ENHANCING SEISMIC RESOLUTION AND FAULT DEFINITION BY USING ADEQUATE PROCESSING PARAMETERS, LOWER INDUS BASIN, PAKISTAN

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DEDICATION

I dedicate this research to my parents and teachers for their encouragement and constant support. Your trust and belief in my capabilities and abilities have been my biggest motivator and bedrock of inspiration and support throughout this journey.

Without your support, this achievement would not have been possible. I am eternally grateful for your selfless contributions and never-ending support.

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ABSTRACT

Seismic data reprocessing means to revisit an acquired seismic data with new processing technologies that involve newer algorithms. Structured set of procedures and algorithms are applied to increase the signal to noise ratio, thus enhancing the resolution of subsurface image and geological structures. This study employed adequate processing algorithms for re-processing of seismic data acquired in 1997 along a 2-D regional seismic line in Kirthar Fold Belt (KFB), Lower Indus Basin, Pakistan. The area has complex geology with well-developed thrust faults due to compressional forces. There are numerous anticlines and faulted structures in the area that are frequent traps for oil and gas accumulations, where cretaceous age formations represent the primary reservoirs of the region. For the identification of structural traps in the area, it is necessary to apply appropriate processing algorithms on the data to get a high-resolution subsurface image. Therefore, the objective of this study is to re-process existing seismic data for an improved resolution of the subsurface that will help identify structural traps in the region and proper delineation of faults in the reservoir area. The desired results were obtained by carrying out accurate pre-processing of seismic data; in which appropriate noise attenuation operations eliminated all kinds of noise from the data. Other types of noise inherent in the seismic data were attenuated by using Time Variant, Bandpass and F-K filters. The application of True Amplitude Recovery (TAR) was utilized to recover and regenerate the reflection energies lost due to the process of inelastic attenuation and geometric spreading. Predictive deconvolution was used to increase vertical resolution, and more sophisticated velocity analysis methods enhanced the sub-surface imaging capabilities. The Pre-Stack Kirchhoff Time Migration (PSTM) technique managed to correctly relocate the dipping reflection events in time as well as space, which resulted in gaining high resolution seismic image with improved imaging of faults within target reservoir. The output (PSTM) and that of the legacy data was then made to be compared and it clearly generated a high-resolution seismic image of the subsurface.

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CHAPTER 1

INTRODUCTION

1.1. Introduction

In Exploration Geophysics, one of the most widely used techniques to study and observe the Earth's subsurface/interior is Seismic. It is a comprehensive way of detecting and measuring the oil & gas reservoirs. Subsurface seismic imaging (mapping the Earth's interior) is one such method that involves remote sensing method for probing into the earth. It detects ground motion at or near the surface and processes the recorded data through a series of steps to create images in terms of variations in seismic velocity and density. Seismic sensors record the ground movements, from which a response of media through with seismic wave energy is traveling can be inferred. Data acquisition creates the basis, processing refines the acquired data, and interpretation converts this data into geological information. Every step involved in the process is critical for better understanding the subsurface geology, and consequently making informed decisions while performing oil & gas exploration/engineering/environmental studies (Aki and Richards, 2002).

Seismic data processing aims to improve the resolution of seismic data. This is what we need to interpret, which means when you are decoding the data, it helps. The idea here is to turn the rather raw data into a form that lends itself nicely for signal extraction. The raw seismic data is both complex and noisy since it consists of wanted reflections signals from the earth subsurface as well as unwanted noise. Data processing techniques are then used to improve the signal-to-noise ratio and provide a more detailed sampling of subsurface structures, hence improving resolution (Zhou, 2014). High resolution seismic helps the interpreters in identifying structural and stratigraphic features with much higher accuracy than before using limited, low-resolution data. The challenges brought about by these noise types are tackled through signal enhancement and optimal utilization of these processing steps to help significantly improve the observation and understanding of geological features in seismic data (Yilmaz, 2001).

The study aims to implement essential processing techniques on the raw seismic data. Seismic data preprocessing followed by processing steps i.e., refraction statics, fine grid velocity modeling and residual statics, random noise attenuation and Pre-stack Kirchoff time migration are some of the techniques that will be applied to refine the data. Alongside, several types of filtering techniques will be applied throughout the process to enhance the resolution of subsurface to better analyze the subsurface faults and structures. Filters like Bandpass filter, F-K filter and Time Variant filter will be applied at various steps to refine the data (Haver, 2008).

The interpretation greatly depends on the quality of the processed seismic data. Insufficient processing techniques have repercussions of wrong interpretations. Sophisticated processing techniques are necessary since they improve the signal to noise ratio and also the resolution of the seismic data. This improvement is crucial in the fact that it allows the interpreters to detect the structural and stratigraphic components with much greater accuracy. In the end, due to the improved processing methods, there is an enhancement in the resolution of seismic images which allows the construction of better subsurface models of geology. Good data interpretation, which is only achievable through advanced data processing, is what can assist energy and petroleum firms to make impeccable decisions about the exploration and extraction of resources. (Nanda, 2021).

1.2. Literature Review

Due to the complex geology controlled by subduction zone, seismic reflectivity in Makran offshore region presents technical challenges for data processing. The tectonic displacement of deep natural gas resources gives rise to mud diapirs and gas hydrates. Consequently, the purpose of this paper is to improve vertical and lateral resolution The Bottom Simulating Reflector (BSR) using new processing algorithm in gas hydrates exploitation. Our new workflow includes preserving true amplitudes, source designature processing by the inversion of direct arrivals from the seismic streamer, noise attenuation algorithms, high resolution velocity analysis, and pre-stack time migration earth. The presented results clearly illustrate improvement in the resolution of BSR with high S/N compared to the results generated using standard industry processing algorithms. The inversion of direct arrivals provided the vertical resolution, whereas horizontal resolution was achieved by the selection of an adequate migration algorithm and velocity model (Kamal et al., 2023).

In 2008, the 2D seismic datasets were acquired in the Spring Coulee Field, Alberta. Line 2008-SC-01 has been reprocessed to yield a clearer visualization of The Madison Formation; ranging between 1300 ms towards1400ms.The Madison formation depicts shallow carbonate shelf deposits. The processing workflow was created by initial testing of different methods, algorithms and parameters to find the best possible solution for our data. The processing steps consisted of elevation statics, noise attenuation, deconvolution and 2D Kirchhoff post stack time migration. To get high resolution seismic image, noise elimination is one of the most important steps for this study as data contain high ground roll and air blast noises. Thus, the recorded ground roll and air blast effects were attenuated with the application of suppress module, bandpass, and F-K filters. The resultant seismic image clearly provides a better understanding of the subsurface (Demir, 2018).

The seismic data acquired in Delaware Basin, which is a part of the Permian Basin in the USA, was reprocessed. The data that was processed previously has a very low signal to noise ratio and the seismic images were not accurately interpreted at the target zone due to low quality seismic. This is due to the presence of near-surface complexities (evaporites and a velocity reversal) that give rise inter-bed multiples, surface waves and diffractions. Recently, an integrated solution was used, and reprocessing has been completed. From the seismic standpoint, better SNR (signal-to-noise ratio), fewer multiples between adjacent beds and reduced noise from surface are also produced with high-resolution turning-ray tomography mechanism plus adaptive denoising, 5D interpolation and structure-oriented filtering algorithms applied to the post-stack images. The intent of the reprocessing was to enhance seismic image quality, allowing clearer interpretation and fault definition, as well as identification of sweet spots within this target zone interval (Yan et al., 2017).

In this study, several newly developed seismic data processing techniques were used to reprocess the regional 2D marine seismic line (in existence since 1986) in order to improve the quality of subsurface information obtainable from regional data which still remains one most essential means for an early look understanding about petroleum prospect prospects in a basin and also test their application over part of Taranaki Basin, New Zealand. The reprocessing operations attenuated certain noise or unwanted signals associated with the seismic data, F – K transform filter filtered out low frequency type of noise in which swell noise is expected to be killed by this process whereas other type of noises summarized for example multiple and coherent interference related in the seismic datasets were reduced through Time Variant Omsby Bandpass filters. Dealing with these periodic undesired signals in addition to multiple water bottom reflections, predictive deconvolution was applied. Repair of missing reflection energies and the display capability to show deeper reflections became possible using full waveform recovery. The dipping reflection events were correctly relocated in time and space to their true positions using high-quality PSTM Post-Stack Time Kirchhoff migration) technology. Both the shallow and deep reflection events were folded into diffraction curves to increase data resolution. Most of the reprocessing boosted signal strength for imaging part of Taranaki Basin with complex subsurface geology in structures and rock association from TRV 434 marine seismic data (Osinowo, 2020).

1.3. Problem Statement

The KFB is one of the prospective zones of Pakistan with respect to the presence and exploration of hydrocarbons. Extensive research in terms of reservoir characterization and petrophysical analysis has been done on the reservoir formations in the region. The KFB has complex geology with well-developed thrust faults representing strong deformation due to compressional forces, where numerous anticlines and faulted structures are frequent structural traps for oil and gas accumulations. Better identification and exploration of these structural traps in the region requires the application of appropriate processing algorithms on the seismic data acquired from the field, to increase the S/N, thus enhancing the resolution of subsurface image and geological structures.

While there is a global emphasis on seismic data reprocessing, with ample published material on the subject, Pakistan lacks a comparable volume of articles in this field. Hence, this research aims to enhance the seismic resolution and imaging of faults in the subsurface by the application of adequate processing algorithms, addressing the existing gap in published knowledge within the Pakistani context. This study is focused on the reprocessing of seismic data for an improved resolution of seismic signal which will aid in the accurate delineation of subsurface faults. It will help gain deeper insights into the geological features and structures, enabling a more precise and comprehensive analysis of the target reservoir.

1.4. Objectives

Main objectives of this research are:

1. To enhance the resolution of seismic image by applying adequate processing algorithms.
2. To improve the fault definition of the target reservoir using finer velocity modeling, accurate migration algorithm, FK filter, and coherency filtering etc.

1.5. Study Area

Due to the confidentiality of the data used in the study, the block name and line name have not been provided. The study area is situated in the Kirthar Fold and Thrust Belt of the Lower Indus Basin, Pakistan. The rugged hilly terrain of the study area is accessible by a network of roads (N-25, N-85 & M-8) from major cities of Pakistan; Quetta, Karachi and Khuzdar. This area is located adjacent to western collisional boundary of the Indian plate. The study area is bound to the west by Khuzdar Knot, east by Kirthar Foredeep which is joined by Kalat Block towards north while the Karachi arc is situated towards south (Khalid et al., 2022).

No Paleozoic sequence has been very well documented in the study area while massive, thick Mesozoic and Cenozoic sequences have been encountered in the area. The Pab Sandstone (Late Cretaceous) and Ranikot Group (Paleocene) being the major productive formations. The deeper reservoirs, which include the Jurassic carbonates and sand bodies with various Cretaceous strata including the Goru and Mughalkot Formations, are also prolific in this area (Halepoto, 2023).

