Improvements in seismic data imaging in thrust-belt areas of northeast India – A case study from OIL's operational areas

Arpita Adhikary[1], Kartik Sharma[1] and Anup Kumar[1]

ABSTRACT

The whole E&P cycle for hydrocarbons is an extensive task to accomplish in terms of the skills as well as the finances required. However, the challenges faced throughout an E&P cycle are dependent on the geology of the study area. As the study area becomes geologically complex, different sets of challenges are faced during its different phases, be it seismic data acquisition, processing, or interpretation, etc., have a cascading effect on the results and targets that we wish to achieve. Having said so, in today's era with growing hydrocarbon demands, the chances of locating newer hydrocarbon reservoirs in geologically simpler areas, i.e. where these challenges are avoidable, are negligible. In other words, mostly all the hydrocarbon reservoirs present in geologically simpler areas have almost been discovered. Therefore, venturing into geologically complex areas to discover new sources of hydrocarbons is no longer a choice but a necessity.

In this study, the authors present the various challenges faced during exploration campaigns to acquire seismic data in fold-thrust belt areas and then go into the details of the processing sequence followed in order to get a reliable image of the subsurface in these areas, and hence showcase the improvements achieved when compared to vintage processed outputs. The study area belongs to the fold-thrust belt regime of Oil India Limited's (OIL) major producing area, which is quite complex. Multiple 2D lines have been taken up for this study which lie at different locations along the Naga Schuppen Fold Belt to demonstrate the improvements that have been brought about using advanced processing algorithms.

KEYWORDS

Thrust-belt imaging, data quality, acquisition, imaging challenges

INTRODUCTION

Hydrocarbon exploration in fold-thrust belt regions presents significant challenges, yet it remains a major undertaking for E&P companies that are striving to meet the rising global energy demand. (Bhartee et al., 2020). Seismic data acquisition in these geologically complex terrains is not only logistically demanding—often requiring extensive planning and resources—but also introduces substantial difficulties during data processing.

This paper elaborates these challenges in detail, focusing on both the acquisition and processing of seismic data in fold-thrust belt settings. It further explores the seismic data processing workflow necessary to produce reliable and geologically conformable images of the subsurface. Finally, the paper evaluates the improvements in seismic imaging achieved through the application of modern processing technologies, comparing these enhanced results with legacy processed outputs to highlight advancements in resolution and interpretability.

OIL's major producing areas falls under two geological regimes, namely the Assam Shelf region of the Upper Assam Basin and the Assam Arakan Fold Belt, also called the Naga Schuppen Fold Belt. The structural configuration of this fold belt is demonstrated in Figure 1.

This fold belt extends to about 25 – 30 km in width and comprises of a series of thrusts and faults trending in the –east-northeast-west-southwest direction (Gerea et al., 2011). As a result of this thrusting, the geology of the area is quite complex with the higher velocity, deeper sedimentary units exposed at the surface as outcrops.

All the major hydrocarbon producing fields in the foreland part, including that of OIL, are situated next to the Naga Thrust and are depicted in Figure 2. Given this structural configuration, it is expected that the reservoirs currently producing in the foreland have their extensions below the Naga Thrust, potentially extending as far as the Disang thrust.

CHALLENGES IN IMAGING THRUST-BELT AREAS

The challenges faced during the process of imaging thrust belt areas for hydrocarbon exploration are three-fold. These start right from the beginning of the seismic data acquisition campaign where acquiring the data itself becomes a challenging task owing to drastic elevation

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variations and rugged topography. These surface challenges are further accompanied by near-surface and subsurface challenges wherein the effect of harsh surface conditions manifests itself in the datasets and poses serious challenges in the processing and imaging stages. The following sections discuss these challenges in detail.

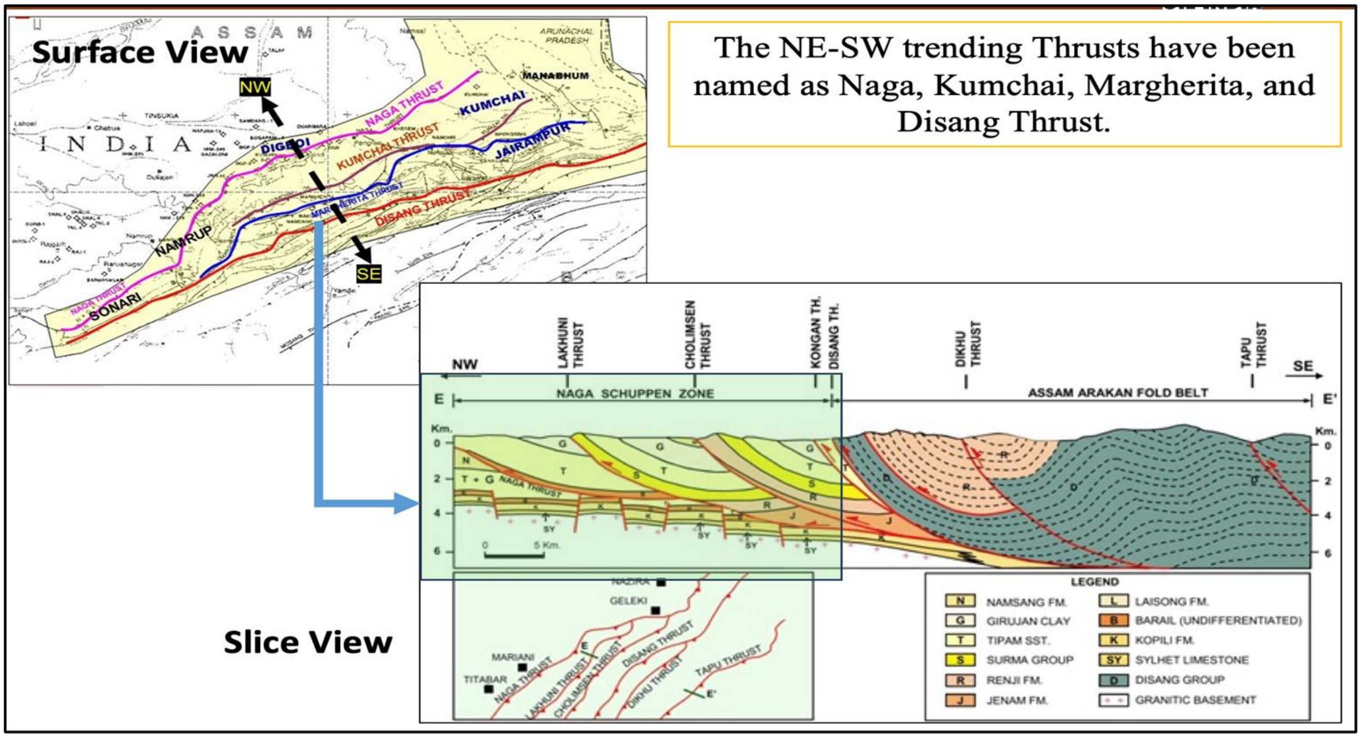


Figure 1: *The structural configuration of Assam Arakan Fold Belt Regime – Naga Schuppen Fold Belt. The study area lies along the Kumchai thrust on the eastern part of this fold belt.*

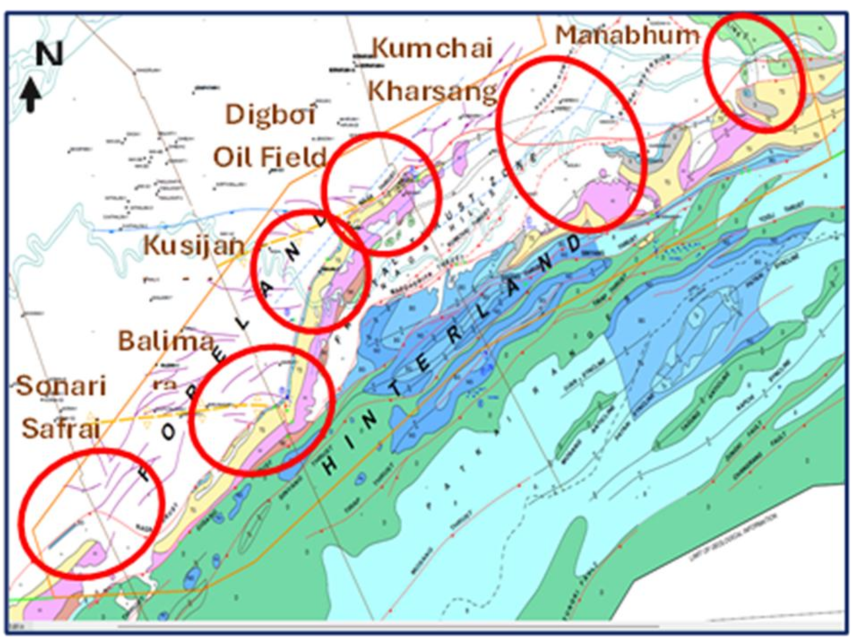


Figure 2: *Major hydrocarbon producing fields of OIL (encircled in red) lie adjacent to the Naga Thrust.*

