Imaging challenges and mitigations in the Tripura Fold Belt areas for reservoir characterization and hydrocarbon prospecting

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ABSTRACT

Even though there have been substantial advancements in seismic data acquisition and processing, imaging in structurally complex regions like fold belts has seen only marginal improvement. In such geologically intricate areas, the conventional imaging approach may not yield satisfactory results. While 3D surface seismic surveys are preferred, acquiring 3D seismic data can be challenging due to logistical constraints. Moreover, the rugged terrain and difficult accessibility in these areas make 3D land seismic data acquisition prohibitively expensive. Conventional 2D land seismic data also has limitations, particularly in accurately imaging anticlinal features. An alternative to traditional 2D surveys in such contexts is the swath-line recording geometry. Swath-line recording offers significantly higher fold (720-fold in the present case), compared to typical 2D land surveys, resulting in data with an improved signal-to-noise ratio. However, several issues adversely impact imaging quality in thrust fold belts. Key factors affecting the quality of processed outputs include geometry, statics, and poor signal-to-noise ratio. Survey objectives may remain unmet unless these factors are addressed or minimized. We utilized a hybrid approach, combining multiple techniques including geometry corrections, nonlinear tomography-based statics solutions, velocity estimation using the CVS method, and leveraging different software suites and algorithms to address these inherent challenges.

Keywords: Tripura Fold belt, Swath-line, CMP line, S/N ratios, Semblance, Constant velocity stack method (CVS), PSTM

INTRODUCTION

Various factors negatively impact the quality of imaging in thrust fold belts. These include geometry, statics, and a poor signal-to-noise (S/N) ratio. Unless these issues are minimized or eliminated, the objectives of the survey may not be achieved. Moreover, processing parameters are highly sensitive to such complex data if the necessary remedies for the aforementioned factors are not considered. Therefore, a systematic approach is crucial to address these inherent problems. The fundamental prerequisites for a good seismic image include a good S/N ratio, a suitable and geologically compatible near-surface model for accurate statics calculation, a good subsurface velocity model, and the best imaging algorithm that fits the geological condition. However, processors in fold belt areas often face challenges in obtaining these processing ingredients easily, leading to significant challenges in processing. Efforts are made to address these major challenges and issues to achieve better data quality. However, no amount of processing effort can fully replace the importance of acquisition efforts. Despite advancements in seismic data processing and acquisition, the improvement in imaging in structurally complex areas like fold belts has been marginal. Traditional imaging methods have not yielded satisfactory results in such geologically complex locations. While 3-D surveys are preferred in these areas, collecting 3-D land seismic data is not always feasible or economical due to issues such as difficult terrain and limited accessibility. The limitations of conventional 2-D land seismic data become especially apparent in fold belt areas, where accurately capturing the anticlinal section can be a challenge.

The aim of the present study is to devise a workflow specifically for the Tripura fold belts, making use of the existing legacy seismic data in our area of study. We are concentrating on tackling various challenges that affect image quality, such as geometry, statics, noise, velocity, and algorithms. When it comes to new data acquisition, our approach is to gather high-quality seismic data using innovative geometry, while taking into account the logistics, scheduling, and cost-effectiveness of fold belt operations. We investigate the viability of 2-D swath-line geometry as a potential solution for the Tripura fold belt region, and present a comparative discussion on the acquisition, processing, and results with traditional 2-D methods in our case study.

STUDY AREA

The Assam and Assam Arakan basin is an onshore basin situated in the north-eastern part of India and has been categorized as a Category-I basin (Rajkhowa et al.,2018). On the basis of morphological characteristics, the Assam and Assam-Arakan basin (A&AA Basin), is subdivided into a foreland and a fold belt. The foreland comprises of area including the Brahmaputra arch and it's southern and northern slopes and is commonly known as Upper Assam Shelf North (UAN); the area encompassing the south eastern slope of Shillong and Mikir Massifs is commonly known as Upper Assam Shelf South (UAS). The A&AA Fold Belt comprises the Naga Schuppen Belt and sigmoidal en-echelon folds of Tripura-Cachar-Fold Belt.

The geomorphology of fold belt is typified by a succession of hill ranges and valleys of meridonial and sub meridonial trends (Dasgupta and Biswas, 2000). The height of these ranges varies from 200 to 500 m. The general elevation increases to the east in the region. Fold-belt has complex evolution history and characterized by series of parallel, elongated and doubly plunging, asymmetric anticlines arranged in en-echelon pattern and separated by wide and narrow synclines like Khowai and Baramura, with the general trend of the anticlines being NNW - SSE to N-S with slight convexity towards west and longitudinal faults bounding the flanks. The intensity of folding increases towards east with progressively older rocks being exposed in the cores of the anticlines. Our study focuses on the Baramura anticline, located in the western Tripura Fold Belt (Figure 1).

Baramura field located in this area is an asymmetric doubly plunging anticline trending roughly north-northeast-to-southwest. Tectonically, Baramura falls in the frontal folded belt of Tripura, which is the western continuation of the Surma Valley folded belt. The eastern flank of Baramura structure has been affected by a westward dipping thrust and with the main hydrocarbon potential falling in Bokabil and Upper Bhuban formations of Miocene age (Chattopadhyay and Ghosh, 2006). Fold belts are regions where the Earth's crust has been deformed and folded due to tectonic forces. These areas are significant for petroleum exploration due to their complex geological structures, which can create traps for hydrocarbons. (Figure 2) depicts the Tripura fold belt area's stratigraphy and petroleum system.

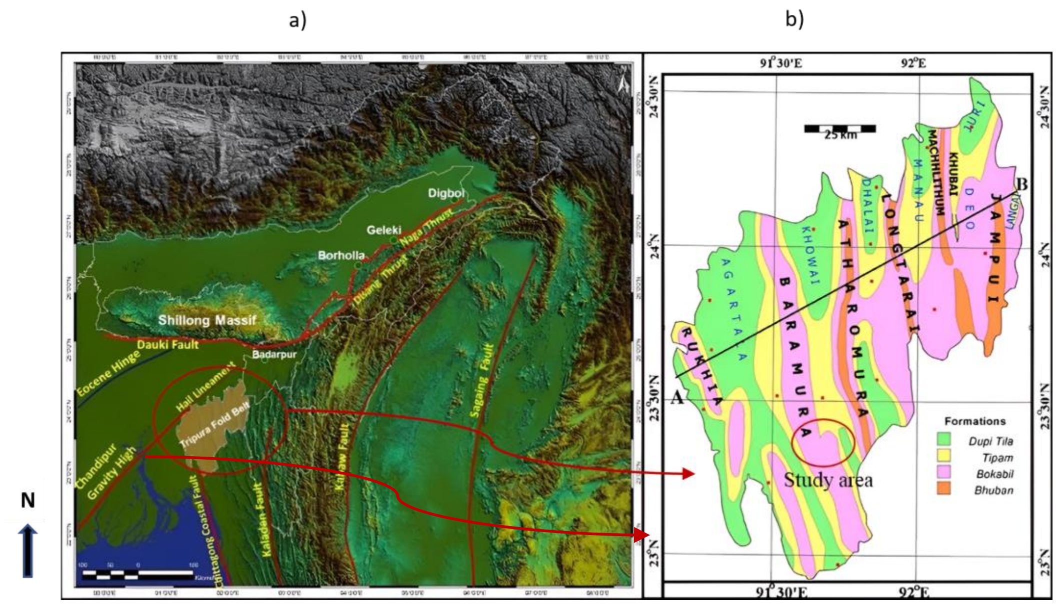

Figure 1. Location of the study area in Tripura, India. **(a)** Regional tectonic elements of Tripura Fold Belt and adjoining areas on Digital Elevation Model (DEM) (after Samal et al., 2017) and **(b)** Alternative anticlines and synclines of Tripura (after Bandyopadhyay et al., 2013)

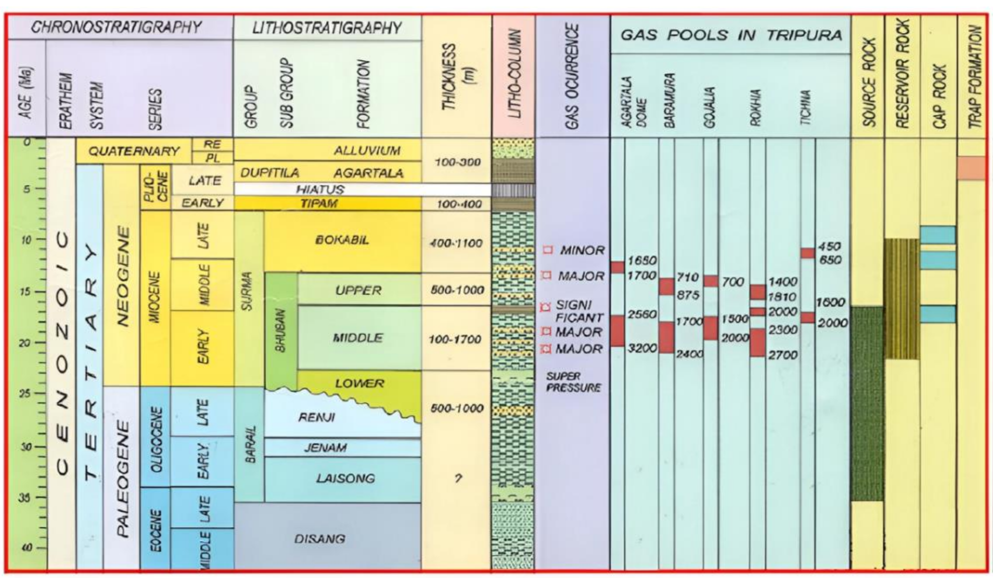

Figure 2. Generalized stratigraphy of Tripura Fold Belt (after Brahma and Sircar, 2018).