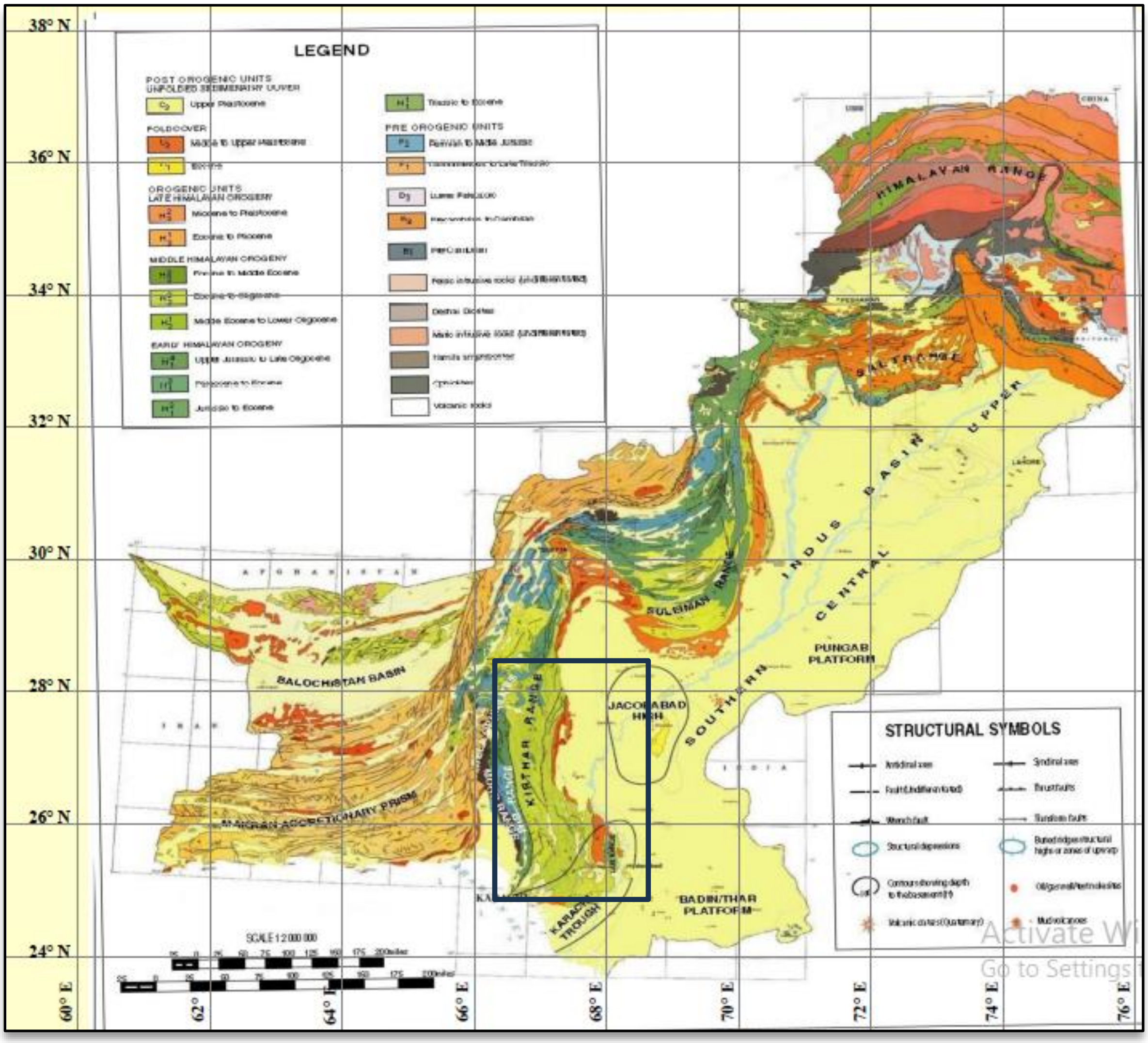


Figure 1.1: Map of Pakistan. The black rectangular boundary represents the study area (Hussain, 2013)

The Kirthar Fold Belt consists of a series of parallel rock hill ridges oriented mostly north–south, with piedmont and piedmont-alluvial plains located between ridges, with dry riverbeds. The ridges rise rapidly over short distances between valleys and ridges (Bannert et al., 1992).

1.6. Dataset and Methodology

Data: 2D Raw Seismic data

Line name: Confidential.

Software: GeoEast.

Methodology: The processing sequence designed to achieve the interpretable image will likely consist of several individual steps. First, data initializing or pre-processing of seismic data is performed which includes data preparation and QC, amplitude recovery, S/N enhancement and deconvolution. In the next phase data refinement and processing of the data takes place which includes refraction statics, fine grid velocity modeling, data conditioning for migration and pre-stack time migration.

A generalized flow is given here, whereas a detailed workflow will be discussed in ***chapter 3***.

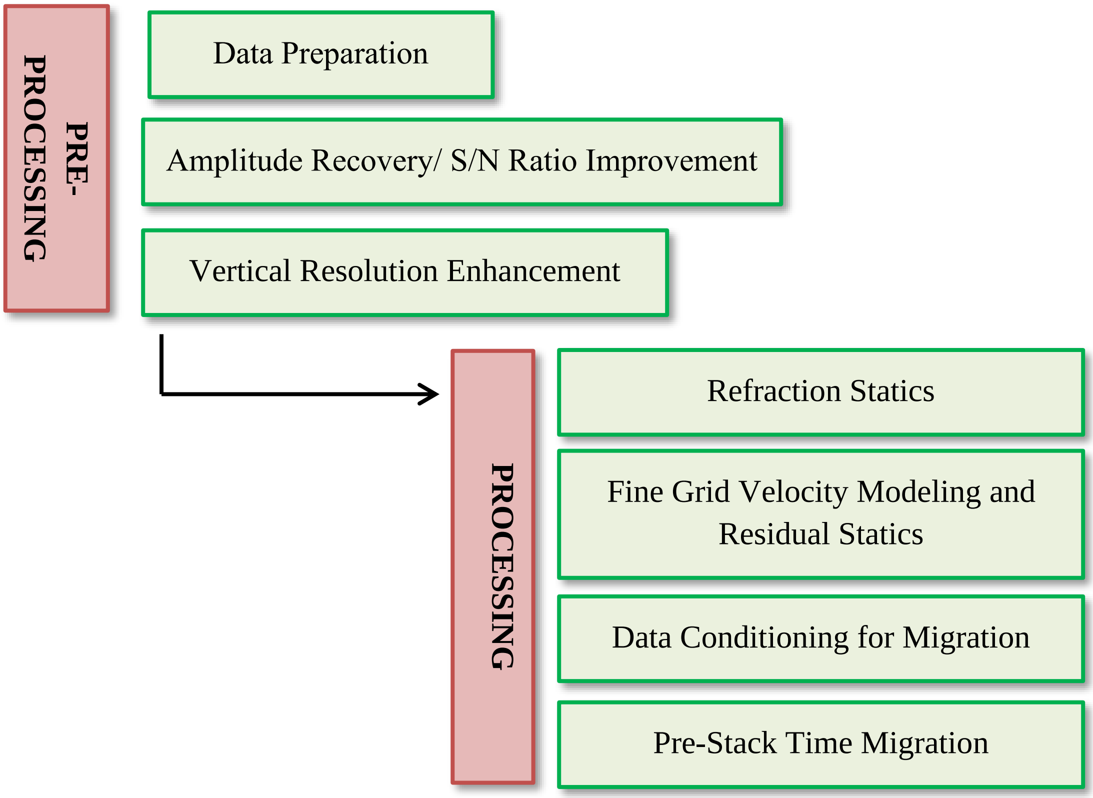


Figure 1.2: Generalized processing flow (This workflow consists of sequential steps involved in the research process)

1. **Data Preparation:** It is basically the QC of data. Where we must kill and remove all the bad records from data for example bad traces, inverse polarity traces, and completely blown out records. Survey data or acquisition field reports are observed in detail and geometry is prepared using source numbers, receiver numbers and the associated elevation, and longitude and latitude data (Yilmaz, 2001).

2. **Amplitude Recovery and S/N Ratio Improvement:** In the amplitude recovery process we have to recover the true amplitudes lost during seismic data acquisition due to inelastic attenuation. Amplitudes are recovered through geometric spreading. Then different types of filtering techniques will be applied to remove the noise from data (Yilmaz, 2001).

3. **Vertical Resolution Enhancement:** This step aims to resolve the resolution of target reservoir by the application of deconvolution. When seismic signals pass through the subsurface, they convoluted with the Earth material, where during the process the higher frequencies get absorbed as Earth acts as a high cut filter. To enhance the temporal resolution, the omitted high frequencies must be recovered. Deconvolution is a mathematical process to reverse the effect of convolution on observed data. deconvolution attempts to introduce these lost frequencies into the data. Therefore, it is also called as inverse filter (Haver, 2008).

4. **Refraction Statics:** Refraction statics are done to remove the effect of weathered layer or low velocity layer using static corrections. It aims to remove the distortion due to surface topography. Refraction statics contribute to a more accurate seismic data interpretation by correcting dispersions in surface elevation and sub-surface layer properties (Haver, 2008).

5. **Fine Grid Velocity Modeling:** Fine grid velocity modeling is done to define a fine grid on our target zone. In this step, different passes of velocity are performed (1st pass, 2nd pass, 3rd pass and 4th pass). During each pass, the velocity analysis is perfomed at

different inetrvals to map the subsurface structures with more accuracy (Yilmaz, 2001). Velocity analysis is done alongside residual statics. Residual statics resolves the static issues in the data.

6. **Data Conditioning:** After applying static correction on data and performing velocity modeling we must look for remnant noises in the data, which will be removed by the application of Pre-Stack Random Noise Attenuation (PreRNA). In Seismic Data Processing, data conditioning before migration is a step that works in preparation to make seismic data good enough or well suited for the migration course. Migration provides the most accurate positioning of seismic events into their correct spatial locations, meaning that the cleaner and more reliable your input data, the more accurate would be the migration (Zhou, 2014).

7. **Pre-stack Time Migration:** A technique used to create a clearer image of subsurface structures by considering the travel times of seismic waves (Yilmaz, 2001).

CHAPTER 2

REGIONAL GEOLOGY AND STRATIGRAPHY OF AREA

2.1. Tectonic History of the Region

In Late Cretaceous, the collision of Indo-Eurasian Plates began due to intraoceanic subduction in Neotethys. There are three phases to this collisional process according to Powell (1979).

i. The northwards movement of Indian Plate towards the Eurasian Plate from Late Cretaceous (70 Ma) up to Early Eocene.
ii. During Eocene, the Indian Plate's northward drift slowed down with the initiation of its anticlockwise rotation.
iii. Slow tectonic drift towards the north with oblique collision from Oligocene till date.