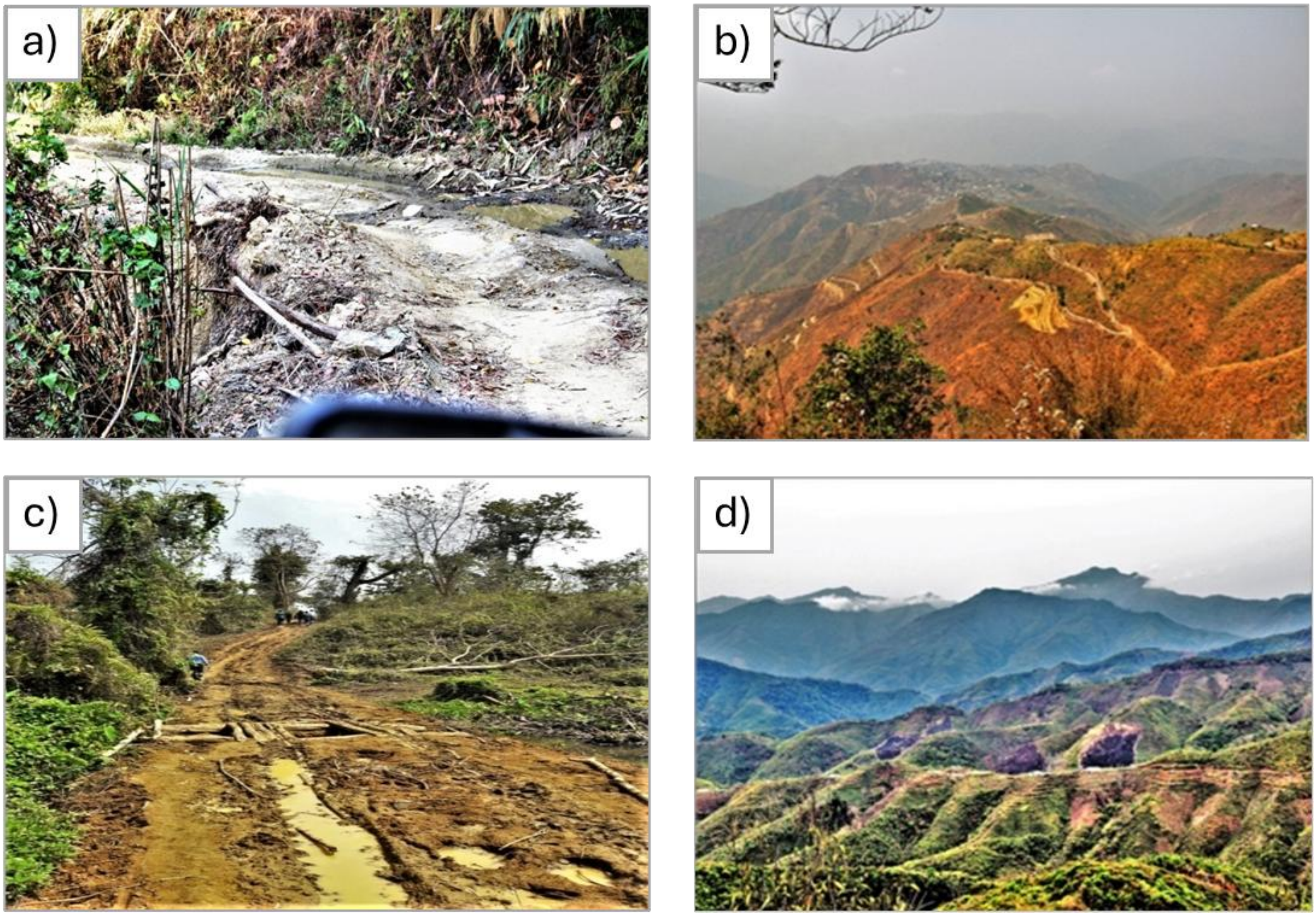


Figure 3: *Surface challenges faced in seismic data acquisition, namely, (a) poor road conditions, (b) elevation variations, (c) broken bridges, and (d) dense vegetation.*

(i) Surface challenges - At the time of seismic data acquisition, a major point of concern is the accessibility of the survey area. In thrust belt areas, this accessibility becomes a huge challenge. These areas mostly have rugged topography with varying elevations and dense vegetations with poor connectivity through roads and bridges. Hence, reaching the survey location with all the manpower and hardware resources required for a seismic survey, becomes a major challenge. Figure 3 depicts a few examples of challenges faced in a tough topographical area.

Apart from reaching the location, the survey area also poses serious challenges in deploying the resources and carrying out the survey as planned in terms of the source and receiver positions. The planned seismic survey is entirely ideal in nature wherein all the receiver and source lines are straight and at the desired locations. However, when the same is implemented in the field, the surface conditions do not favor the theoretical plans which are evident from the acquired dataset wherein the source and receiver lines are not straight, and sources must be, at times, skipped even in locations where it is impossible to place a shot.

The presence of boulder beds in these areas also poses issues in drilling of shot holes and effective planting of the geophones which in turn degrade the data quality. Figure 4 gives a visual representation of these above-mentioned challenges.

(ii) Near-surface challenges – The impact of the surface challenges as discussed above manifests itself in the acquired datasets in the form of near surface challenges. The insufficient shot hole depths caused due to drilling on hard boulder bed areas not only lead to improper distri-

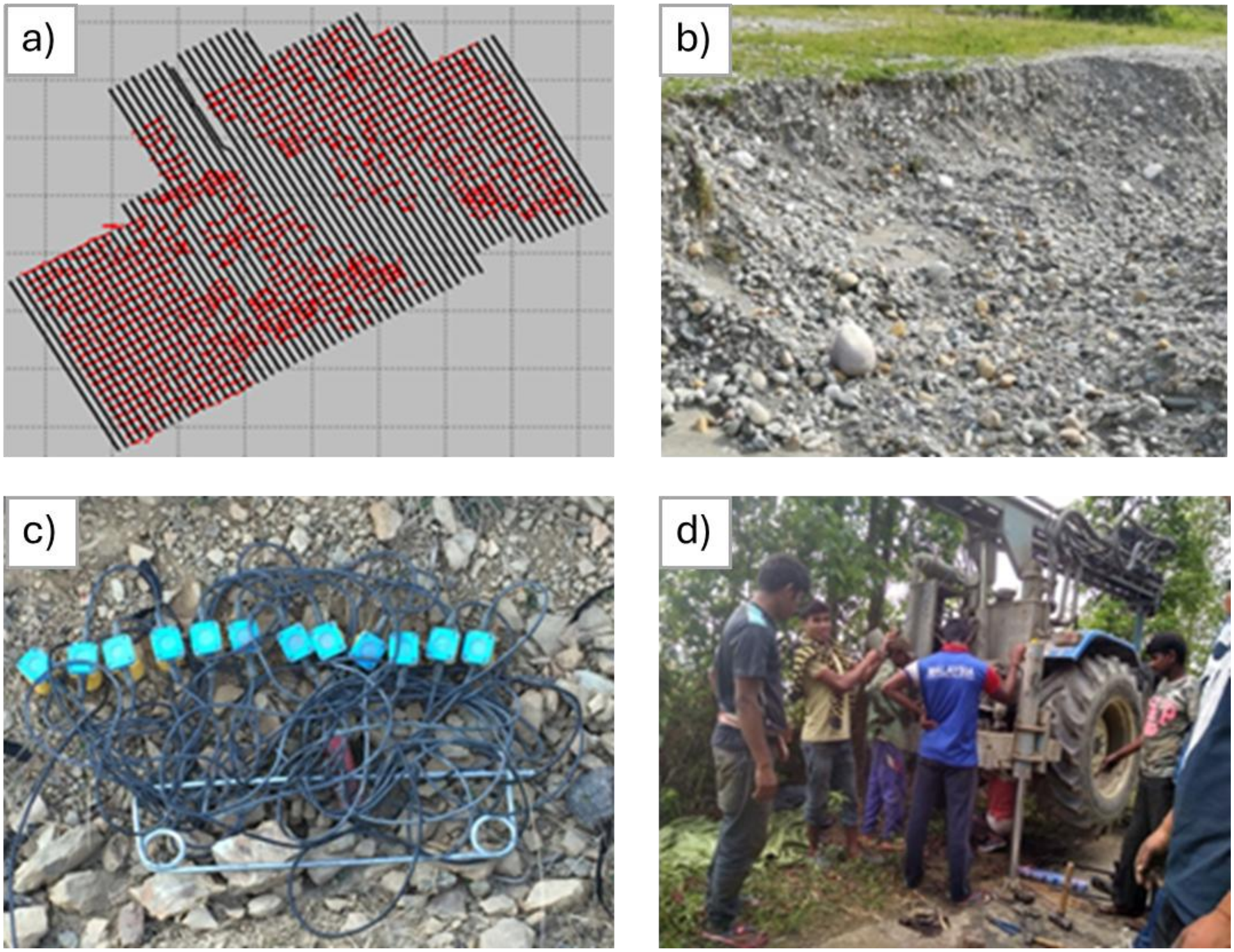


Figure 4: Surface challenges faced in seismic data acquisition, namely, (a) variations in planned source and receiver locations which lead to skipped sources and deviated source and receiver lines, (b) hard boulder beds on the surface, (c) boulder beds resulting in inefficient geophone coupling, and (d) difficulty in drilling for shot holes.

bution of the shot energy, which is mostly dissipated at the surface in case the shot holes are too shallow but also result in energy penetration issues due to which enough shot energy is not able to travel to deeper parts of the subsurface. Poor geophone coupling and the significant shot generated backscattered noise, results in noisy shot gathers with poor signal-to-noise ratio. This often results in poor quality of the first break picks which cause a serious amount of uncertainty in calculation of statics solutions. The near surface heterogeneity and irregular topography lead to significant lateral velocity variations which pose a challenge in determining the near surface velocity model which in turn hampers the imaging of the subsurface reliably.

(iii) Subsurface challenges – The near surface and subsurface challenges faced while imaging the thrust belt areas are intertwined. Some of the subsurface challenges faced while imaging thrust belt areas are as follows:

- Poor signal-to-noise ratio (SNR) because of limited energy penetration and backscattered noise (Picha, 1996).
- Data gaps due to shot skipping or inadequate geophone layout due to inaccessibility of complex surface terrain (Picha, 1996).
- Substantial lateral and vertical velocity variations due to complex geology.