METHODOLOGY

To establish a fold belt-friendly workflow, several seismic legacy data from nearby study areas have been reprocessed with several quality checks. The effectiveness of this approach is evident in addressing various challenges related to image quality, including geometry, statics, noise, velocity, and algorithms.

Geometry QC

Difficult logistics leads to relocation of shots/receivers from planned pickets and if it's not updated properly such positional errors leads to incorrect geometry merging and further leads to wrong CMP and offsets computation. These issues require proper reconciliation, every shot record needs to be viewed and checked for correct coordinate assignment. Misplaced shots must be relocated to its correct position, shot by shot, interactively. This problem is commonly observed while reprocessing vintage data. Hence, these should be checked during merging, (Figure 3) shows the correction of shot position and its effect.

Solution for statics corrections

In conventional processing scenario, statics applied on the geometry merged gather are actually supplied by field crews and derived on the basis of near surface model estimated using sparse uphole data or shallow refraction survey. But in case of fold belt data in areas like Tripura; Assam and Assam Arakan Basin, this is no longer valid due to highly undulated acquisition surface and complex near surface geology (Berryhill, 1979; Beasley and Lynn, 1992, Bhartee et al., 2022).

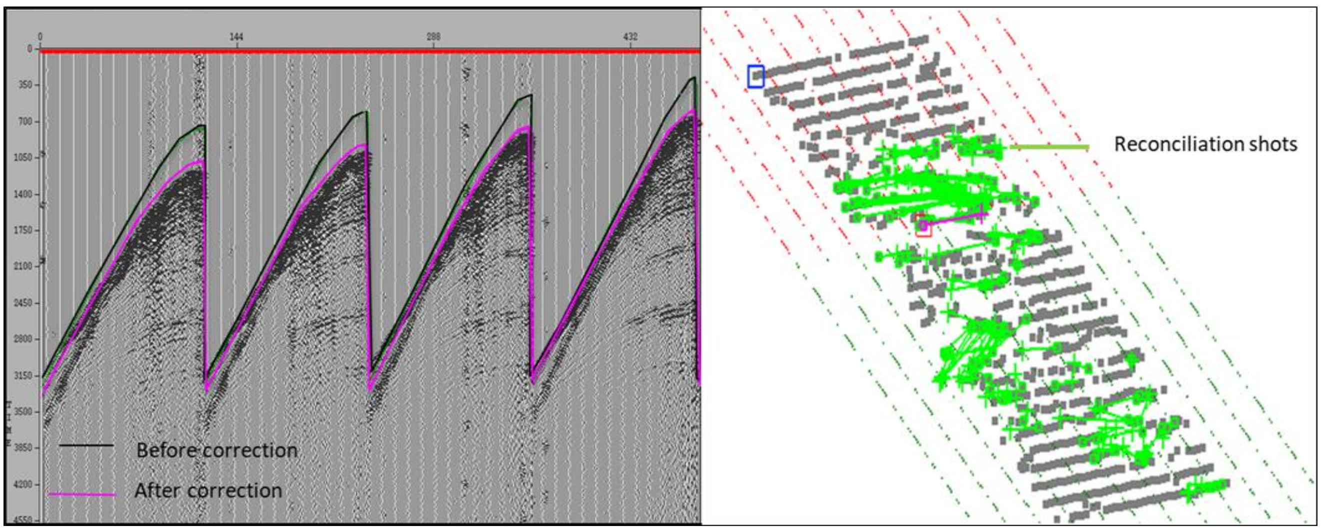

Figure 3. Example of shot point correction on a legacy 3D data from study area.

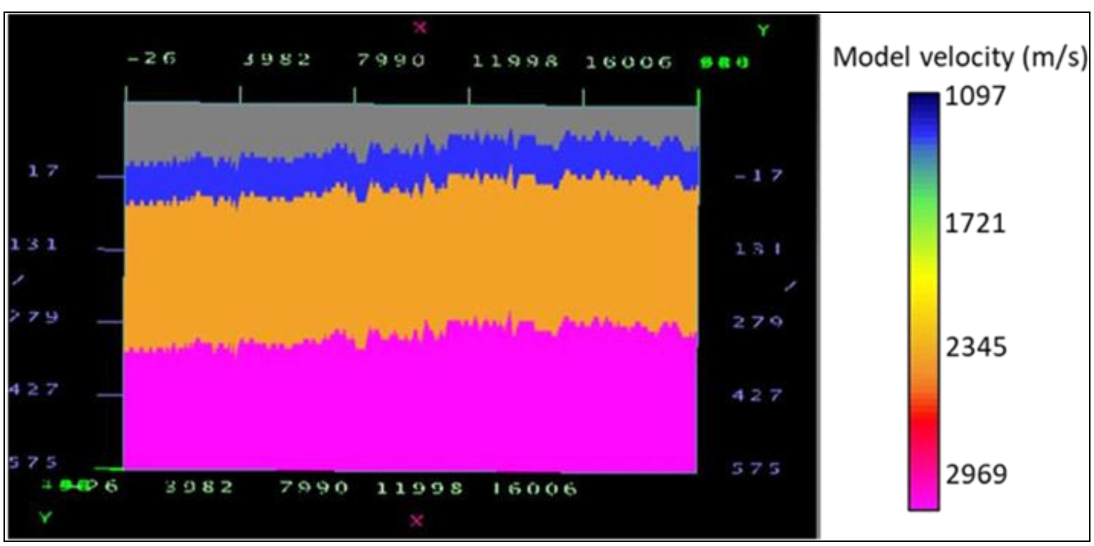

Figure 4. A workstation screenshot showing the initial near-surface velocity model used for computation of refraction statics.

First arrival turning ray tomography (Zhang and Toksoz, 1998: Zhu et al., 2000) also called nonlinear tomography (Tomostatics) based static solutions are more beneficial for deriving both weathering statics as well as near surface velocity model for proper imaging. Tomostatics is an iterative algorithm designed to minimize the difference between observed and predicted first arrival travel times, based on a user-supplied initial near-surface model (Figure 4). Observations suggest that in fold belt areas, Conventional field statics often fail to produce geologically plausible near-surface models. Conversely, tomostatic-derived models tend to provide a more accurate fit. The efficacy of the tomostatics in fold belt areas are shown on gather level in (Figure 5) and stack level in (Figure 6). It is easily understood that the meaningful seismic events have been shaped after application of tomography-based refraction static solutions for near surface model.

