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Kirchhoff Pre-Stack Depth Migration: effective tool for depth imaging

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Summary

Prestack Depth Migration (PSDM) is one of the most reliable seismic techniques for imaging subsurface structures because of its ability to focus and position reflections in areas with strong lateral velocity variations. The comparison between velocity sections obtained initially by velocity analysis in time domain on CMP gathers and the same obtained by horizon velocity analysis shows the latter to be more coherent and geologically meaningful. Techniques based on model ray tracing, such as coherency inversion allows more precise estimates of interval velocity to produce superior velocity models for PSDM. This paper is an attempt to study the methodology and application of Kirchoff PSDM through model based interval velocity estimation using coherency inversion technique followed by interval velocity depth model refinement using horizon based tomography and subsequent Pre-Stack Depth Migration. The CMP gathers of an arbitrary 2D seismic line and the Pre-Stack time migrated gathers generated from it were first analysed and by applying the above technique, PSDM sections showed considerable improvement in imaging the subsurface picture in this particular case suggesting that in structurally complex areas, this methodology can be suitably applied to derive much better geological result.

Introduction

Migration is a seismic data processing technique to map seismic events onto their appropriate positions (*Sheriff & Geldart, 1995*). Migration is done either in time domain or depth domain depending on the complexity of lithology. Time migration yields an inaccurate image in the presence of strong lateral velocity variation associated with complex overburden structure. In such a case, earth imaging is done by depth migration. Strong lateral velocity variation causes significant ray bending at layer boundaries, it gives rise to non-hyperbolic behaviour of reflection times on CMP gathers. As a result, amplitudes and travel times associated with the reflection events with non-hyperbolic moveout are distorted during conventional CMP stacking which is based on the hyperbolic moveout assumption. This causes CMP stack to depart from an ideal zero offset wave field. Therefore, when depth migration is needed, in principle, it is done **before stack** and not after stack (*Yilmaz, 2001*).

The first step in depth migration is to choose an interval velocity depth model. The quality of the depth image depends heavily on the input data, the inversion algorithm, and a chosen class of models (number of reflection interfaces, parameterization for interfaces, geometry and velocities within the layers etc). Both Time and Depth migration use a diffraction term for collapsing energy along a diffraction hyperbola to its apex, only the depth migration algorithms implement the additional **thin-lens term** that explicitly account for lateral velocity variation. The general workflow for pre stack depth migration (*Furniss***,** *2000*) is as given below:

- Stacking velocity analysis along time horizons
- RMS velocity analysis along time migrated horizons
- Stacking velocity refinement along time horizons
- RMS velocity refinement along time migrated horizons
- Interval velocity and depth model creation (coherency inversion)
- Interval velocity and depth model refinement and modelling (tomography)

Velocity Estimation

The simplest method for estimating layer velocities is Dix conversion of RMS Velocities (Dix, 1995). Dix Equation is based on the assumptions that the layer boundaries are flat and the offset range in estimating RMS velocities

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corresponds to small spread. Additionally, RMS Velocities used in the equation are based on straight ray assumptions thus ray bending at layer boundaries are not accounted for. Thus for a layered earth model with dipping layer boundaries and layer velocities with vertical and lateral variations, more accurate methods are required to estimate interval velocity such as Stacking velocity inversion or Coherency Inversion.

Coherency Inversion

Coherency inversion is a process to identify the interval velocity of a layer by using the propagation of ray tracing along the model of time gather space. Velocity estimation by coherency inversion provides a velocity-depth macro model of the subsurface (*Landa et al., 1988)*. The accuracy for this model is critical for imaging technique such as depth migration and inversion. At a given CMP, for a set of interval velocities, travel times are computed over a range of offsets based on ray tracing and compared with the actual travel time curve observed on the CMP gather. Best fitting curve as shown in Figure 1 identifies the proper interval velocity at a given CMP. A velocity depth model estimation using coherency inversion is conducted layer by layer starting from the surface. The interval velocity profile for the first layer H1 estimated from the Dix conversion is first adopted and then the application of coherency inversion is started with layer H2. Assuming that the velocity depth model for the first (n-1) layers already has been estimated, then for the nth layer, following are the steps to do *coherency inversion*:

