model. This residual error is used as inputs for tomographic updates and attempts to find an alternate model, which minimizes the errors. Traveltime tomography is basically an inversion method for estimating the model parameters from the reflection times associated with the observed seismic data. The small changes in reflection traveltimes are linearly related to small changes in earth model parameters.

Solving the tomographic linear equations system the functional are -

$$F = F_{data} + F_{trend} + F_{smoothing} \qquad \textbf{...(2.1).}$$

where, F_{data} is the data term created in the build stage of tomography, F_{trend} is the trend term stabilize the inversion results and $F_{smoothing}$ term penalize solutions which are not smooth.

The smoothing operator guides the inversion toward smooth solutions i.e., this operator penalize solutions which are not smooth or oscillatory. Whereas, the trend operator guides the inversion toward small solutions (suppress large solutions). That is, the updated velocity will not be very different than the background velocity, and helps the inversion to converge by eliminating zero and very small eigenvalues.
The sensitivity factor of trend term plays a crucial role in tomographic updates as it influences both velocity and anisotropic parameters.

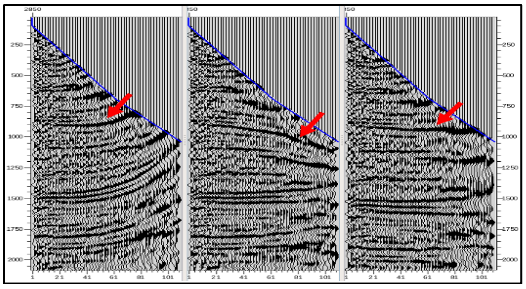


Fig.02. Gather after initial iteration (left), Second-iteration with global sensitivity 1.0 (middle) and Second-iteration with depth controlled sensitivity (right).

For global sensitivity gathers flatten faster at shallower levels compared to deeper depths. Therefore, in subsequent tomographic iterations, more attention and QC are required, to decide depth-varying sensitivity control for updating velocity and anisotropy parameters.

See in Fig.02, the gathers were affected at far offset; in shallower depth (approx. from 700m to 1250m) for global sensitivity. This problem could be tackle with depth varying sensitivity factor 0.3 for 700m, 0.5 for 1000m and 1.0 for the deeper. It is, obvious to note that variation of sensitivity parameter should kept minimum in tomographic update, as it could generate stretching at the boundary.

The seismic tomography aims to minimizes, model perturbation, traveltime error (or modelling uncertainties) and the misfit between data and model. The tomographic equation in compact matrix form for all the traveltime perturbations are given as *(Lior Liram, Yoav Naveh*, Gali Dekel, Zvi Koren, Paradigm, SEG 2014) -*

$$A\Delta m = \delta t \qquad \textbf{...(2.4)}$$

$$\Delta m = \begin{pmatrix} \Delta V \\ \Delta \varepsilon \\ \Delta \delta \\ \Delta z \end{pmatrix} \qquad \textbf{...(2.5)}$$

$$A = (A_v\ A_\varepsilon\ A_\delta\ A_z) \qquad \textbf{...(2.6)}$$

$$\delta t = (t_{observed} - t_{calculated}) \qquad \textbf{...(2.7)}$$

where, Δm is desired unknown (model perturbations), A is tomography matrix, and δt is traveltime error in the input data along different rays path traveling across the model.

3. Well-tie Tomography

The objective of welltie-tomography is mainly to update anisotropic delta parameter and vertical velocity. So that, when it is used for migration yields flat gathers, and the reflectors seen in the image, tie to the well markers. In order to perform welltie tomography, the initial mistie maps were calculated using the initial model grids and well markers. We utilized an isotropic velocity volume, maintaining an initial delta value of zero ($\delta = 0$). The welltie tomography process yielded a geologically consistent velocity volume and minimized the mistie between horizons and well markers. Our updates were limited to velocity and delta during the welltie process.