During the Paleocene, this off-lateral collision resulted in obduction of ophiolites at western margin of Indian Plate like Bela-Waziristan ophiolites. The anticlockwise rotation led to a collision of the Indian Plate with the Afghan block which resulted in reduced drift velocity of the Indian plate and initiated an oblique collision with the Afghan block. The Oligocene-Miocene marks a period of strong oblique collision. This oblique collision combined with counterclockwise rotation impacted the regional geology with the origination of Chaman Transform Zone at western margin of Indian Plate. This zone manifests the presence of three regional faults which are Chaman Fault, Ghazaband Fault and Ornach-Nal sinistral faults. This in turn produced intricate fold and thrust belts i.e., Kirthar & Sulaiman fold and thrust belts in the region as well as other transpressional structures (Fowler et al. 2004).

2.2. Tectonic and Structural Geology of the Area

The study area lies in the Lower Indus Basin, which is one of the sedimentary basins of Pakistan and is located just south of the Sukkur Rift. Geographically the Lower Indus Basin is situated in Sindh Province of Pakistan. It stretches roughly between 24°-

28° N and 66° E to the southern border of Pakistan. On the regional scale, it is a north-south trending sedimentary basin, as shown in Figure 2.1. It includes thicker tertiary sequence conformably underlying thin Quaternary sediments. The Kirthar Fold and Thrust Belt marks the western margin of Lower Indus Basin (Khalid et al., 2022).

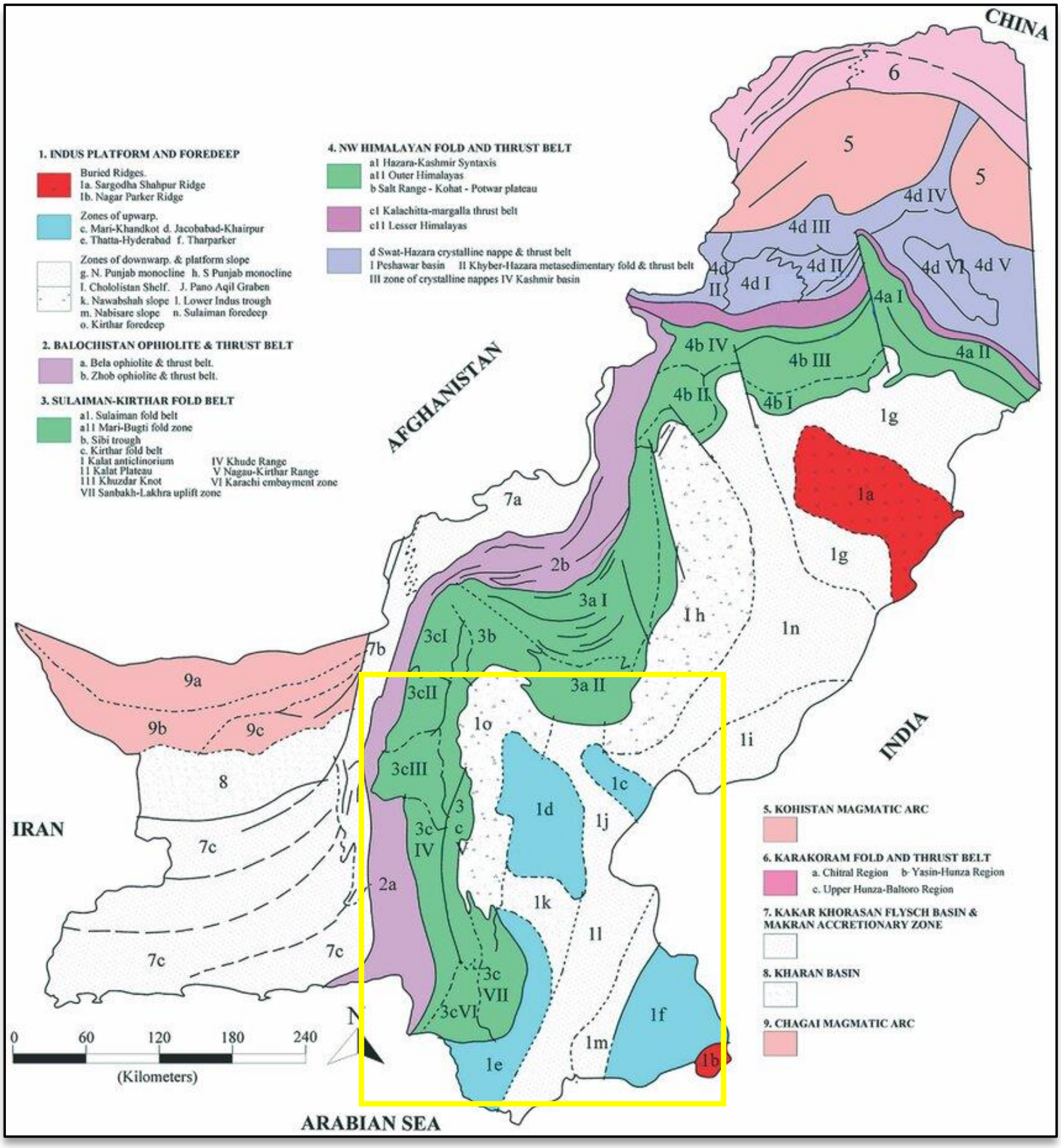


Figure 2.1: Tectonic Map of Pakistan. The rectangular boundary is representing the Lower Indus Basin of Pakistan (Kazmi & Jan, 1997)

The collision of the Indian plate with Eurasian led to deformation in two directions within this area. The first phase was in northward direction corresponding to the Indo-Pakistan plate movement during Paleocene and Eocene. During the second phase of deformation, the region was dismembered by a left lateral fault system which leads to shear motions between the blocks during further collision development. This shear movement of blocks formed a zone of transpression and compression which is defined by strike-slip and thrust faulting in the area, due to which major fold and thrust belts have emerged in the area where Kirthar Fold and Thrust Belt is one of them (Hinsch et al., 2019).

Owing to the deformation in the area, the Lower Indus Basin is structurally divided into 5 units as shown in Figure 2.2. These are.

i. Thar Platform
ii. Karachi Trough
iii. Kirthar Foredeep
iv. Kirthar Fold Belt, and
v. Offshore Indus

The Lower Indus Basin is confined between Indian shield in the east and marginal zone of Indian plate to the west. Its southern prolongation is terminated by the offshore Murray Ridge-Oven Fracture plate boundary while it is separated from the Middle Indus Basin by Sukkur Rift. (Kadri et al., 1994).

2.2.1. The Kirthar Fold Belt Zone

The Kirthar Fold and Thrust belt, a north-south trending fold belt zone represents the eastern boundary of Lower Indus Basin. It is the southern extension of the Fold belt zone in the Lower Indus Basin and is present adjacent to the present-day strike-slip western margin of the Indo-Pakistan Plate represented by the Ornach-Nal Fault System (ONF) and the Chaman Fault.

Towards east, the Kirthar Fold Belt grades into the undisrupted Indian foreland. Kirthar Fold and Thrust Belt extends into Offshore SW-NE-striking Murray Ridge, in the south-west. In the north, it joins Kalat Plateau while it extends towards Karachi Arc in the south. The deformation in Kirthar Fold Belt is marked by presence of three basement faults i.e. Kirthar Basement Fault, Sulaiman Basement Fault, Jhelum Basement Fault (Khalid et al., 2022).

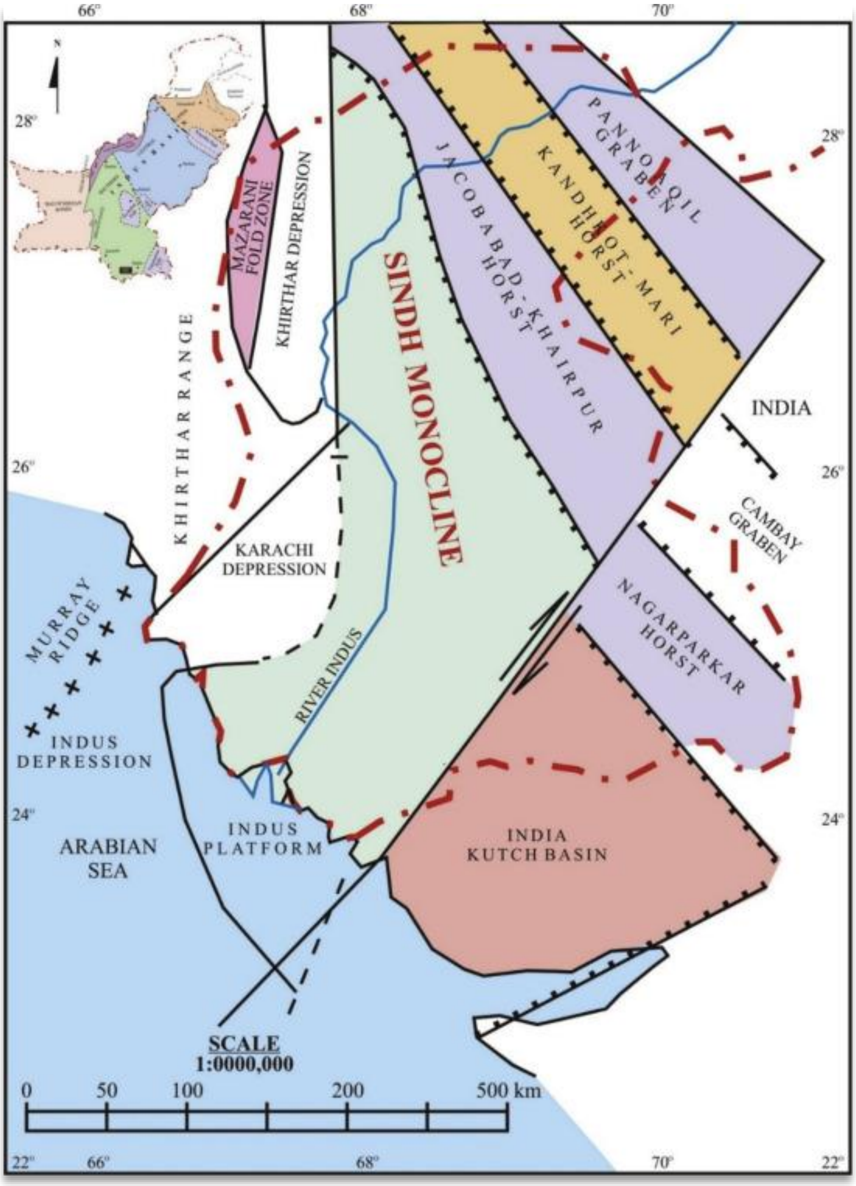


Figure 2.2: Structural units of Lower Indus Basin (Raza et al., 1990)

2.3. Stratigraphy of the Area

Tectonic events related to Indian-Eurasian plates collision which affected the Indo-Pakistani Basin since Cretaceous are considered as a major cause of sharp contrast in stratigraphy of Pakistan. The stratigraphy of the Lower Indus Basin (figure 2.3) is complex. Sedimentary rocks up to several thousands of meters of thickness deposited during the Mesozoic and Cenozoic times, are best developed in Lower Indus Basin, consisting mainly of calcareous and argillaceous sediments (Quadri and Shuaib, 1986).