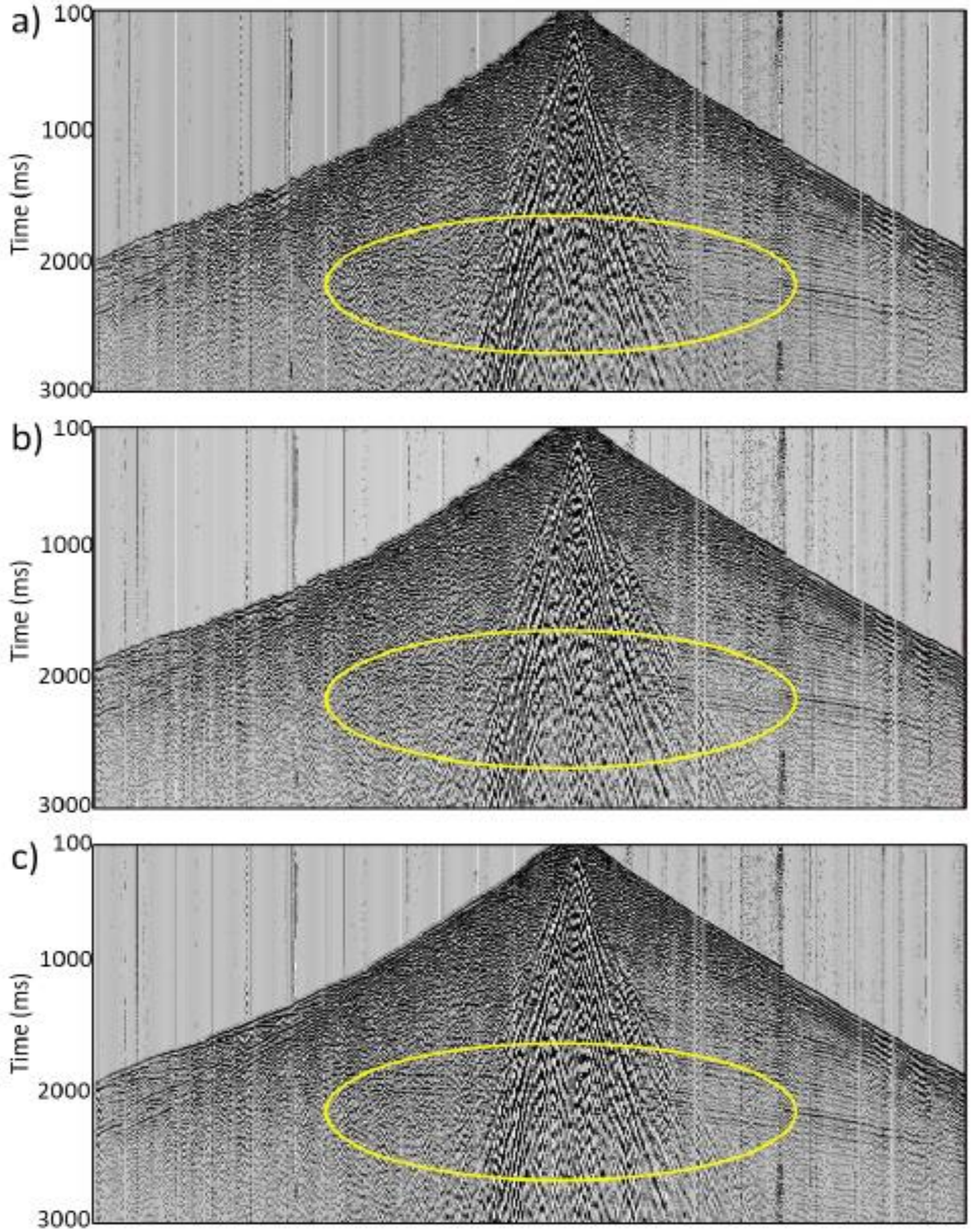

Figure 5. Comparison of a shot gather from a single receiver line of swath-line with **(a)** no field statics applied, **(b)** after application of field statics, and **(c)** after application of refraction statics the improvement in the coherency of reflection events is evident.

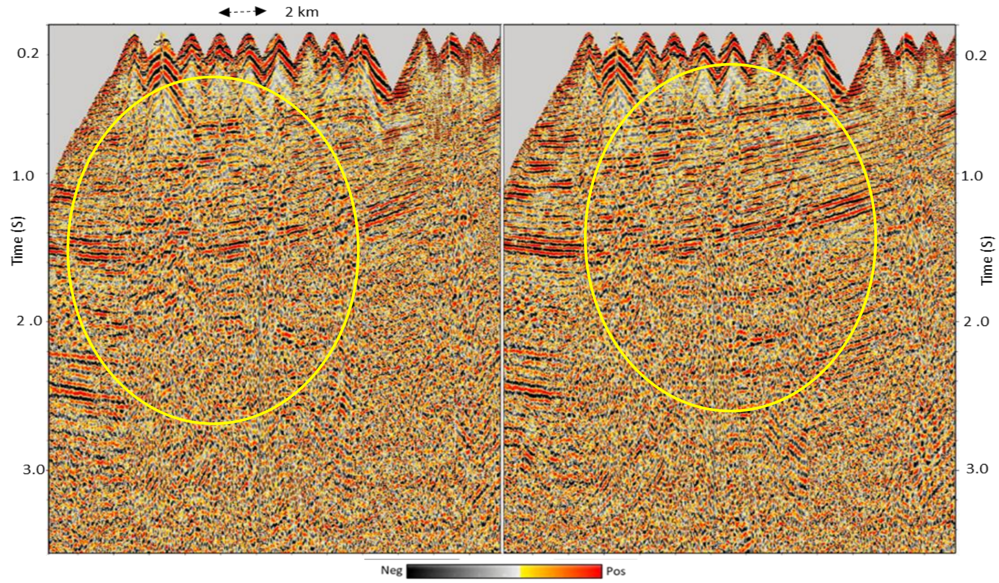

Figure 6. Comparison of stacks with application of field statics (left) to refraction statics (right)

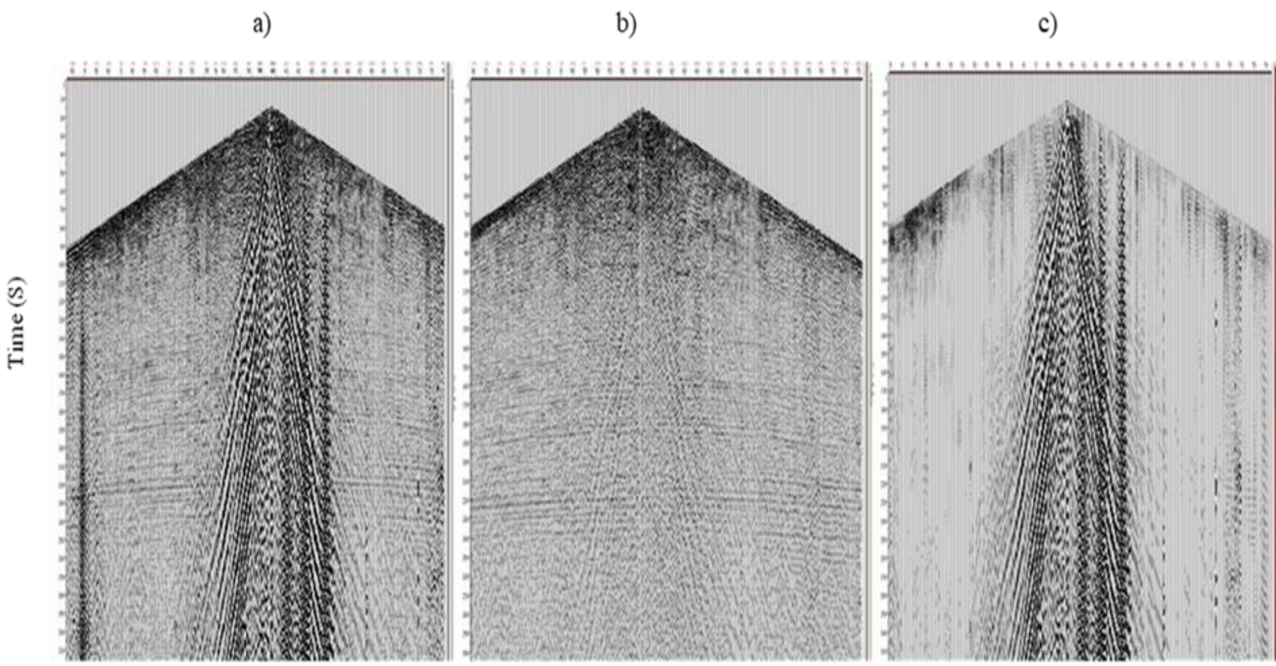

Figure 7. Progression from raw data **(a)** to denoised data **(b),** and finally to the removal of noise **(c).**

Noise Attenuations

Signal to noise ratio (S/N) in fold belt seismic data especially over exposed anticlines is very poor (Dutta et al., 2015**).** Reflection hyperbolae pattern is hardly observed. In structurally complex areas out of plane reflections are very common. Hence, it is important to get rid of masked noise in data cautiously. Carried out frequency dependent noise attenuation in narrow bands and thereby enabling searching of anomalous amplitudes and subsequent attenuation (Yilmaz, 1987). (Figure 7) illustrates a shot gather before and after denoising.

Velocity Analysis

Velocity analysis plays a crucial role in the fold belt data (Dutta et al., 2015). As the consistent reflection hyperbolae are nearly absent in gather level, it becomes difficult to carry out velocity analysis based on flattening of hyperbolae (Figure 8). Semblance based approach on super gather also does not give reliable estimate of the velocity.

Under these circumstances constant velocity stack method (CVS) of velocity analysis is helpful to get an initial estimate of velocity (Figure 9).