1. Perform normal incidence travel time inversion to convert the time horizon corresponding to the base layer boundary to a trial depth horizon using a trial constant velocity assigned to the nth layer.
2. Compute CMP travel times of the nth layer for specific analysis location using the known overburden velocity depth model. The ray tracing is used to compute the travel times to account for ray bending at layer boundaries and incorporated vertical gradient within the layer above.
3. Semblance is then computed at each CMP location to measure the correlation between the recording CMP gathers and model travel times curves for each trial interval velocity value.
4. Pick the constant trial velocity as the nth layer velocity for which the semblance is maximum. The maximum semblance values describe the speed that makes the CMP gathers flat.

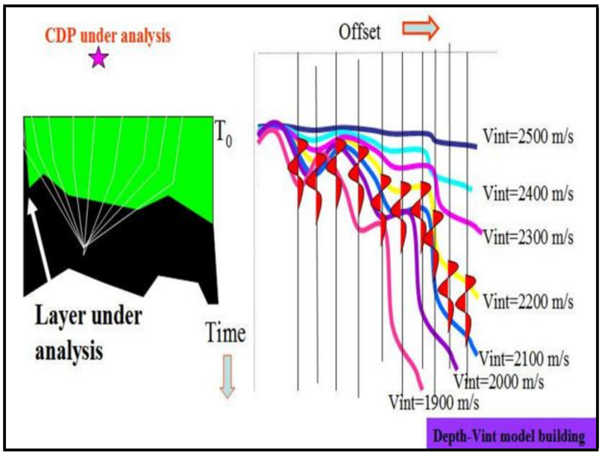


Figure 1 Principle of coherency inversion

Model refinement through Tomography

Tomography is based on the principle that if migration is carried out with correct velocity depth model, the image gathers should be flat i.e. event depth is same at all receiver (*Tian-wen Lo et.al, 1994*). It attempts to correct errors in the velocity depth model by analysing the residual delays after PSDM. Tomography of depth migrated gathers is a method for refining the velocity-depth model. When pre-stack depth migration is performed with an initial incorrect velocity model derived from inversion methods based on non-global approaches, the depth gathers will exhibit non-flatness. The degree of non-flatness is a measurement of the error in the model. Tomography uses this measurement of non-flatness (residual moveout) as input and attempts to find an alternative model, which will minimize the errors. The tomographic principle attributes an error in time to an error both in velocity and depth.

Tomography principle

Reflection travel time tomography is based on perturbing the initial model parameters by a small amount and then matching the change in travel times to the travel time measurements made from residual velocity analysis of image gathers (*Sherwood et al., 1986; Kosloff et al., 1996*). In the usual implementation of reflection travel time tomography, the model parameters are perturbed while preserving the offset value of the seismic data. The tomographic update ∆p to the model parameters that comprise the changes in the slowness and depths to layer boundaries is given by the generalized linear inversion (GLI) solutions (Eq. 1),

$$\mathbf{\Delta p= (LT\ L)\text{-}1\ LT\ \Delta t}\ldots\ldots\ldots\ldots\ (1)$$

Where ∆t denotes the column vector that represents the residual velocity move out times measured from the image gathers, L is a sparse matrix – Its elements are in terms of the slowness and depth parameters associated with the initial model and T denotes the matrix transposition.