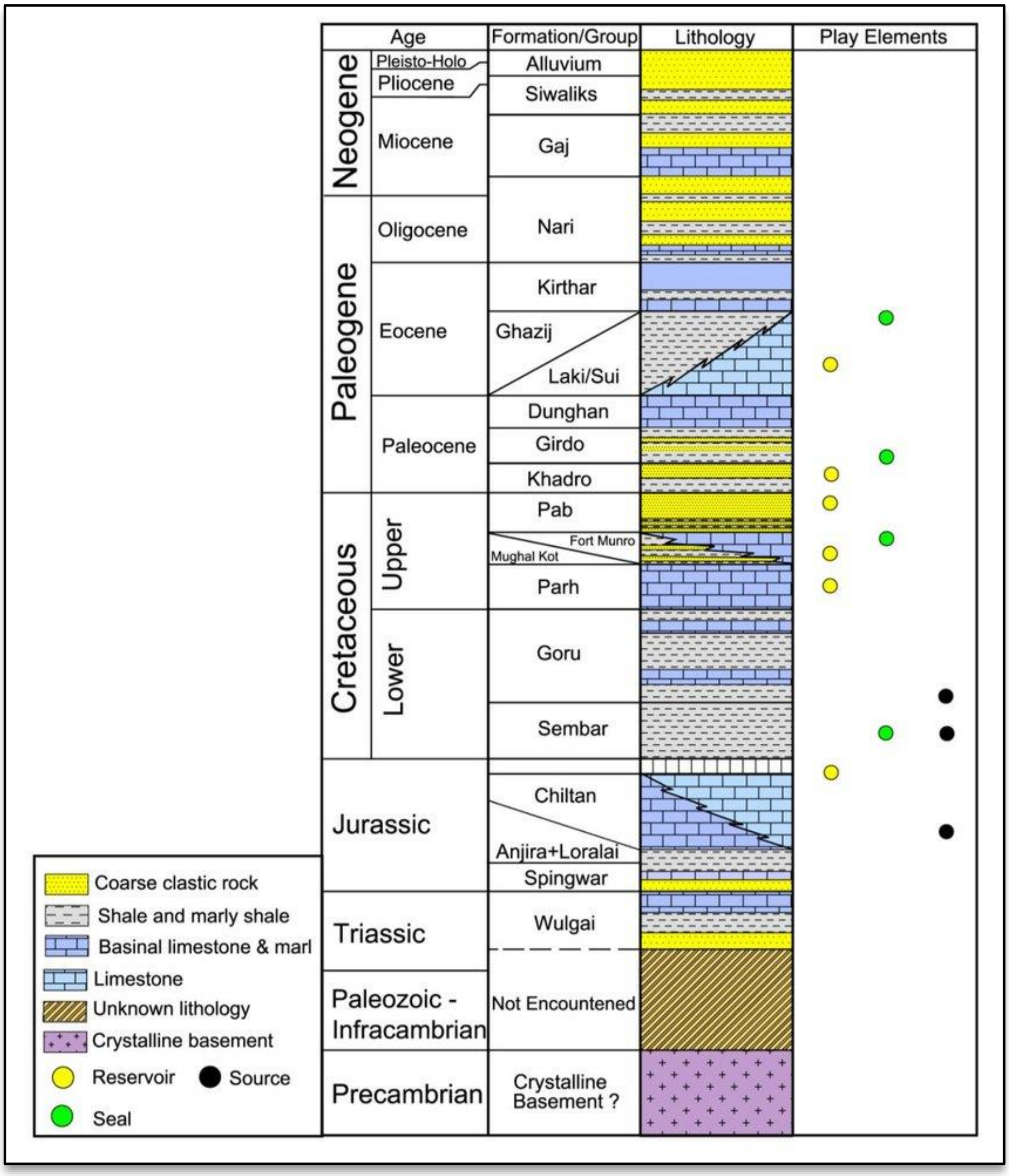


Figure 2.3: Generalized Stratigraphical column of Kirthar Fold and Thrust Belt showing the lithostratigraphic overview and petroleum elements (Hinsch et al., 2018).

2.3.1. Mesozoic Rocks

Western part of the study area is taken up by Jurassic Chiltan and Cretaceous Parh Series. The Chiltan Formation of Early Jurassic is identified by thick bedded limestone, coarse grained and is oolitic. The color of limestone is light gray to dark gray. Some members of Cretaceous rocks are not properly developed in Kirthar Fold Belt, so it is known as the Parh Series Undifferentiated. Parh Series comprises Sembar, Goru, Parh Limestone, Mughal Kot Formation, Fort Munro, Pab and Moro Formations. The formations in this group typically consist of limestone, calcareous shale and marl (Khalid et al., 2022).

2.3.2. Cenozoic Rocks

The Paleocene Dungan Formation is characterized largely by brownish gray thick bedded nodular limestone. This formation is also comprised of some shale, marl & conglomerate. It is conformably overlain by the Early Eocene Ghazij Formation. The Ghazij Formation comprises mostly shales of greenish grey to olive color shales with claystone. Its upper contact is transitional with the Kirthar Formation of Mid-Late Eocene age. Kirthar Formation is largely composed of limestone with some shale and marl. It has transitional contact with the lower Ghazij Formation and while it has a conformable upper contact with the Oligocene Nari Formations. Nari Formation has a transitional contact with overlying Gaj Formation. Gaj and Nari Formations form the Momani Group (Khalid et al., 2022).

2.3.3. Siwaliks

Soan, Dhok Pathan, Nagri, and Chingi Formations collectively form the Siwaliks group. Nagri Formation is characterized by sandstones of greenish gray color, olive green shales, reddish brown siltstone and light to dark gray conglomerates. The Siwaliks group is underlain by Gaj Formation with a transitional contact (Khalid et al., 2022).

2.4. Petroleum System in the Study Area

In the Lower Indus Basin, the Lower Cretaceous Shale of Sembar Formation and the shales present in Lower Goru sands have been implicated as primary source rocks (Raza et al., 1990). These shales are the major source of hydrocarbon in this region, owing to their high organic content and good thermal maturity. The main producing reservoirs in the Kirthar Fold Belt are Pab Sandstone of Late Cretaceous age and Ranikot Group of Paleocene age. The overlying Shale of Khadro/ Ranikot serves as a top seal for the underlying reservoir i.e., Pab sandstone. Many wells in the area have demonstrated these shale beds to be efficient seals. Along with these, shales of Ghazij Formation in certain localities also provide a good seal in the area (Naeem, 2016).

CHAPTER 3

METHODOLOGY

3.1. Seismic Data Reprocessing

Seismic data reprocessing means to revisit an acquired seismic data with new processing technologies that involve newer algorithms. Re-processing seismic data is a process utilized for evaluating the existing oilfields. This is an essential step for improving the subsurface seismic image in both quality and accuracy. The detailed workflow adopted to get the desired results is given at the figure 3.1.

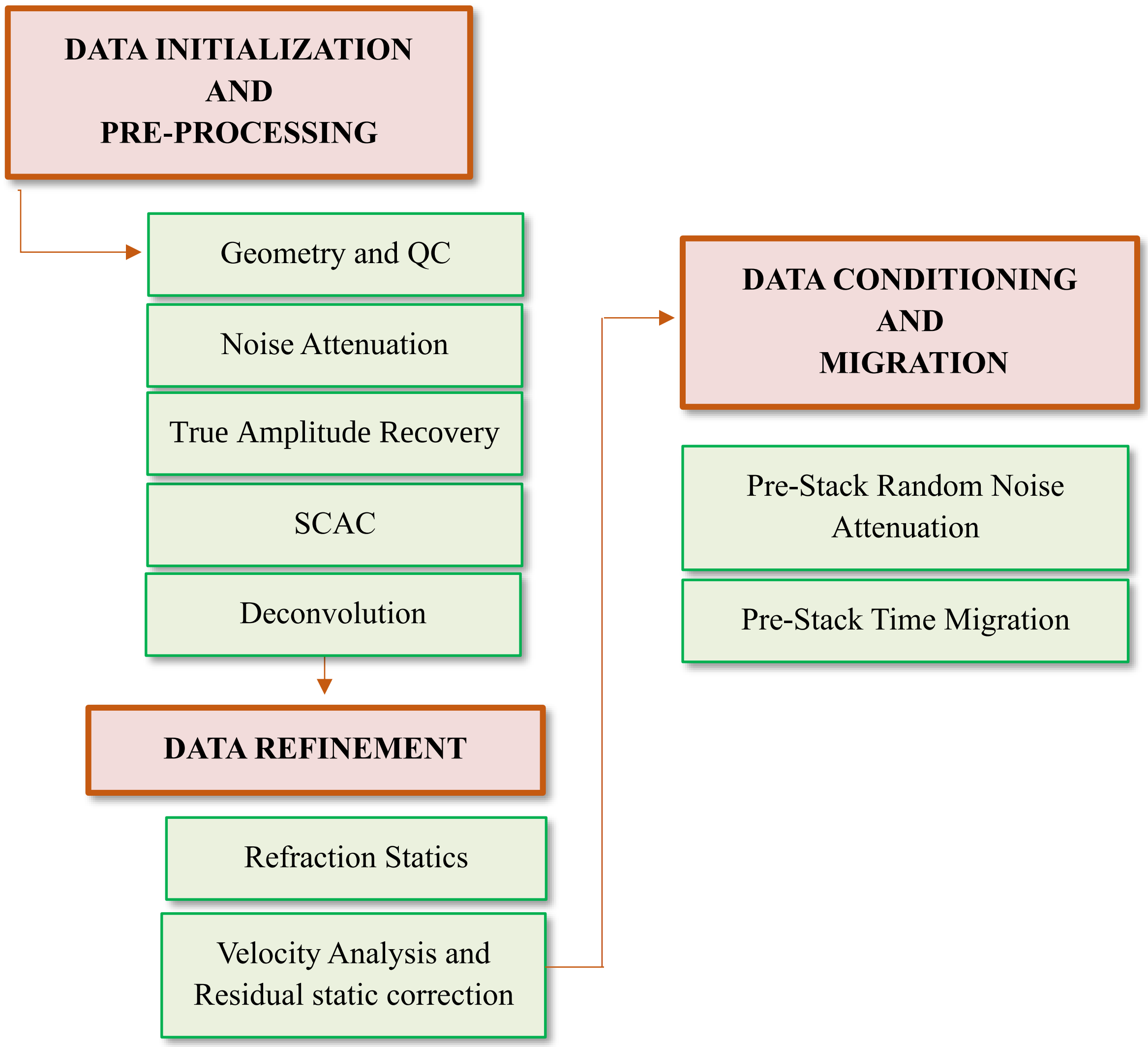


Figure 3.1: Detailed Seismic Data Processing Workflow

3.2. Data Initializing and Pre-processing

3.2.1. Geometry Data

Geometry data contains information about source and receiver intervals, total number of shot points, number of channels, maximum fold and in general, all the information related to seismic data acquisition. The information is needed to process 2D field records which are usually recorded on a SEG-Y tape. Geometry information is originally stored in the SPS File. Incase SPS file is not provided, it can be generated using observer's log report. The acquisition data stored in the SPS file or observer log report is used to define the geometry of the data, and consequently set up geometry in such a way that all the traces get projected onto how they were recorded at the time of acquisition. Geometry preparation is done to make data appear globally configured and hence makes it easy for the software to process it (Yilmaz, 2001). After the geometry is loaded successfully using the SPS file, the data quality check was performed to ascertain if the geometry set up is appropriate.