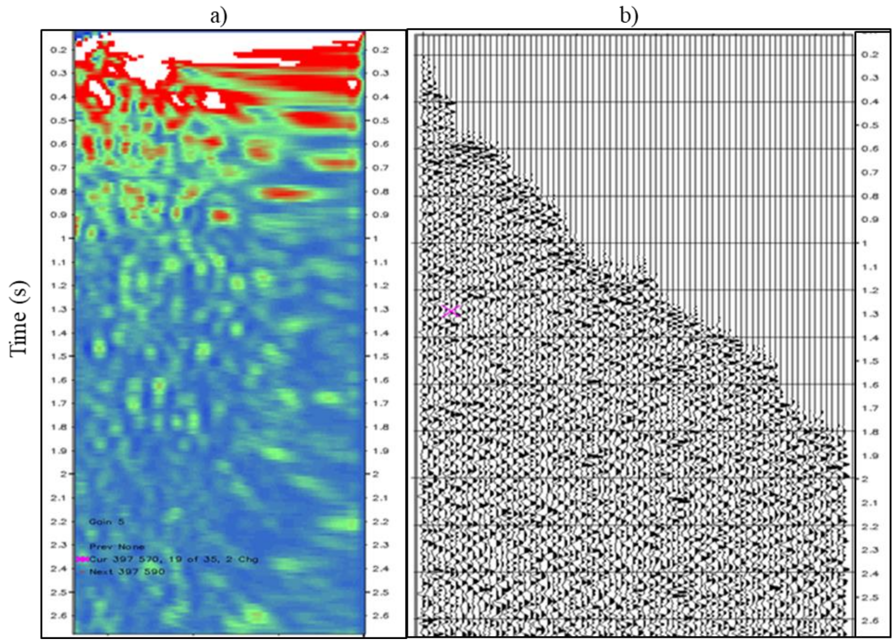

Figure 8. Poor semblance near anticlinal part **(a)** and absence of hyperbolic events on corresponding CMP gather **(b).**

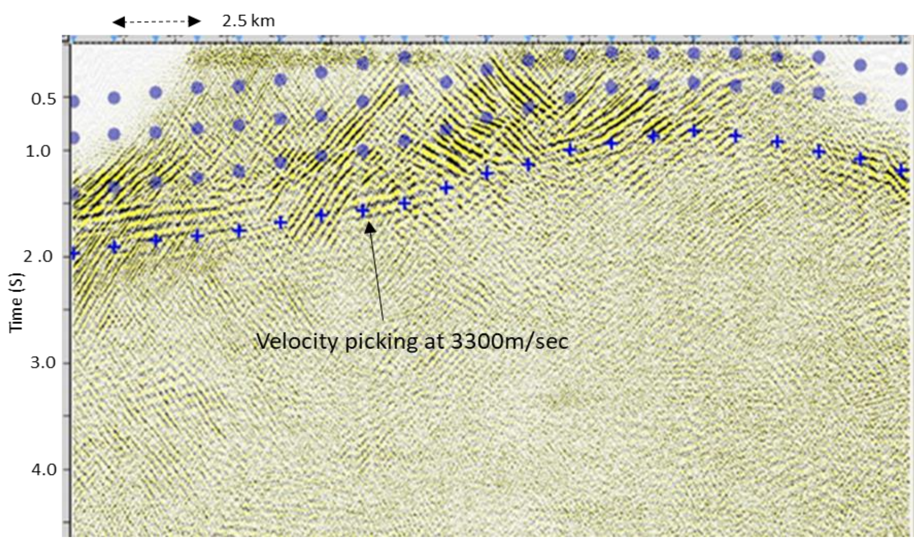

Figure 9. Constant Velocity Stack (CVS) for velocity picking

Multiple iterations of CVS velocity estimation need to be carried out to get the optimal stack result. In order to pick CVS based velocity, a prior knowledge of geological structure is essential. Velocity analysis on post stack migrated output with velocity perturbation is also provide better image quality in some area where S/N is poor.

The quality of vintage data from the Tripura fold belt areas improved significantly by implementing the special quality control steps and parameters mentioned above during processing. A comparison of the PSTM stack of the vintage 2D line is shown in (Figures 10). PSTM stack (10a) was processed using field statics and semblance-based velocity estimation, while (10b) was processed following fold-belt-friendly processing steps as discussed earlier.

Technological advancements in processing algorithms and human efforts consistently yield high-quality results. However, setbacks during data acquisition can never be fully mitigated. Acquiring and processing new data with a geometry suited for fold belt areas is crucial for a better understanding of the subsurface. More importantly, implementing this geometry on the ground while addressing the challenges of the fold belt area is a significant task. An innovative geometry, the ‘2D swath-line’ seismic data acquisition, could potentially alleviate these imaging difficulties in the fold belt.

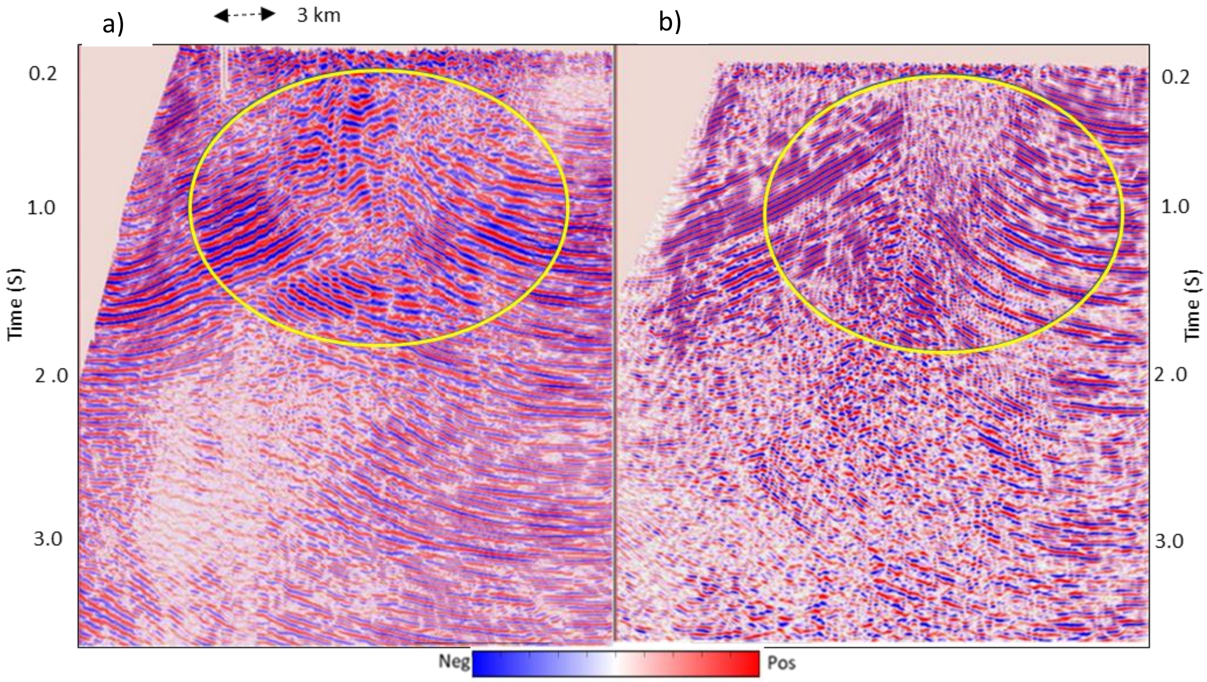

Figure 10. Comparison of PSTM stacks of a vintage 2D line **(a)** of Tripura fold belt area and by adopting special processing steps **(b)**

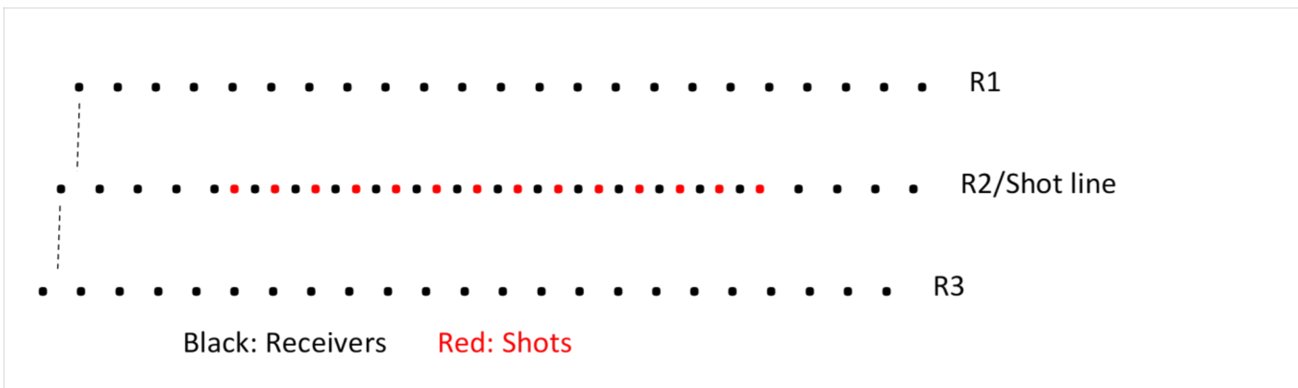

Figure 11. The swath-line recording geometry adopted in the seismic data acquisition.