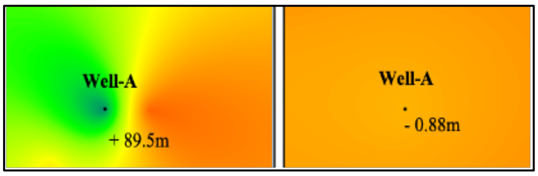


Fig. 03. Initial mistie for horizon H2 at Well-A was **(+ 89.5m)** (left) and Final mistie after welltie tomography **(- 0.88m)** (right).

4. Estimation Anisotropy Parameters

Thomsen Leon (1986), defined the P-wave phase velocity as function of anisotropic parameters ε (epsilon) and δ (delta):

$$V_p(\theta) = Vp(0^\circ)[(1 + \delta sin^2\theta cos^2\theta + \varepsilon\, sin^4\theta)] \qquad \textbf{...(4.1)}$$

where, *Vp* is phase velocity, depends on the deviation angle, θ from the vertical axis, *Vp(0°)* is vertical velocity, *θ* is the deviation, *ε* (epsilon) and δ (delta) are anisotropy parameters. *For isotropic earth* $\varepsilon = \delta = 0$. Then, we can write –

$$V_p(\theta) = Vp(0^\circ) = \textit{Vertical Velocity} \qquad \textbf{...(4.2)}$$

Let us take, $\theta = 90^\circ$

We can write from eqn. (4.1) -

$$\varepsilon = \frac{[Vp(90) - Vp(0)]}{Vp(0)} \qquad \textbf{...(4.3)}$$

where, *Vp(0)* is vertical, and *Vp(90)* is horizontal p-wave velocity.

And also, for $\theta = 45^\circ$ the eqn. (4.3), can be written as-

$$\delta = 4 * \left[\frac{Vp(45)}{Vp(0)} - 1\right] - \varepsilon \qquad \textbf{...(4.4)}$$

where, *Vp(0)* is vertical, and *Vp(45)* p-wave velocity at angle *45°*.

A VTI velocity field requires three parameters namely the symmetry-axis velocity (vertical) and two Thomsen parameters δ and ε. The vertical velocity together with δ control the second order moveouts, whereas the vertical velocity with ε control the fourth order moveouts.

The computation of delta (δ) is described below -

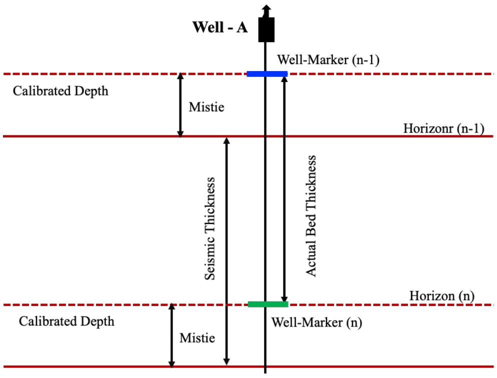


Fig. 04. Schematic diagram describes the estimation of delta (δ).

We can estimate delta parameter (δ) with the following steps: 1) Interpret key seismic horizons. 2) Calculate anisotropic delta parameters from existing wells with the following relationship (*Alkhalifah and Tsvankin, 1995*) -

$$\delta_n = \frac{1}{2}\left[\left(\frac{\Delta Z^I}{\Delta Z^A}\right)^2 - 1\right] \qquad \textbf{...(4.5)}$$

where, ΔZ^I is *Isotropy Layer Thickness* (measured from the structural model and seismic velocity).

ΔZ^A is *Anisotropy Layer Thickness* (measured from the well time–depth pairs log between two well-markers at well locations).

To estimate anisotropic velocity by populating isotropic model with anisotropic parameters delta (*Thomsen, 1986*):

$$V_0^a = \frac{V_0}{\sqrt{1+2\delta}} \qquad \text{… (4.6)}$$

where, V_0 represents the isotropic interval velocity.

Normally, horizontal velocity is faster than the vertical velocity, therefore the ε (epsilon) and δ (delta) are positive.