Representation of the subsurface

An important issue which needs to be addressed before carrying out velocity analysis is the representation of the subsurface. In the **model based approach**, the subsurface is represented by formations which are separated by interfaces. Within each formation, the velocity is defined by a single valued velocity function of the form (Eq. 2)

$$V\ (x,y,z) = v0(x,y) + g(x,y) * z \qquad \ldots\ldots\ldots\ldots(2)$$

Where x and y represent the horizontal coordinates, and z is the depth. v0(x,y) and g(x,y) are the background velocity and the vertical gradient respectively. The model includes a representation of the reflecting surfaces. One type of model uses a layer-cake type formation sequence, where the depth of each interface is given by a function of the horizontal coordinates. A second approach uses a solid model with closed triangulated surfaces which is able to handle complex non layer-cake type structures. In the **grid based approach**, the subsurface is represented by a three dimensional velocity grid, where each grid point has an assigned velocity. For each type of subsurface representation there is a corresponding velocity determination technique. As for global methods; *model based tomography* updates a subsurface model, and *grid based tomography* updates a velocity volume. Due to non-uniqueness, the two approaches can yield quite different results. Model based approaches are based on generating a model from seismic interpretations and thus include geological information. Therefore, whenever possible, model based approaches should be preferred. However, there are situations with low quality data when it is difficult to define a model. Then the grid based approach is more applicable.

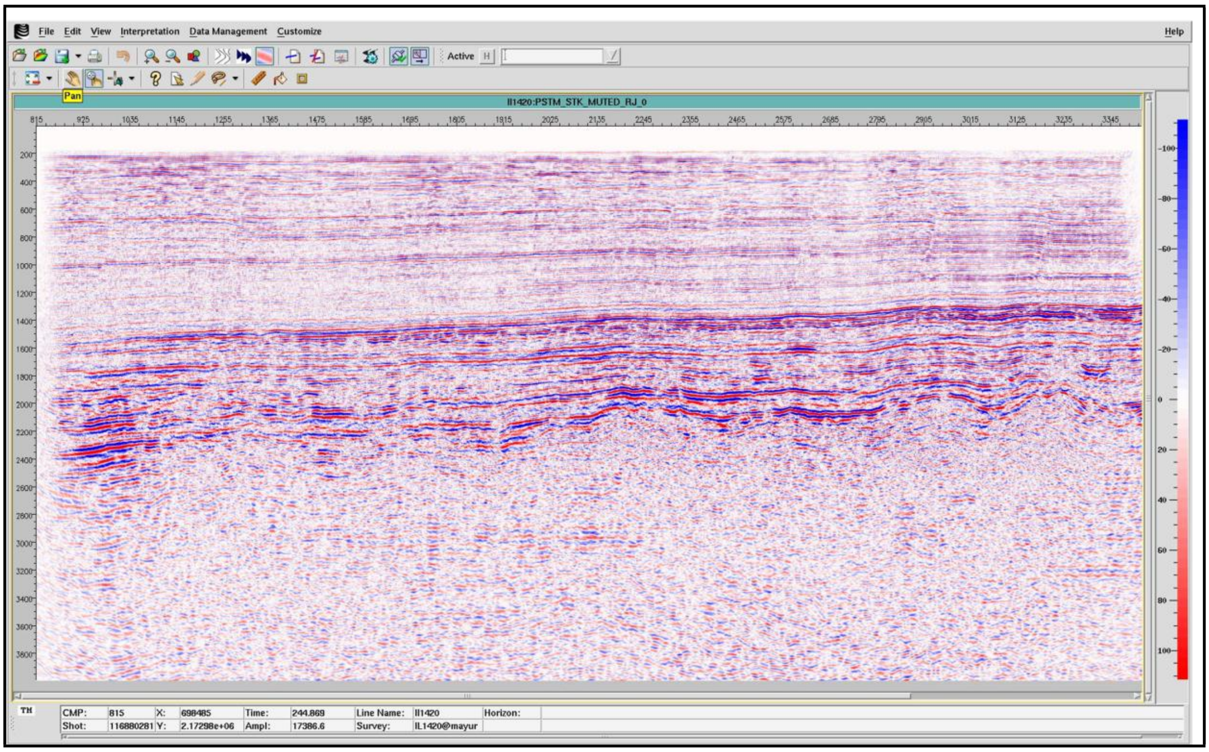
There are situations where it is best to carry out part of the analysis with a model based approach and another part with a grid based approach. For example, in many cases it is possible to build a model for the upper formations, but the lower reflectors are not clearly interpretable across the section. In such a situation it may be appropriate to use a model based approach for the upper formations first, and use a grid based approach for the deeper formations afterwards. A typical update grid size is 50 CMP spacing's in the horizontal direction, and 200m in the vertical direction. Within each grid cell, the slowness updates are interpolated to the original velocity section sampling increments by bilinear interpolation. This interpolation assures smooth updates and avoids over parameterization beyond the resolution of the seismic data.