3.2.1.1. Quality Check of Geometry Data

Once the data is loaded successfully, it is followed by necessary quality control checks. Quality Control (QC) in seismic data processing is an essential and one of the initial steps to verify the correctness and adequacy of the seismic data prior to further data analysis. Where bad traces are killed during trace editing and completely blown out or missing records are removed from the data (Yilmaz, 2001). Other types of quality checks are:

1) Offset QC
2) Source deviation check

3.2.2. Amplitude Scaling and Phase Conversion

When the data comes from mixed sources, it undergoes amplitude and phase conversion. Dynamite and vibroseis data are identified by their phase characteristics with dynamite as minimum phase data and vibroseis as zero phase data. For dynamite, its energy is minimum at zero, while vibroseis has maximum energy at zero (Yilmaz, 2001). Furthermore, these data types are distinguishable visually. As in the case of vibroseis data, the ground rolls are far more pronounced due to strong engine noise whereas the appearance of ground rolls is less prominent in the dynamite data.

The mixed source data can be separated by making the use of ***hole depth*** parameter. Once the data is separated, the vibroseis data goes through amplitude scaling and phase conversion to ensure consistency in both amplitude and phase across the dataset.

This process consists of the following steps:

- **i.** **Step 1:** Data splitting and amplitude balancing, i.e., the data is split into dynamite data and vibroseis data. After splitting, amplitude scaling is applied on the vibroseis data.
- **ii.** **Step 2:** Phase conversion, i.e., in this step the vibroseis data is converted from zero phase to minimum phase.
- **iii.** **Step 3:** Trace editing, i.e., the data goes through a round of trace editing during which all the bad traces are removed from the data.

3.2.3. Noise Attenuation

Denoising is a significant step in seismic data processing where coherent and random noise present in the data gets removed to enhance the S/N of the data. Coherent noise is a predictable type of noise that follows the same pattern continuously. It is highly likely to be associated with some characteristics or sources and repeats in a predictable manner. On the other hand, random noises or non-coherent noise have an irregular and unpredictable nature (Yilmaz, 2001).

Ground roll is a type of surface wave (a secondary wave) that travels along the boundary between differing media, such as between earth and air or water. It is featured by low speed, low frequency, high amplitude and great energy. However, in petroleum seismic explorations ground roll is one of the most usual and prevalent noise (coherent noise) sources. It is characterized by higher amplitude as well as stronger energy relative to reflection signals, and thus the ground roll obscures the near-offset reflections, and it can also mask the deep reflections recorded at far offset. In addition, the reflection signals also get distorted when overlapped by ground rolls (Halliday et al., 2015).

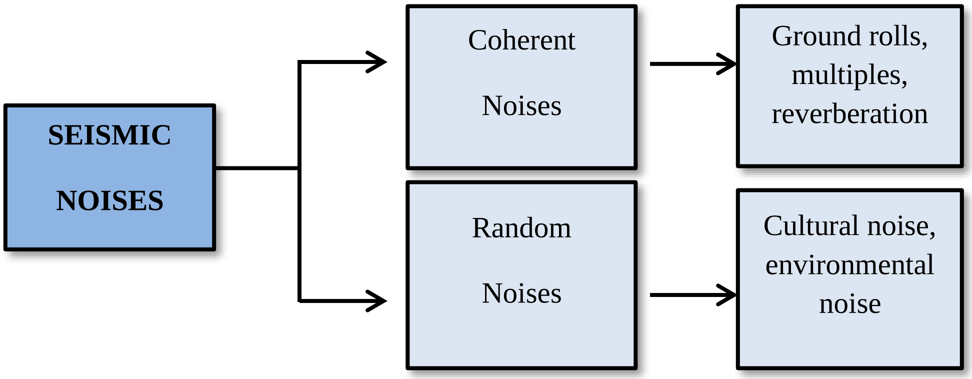


Figure 3.2: Types of noises present in seismic data

Noise attenuation is a step wise process. It involves,

i. **Step 1:** The first step particularly involves the removal of ***ground rolls*** from the data by the application of a specialized algorithm, shown in Figure 4.14.
ii. **Step 2:** Subsequently, if any other ***coherent noise*** present in the data is further addressed, and gets eliminated, shown in Figure 4.15.
iii. **Step 3:** This is followed by applying the ***KL transform*** to remove any remaining noise still present in the data, shown in Figure 4.16. The KL transform helps decompose the data into components that capture most variance (signal) and those which capture less variance (noise). This helps to segregate the data into signal and noise and makes it convenient to remove noise from the data. Thereby increases the signal to noise ratio of data.
iv. **Step 4:** In the final step, the data gets further cleaned up by the removal of ***wild amplitudes***, shown in Figure 4.17.

3.2.4. True Amplitude Recovery (TAR)

The application of True Amplitude Recovery (TAR) is utilized to recover and regenerate the reflection energies lost due to the process of inelastic attenuation and geometric spreading (Hale, 2009).

i. ***Elastic attenuation,*** Seismic waves lose energy as they propagate within Earth, mainly due to scattering and absorption. Recovering true amplitudes means removing that attenuation effect, allowing the measured amplitude in your record to reflect what was there with respect to energy in the source signal (Yilmaz, 2001).
ii. ***Geometric Spreading,*** Seismic waves lose energy with increasing distance from the source as they move away in different directions causing attenuation of amplitude. Since the amplitude decay with distance reflects this geometric spreading, true amplitude recovery scheme corrects for it to return amplitudes to their level at some standard reference distance (Yilmaz, 2001).

3.2.5. Surface Consistent Amplitude Compensation (SCAC)

Surface Consistent Amplitude Compensation (SCAC) is a seismic data processing technique to remove amplitude variation that occurs due to changes in recording condition at surface. This is required to ensure that the seismic data correctly represents underlying subsurface properties instead of being influenced by surface related factors (Henin et al., 2014).

Surface effects are differences in seismic amplitudes because of varying source-receiver geometry and surface conditions. This variability can mask the actual subsurface reflectivity, which in turn complicates seismic interpretation. Noticeable differences in the amplitudes are largely controlled or compensated using amplitude compensation technique (Schuster, 2022).

Surface consistent amplitude compensation aims to normalize these particularities and provide a true reflection of what seismic waves encountered beneath the earth's surface. This includes source, receiver and geometric statics applied to the seismic data. This technique relies on the fact that amplitude variations can be divided into consistent components, associated with surface factors. By isolating and correcting these components, the resulting data set is a truer representation of subsurface features (Schuster, 2022).

SCAC was carried out for the analysis of five components:

1. Source
2. Receiver
3. Offset
4. Geology
5. Trace

This was done to find out which parameter or component brings in the largest amplitude attenuation. The target was to find out the major amplitude reduction components and to make up for that loss by individually adding the lost amplitudes back.

i. **Step 1**. SCAC was performed for source and receiver components (Figure 4.23 and Figure 4.24).
ii. **Step 2:** SCAC was done for source, receiver and offset component (Figure 4.25 and Figure 4.26).
iii. **Step 3:** Source, receiver, offset and geology were incorporated in the process (Figure 4.27 and Figure 4.28).
iv. **Step 4:** Along with these components, trace was also included (Figure 4.29 and Figure 4.30).

3.2.6. Deconvolution

Surface Consistent Deconvolution (SCDC) incorporates any source, receiver, offset or CDP combinations when calculating the power spectrum and carrying out deconvolution. The seismic signal can be regarded as the convolution of the source signal, the instruments that are geophones or a combination of both and the response of the earth. It is believed that seismic waves are also filtered by the ground surface conditions. Such effects can not only produce time lag but can also influence the amplitude of waves and can cause phase shift. The objective of surface-consistent deconvolution is to remove such distortion caused by earth filter (Yilmaz, 2001).

So, deconvolution is a mathematical technique used to reverse the effects of convolution on recorded data. As convolution of a seismic wavelet with the real reflectivity of the subsurface produces seismic data but subsurface heterogeneities, can cause waves to become stuck in strata, reflect several times, and ultimately rise to the surface as multiples that are interpreted as noise in the seismic data. To remove the effects of source signature and noise from the data, ***predictive deconvolution*** is used. Determining an **operator length** and **prediction distance** are important steps in this procedure.

- **i.** ***Operator Length:*** The operator length is designed in accordance with the observed multiples to lessen the effects of multiples. Autocorrelation is used to evaluate the similarity between traces. During the autocorrelation, primary reflections are plotted at zero time, whereas multiples (secondary and tertiary reflections) appear at non-zero times.
- **ii.** ***Prediction Distance:*** The predictive distances (or gaps) are multiples of the sample interval. These gaps are tested to subtract the wavelet or source signature from the true reflectivity. To get optimal resolution, a spike should ideally be sent into the subsurface and receive at the surface with a sample interval of two milliseconds. During the process, the wavelet at different gaps (4 ms, 8 ms, 12 ms, 16 ms, 20 ms, 24 ms, 28 ms, and 32 ms) can be predicted. Next, the resolution of these gaps is compared to the spiking data at the 2 ms sample interval; the best resolution is obtained from the closest match. To isolate genuine reflectivity, the gap is removed from the data once it has been identified.

3.3. Data Refinement

3.3.1. First Breaks and Refraction Statics

The first arrivals on a shot gather are usually associated with the refracted energy that is generated from the base of the weathering layer, and these arrivals are termed as first breaks (Yilmaz, 2001).

These seismic waves are the first ones to arrive at the receiver. First break picking is useful in estimating the delays in travel times of seismic waves that occur due to the presence of low velocity layer (LVL) in the subsurface. Picked times may be employed to predict velocities of the near-surface layers. To do this, the time differences between first breaks are analyzed to construct a near-surface velocity model based on these first breaks (Yilmaz, 2001). The variation in velocity in subsurface due to LVL leads to late arrivals at geophones, which is adjusted by the application of *Refraction static correction* as shown in figure 4.39 and figure 4.40.