5. Estimation of Q-Volume

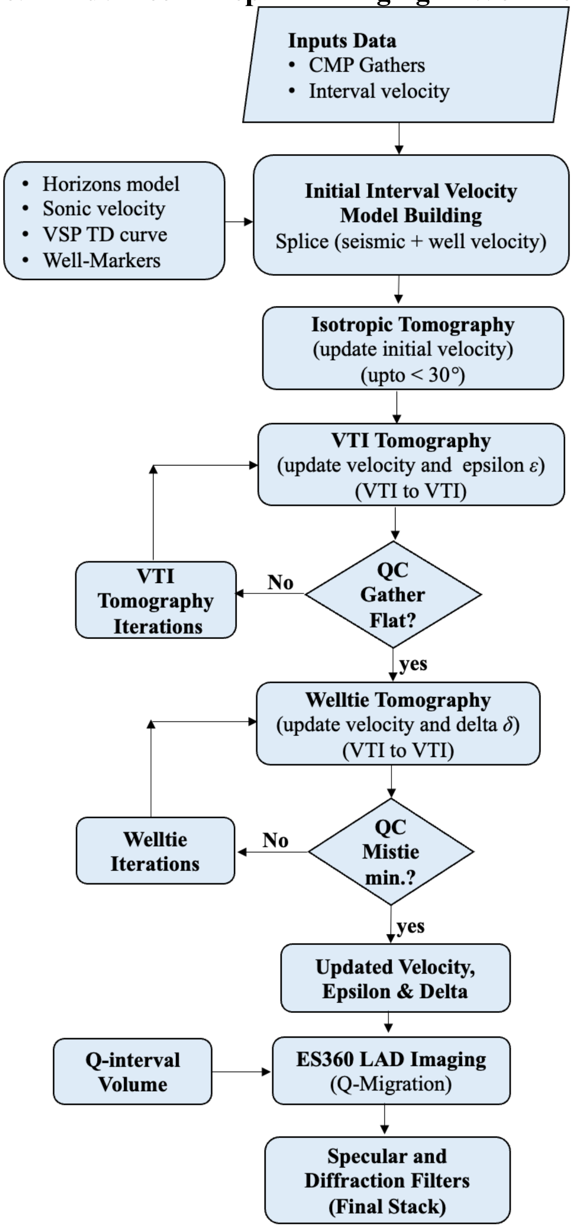
To estimate Q for a given seismic trace S(t), we follow these steps: First, we obtain a time-frequency decomposition of the trace as S(f, t) using the Gabor transform, where t denotes travel time and f represents frequency. We can express the amplitude as (*Yanghua Wang, 2004*):

$$A(f,t) = A0\, exp\left\{-\frac{2\pi f t}{2Q}\right\} \qquad \text{…(5.1)}$$

where, A_0 is the amplitude at t_0, constant Q^{-1} is the effective inverse Q between t_0 and current time t.

In current study the effective Q-factor has been estimated from the corridor stacks of VSP data available at different well locations in the project area, using 'qest module in *Echos*' software. The estimated vertical function (Q-function) has been transformed to depth interval volume using '*volume-manipulations'* utility in *GeoDepth Software.* Latest updated depth interval velocity volume has been used for depth conversion. The estimated value of Q-varies from 30 to 250.
The estimated Q-interval volume has been used as input for depth imaging in local angle domain. The Q-compensation in LAD (local angle domain) is applied to the seismic trace after ray tracing and traveltime computation, but prior to the imaging stage, which compensates seismic trace for attenuation and dispersion effects.

6. Advance Depth Imaging Workflow



The advance depth imaging workflow involves several key steps to create accurate subsurface images from seismic data. It encompasses velocity model building, iterative updates with tomography, migration in local angle domain, and post-migration filters and stacking.

The sequence of workflow is highly optimum for the present study area, although minor adjustments might be needed based on the data at hand.