Case study

CMP gather data along a 2D seismic line with their RMS Velocity Model was used to perform Pre-Stack time Migration to get a preliminary subsurface image (Figure 2) and RMS velocity (Figure 3). To get more accurate image, PSDM was performed.

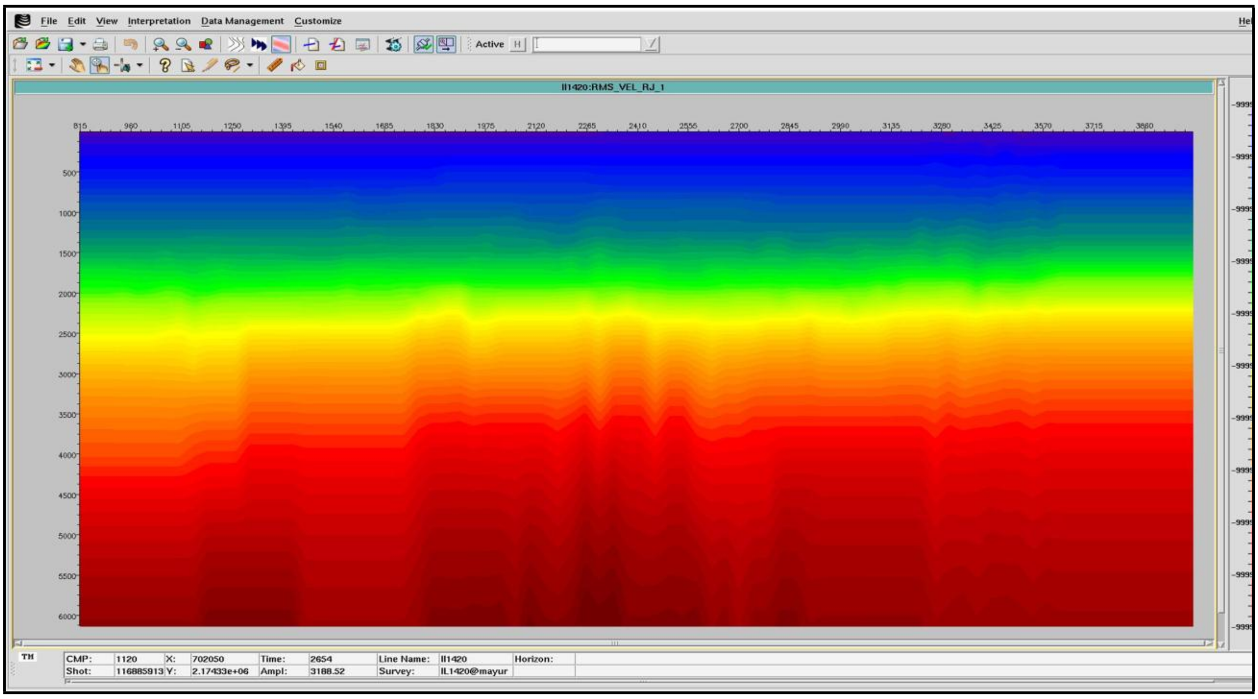
Dix conversion is valid only for horizontally layered earth models with constant layer velocities and small offsets, which is not the case here so coherency inversion was performed to get true interval velocities for each horizon. A total of 7 Horizons were picked on PSTM section with the help of seismic marker. For each horizon (H1-H7), coherency inversion on CMP gather was performed to get Horizon layer velocity. Coherency Inversion for horizon 2 is shown in Figure 4, where we can see the CMP raypath tracing at a particular analysis location (yellow colour), their corresponding CMP gathers and horizon-velocity semblance spectrum (maximum in red colour).

