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Thrust Belt Imaging: Challenges and their possible solutions with special reference to Upper Assam Basin

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Introduction

Folded thrust belt (FTB) developed at convergent plate boundaries contributes around 14% of the world's discovered hydrocarbon reserves and it is estimated that about 15% of the total undiscovered hydrocarbon resources lie in the folded thrust belts (USGS, 2000). Among others, Naga thrust belt, situated in Assam Arakan Basin is one of the highly prospective folded thrust belts for hydrocarbon provinces. Naga thrust belt is a narrow, elongated zone of imbricate thrusts about 20 to 35 km wide, extending for about 200 km in NE-SW direction (Fig.1). Though, Upper Assam basin is one of the mature basin in context of hydrocarbon exploration & production, most of the exploration activities are limited to the foreland part of the basin. The seismic exploration in folded thrust and over thrust regions of the basin is hindered due to tough logistics, lack of accessibility and most importantly technological limitations. Apart from the illumination issues, subsurface image in most of the vintage 2D seismic lines suffer due to limited understanding of the thrust belt geology. The complex surface, near-surface and subsurface geological structures necessitate to pay special attention during the data processing stage.

Challenges in Thrust Belt Exploration

Folded thrust belt contains steeply dipping layers with significant horizontal & vertical velocity variation. Manifestation of complex geological structures can be seen on the surface as well. This particular set-up of dipping layers exhibits inherent anisotropy with tilted axis of symmetry (Tilted transverse isotropy, TTI) (Fig.2). Thus, the conventional approach for seismic data acquisition and seismic imaging assuming isotropic layers does not hold true in thrust belt environments.

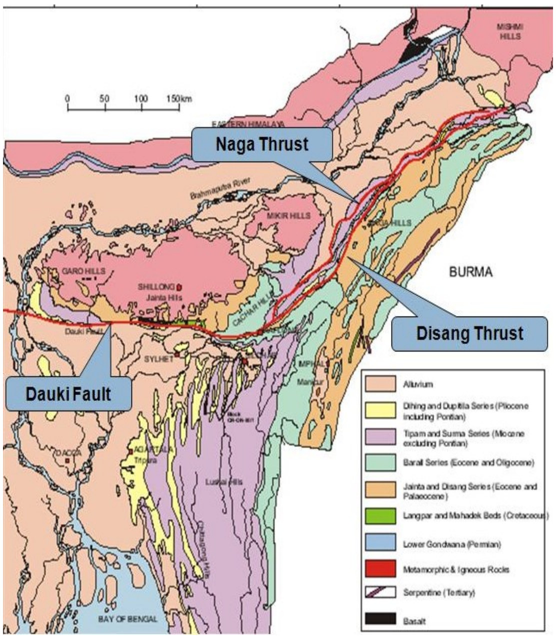

Figure 1: Lateral extension of Naga thrust belt. Challenges in Thrust Belt Exploration

Most of the vintage seismic data acquired with the limited channel counts due to technological limitations could not illuminate the thrust belt areas properly and moreover the sub-surface image quality suffered due to limited application of conventional processing and imaging algorithms (Fig.3).

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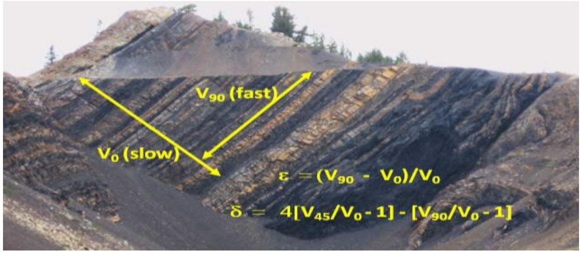

Figure 2: The steeply dipping layers with significant horizontal & vertical velocity variation exhibits inherent anisotropy (TTI).