The 2D swath-line acquisition geometry combines the concepts of stack array with 3D acquisition techniques; here in this case study, it consists of one additional receiver line on both sides of conventional 2D seismic survey. This geometry provides excellent protection against scattered and out-of-plane surface noise, while permitting the use of limited crossline aperture and 3D swath processing techniques to preserve signal fidelity. Swath-line seismic data were acquired as a practical alternative to conventional 2D land data acquisition to map an anticline in an area situated in the north-eastern part of India with rough topography and difficult accessibility. The recording geometry consists of three parallel receiver lines at 40 m separation and a single shot line along central receiver line (Figure 11).

The receiver interval was 10 m. Symmetrical split spread geometry with 480 + 480 active channels in each receiver line and total 2880 channels in an active temple was used. Full-fold coverage along the CMP line is 720; significantly higher than the fold that can be attained by conventional 2-D surveys. (Figure 12) shows the raw shot gather of the swath-line acquisition geometry, while (Table 1) lists the important recording parameters. A total of nine sets of 2D swath line data were acquired: six aligned in the dip direction and three in the strike direction, aimed at mapping the South Baramura anticline. All these lines are illustrated on a Google Map and Geological Map in (Figures 13a and 13b**)**, respectively.

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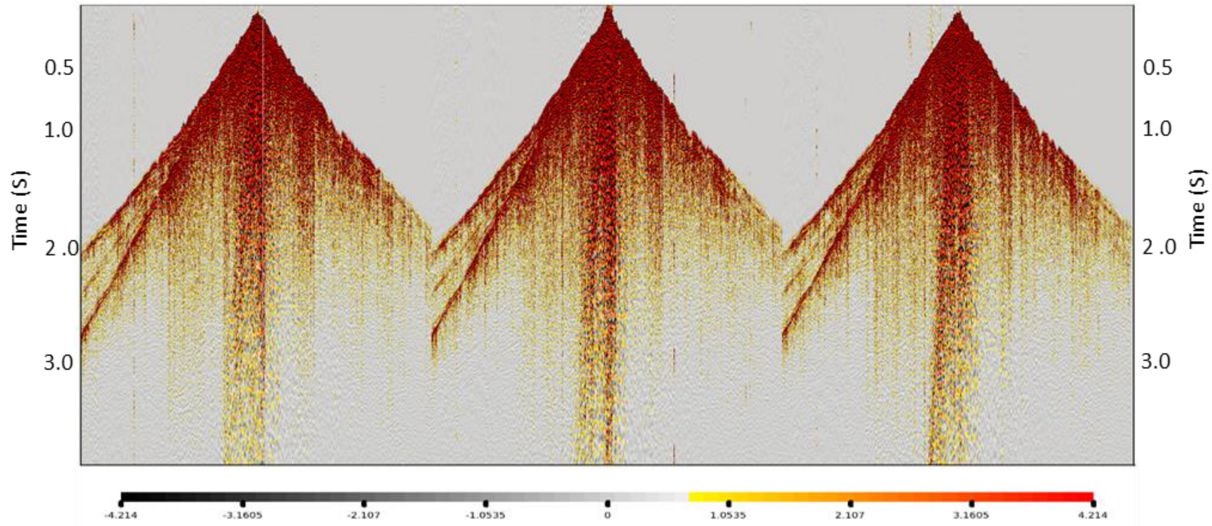

Figure 12. Raw shot gather with swath-line acquisition geometry

Table1. The swath-line acquisition parameters

Receiver line spacing	40 m
Receiver interval	10 m
Shot interval	20 m
Number of channels per receiver line	960
Number of receiver lines	3
Total number of channels	2880
Number of shot lines	1
Min/Max offset	5 m/4800 m
Fold along the CMP line	720

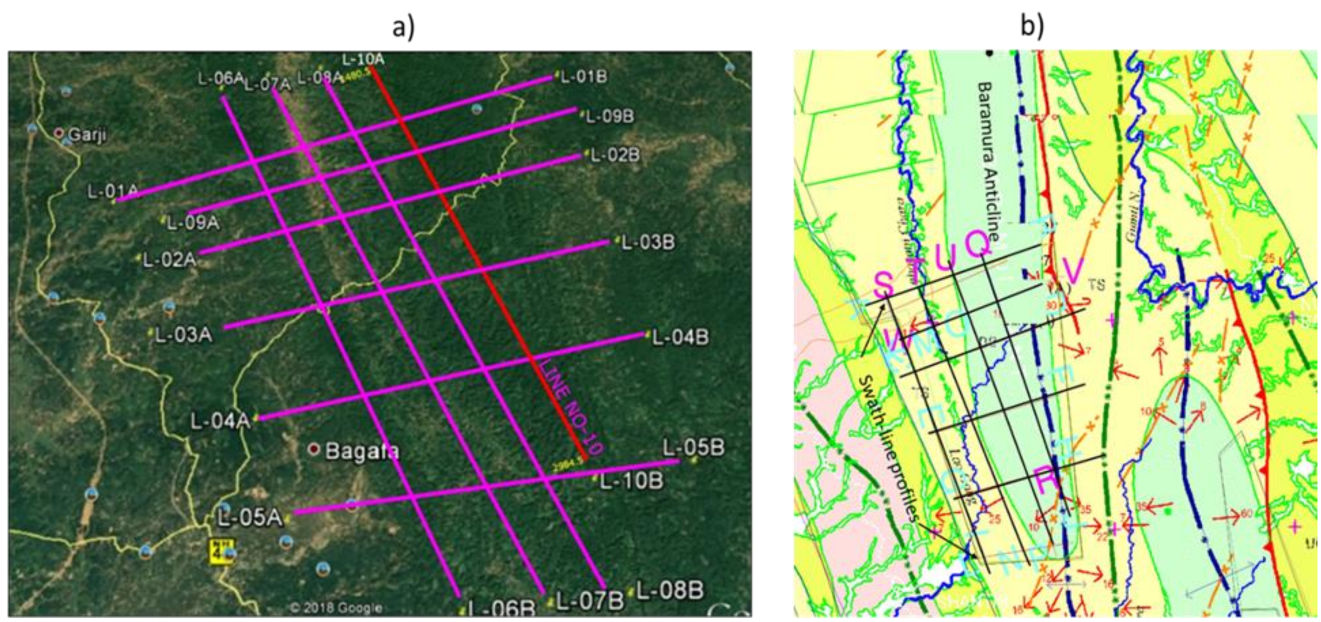

Figure 13. Swath line profiles shown on **(a)** Google Map and **(b)** Geological Map of the South Baramura Anticline.

Data analysis

Swath-line data must be treated as 3D data during most of the stages of processing, including near-surface modelling and subsurface imaging. Topography variation is very high and rapid in the survey area. An elevation profile of receivers along the dip direction in a swath line shows the variation to be between 10 and 130 m (Figure 14), and a profile of shots along the central shot line shows the variation to be between 40 and 130 m (Figure 15). The nonlinear travel time tomography (Zhang and Toksoz, 1998) was applied to the first-arrival times picked from the shot gathers and estimated a near-surface velocity model for statics corrections.

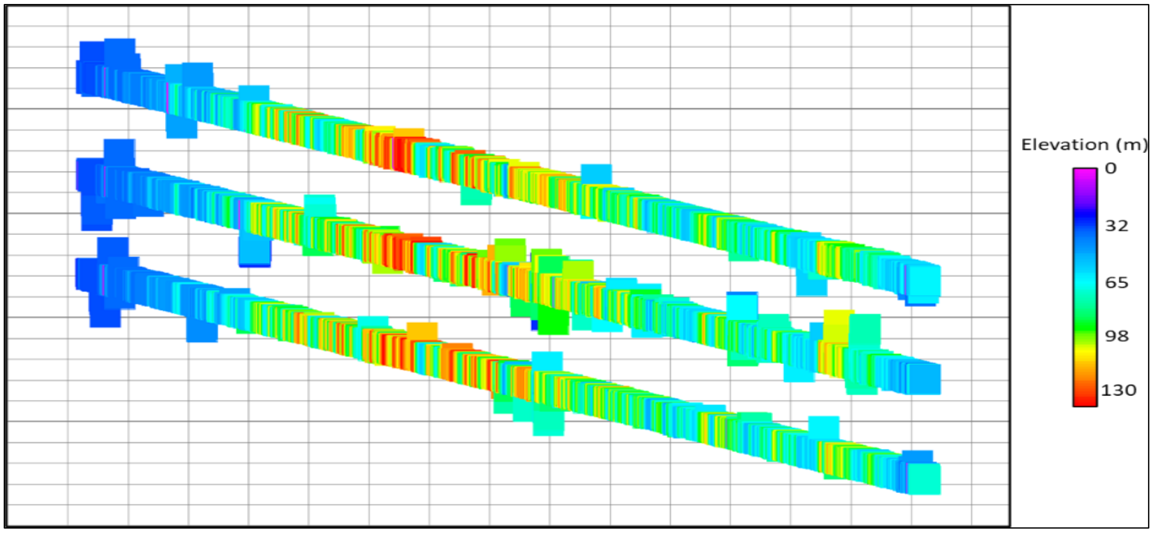

Figure 14. The elevation profile of receivers along the swath lines showing the variation to be between 10 and 130 m.