Interval velocity section was generated with the help of coherency inversion for the area shown in Figure 5. Now Prestack depth migration using Kirchhoff's algorithm was carried out with the below depth interval velocity model and time gathers as input. Here Quality control is required whether our depth migrated gathers are flat or not after PSDM. The output depth gathers were stacked separately after proper mute as shown in Figure 6. The depth migrated gathers were observed to be still not perfectly flat at larger offsets, so further refinement in interval velocity model was needed. To increase the reflection flatness in depth gather, residuals were picked for each of the horizons and the depth interval velocity model was updated using horizon based tomography and final interval velocity was generated. With this updated interval velocity and depth model, PSDM was carried out. The resulting depth gathers were found to be flat and the corresponding depth section shown in Figure 7, showed improved structural features with better standouts of the events in the zone of interest.



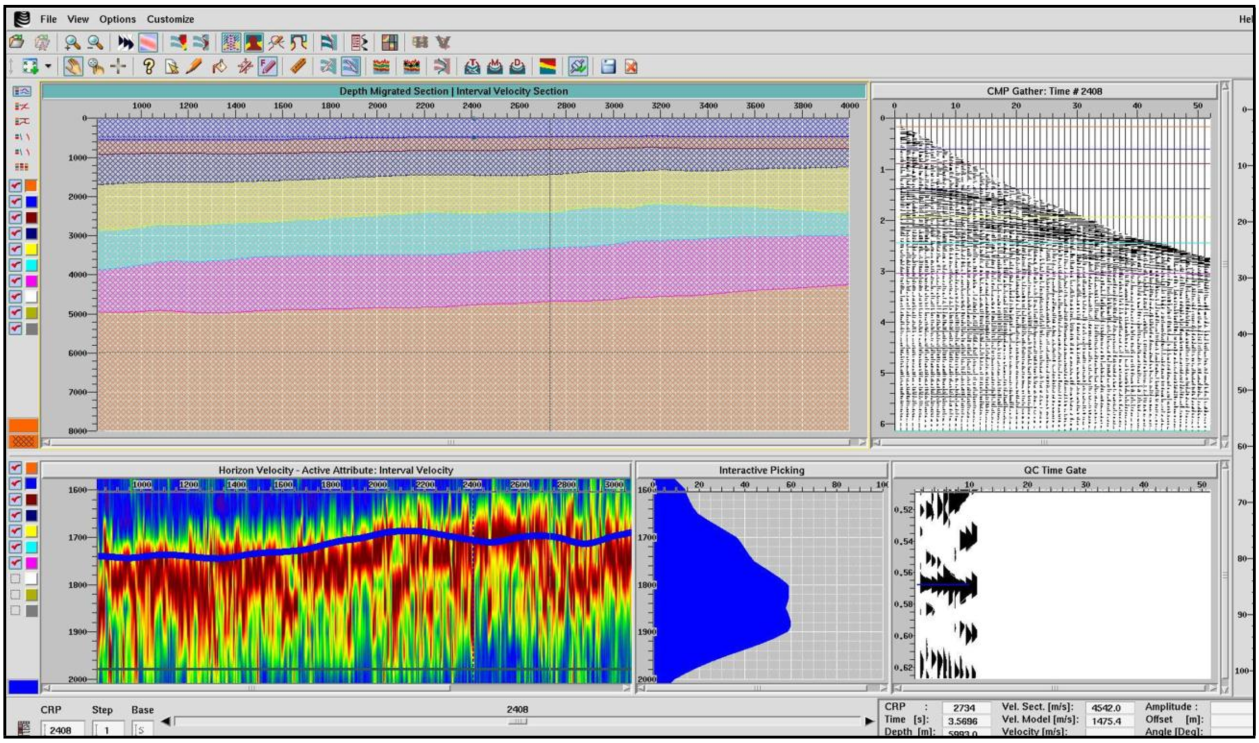
CMP: 815
X: 698485
Time: 244.869
Line Name: Il1420
Horizon:
Shot: 116880281
Y: 2.17298e+06
Ampl: 17386.6
Survey: IL1420@mayur