- Poor quality first breaks leading to unreliable near surface velocity model which results in low confidence of the calculated statics solution (Vestrum and Cameron, 2022).

Figure 5 shows three shot gathers depicting the various near surface and subsurface challenges faced while imaging in geologically complex thrust belt areas. Also, drastic changes in the quality of the semblance plots for vertical velocity analysis for the shelf and thrust regions are also shown in Figure 5.

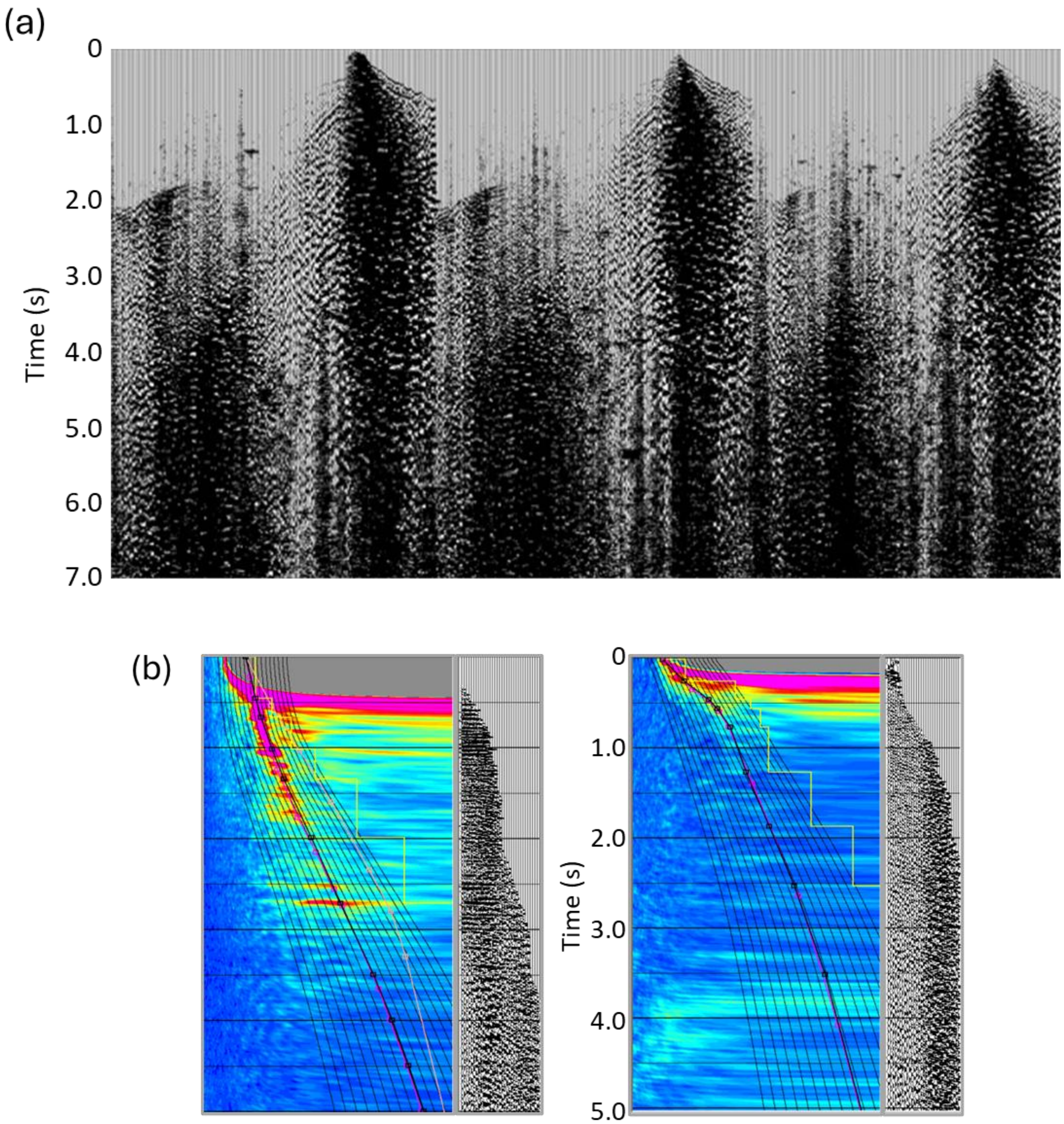


Figure 5: *(a) Shot gathers depicting the near-surface and subsurface challenges faced in seismic data acquisition. Due to the poor shot hole depths and inefficient geophone coupling, the shot gathers have poor signal-to-noise ratio with very feeble first break picks which in turn results in unreliable near surface velocity modelling and refraction statics calculation. The variations in the elevation of the topography also impact the first arrivals. (b) Semblance plots along with CMP gathers for vertical velocity analysis for the shelf region (left) and the thrust belt region (right).*

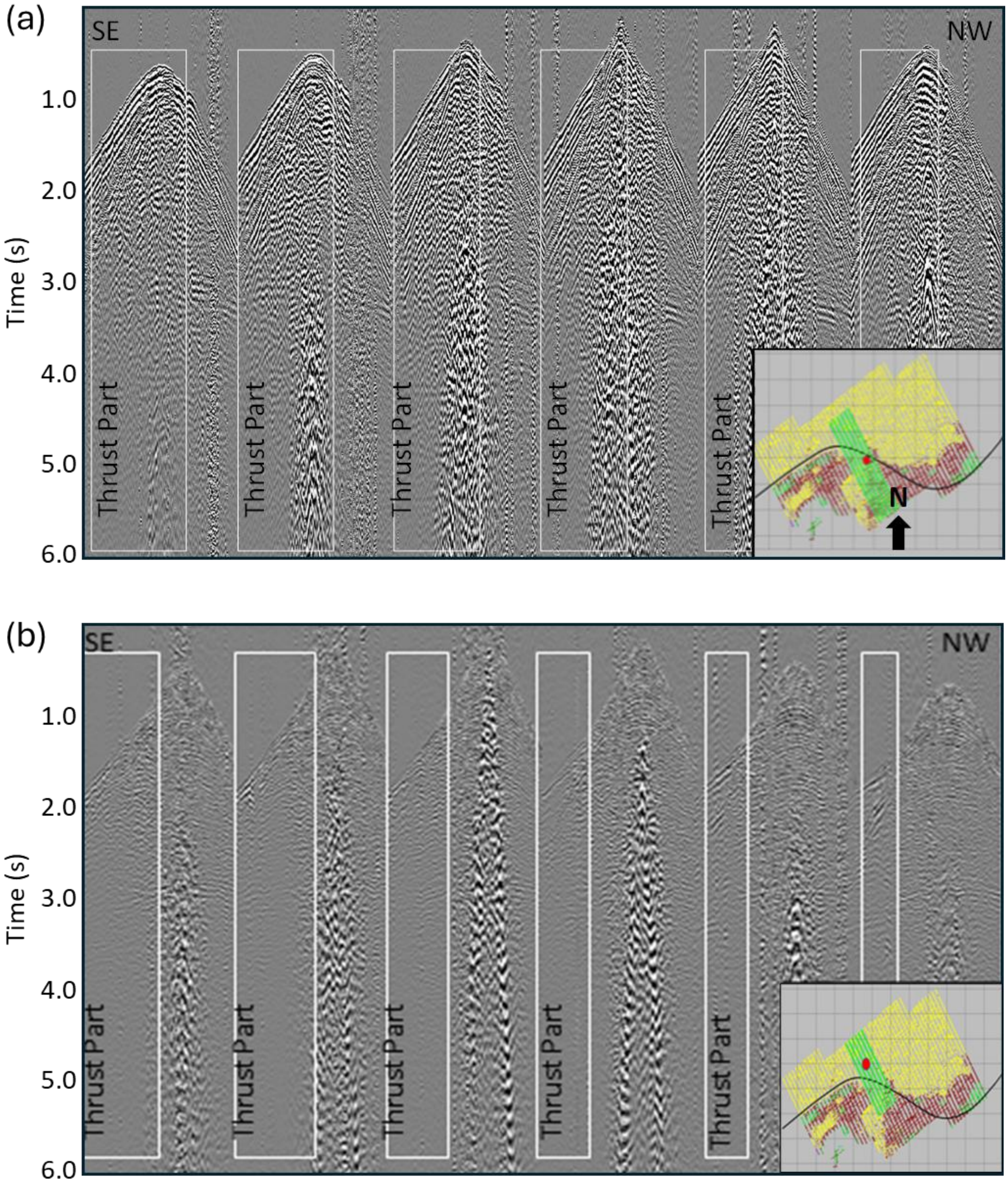


Figure 6: *Shot gathers are shown when the shot is blasted (a) near the thrust, and (b) away from it. The red dot is the position of the shot with active receivers in green; the black line is the surface manifestation of the thrust. Receivers located within the thrust-affected zone are highlighted by white boxes. Noticeably, as the shot location moves away from the thrust, the data quality improves with increased SNR and visible reflection hyperbolas.*