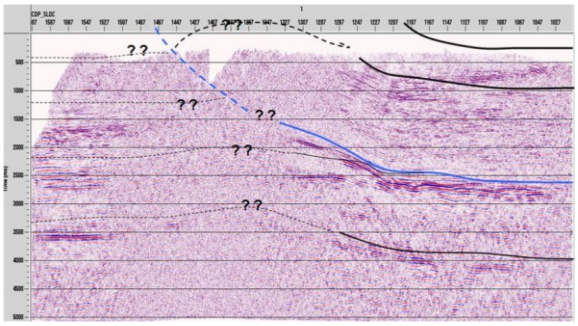

Figure 3: Sub-surface image quality suffered due to limited application of conventional processing and imaging algorithms in thrust-belt

The challenges during imaging of thrust belt can be categorized as follows:

Survey Designing Challenges

The complex surface and subsurface geological structures restrict the reach of the seismic waves, resulting limited seismic illumination in the folded thrust belt. The complex geological structures in the Naga Thrust belt could not be illuminated properly either due to acquisition constraints or imaging issues. The limited offsets in the vintage seismic data and the conventional imaging algorithms are found insufficient for proper illumination in these regions. The recent advancements in the seismic instrumentation offer to acquire densely sampled long offset seismic data, which enhances the illumination of unseen subsurface. Model based seismic data acquisition approach in folded thrust belt areas is felt essential for ingenuous assessment of the subsurface delineation; subsequently target oriented survey designs are required (Blangy, 2002).

Near Surface Challenges

Like most of the FTB worldwide, Naga Thrust belt shows the surface manifestation of complex geological structures, and hence results undulating topography and complex near surface velocity structures. In order to image the deeper structures accurately during seismic reflection processing, the knowledge of the near-surface layers is essential. The anomalies in near surface velocity determination distort the image of subsurface and decrease the integrity of the deeper structures as well. The irregular topography and complex near surface structures distort the near surface ray paths severely and the conventional algorithms for static correction which assume the vertical near surface ray-paths are not valid (Berryhill, 1979; Beasley and Lynn, 1992).

Velocity Analysis/Modeling Challenges

Imaging in the folded and steeply dipping layers with significant lateral and vertical velocity variations require appropriate migration algorithm and accurate velocity modeling. The conventional algorithms of velocity analysis assume the isotropic subsurface and their application is limited to the analysis of hyperbolic move-out over a shorter spread length. Since, the two term hyperbolic normal move out (NMO) equation loses its accuracy with induction of anisotropy (Thomsen and Tsvankin, 1994), the determination of velocity in most of the vintage thrust belt data, suffers due to very limited resolution of the derived semblance compared with the foreland part (Fig.4).

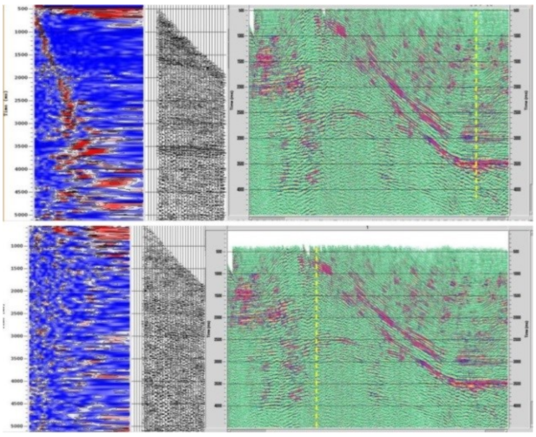

Figure 4: The resolution of derived semblance deteriorates severely towards thrust region, and the accuracy of determined velocity is limited compared with foreland part.