Figure 2 PSTM Stack data along a 2D seismic line



CMP: 1120 X: 702050 Time: 2654 Line Name: Il1420 Horizon:
Shot: 116885913 Y: 2.17433e+06 Ampl: 3188.52 Survey: IL1420@mayur

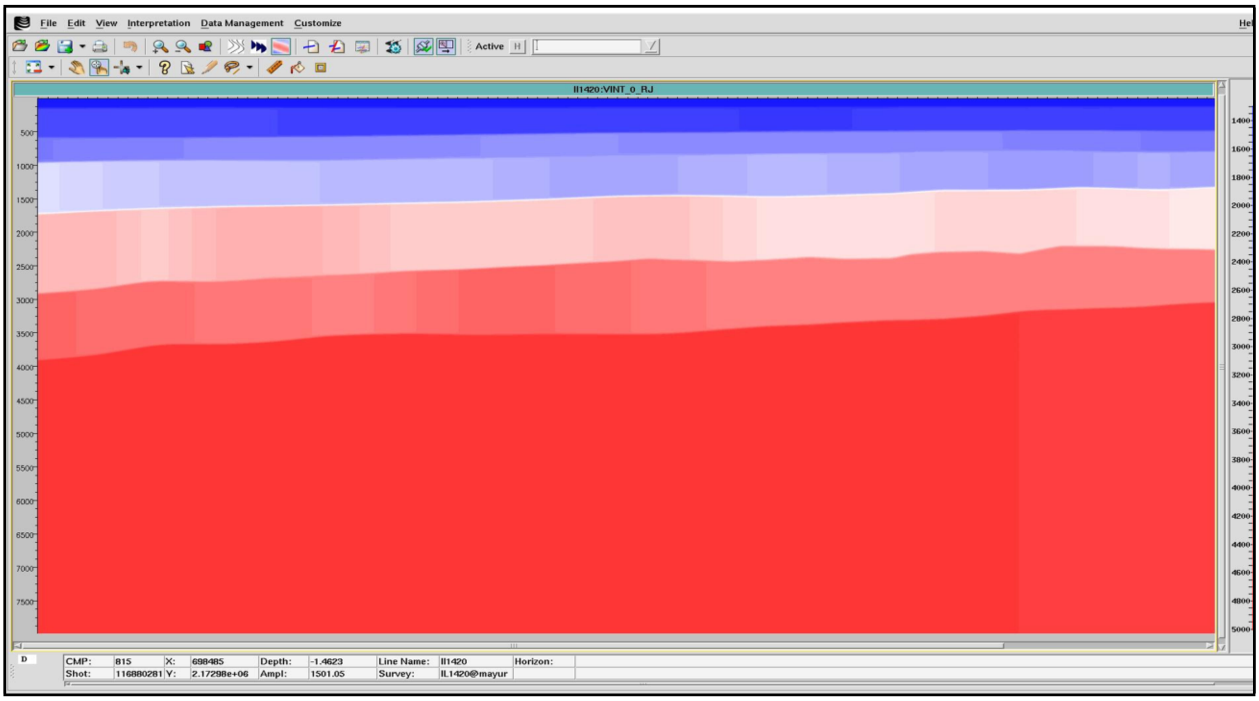
Figure 3 RMS Velocity Model