7. Results and Discussion

Seismic exploration involves the propagation of seismic waves to accurately depict subsurface geology, but unfortunately, these waves are influenced by numerous subsurface factors, including the initial frequency, which impacts resolution and depth of penetration. High-frequency waves offer higher resolution but less depth, while low-frequency waves provide greater penetration depth but lower resolution. Frequency content reduction is typically observed in local angle domain (LAD) imaging.

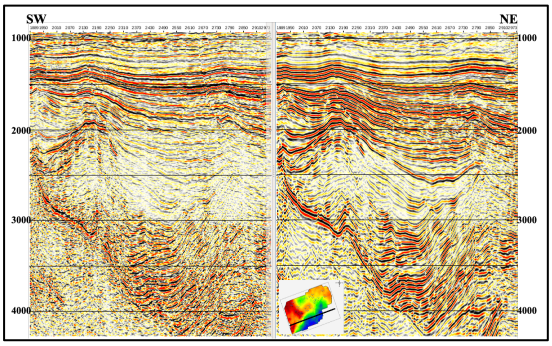


Fig. 06. PSTM Stack (left) and ES360 in Time Domain (right).

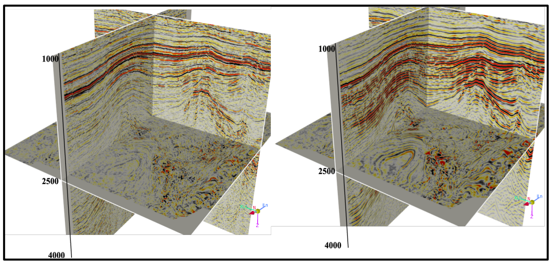


Fig. 07. 3D view: PSTM Stack (left) and ES360 in Time Domain (right).

Fig. 05. Comprehensive depth imaging flow-chart.

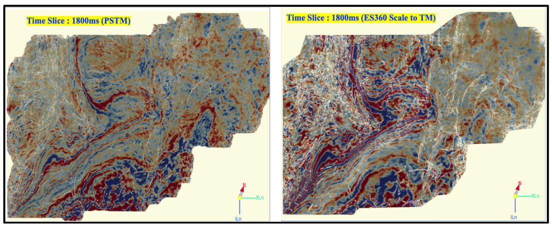


Fig. 08. (TimeSlice-1800m): PSTM (left) and ES360 Specular blended with Coherence (right).

The coherence and specular blending, show significant improvement in continuity and give better fault definition.

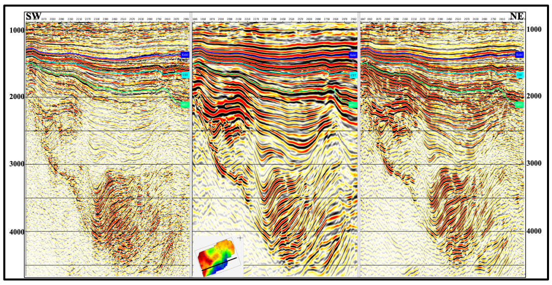


Fig. 09.: PSTM (left), ES360 Specular Stack without Q (middle) and ES360 Specular Stack with Q-migration (right).

The application of Q, significantly enhance the frequency contents and nicely balance amplitude at all level.

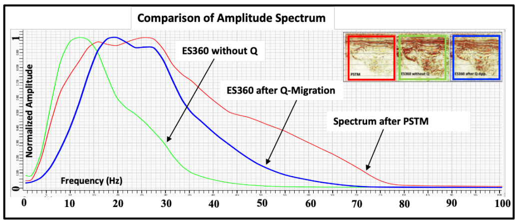


Fig. 10. Significant spectral broadening can be seen after Q-migration as compared to ES360 without Q.

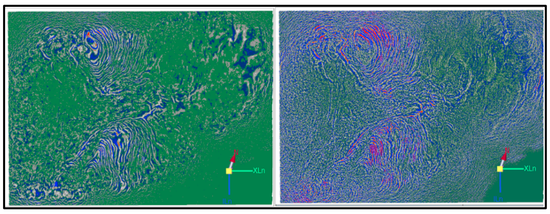


Fig. 11. (DepthSlice-5000m): Specular Stack (left) and Diffraction Stack blending with Coherence (right).