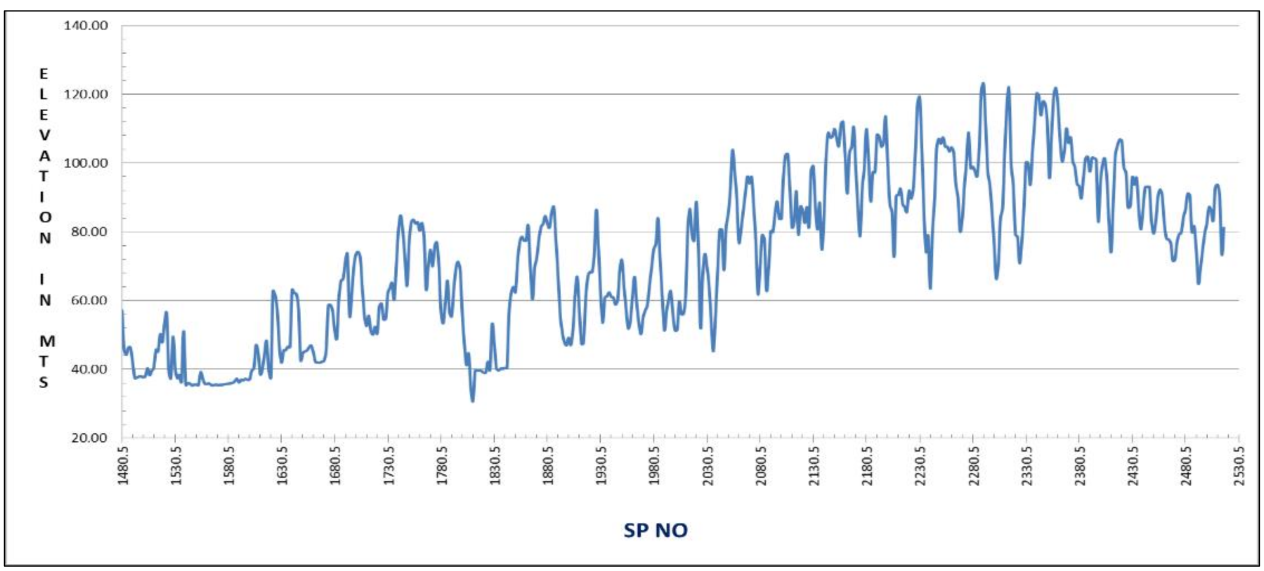

Figure 15. The elevation profile of shots showing the variation to be between 40 and 130 m.

The workflow mentioned in (Figure 16) was applied to process the data, which included geometrical spreading correction, followed by cascaded application of noise attenuation in the shot and CMP domains, aimed at reducing the strength of surface waves and guided waves. It is often found that in the seismic data from fold belt areas, the signal-to-noise ratio (S/N) over anticlines is low due to complex geological structures, shadow zones, out-of-plane reflections, and surface noise. The coherent reflection hyperbolic patterns are usually not visible. Therefore, it is important to eliminate noise to enhance the reflection strength. A processing flow chart is depicted in (Figure 16).

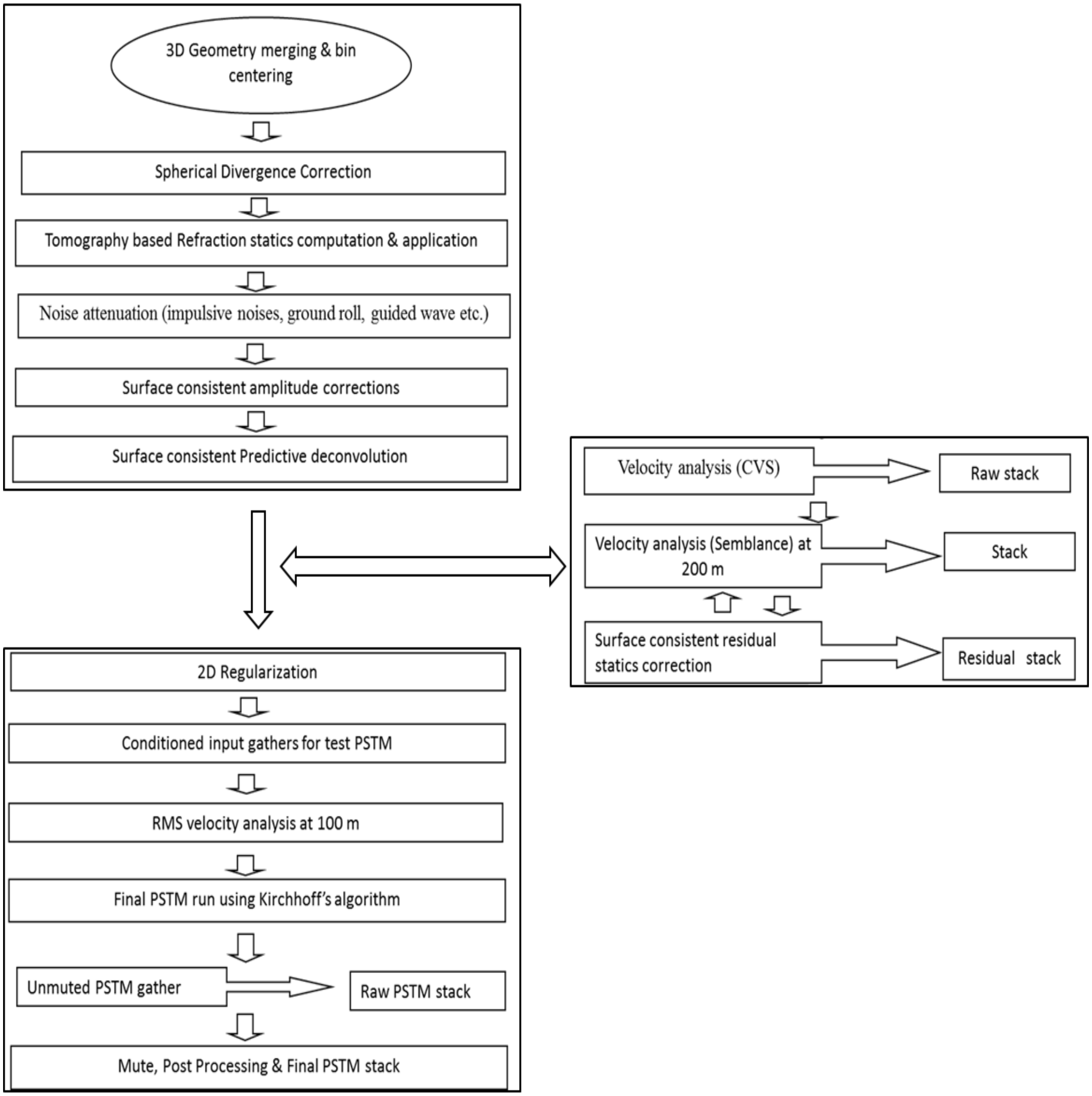

Figure 16. Processing flow chart of swath line data.

Typically, noise removal algorithms assume that the signal strength is significantly greater in magnitude than the interfering noise. However, in this specific context, the signal-to-noise ratio is small. As a result, we performed frequency-dependent noise attenuation within narrow frequency bands. This approach allowed us to identify anomalous amplitudes and apply appropriate attenuation techniques. At the initial stage, minimal noise removal is applied to preserve the signal. Subsequently, signal enhancement occurs after velocity refinements and on the post-stack level, as needed. In this dataset, velocity analysis plays a critical role due to the scarcity of consistent reflection hyperbolae in seismic gathers. Consequently, traditional velocity analysis methods based on hyperbola flattening become challenging. Even a semblance-based approach with super gather fails to provide reliable velocity estimates. Under these circumstances, the constant velocity stack (CVS) method proves valuable for obtaining an initial velocity estimate. We iteratively refined the velocity to achieve optimal stacked results.