CRP: 2408 Step: 1 Base: 5
2408

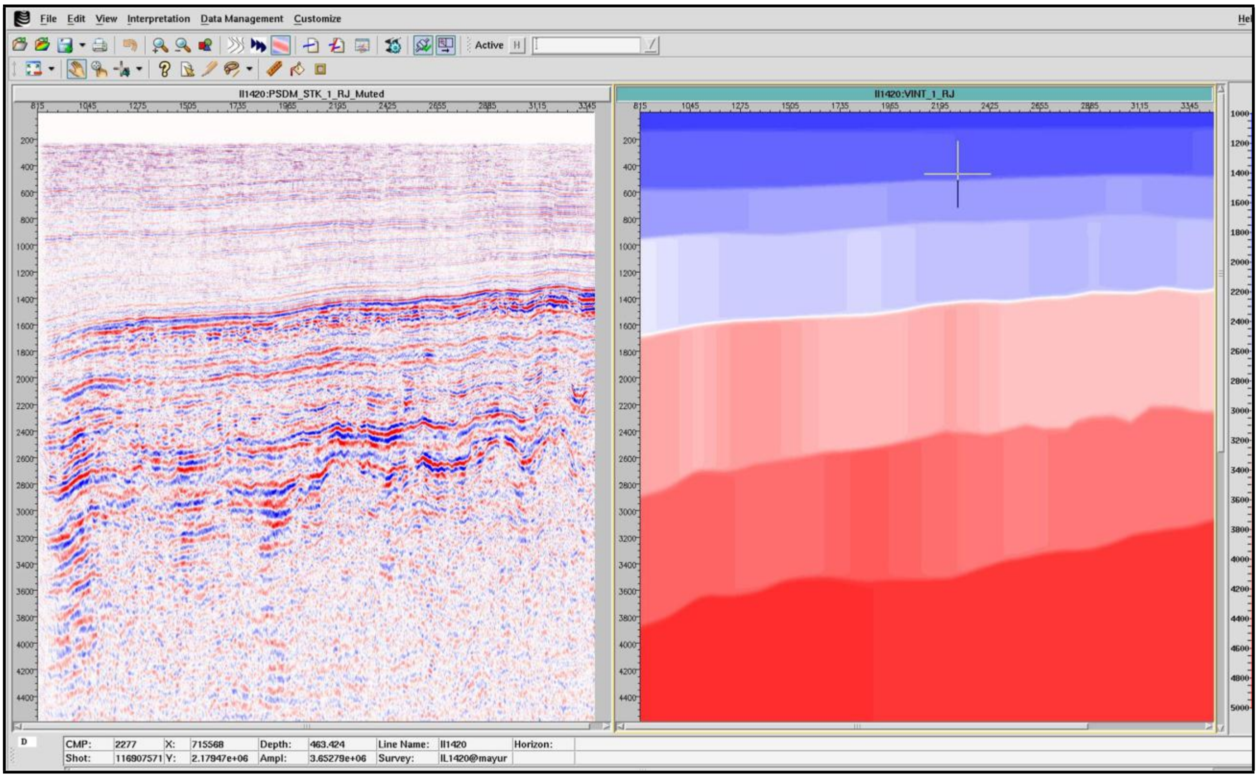
CRP : 2734 Vel. Sect. [m/s]: 4542.0 Amplitude :
Time [s]: 3.5696 Vel. Model [m/s]: 1475.4 Offset [m]:
Depth [m]: 5993.0 Velocity [m/s]: Angle [Deg]:

Figure 4 Coherency Inversion for Horizon 2 using GeoDepth Software



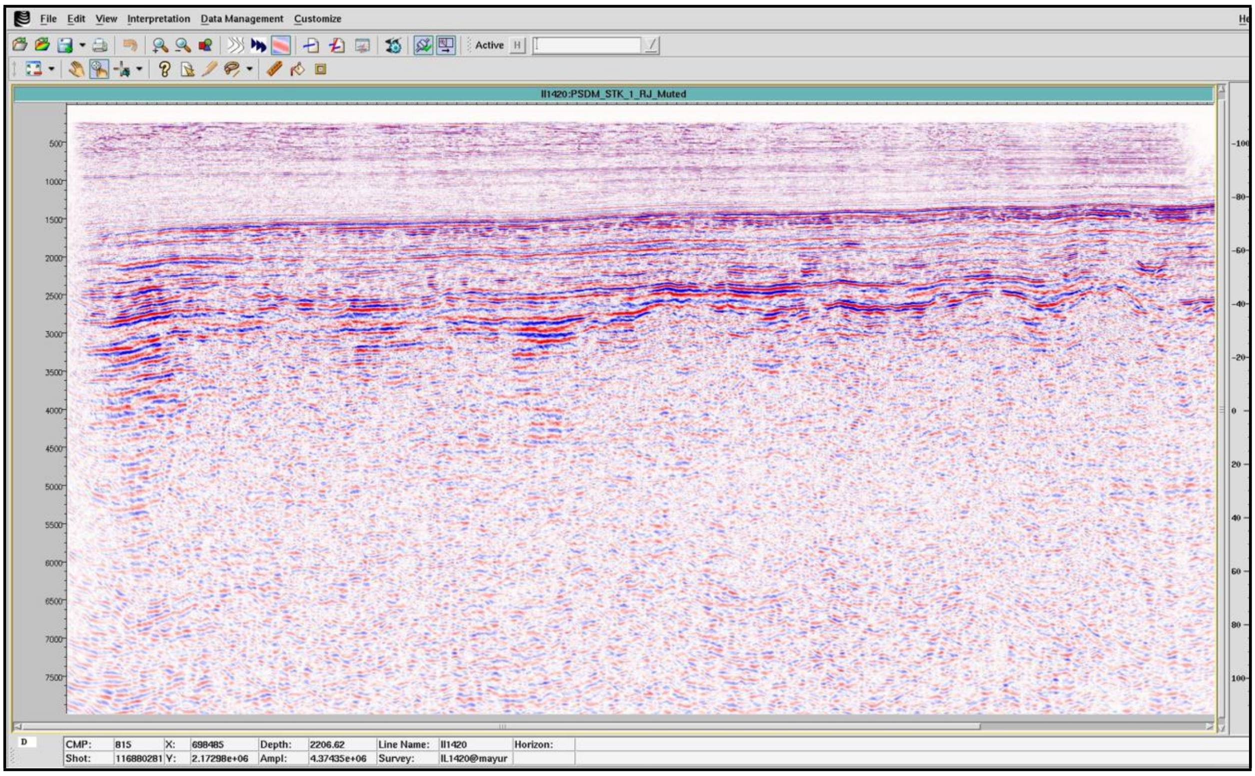
CMP:	815	X:	698485	Depth:	-1.4623	Line Name:	Il1420	Horizon:
Shot:	116880281	Y:	2.17298e+06	Ampl:	1501.05	Survey:	IL1420@mayur	

Figure 5 Interval Velocity Model generated by coherency Inversion



CMP:	2277	X:	715568	Depth:	463.424	Line Name:	Il1420	Horizon:
Shot:	116907571	Y:	2.17947e+06	Ampl:	3.65279e+06	Survey:	IL1420@mayur	

Figure 6: Prestack depth migrated stacked section and interval velocity section after coherency inversion



CMP: 815 X: 698485 Depth: 2206.62 Line Name: Il1420 Horizon:
Shot: 116880281 Y: 2.17298e+06 Ampl: 4.37435e+06 Survey: IL1420@mayur

Figure 7 Final Depth Stacked Section after horizon based tomography

Conclusions & Recommendations

1. Pre Stack Time Migration can effectively image subsurface features when geology is not complex and there are no lateral velocity changes.

2. Pre Stack Depth Migration is the most efficient method to image subsurface when there is structural complexity as well as lateral velocity variation.

3. For building a depth interval velocity model, the ray tracing technique instead of usual conventional Dix's approach should invariably be used.

4. To take this work further, an attempt can be made to find a better algorithm than coherency inversion which requires less labour and gives more accuracy in the interval velocity model. Velocity estimation with null space (Clapp, 1998) or interval velocity estimation using edge preserving regularization (Valenciano, 2004) may be helpful to start with a new algorithm.

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