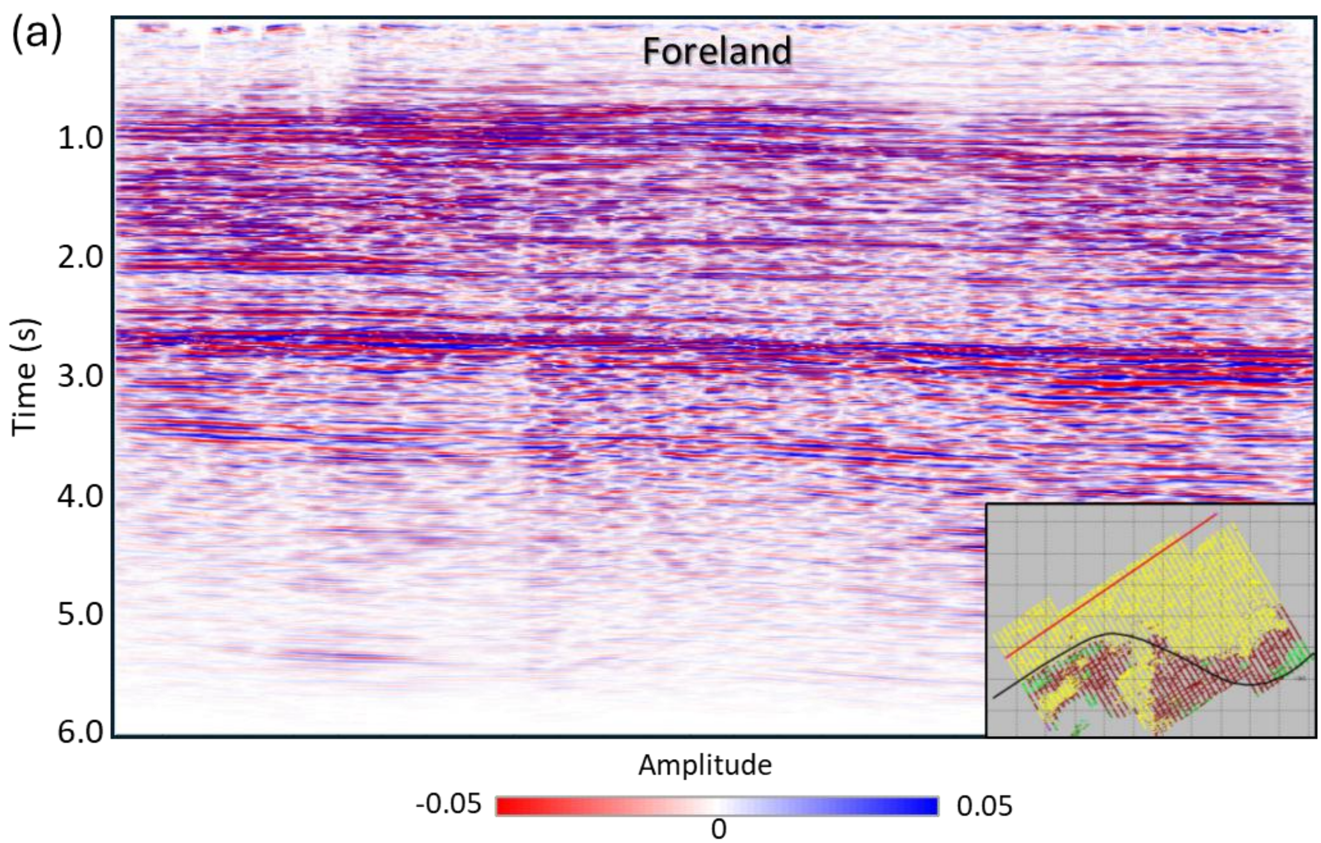
IMPACT ON DATA QUALITY

The impact on data quality of acquiring seismic datasets in geologically challenging thrust belt areas can be visualized in the gathers as well as stack sections.

Figure 6 shows the shot records for two shot positions. One where the shot is blasted close to the thrust belt and the other where it is far from it (Figure 6 a and b). The shots in the location maps shown in both the figures are depicted as red dots, where the green lines represent the active receiver spread. The background colors on the survey map show the elevation variations where yellow represents lower elevations as compared to brown colored locations. The black curved line on the map represents the surface representation of the thrust.

It is evident from the shot records that the data quality improves when we move away from the thrust-fold area. The white boxes on shot gathers represent the receivers which fall within the thrust regions of the survey. As we move away from the thrust-fold area, SNR improves as well as reflection hyperbolas become more evident in the shot gathers.

A similar representation is shown in Figure 7 in the form of stack sections where the red line on the location maps shows the position of the displayed image with respect to the thrust. It is evident again that the imaging quality is far better when shots are taken away from the thrust, that is, in the foreland part, and degrades drastically as the shots are placed closer to the thrust-fold part.



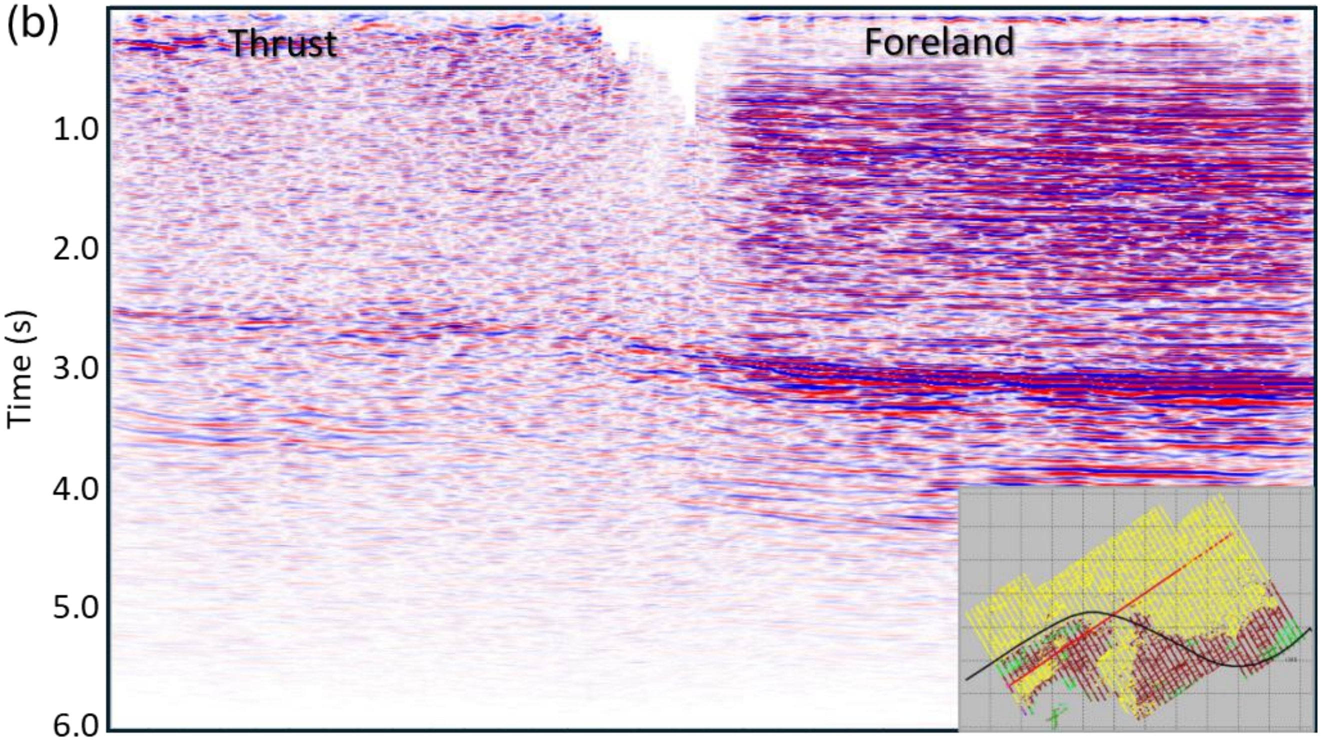


Figure 7: *Segments of stack sections visualized in the (a) foreland part, and (b) region where it crosses the thrust-fold. The red line is the position of the stack section, and the black line is the surface manifestation of the thrust-fold. The section appears to be of good quality with continuous reflection events in the foreland part, but its quality deteriorates in the thrust-fold part, with very feeble reflector events.*

METHODOLOGY

So far, we have drawn attention to the challenges faced while acquiring and imaging seismic data in the thrust-belt regions. We now focus on the aspects of mitigating those challenges and coming up with the best possible geologically reliable images within the purview of the dataset at hand and how technological advancements have helped in improving the images obtained previously. The 2D seismic profiles used for depicting the same belong to different vintages and lie on different locations along the Naga Schuppen Fold Belt. All these lines were processed previously and now have been reprocessed, keeping in mind the technological advancements using the industry standard software and workflow as depicted in Figure 8.

Some of the processing steps which proved to be the most challenging are discussed below:

1. Noise attenuation: As discussed previously, the inadequate shot hole depths and poor geophone coupling result in a lot of complex noise patterns in the shot gathers with poor SNR. As can be seen from Figure 9a – the raw shot gather is infested with significant scattered noise. Complex dispersive aliased ground rolls and random high and low frequency noises which are present on several consecutive traces completely mask the reflection hyperbolas, if at all present, especially at later times. Hence, to remove these unwanted amplitudes, several noise attenuation techniques were applied iteratively, targeting one set of noise per iteration, to achieve the noise attenuated shot gathers shown in Figure 9b.

Initial passes of noise attenuation are mostly mild to prevent any signal leakage in the initial stages of the processing sequence. Hence, not all noise has been removed from the output gathers. Intensive testing was carried out at each iteration to optimize the most suitable parameters to remove the majority of the noise with zero signal damage.