3.3.1.1. First Break Picking

First-break picking can be conducted automatically, manually, or as both depending on the data. Before initiating picking, Linear Moveout (LMO) is applied on the data for the reliable and most accurate first breaks picking. It is important to mention that the efficiency of any static correction, be it based on refraction or reflection, depends on how reliable the first breaks picks are.

The first breaks were picked at every SP, as shown in figure 4.39. And the required QC was also performed to remove any error if present in the data. There is a built-in tool in GeoEast that is specialized in indicating any error or inconsistency in picks. The tool allows reviewing the FB picks and any wrong or poor picks can be easily managed and corrected by a simple click. Click on the pick and make the required edit by adjusting the picked first break, as shown in figure. The first breaks data was utilized in the process of refraction static correction to create reliable subsurface model, as shown in figure 4.40. First break picking needs to be done accurately, as any inconsistency in the picking process can lead to inaccurate time calculation which affects the further analysis.

3.3.1.2. Refraction Statics

Refraction Statics is one of seismic data processing techniques, which is used to correct changes in travel times of seismic waves caused by variations in near-surface low velocity zone, due to LVL. LVL is a type of subsurface layer with very low seismic wave velocities as compared to surrounding layers. This effect can be observed in unconsolidated sediments, soft clays or porous saturated rocks. Weathered or fractured rock zones also cause the velocity of seismic waves to drop. This correction is essential in locating seismic events accurately and getting an accurate image of the subsurface (Saha et al., 2012).

3.3.2. Velocity Analysis and Residual Statics

Velocity Analysis is done on selected CMP gathers or sometimes on a collection of CMP gathers. The velocity analysis yields data in the form of a table of numbers that contains velocity versus two-way zero offset time also called a velocity spectrum. This measure shifts in the semblance across each hyperbolic move out time controlled by time, offset and velocity. When performing velocity analysis, Normal Move Out (NMO) processing is what underlies the technique. Attempts can be made to correct NMO using the obtained velocities before the actual stacking of the CMP gathers so that the CMP reflections are surfaced preceded by ringing effects. Reliable velocity models are essential for the estimation of travel times of seismic waves which are useful in mapping the depth and location of subsurface features. Accurate velocity models lead to better understanding and imaging of the subsurface features (Yilmaz, 2001).

Finer velocity modeling involves more intricate velocity modeling and permits different passes of velocity which produces more reliable velocity models. During each pass, velocity is chosen in discrete intervals to render more precise and accurate structural details of the subsurface.

Residual static corrections are introduced to the seismic data to eliminate the differences that occur between the observed travel times of a seismic wave and those which were predicted from an initial approximation. These differences often resulted from the presence of the heterogeneities and the irregularities in the near subsurface, that cause distortions of the seismic signals prior to reaching the geophones (Yilmaz, 2001).

A primary model of velocity is used to observe the seismic waves travel times. On the contrary, the observed travel times can be influenced and subject to variation by the near surface effects. A set of residual statics is applied after the initial correction to the travel times. These are minor corrections to the initial adjustments for the purpose of correcting the lateral misalignments in the seismic data (Yilmaz, 2001).

3.3.2.1. Process

The application of **finer velocity modeling** and **residual statics** is attributed to the improvement of the quality of seismic data. Information about the subsurface is improved through finer velocity modeling and near surface distortions are corrected by residual statics. In an iterative process these operations are carried out alternatively to ensure that seismic practice assimilates both subsurface velocity gradients and surface effects which enhance the efficiency of capturing images. This sequential operation results in accuracy of the interpretations made on the seismographs and geo-physical readings.

i. **Velocity Analysis 1st Pass:** First, an initial velocity model is used for conducting initial stacking and imaging. This facilitates getting an overview of subsurface geology as well as detecting important features (figure 4.41).

ii. **Residual Statics 1st Pass:** Implementation of the residual statics deals with distortions created by non-uniformity of the near-surface layers. The near-surface distortion is corrected using residual statics. This step enhances the quality of the stacked seismic data given and makes the subsequent processing more precise (figure 4.42).

iii. **Velocity Analysis 2nd Pass:** Once residual statics are applied to the data, this data can be utilized to improve the velocity model further. This updated model can then give a more realistic subsurface imaging, which is quite important for the enhancement of the seismic images (figure 4.43).

iv. **Residual Statics 2nd Pass:** The refined velocity model with go through another round of static correction to remove any irregularities in the data (figure 4.44).

3.4. Data Conditioning and Migration

3.4.1. Pre-Stack Random Noise Attenuation (PreRNA)

During the pre-processing stage, the process of ‘Noise Attenuation’ is utilized to refine the data. The elimination of noise and refinement of data enhances the signal to noise ratio of data. High signal to noise ratio enhances the overall resolution of the data. High resolution seismic data allows for better imaging and interpretation of subsurface faults and structures.

After static modeling and velocity analysis, the data is checked for any kind of remnant noises still present. Before migration, the data requires further pre-conditioning. During this stage of the process, firstly the data will go through pre-stack random noise attenuation (PreRNA) algorithm, as shown in figure 4.45. The refined output with high signal to noise ratio will go through another pass of velocity analysis i.e., 3rd Pass Velocity Analysis, shown in figure 4.46. This refined velocity model will be utilized further in the process of pre-stack time migration. The velocity model after the 3rd pass will be Final Stack data i.e., Unmigrated seismic section (figure 4.46).

3.4.2. Pre-Stack Time Migration (PSTM)

Pre-stack time migration (PSTM) is a technique in geophysics that is aimed at correcting lateral displacements of certain seismic events arising from lateral velocity changes in seismic sections prior to stacking (Yilmaz, 2001). The objective of PSTM lies in bringing correct images of seismic events by shifting seismic reflections to their correct time level to have a better estimation of the subsurface events. This aids in proper delineation of subsurface faults and other geologic structures.

Pre-stack time migration operates in the time domain. Its essence consists in positioning the seismic reflections as they are supposed to be in the subsurface based on the given velocity model. One of the more frequently used techniques is Kirchhoff Migration, where the displacement of reflections in time is estimated and is corrected based on a velocity model (Yilmaz, 2001).

A time migration seismic image result is produced in which all the reflections have been time reset to the correct positions in time so that the depiction of the subsurface is clearer and more accurate. It must be noted that the success of PSTM depends on how accurate the velocity model is. An incorrect model will, in practice, give inaccurate results following migration.

3.5. Framework

The desired results were obtained by carrying out accurate pre-processing of seismic data. Observer’s log data were used to prepare the ***geometry*** following necessary quality control (QC) steps over the initial data load. As it was initially a mixed source data, so to convert the acquired data into single phase we made it go through ***amplitude scaling*** and ***phase conversion*** techniques. This was followed by a round of trace editing to remove any unwanted traces from the data set. S/N was improved by the application of ***noise attenuation*** algorithms where different types of noise (coherent noise, ground rolls, and linear noise) were removed from the data. ***True Amplitude Recovery*** (TAR) method was applied to recover the true amplitudes lost due to elastic attenuation followed by the application of ***Surface Consistent Amplitude Compensation*** (SCAC) which sought to correct the trace energy inconsistencies occurred due to the difference in sources and receivers. ***Deconvolution*** was performed to enhance the vertical resolution of seismic data particularly target reservoir. This all-inclusive approach is considered as a pre-processing of seismic data.

Following the first break picking, ***refraction statics*** were performed. This included using the dataset of first break pick times extracted from the trace headers and analysis of refraction velocities from these pick times to build subsequent models of Earth. This time around, we implemented more sophisticated ***velocity analysis*** and ***residual static correction*** methods. Moreover, S/N was greatly improved by the application of ***pre-stack random noise attenuation***. Several filtering processes (e.g., Time Variant Filter, Bandpass Filter, and FK Filter) were implemented at various processing stages, adjusting the settings and parameters as required by the data, to remove remaining noise artifacts. Finally, the technique of ***Pre stack Kirchhoff time migration*** was applied, which showed better results in terms of resolution and clear depiction of subsurface structures based on travel times of seismic waves. The output (PSTM) is then compared with the legacy data, and it clearly provided a high-resolution seismic image of the subsurface.

3.6. Advantages of Seismic Data Re-Processing

3.6.1. Enhanced Seismic Quality

Seismic processing technologies and computational techniques have evolved in recent years leading to the ability to use more complex algorithms improving image quality. Re-processing can eliminate some of the distortions and artifacts in the initial data, thereby offering a clearer and more accurate image beneath (Osinowo, 2020).

3.6.2. Higher Resolution

Re-processing of seismic data produces higher resolution seismic images. In complex geological settings, where the interpretation is very detail-oriented this can be particularly advantageous (Kamal et al., 2023).

3.6.3. Accurate Interpretation and Resource Potential Assessment

In regions with complex geotectonic, such as areas affected by strong folding, faulting or other more complicated geological mechanisms the seismic waves can suffer distortions and multiple scatterings. Re-processing past data can reduce these issues and as a result the interpretation of data gets easier helping understand the geometry and properties of subsurface structures. Hence, it enables more accurate evaluation and assessment of resource potential. (Yan et al., 2017).

3.6.4. Noise Reduction

The original seismic data is always filled with noise and artifacts that can mask out real geological signal. Sophisticated re-processing technology allows us to filter out this unwanted noise and enhance signal-to-noise ratio making it easier to identify specific subsurface features (Yilmaz, 2001).

3.6.5. Advanced Techniques

As we develop new ways to get data (new acquisition methods) or as better methodologies become available for processing existing datasets, re-processing makes it possible to combine these developments with existing assessments. This may ultimately lead to a better real-time understanding of the subsurface (Osinowo, 2020).

CHAPTER 4

SEISMIC DATA PROCESSING ANALYSIS

The seismic data set line X, acquired in the Kirthar Fold and Thrust Belt area in the Lower Indus Basin by an exploration company in October 1997, were used for this study. The acquisition was carried out with mixed-source technique i.e., both vibroseis and dynamite were employed in the process as source while geophones as receivers. The data acquisition starts with the first shot that occurred at source station 101 and the last shot at source station 1188 with the total number 793 source points (after QC the total number of source points were reduced to 777), and the source and receiver intervals set as 50 m and 25 m. The near offset and far offsets were situated at 62.5 m and 3037.5 m, respectively. The acquired data (SEGD) were originally de-multiplexed and converted to SEGY.

Data reprocessing operations commenced with data pre-processing and subsequently, the actual processing operations. The pre-processing operations include data Geometry set up followed by quality check procedures, trace editing, phase conversion and amplitude scaling, True Amplitude Recovery (TAR), noise attenuation, Surface Consistent Amplitude Compensation (SCAC) and Deconvolution. The processing operations on the other hand include Refraction Statics, Finer Velocity Analysis, Residual Static, Pre-Stack Random Noise Attenuation (PreRNA), and Pre-Stack Time Migration (PSTM).