The comparison of seismic data stacks across different processing stages, is denoted as (a) to (d) in the (Figure 17). Notably, improvements have been consistently observed at each processing stage. A detailed parameter testing and comprehensive quality control checks have been meticulously implemented across the entire processing workflow.

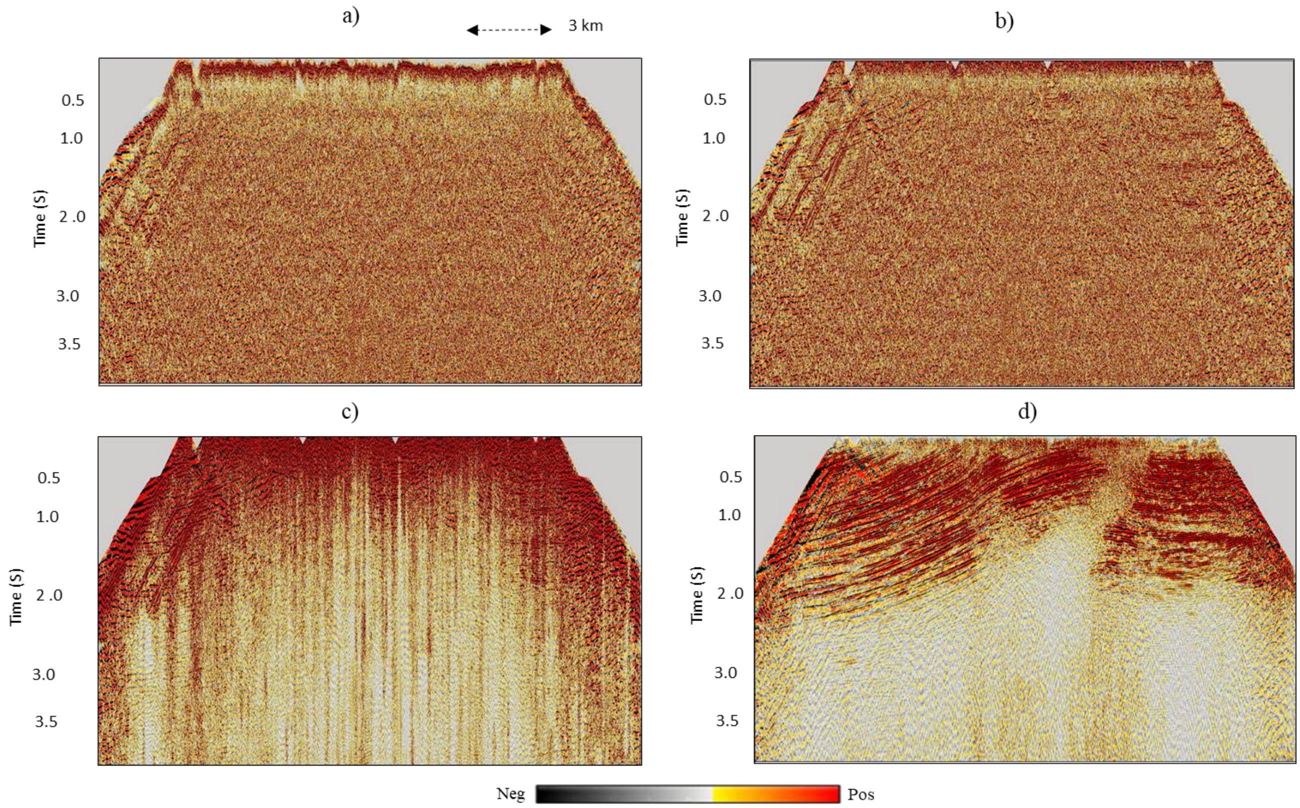

Figure 17. A comparison of stacks at various processing stages, **(a)** brute stack with field statics applied, **(b**) brute stack with refraction statics applied, **(c)** stack after initial denoising and first-pass velocity analysis and, **(d)** stack after applying surface-consistent deconvolution and residual statics with finer velocity analysis.

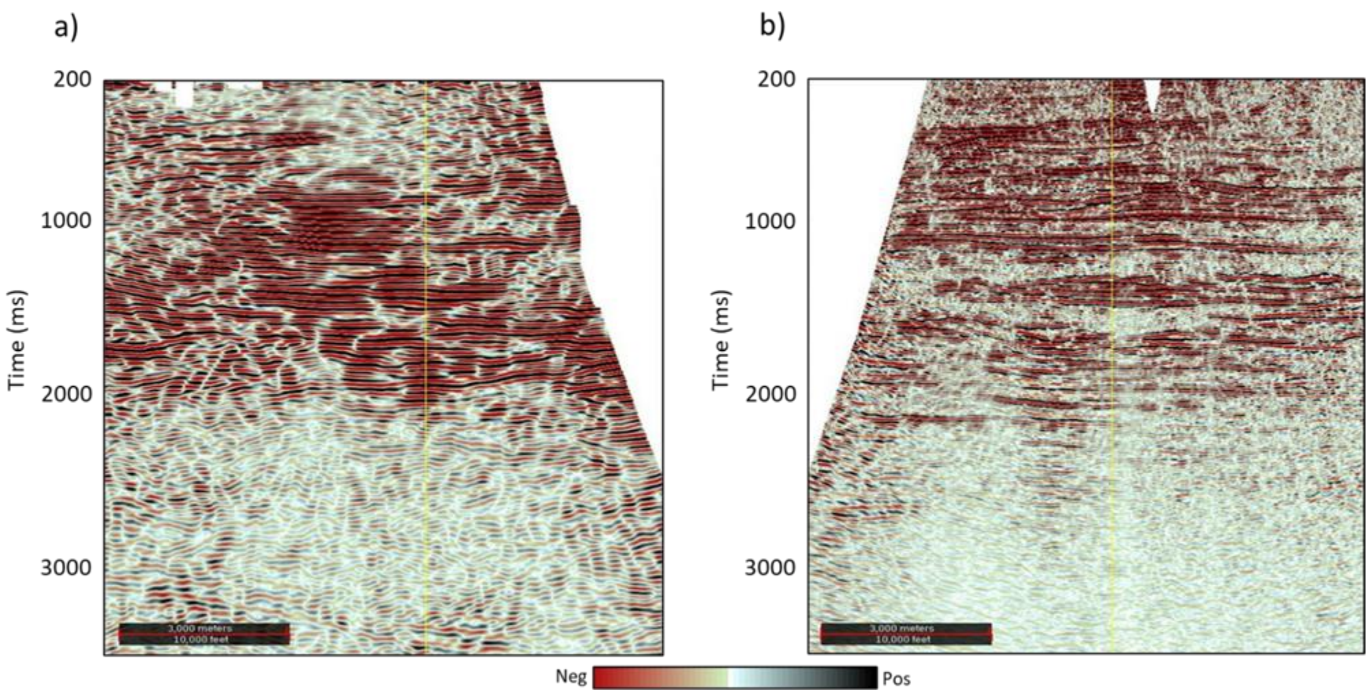

Figure 18. Comparison of 2D seismic profile segments from **(a)** vintage data, and **(b**) swath-line data. The segments have been included from only the overlap portions of the two profiles.

RESULTS

Significant enhancements have been observed in all nine swath line seismic data, particularly in the dip lines. The anticline features are now well-defined, showing clear fault boundaries and other reflectors. Additionally, the strike lines have been accurately resolved compared to the existing conventional 2D seismic data. A comparison of swath line data with vintage 2D is shown in (Figure 18**)**, the improvement in the signal-to-noise ratio by swath-line recording is markedly evident.

In order to compare the 2D swath-line geometry with conventional 2D geometry in the study area, we processed the swath-line data twice. In the first case, we utilized all three receiver lines, following the standard swath-line processing approach. In the second case, we focused solely on the central receiver line, resulting in a geometry resembling conventional 2D acquisition. All other parameters, including velocity, deconvolution operators, and migration parameters, remained consistent. The comparison of the final seismic stacks is presented in (Figures 19 and 20**)**, corresponding to the dip direction and strike direction, respectively. Notably, the swath-line processing with three receiver lines significantly improved image quality, particularly over fault zones near the anticlinal portion in the dip line. Additionally, events are clearly resolved in the strike direction.