The steeply dipping layers with significant lateral velocity variation in the folded thrust belts cause azimuthally anisotropy (TTI) media and the reflection move-outs are azimuth dependent and non hyperbolic in nature (Alkhalifah and Tsvankin, 1995). Thomsen's anisotropic parameters (ε & δ) are the two important parameters, which describe the behavior of the seismic velocities in anisotropic media (Thomsen, 1986). The exact move-out equation in TTI media includes the higher term in the two-term equation, where the coefficient of the higher term is described in terms of the Thomsen's anisotropy parameters (Pech and Tsvankin, 2004). Alkhalifah & Tsvankin (1995) concluded that the fourth order coefficient may be described by single anisotropy parameter, i.e., anellipticity parameter (η), which in fact depends on the difference of the Thomsen's anisotropy parameter. Inversion of dip-dependence of normal move-out velocity provides the anellipticity parameter (η) and describes the long-spread (non-hyperbolic) move-outs but it cannot resolve the vertical velocity and anisotropic coefficients individually. The accurate modeling for anisotropic velocity fields in terms of vertical velocity and anisotropic coefficients require essentially for imperative depth imaging in the folded thrust part of the Upper Assam basin.

Imaging Challenges

The complex geological structures and significant velocity variations necessitate the depth migration before stack (PreSDM) (Schultz and Sherwood, 1980) in order to get superior image of the folded thrust region of Upper Assam Basin. Depth migration handles the significant lateral and vertical velocity variations in the subsurface precisely. The conventional depth migration algorithms were designed for the isotropic medium and the dipping anisotropic layers in fold and thrust belts miss-positions if not corrected for anisotropy during migration (Larner and Cofen, 1993). Anisotropic depth migration in thrust-belt environments provides the most accurate lateral positioning of reflection events (Fig.5) and hence provides better image of the subsurface (Ball, 1995; Vestrum et al., 1999). The irregular acquisition geometry, rough topography and limited energy penetration complicates the imaging in folded thrust belt.

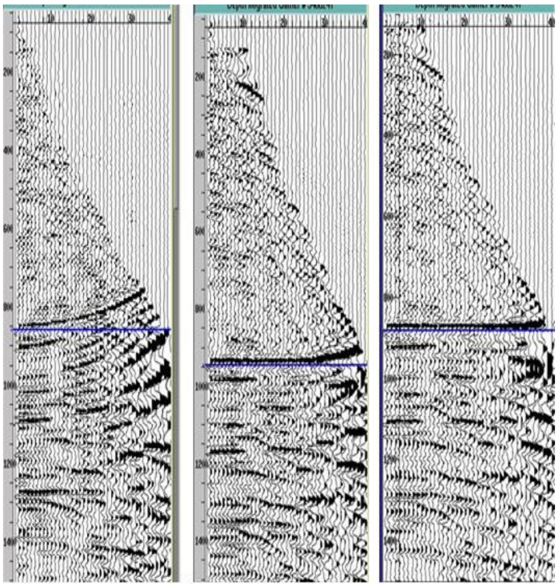

Figure 5: Pre-stack migrated gathers a) Pre stack time migrated Gather; b) Pre-stack depth migrated gathers c) Anisotropic pre-stack depth migrated gathers.

Promising Solutions

The exploration activities in the Naga Thrust Belt regions started long back and a number of geo-scientific studies including 2D & 3D seismic investigations are accomplished (Fig.6). Most of acquired vintage 2D seismic lines along and across the thrust belt need to be re looked for better imaging of the underlying subsurface.