4.1. Data Initializing and Pre-Processing Results

4.1.1. Results of Geometry Setup

By making the use of observer's log report, a relation file was prepared. A relation file in seismic data processing is usually a structured file that creates connections between various parameters or datasets. It helps to connect different seismic data acquisition parameters, like number of channels, total number of SPs, source and receiver interval, line number, and type of sources used throughout the acquisition procedure. the relation file (X file), source file (S file) and receiver file (R) were loaded in the software to create SPS file. The data geometry is then defined using the acquisition data that is saved in the SPS file. With this configuration, all traces are projected precisely as they were captured during acquisition.

4.1.1.1. Quality Check of Data

During the QC, it was observed that data was missing at number of source points. The FFIDs associated with those SPs were simply removed from the data. For example, at SP 554 the data record was incomplete as shown in Figure 4.1.

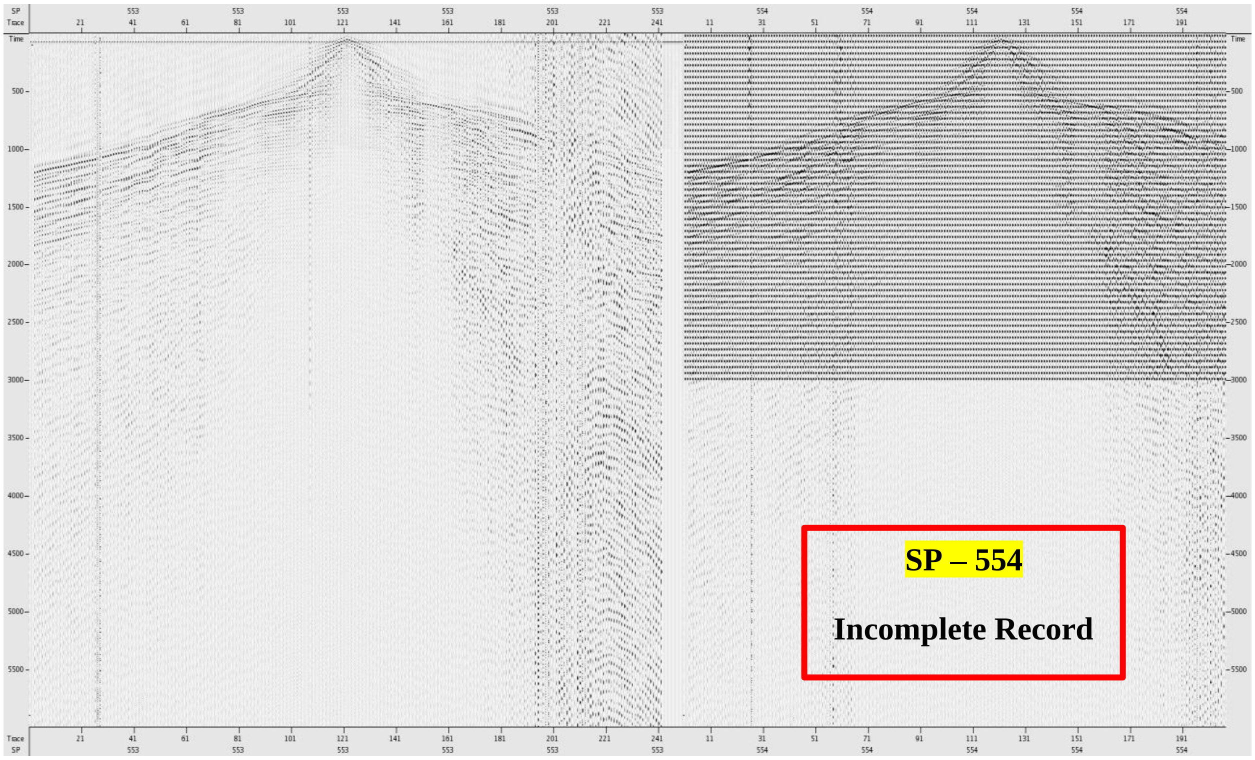


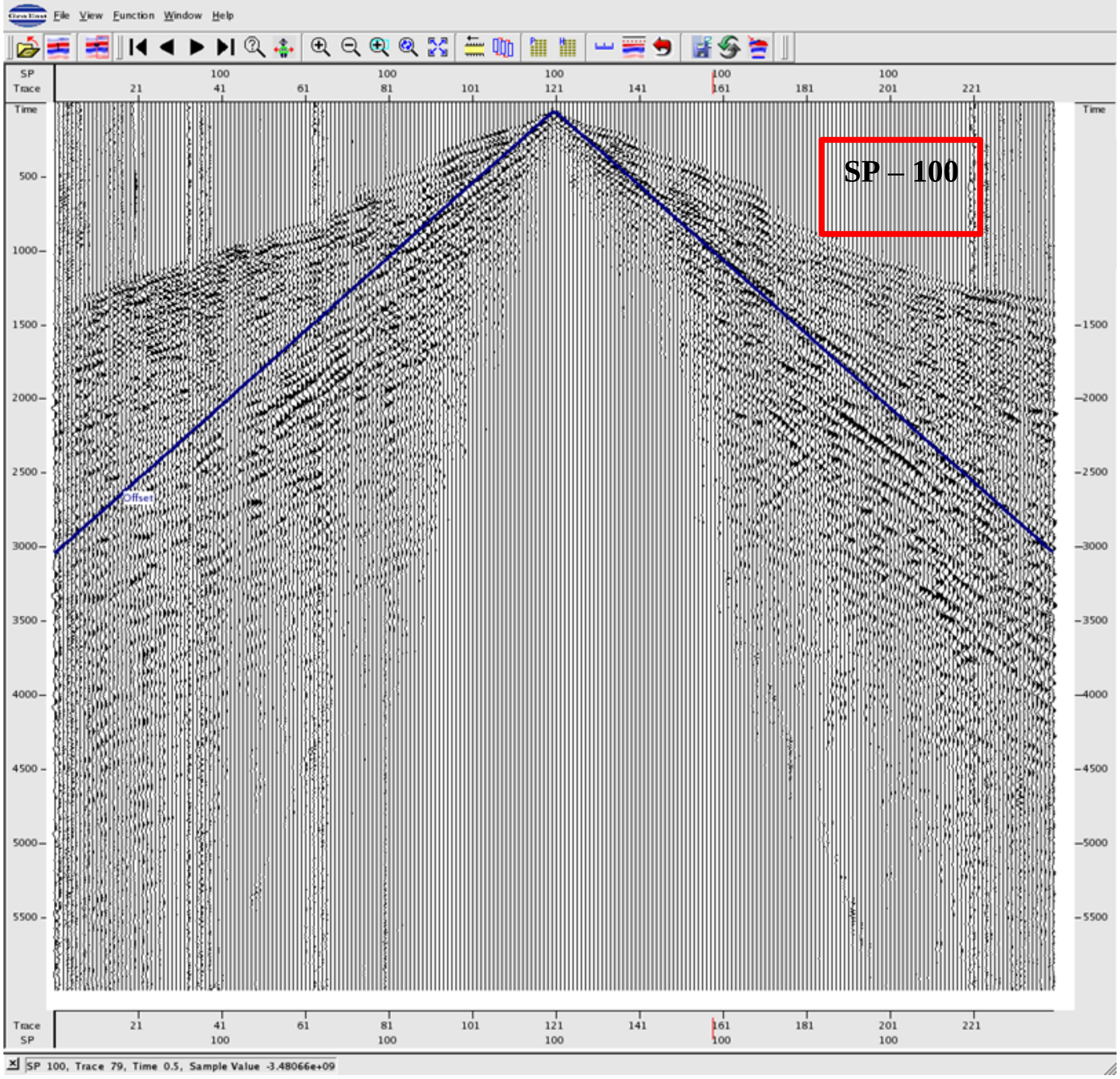
Figure 4.1: At SP 554, the data record is missing

After removing the bad records from the data, generally two types of quality checks are performed to confirm the accuracy of geometry data being loaded.

- Offset Check
- Source Deviation Check

1. Offset Check

Once the geometry data has been loaded in, this QC simply consists of checking that the recorded seismic data coincides with spatial relationships between source and receivers as shown in Figure 4.2. Checking the distances between seismic sources and receivers are accurately logged, to correspond to their expected values from survey design. Where any discrepancies found may point to data acquisition or geometry problems (Sheriff, 1995). If any discrepancies or error is identified in the source and receiver offset with reference to any SP then that SP will be excluded from data.