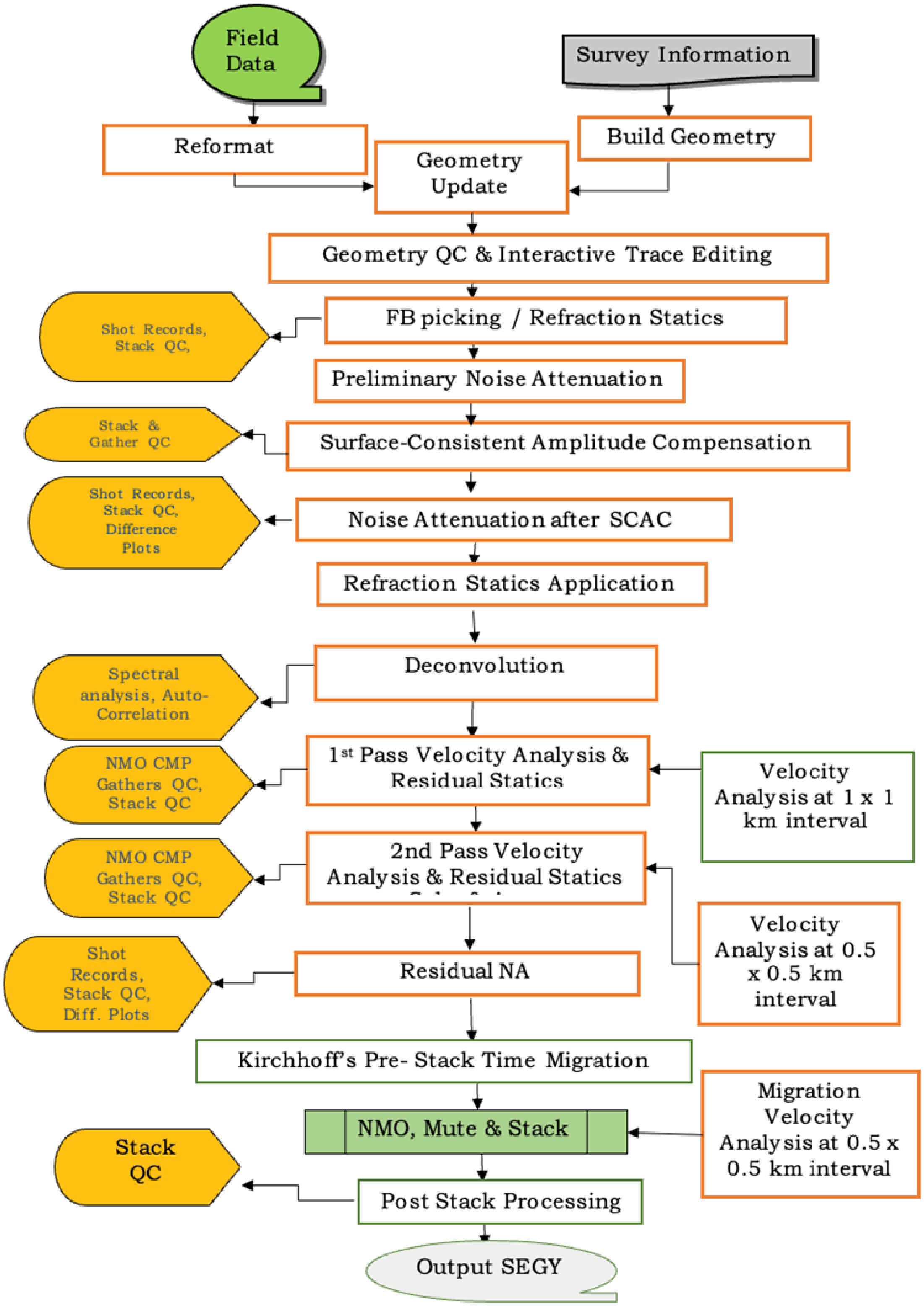


Figure 8: The processing workflow followed for reprocessing the seismic profiles.

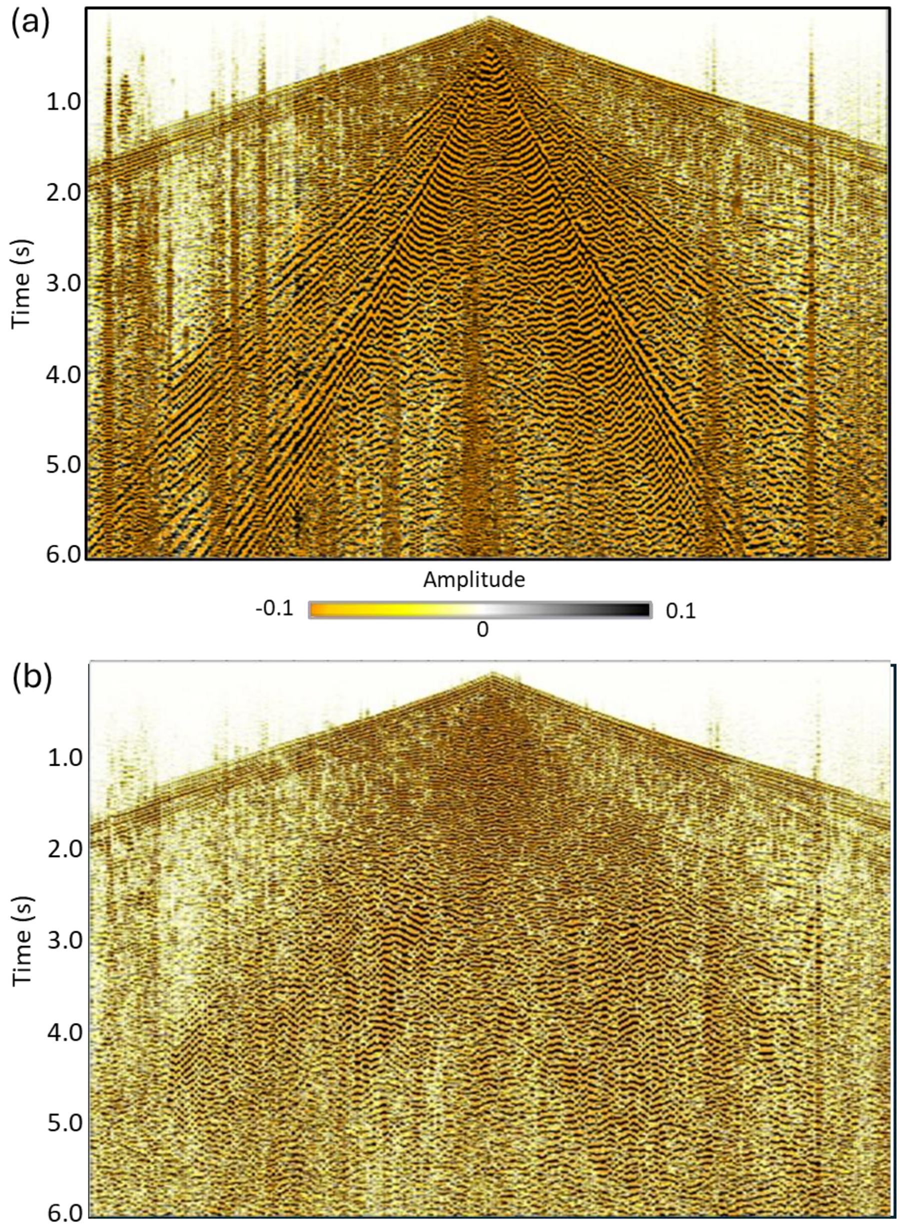


Figure 9: *Shot gather (a) before, and (b) after the application of preliminary passes of noise attenuation. Modeling of ground roll by characterising it through velocity and frequency parameters allows effective removal of ground roll.*

2. Statics computation and application – The complex noise patterns with varying elevations within shot gathers and along a survey profile, as depicted in Figure 10, pose a serious issue in picking the first arrivals. In such cases, most commercially available automated first break picking solutions are unable to pick first breaks reliably and therefore exhaustive manual quality checks need to be performed to ensure that the first break picks are consistent (Vestrum and Cameron, 2022).

Even after intensive manual QC, the first breaks in these areas vary with offsets for different shot gathers and give a broad offset versus picked time plot as shown in Figure 11.