The diffraction blending, give significant improvement in the fault definition and continuity extension at fault locations.

Conclusions

To obtaining a geologically accurate velocity model is difficult in complex geological setup, due to poor signal-to-noise ratios on the seismic records.

An initial velocity derived from sonic log provided more accurate initial model, reduced uncertainty and converse faster.

To tackle the imaging challenges, velocity refinement has been achieved through an iterative process involving traveltime and well-tie tomography, which provides an accurate time-depth conversion, and the seismic data perfectly match with well-markers (see, Fig. 03).

The sensitivity factor plays a very crucial role in tomographic updates for complex sub-surface, an accurate gather flattening could be achieved with depth varying sensitivity.

In the depth domain, seismic data is analyzed based on the arrival times of waves at different depths. The high-frequency components effectively 'outrun' the low-frequency components, leading to a decrease in the overall observed frequency content as depth increases.

The application of Q-compensation in the local angle domain, compensates seismic trace for attenuation and dispersion effects, which enhances the frequency content in seismic sections, resulting in improved imaging of deeper targets.

The result shown after Q-compensation depicts significant improved imaging when compared with the PSTM stack section and enhances amplitude spectrum and bandwidth (see, Fig. 09 & Fig. 10).

The diffraction blending, give significant improvement in the fault definition and continuity extension at fault locations (see, Fig. 11).

The workflow significantly improves imaging results and optimizes project performance.

Acknowledgement

I, would like to thanks ONGC for giving permission to publish this paper.

I, express my gratitude and sincere thanks to *Shri PR Mishra, ED-Basin Manager, WON Basin, ONGC Vadodara,* to providing the opportunity to work on project. I, also thanks to *Shri Dipanjan Karmakar*, and *Shri* Amit Kumar, from *AspenTech (India),* for technical and software support.

References:

Alkhalifah, T., and Tsvankin, I., 1995, Velocity analysis for transversely isotropic media: Geophysics, 60, 1550-1566.

Ajeesh Gupta1, T.R. Muralimohan1, C.M. Vardarajan1, S.P. Singh2, Pramod Kumar2, Well Tie Tomography an *accurate Time-Depth Conversion, GEOHORIZONS July 2014.*

Dekel Gali, Chase David, Paradigm Geophysical, Kowalski Henryk, Kobusinski Wojciech, Podolak Michal, Geofizyka Torun S.A., Q-compensation imaging in the local angle migrated domain for deep targets, Petroleum Exploration in the Subandean Basin, XII BOLIVARIAN Symposium, September, 2016.

Fabio Mancini, High Resolution time-to-depth conversion using 3D Grid Tomography, 23rd International Geophysical Conference and Exhibition, 11-14 August 2013 - Melbourne, Australia.

Hohn, Michael Edward, 1988, GeoStatistics and Petroleum Geology, Van Nostrand Reinhold, NY. Xu et al., 1992; Goovaerts, 1998.

Lior Liram, Yoav Naveh, Gali Dekel, Zvi Koren, Paradigm; Time preserving tomography, SEG Denver 2014 Annual Meeting, Page 4793- 4797. DOI http://dx.doi.org/10.1190/segam2014-0116.*

M S Rosid et al 2018 J. Phys.: Conf. Ser. 1120 012058, Estimation of Seismic Anisotropy Parameter and AVO Modelling of Field "G", Journal of Physics

Pavan Elapavuluri and John C. Bancroft; Estimation of Thomsen's anisotropy parameter, delta, using CSP gathers; CREWES Research Report — Volume 13 (2001) P.479-490.

Thomsen, Leon, Weak Elastic Anisotropy. Geophysics Vol.51 No.10, (October, 1986) P.1954–1966. DOI 10.1190/1.1442051.

Yanghua Wang, "Q Analysis on Reflection Seismic Data." Geophysical Research Letters 31.17 (2004).

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