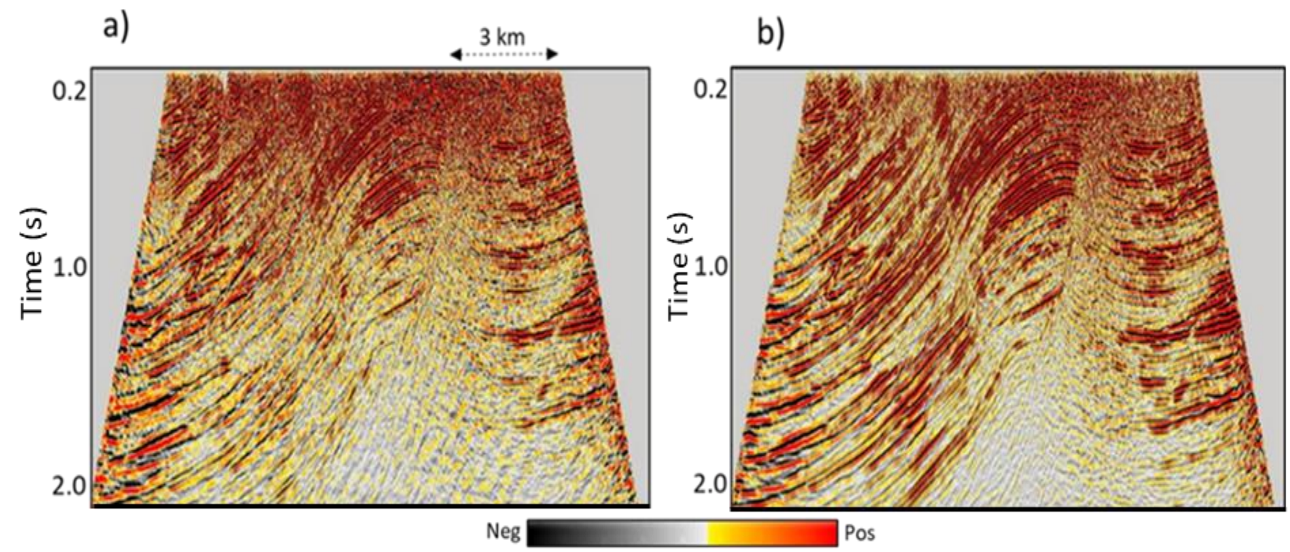

Figure 19. Comparison of stacked sections from swath-line, with **(a)** single receiver line, and **(b)** three receiver lines along dip direction. The image quality significantly improves, and faults are more distinct in **(b).**

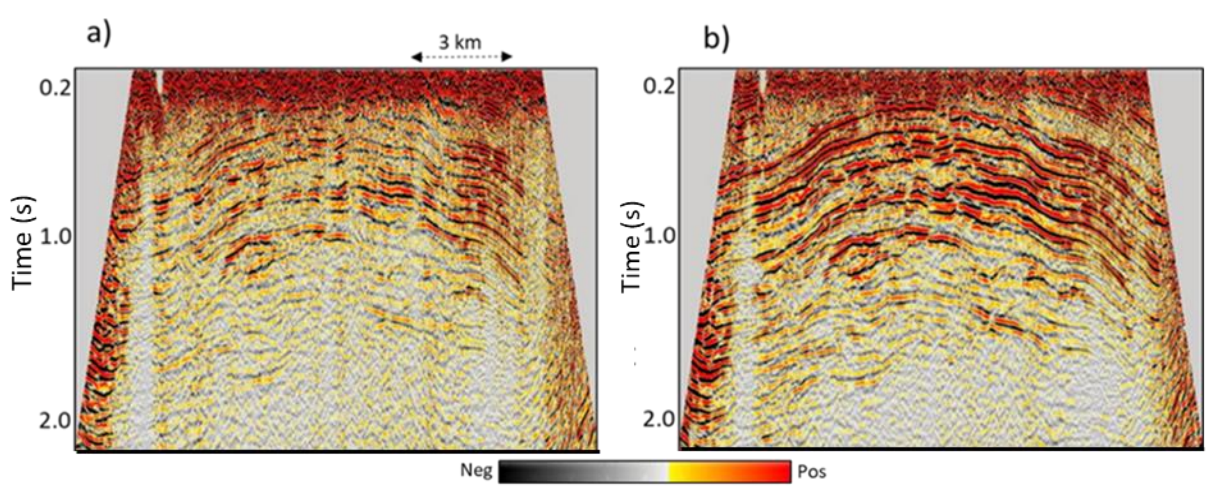

Figure 20. Comparison of stacked sections from swath-line with **(a)** single receiver line, and **(b)** three receiver lines along strike direction.

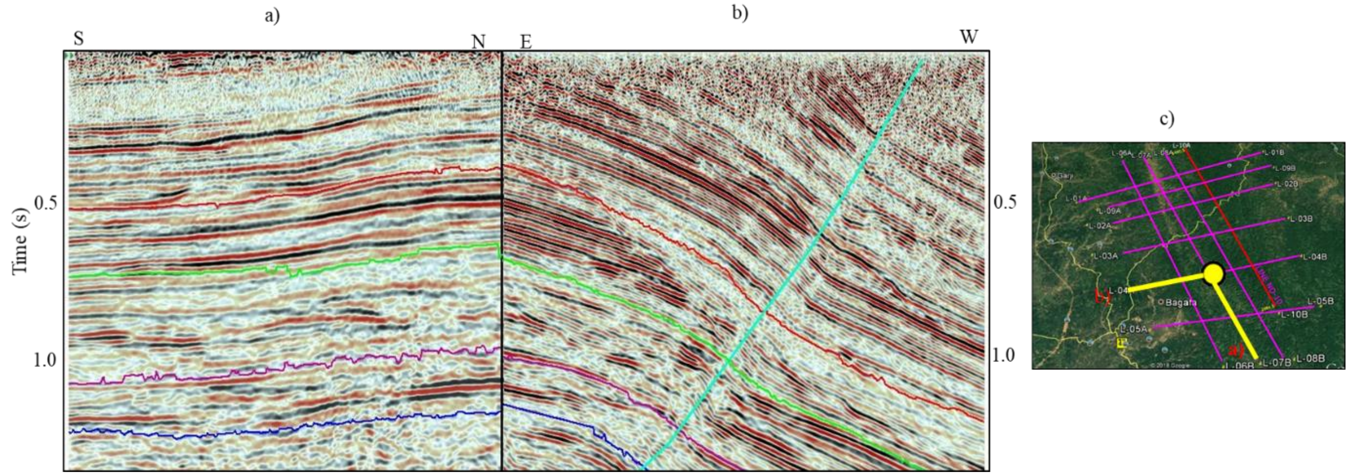

Figure 21. Interpreted RC line trough intersection of two swath lines, **(a)** section of a line along strike direction in N-S direction from intersection point, **(b)** section of a line along dip direction in E-W direction from intersection point, and **(c)** representation of lines on location map.

(Figure 21) illustrates an interpreted RC line derived from the intersections of a dip and strike line. Section **(a)** represents a line along the strike direction in the N-S direction, originating from the intersection point and section **(b)** corresponds to a line along the dip direction in the E-W direction, also starting from the intersection point. There is good match and continuity observed on the both sections at intersection point. While 2D swath line seismic data offers several advantages, it also comes with some limitations that we address during geometry planning. Due to the varying topography between receivers, especially in the strike direction of the anticline, swath line geometry often involves three receivers positioned at different elevations, which may fall into the same bin. When this elevation variation is more pronounced in the crossline direction, midpoints may coincide within the same bin during geometry merging. This arrangement occasionally results in smeared reflection events, leading to a low-frequency appearance in the output data. To address this limitation, it becomes necessary to maintain an optimal offset for the additional two receiver lines from the central line, especially when elevation variation is substantial in that direction (such as the lines parallel to the strike direction of the study area).

CONCLUSIONS

In areas with rough topography and difficult accessibility like Tripura fold belt, high-fold swath-line data acquisition proves more beneficial than conventional 2D land seismic methods. This is especially true when 3D land seismic data acquisition is cost-prohibitive. Treating swath-line data as 3D during most of the processing stages, including near-surface modelling and subsurface imaging, is crucial. Swath-line recording provides significantly higher foldage compared to typical 2D surveys, resulting in improved signal-to-noise ratios essential for imaging in fold belt areas. Addressing image quality issues related to geometry, statics, noise, velocity and algorithms, required a pragmatic approach. We employed a mix-and-match strategy, drawing from various software suites, recognizing that no single suite provides an optimal solution for all challenges.

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Authors contribution

The first author conceptualized, analysed, and processed the data. Manuscript review and correction were carried out by Uma Shankar and Yadunath Jha. Concept, corrections, and editing were done by Nani Madhab Dutta. All authors read and approved the final manuscript.

Data availability

The data used in this study is confidential and owned by ONGC Ltd., the geology and petroleum system of the area are freely accessible on the Directorate General of Hydrocarbons website (www.dghindia.gov.in).

Compliance with ethical standards

The author declares that they have no conflict of interest and adhere to copy right norms.

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