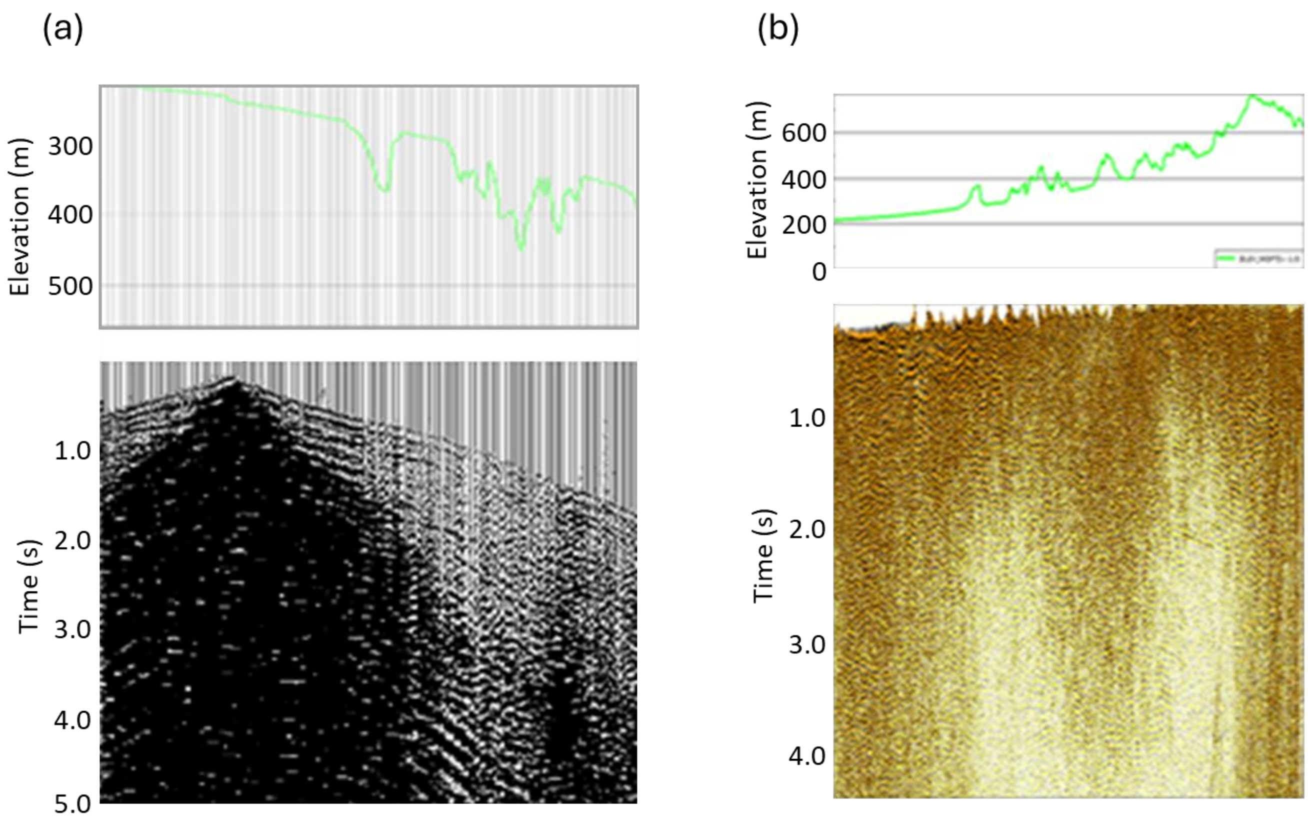


Figure 10: *Elevation variations (a) within a shot gather, varying from 200 m to approximately 450 m, and (b) along a seismic profile, where elevations vary from 200 m to over 600 m.*

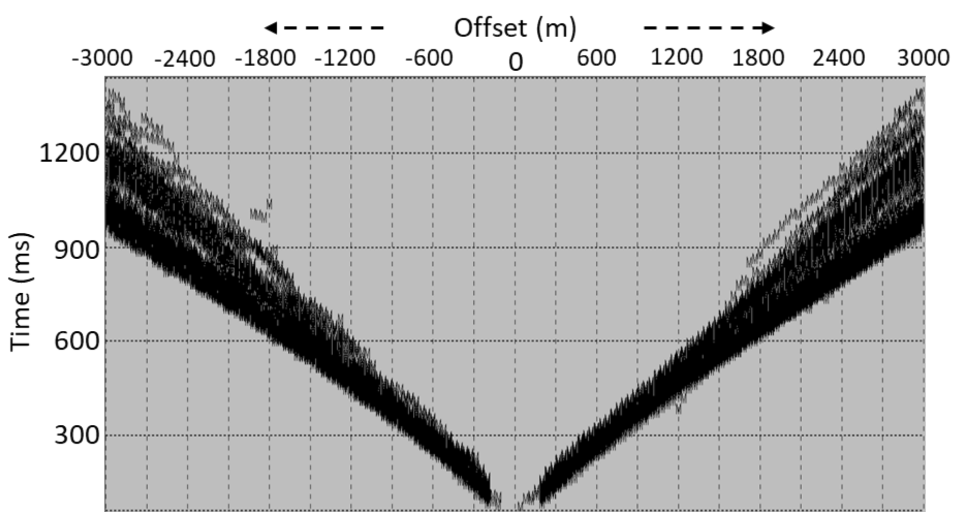


Figure 11*: Plot showing the first break pick times (in ms) along the y-axis and offset (in m) along the x-axis.*

3. Refraction statics - For complex geological settings, relying on elevation statics corrections alone is not apt since the near surface velocity models play a vital role in imaging of the sub surface. Hence to correct for such near surface velocity variations refraction tomography statics solutions have been computed and applied. Now these refraction statics solutions are quite sensitive to the quality of the first break picks in deriving the near surface velocity model. Hence, the first break picks need to be as close to the actual values as possible.

Figure 12 shows the shot gathers before (Figure 12a) and after (Figure 12b) the application of refraction statics. Focusing on the highlighted portions of the gathers, the first arrival events have become straight, removing the effects of elevation variations, and the reflection hyperbolae have aligned which were not coherent in the gathers before the application of refraction statics.

Similarly, Figure 13 depicts the structural improvements on the stack sections (highlighted) with elevation statics (Figure 13a) and refraction statics (Figure 13b).

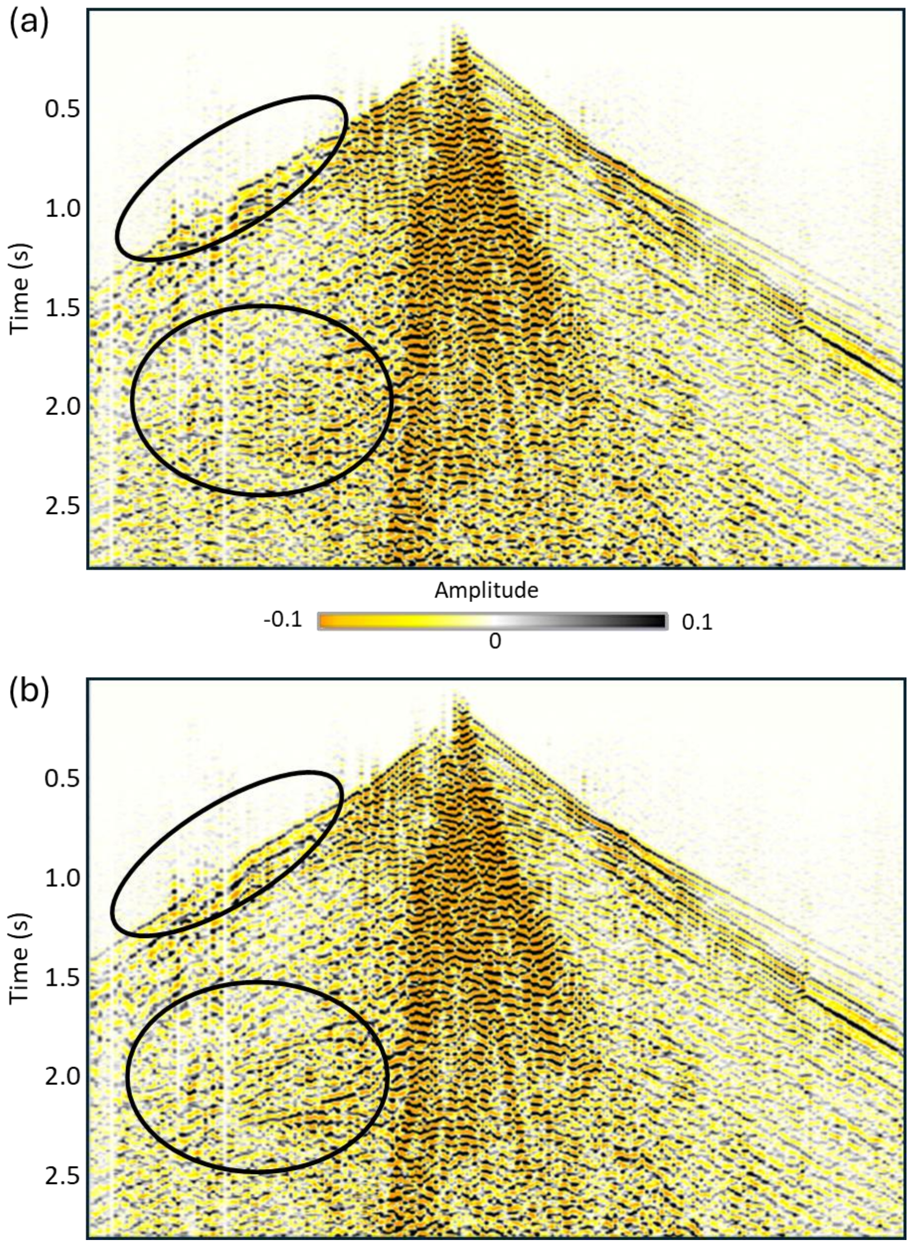


Figure 12*: A shot gather (a) before, and (b) after the application of refraction statics. These statics values have been calculated by near surface velocity modeling using a refraction tomography approach. This approach shows that if the near surface velocity, which varies significantly in thrust belt regions, is accurately estimated and is used to calculate the statics values, then the structural features of the dipping reflections can be mapped effectively.*

4. Pre-stack time migration – The vintage stacks were obtained using post-stack time migration (Figure 14a). However, the reprocessing has been carried out using pre-stack Kirchhoff time migration (Figure 14b).

Imaging the data in the pre-stack domain has helped in imaging the thrust which was missing in the vintage processed output. The shallower regions of the stack section have also drastically improved and so has the frequency content. The temporal and spatial resolution of the image has also improved. Overall, the final image obtained because of this processing is better at interpreting the thrust.