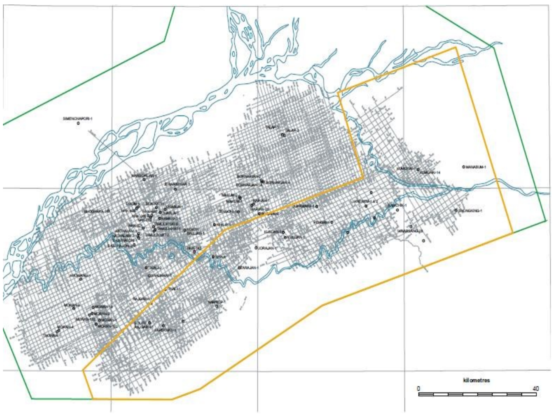

Figure 6: Seismic Data Coverage over Naga Thrust Belt

The surface manifestation of Naga thrust belt results undulating topography and complex near surface velocity structures and high resolution near surface velocity model is required essentially for accurate static calculations. Since, seismic reflection signals contain little information about the near surface due to low trace density; near surface velocity model is required to derive by first arrival tomography (Stefani, 1995). The first arrivals (i.e. direct & refracted waves) will be picked along the seismic profiles and multi-scale seismic waveform inversion (Bunks et al., 1995; Ravaut, 2004) of the first arrival will produce a high resolution near-surface velocity model. Jaiswal et al. (2009) have performed this study in some selected seismic profiles across the Naga thrust belt and derived the velocity model along the seismic profile; this study needs to be extended by performing multi-scale seismic waveform inversion of first arrivals on various 2D seismic profiles along & across the folded thrust belt to get a regional scale near surface velocity model of thrust belt of Upper Assam basin.

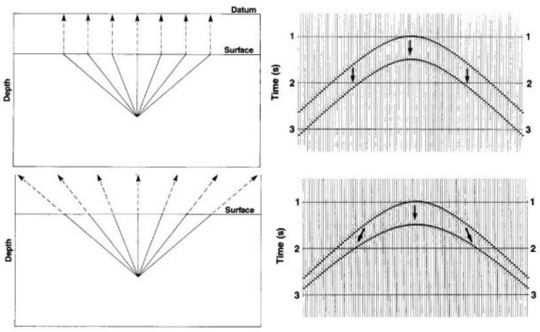

Figure 7: Non-vertical near surface ray path of seismic waves in case of high velocity contrast between weathering and sub-weathering layer.

The conventional methods of static calculation assume the vertical near-surface wave-path, which is not true in thrust-belt environment (Fig.7); wave equation datuming (Berryhill, 1979) for precise imaging of near surface layers must be preferred, which in turn will assure the improved imaging and enhanced integrity of the deeper subsurface layers. During the process of wave equation datuming the migration should be done from surface (Gray & Marfurt, 1995) with zero layer velocity replacement between the surface and datum (Lines et al., 1996).

The low energy penetration, low multiplicity, and low S/N ratio in vintage seismic data in folded thrust belt makes the conventional velocity analysis procedure using the semblance curves very vulnerable. Waveform inversion of the reflection travel times (Murphy and Gray, 1999) is one of the plausible approaches to derive better velocity model.

Though, most of the vintage data contain limited offsets, in order to get anisotropic velocity fields, the travel times may be inverted using non-hyperbolic moveout equations (Thomsen and Tsvankin, 1994; Kumar et al. 2004). The anisotropic velocity field is required essentially to avoid the miss-positioning during depth imaging. Since the vintage seismic dataset contains PP reflection only (not multi-component data), exact decomposition of anisotropic parameters is possible only with sufficient well control (Bakulin et al., 2010) during inversion process. The other alternatives for the determination of anisotropic parameters are the walk-away VSP and cross-hole tomography. Leslie et al. (1999) illustrated the determination of anisotropic parameters from refraction events. Focusing analysis (He et al. 2009), which includes the determination of migration operator followed by translation of migration operator into velocity depth model is another approach for anisotropic velocity modeling. Issac and Lawton (2004) derived the anisotropic velocity model based on the smear differences between near and far offset data.

The feasibility & results of various techniques for determination of anisotropy parameters in Naga thrust belt and subsequently various migration algorithms should be investigated for imaging performance.

Lastly, with the derived velocity model of the Naga thrust belt, ray trace modeling study to understand the limitation of illumination and consequently design for 3D seismic data acquisition is desired.

Conclusion

The sub-surface image of Naga thrust belt could not be illuminated properly due to complex surface and sub-surface structures. The incorporation of wave equation datuming, determination of velocity through travel time inversion, estimation of anisotropy and anisotropic pre-stack depth migration during seismic data processing can improve the image of the subsurface. The regional scale velocity model must enhance the future understanding of the thrust belt and the improved images along various profiles of the thrust belt will allow re-looking the hydrocarbon potential zones.
An improved regional velocity model can assist to understand the elimination limits, and, consequently, a

model based 3D seismic data acquisition for superior delineation of subsurface structures is desired for future exploration activities.

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