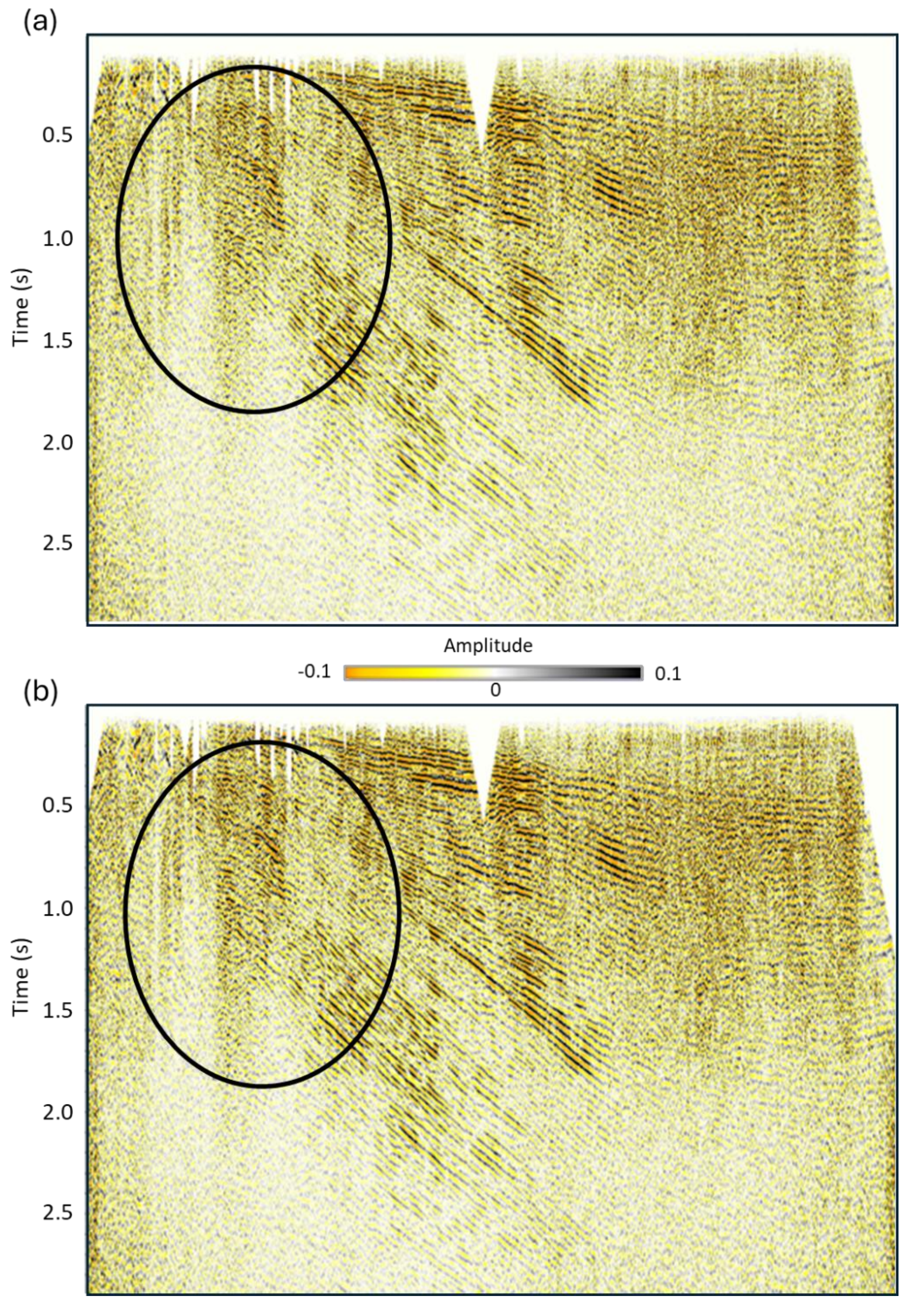


Figure 13: *Stack section with (a) elevation statics applied, and (b) after the application of refraction statics. Notice the improvement in the continuity of the dipping reflections after application of refraction tomography-based statics application. This highlights the importance of modeling near-surface velocity accurately in thrust belt regions because of the near-surface velocity variations.*

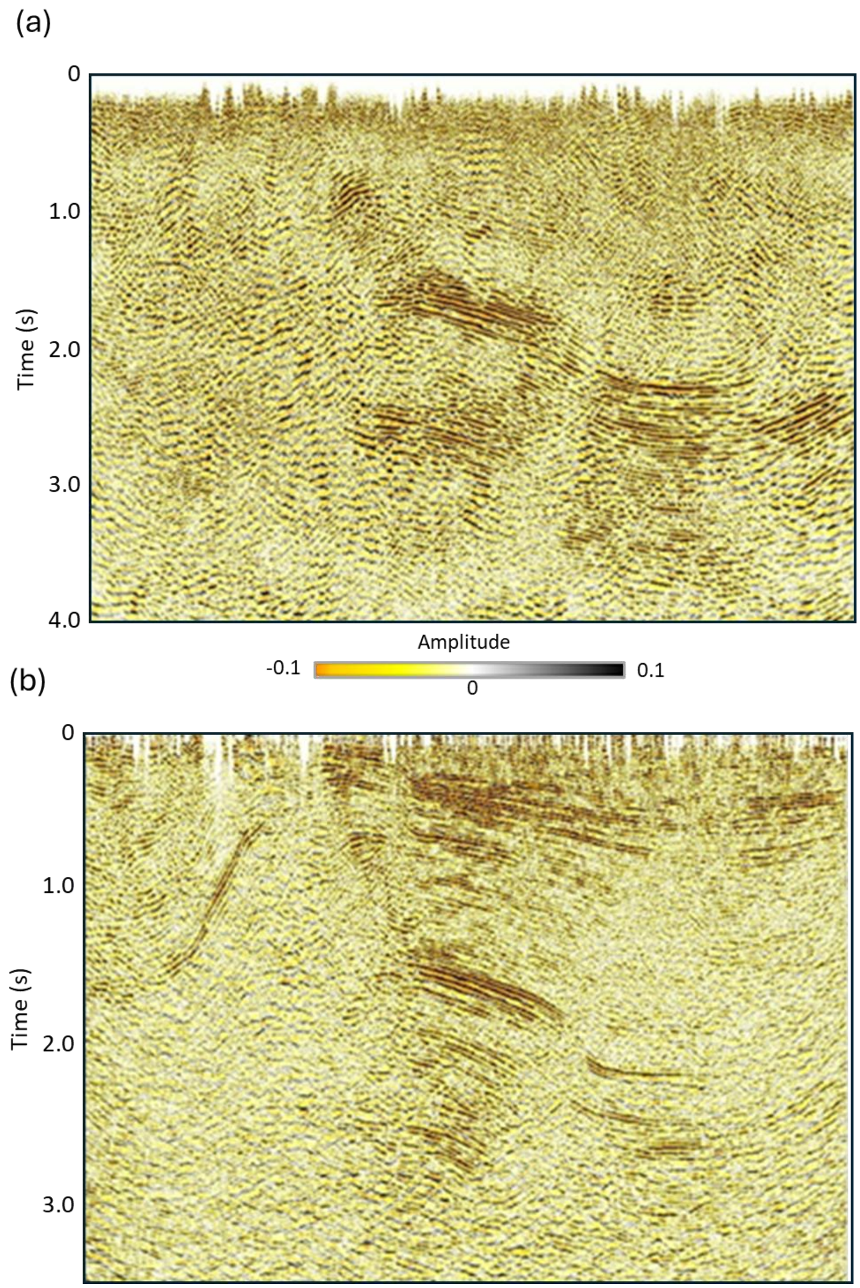


Figure 14: *Comparison of stack section segments from (a) post-stack time migration of vintage seismic data, and (b) pre-stack time migration of reprocessed seismic data.*

RESULTS

A comparative analysis of the reprocessed seismic profiles with their corresponding vintage datasets—representative examples of which are shown in Figures 15 to 17—revealed several key improvements:

1. *Enhanced thrust-fold imaging:* The thrust-fold structures, which were poorly resolved in the vintage datasets, are now more clearly and accurately mapped in the reprocessed outputs.
2. *Improved frequency content:* The reprocessed data exhibit a richer high-frequency spectrum, much of which was attenuated or lost during vintage processing as shown in Figure 18.

3. *Greater clarity of shallow events:* Shallow reflectors are significantly more prominent in the reprocessed sections, enabling better interpretation of near-surface geology.

4. *Higher resolution:* Both spatial and temporal resolution have improved considerably in the reprocessed data, resulting in a much sharper and more coherent seismic image across the entire section.

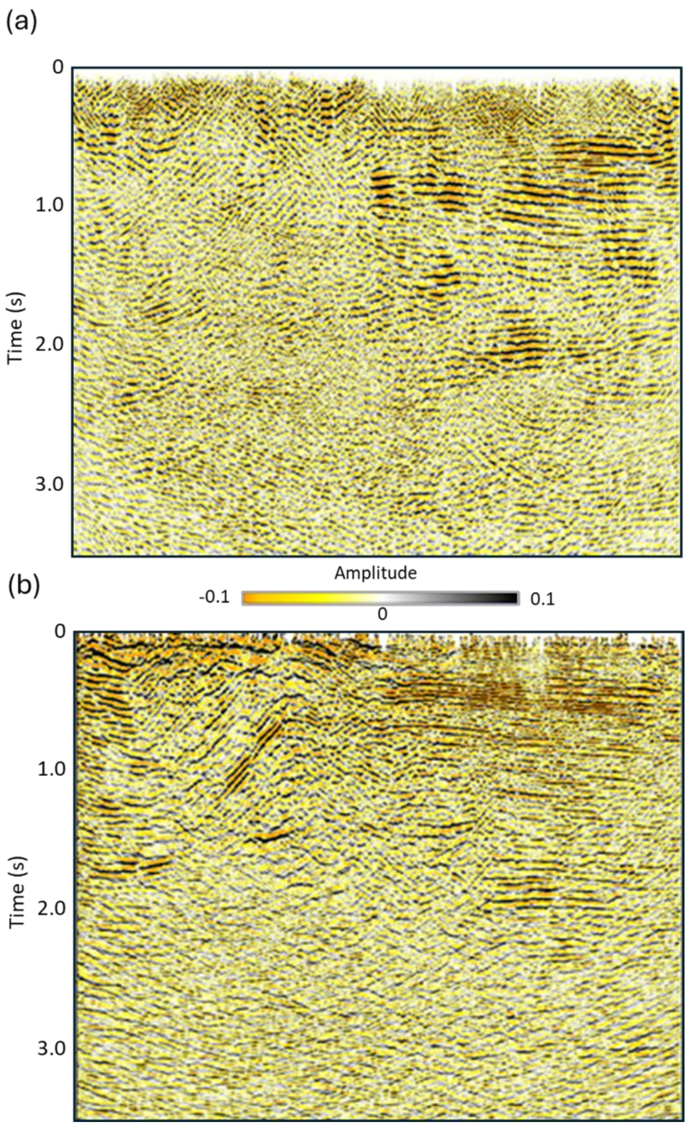


Figure 15: *Comparison of stack section segments from (a) post-stack time migration of vintage seismic data, and (b) pre-stack time migration of reprocessed seismic data.*

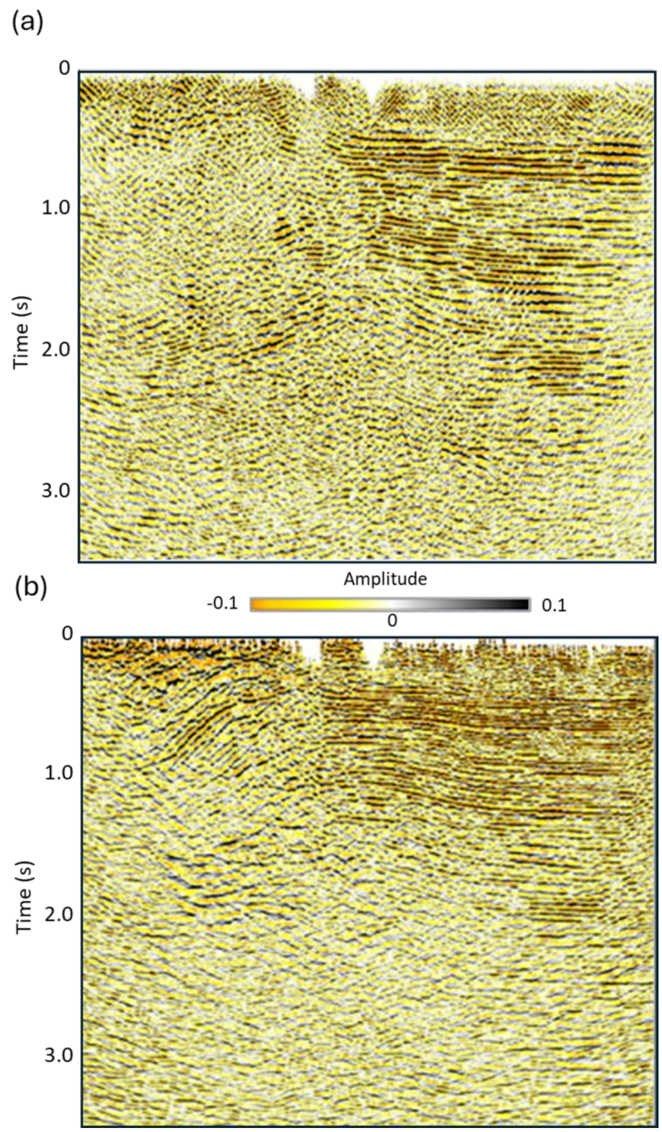


Figure 16: *Comparison of stack section segments from (a) post-stack time migration of vintage seismic data, and (b) pre-stack time migration of reprocessed seismic data.*

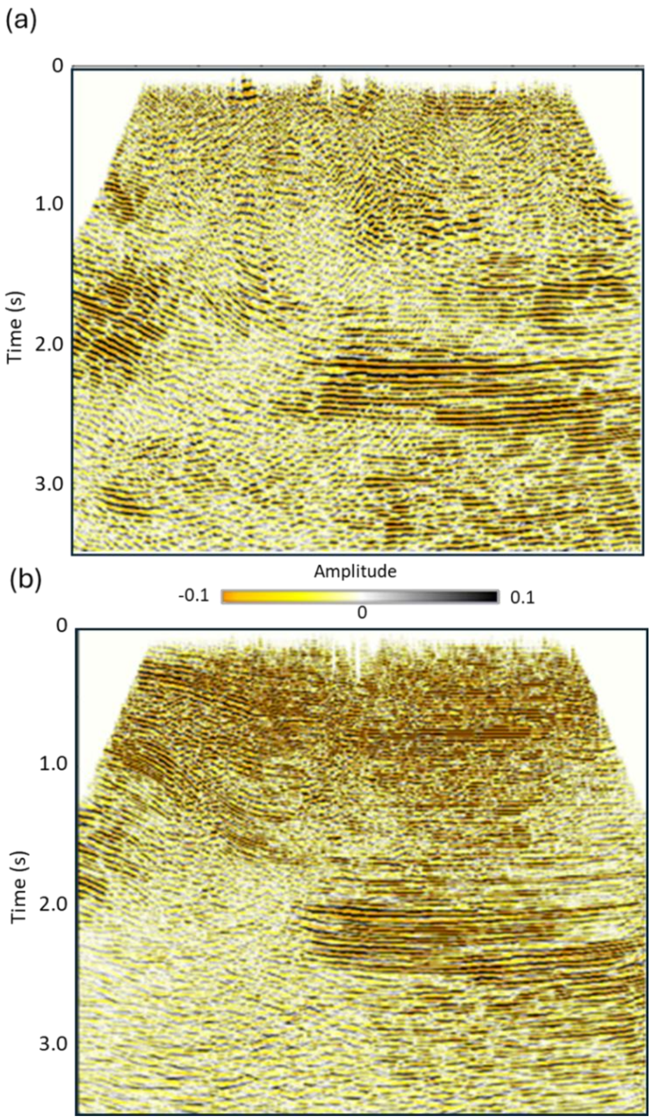


Figure 17: *Comparison of stack section segments from (a) post-stack time migration of vintage seismic data, and (b) pre-stack time migration of reprocessed seismic data.*

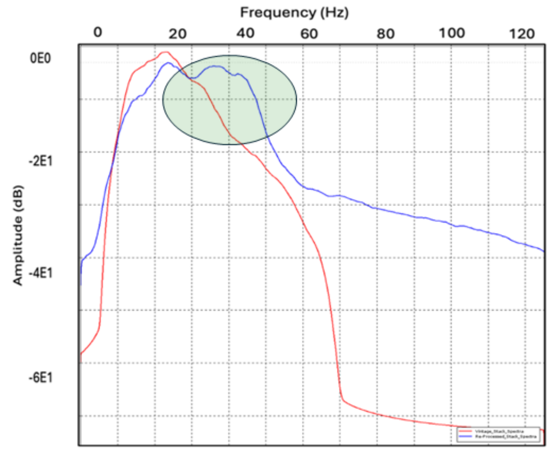


Figure 18: *Comparison of frequency spectra of vintage stack (red) and reprocessed stack (blue) shows the improved frequency content of the latter.*

CONCLUSIONS

Challenges during seismic data acquisition, such as difficult terrain and poor access, often result in low signal-to-noise ratio (SNR) and other artifacts. These issues degrade data quality and propagate through processing and imaging, making it harder to produce geologically meaningful subsurface images.

We have demonstrated that such challenges can be effectively mitigated through a robust, customized imaging workflow. Key steps include accurate first-break picking, near-surface velocity modeling for refraction statics, model-based noise attenuation to enable spiking deconvolution, and careful velocity analysis. These steps are critical for generating geologically conformable images, especially in thrust belt regions.

While high-end imaging techniques such as Kirchhoff PSDM, RTM, and full-azimuth imaging are commonly applied to thrust belt datasets, it is often overlooked that these methods rely on gathers conditioned during time imaging. Therefore, a comprehensive and reliable time imaging workflow is not only foundational but essential to fully realize the benefits of these advanced imaging algorithms.

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BIOGRAPHIES

Arpita Adhikary earned her master's degree in geophysics from the Indian Institute of Technology, Kharagpur in 2017, securing the top rank and a silver medal for academic excellence. Since 2018, she has been working as a geophysicist at Oil India Limited (OIL), a Maharatna National Oil Company, working in the Seismic Imaging and Modeling Centre as a processing geophysicist. With over seven years of experience, she specializes in onshore 2D/3D seismic imaging in both time and depth domains across diverse Indian basins, including Assam Shelf, Rajasthan, Mahanadi, and thrust belt regions. Given her proficiency in advanced processing software and tools such as Omega, GeoDepth, and ES 360, Arpita has successfully led multiple high impact imaging projects, contributing significantly to OIL's exploration and development efforts.

Kartik Sharma studied B.Sc. (Hons.) in physics from Kirorimal College, University of Delhi and thereafter completed M.Tech. in applied geophysics from Kurukshetra University. He has over eight years of upstream hydrocarbon exploration experience—ranging from land and marine 2D/3D seismic acquisition to anisotropic TTI seismic imaging—gained while working for India's Maharatna National Oil Company, Oil India Limited. He has a thorough hands-on experience of carrying out 2D/3D seismic data imaging—both in time and depth domains—from various sedimentary basins of India, ranging from the thrust-belt areas of Assam-Arakan Basin, Mahanadi Basin to the desert regions of Rajasthan.

Anup Kumar works as Chief General Manager (geophysics) at Oil India Limited (OIL), brings over three decades of expertise in geophysics to OIL, India's Maharatna National Oil Company. His academic background includes a M. Tech. in applied geophysics from Kurukshetra University and a general management and leadership programme from the Indian Institute of Management, Bangalore. Over his career, Anup has played a pivotal role across geophysics functions—ranging from seismic data acquisition and processing to interpretation and exploration monitoring. He is currently serving as the head of geophysical activities at OIL and has served as the nodal officer for India's National Seismic Program, overseeing geophysical activities organization-wide.