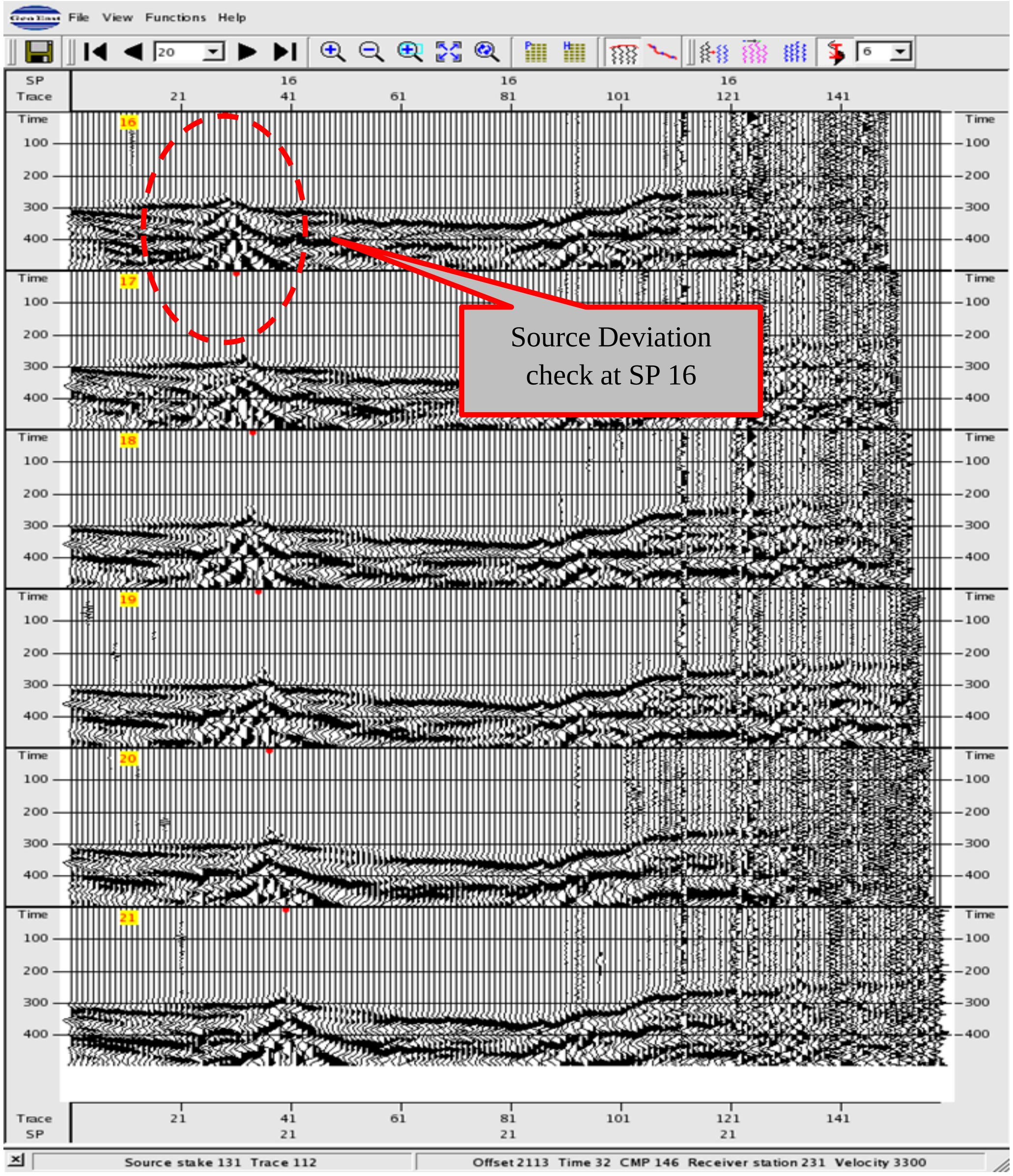


SP 100, Trace 79, Time 0.5, Sample Value -3.48066e+09

Figure 4.2: Offset Quality Check (Offset QC at SP 100)

2. Source Deviation Check

This QC ensures the correctness of source locations in the geometry data as shown in Figure 4.3. It verifies the seismic source locations according to the survey design. at every SP, the source position is evaluated and if there is any deviation in the source position at any SP, it adjusted by removing that SP from the dataset (Sheriff, 1995).



Source Deviation check at SP 16

Source stake 131 Trace 112

Offset 2113 Time 32 CMP 146 Receiver station 231 Velocity 3300

Figure 4.3: Source Deviation Quality Check (Source deviation QC at SP 16, 17, 18, 19, 20, and 21)

4.1.2. Results of Phase Conversion and Amplitude Scaling

As it was initially a mixed source data, there is difference in the amplitudes and phase of both due to difference in the energies of sources. Amplitude scaling and phase conversion techniques have been used to balance out the amplitudes and convert the data into a single phase. In particular, the zero-phase vibroseis data was converted to minimum phase by phase conversion technique. After stacking is applied, the Brute stack showed balanced amplitudes. This was followed by a round of trace editing to remove any unwanted traces from the data set.

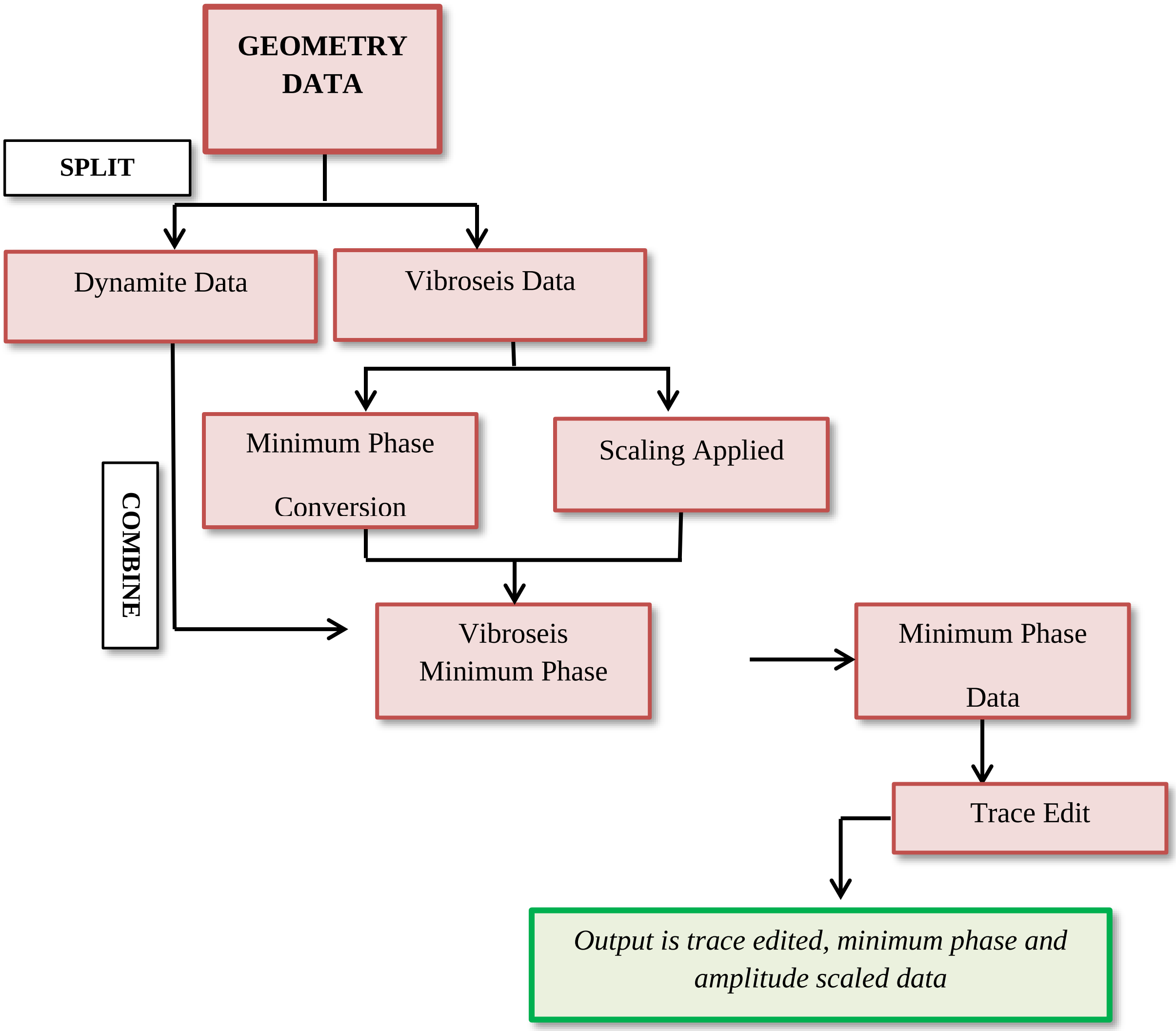


Figure 4.4. Flow of amplitude scaling and phase conversion done on vibroseis data

1. Data Splitting and Amplitude Balancing

Simply split the geometry data (figure 4.5) based on source type i.e., dynamite and vibroseis. This distinction is important, because the two sources have different energy and phase. Two parameters utilized for the separation of data into dynamite and vibroseis data are ***hole depth*** and ***SP range***. The SP range is already specified. The dynamite data ranges from SP 1 to 276, while the vibroseis data ranges from SP 277 to 777.

Scaling/amplitude balancing is applied on the vibroseis data because vibroseis data is zero phase data, and its energy is maximum at time zero. Maximum energy in sent into the subsurface and seismic wave tends to keep itself consistent with depth. Incase of mixed source acquisition, scaling is applied on the vibroseis data to tone down its amplitude and equalize its amplitude with the dynamite data.

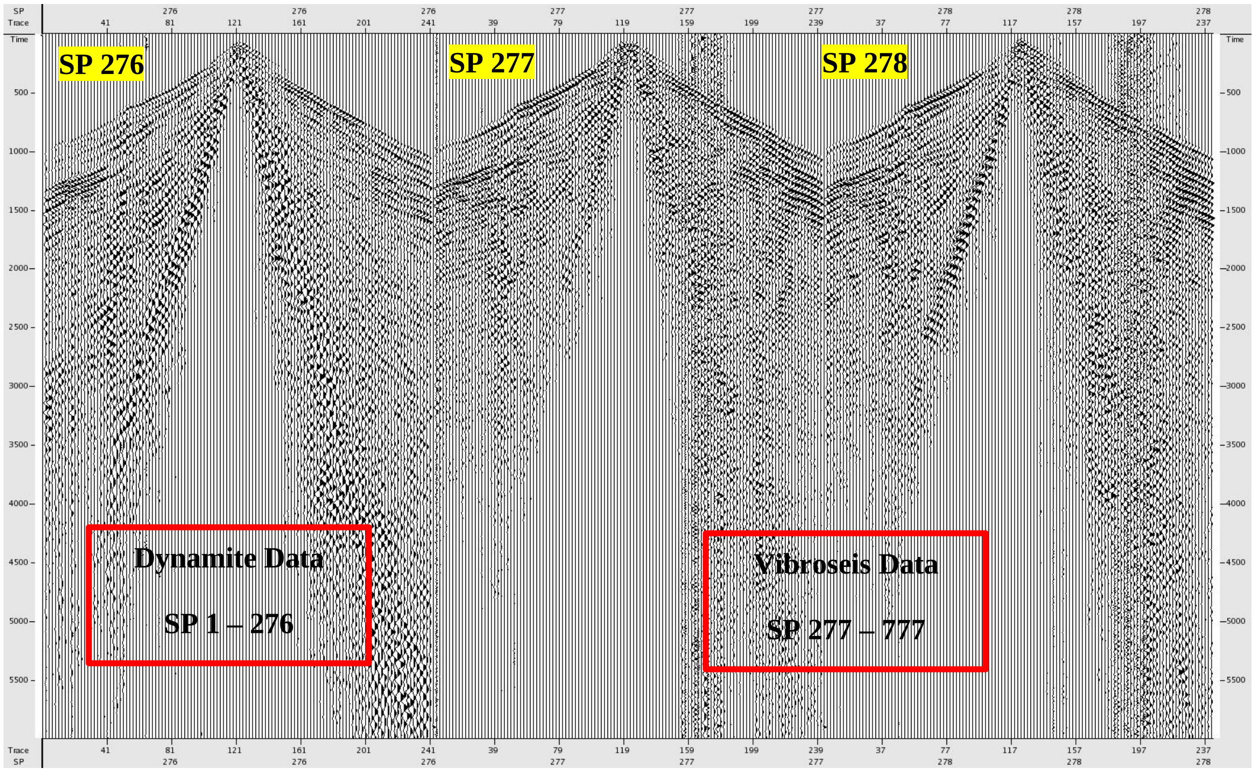


Figure 4.5: Original geometry data (Not scaled and phase converted)

After successfully separating the data, scaling is applied on the vibroseis data to balance the amplitudes and equalize its amplitude with the dynamite data (figure 4.7).

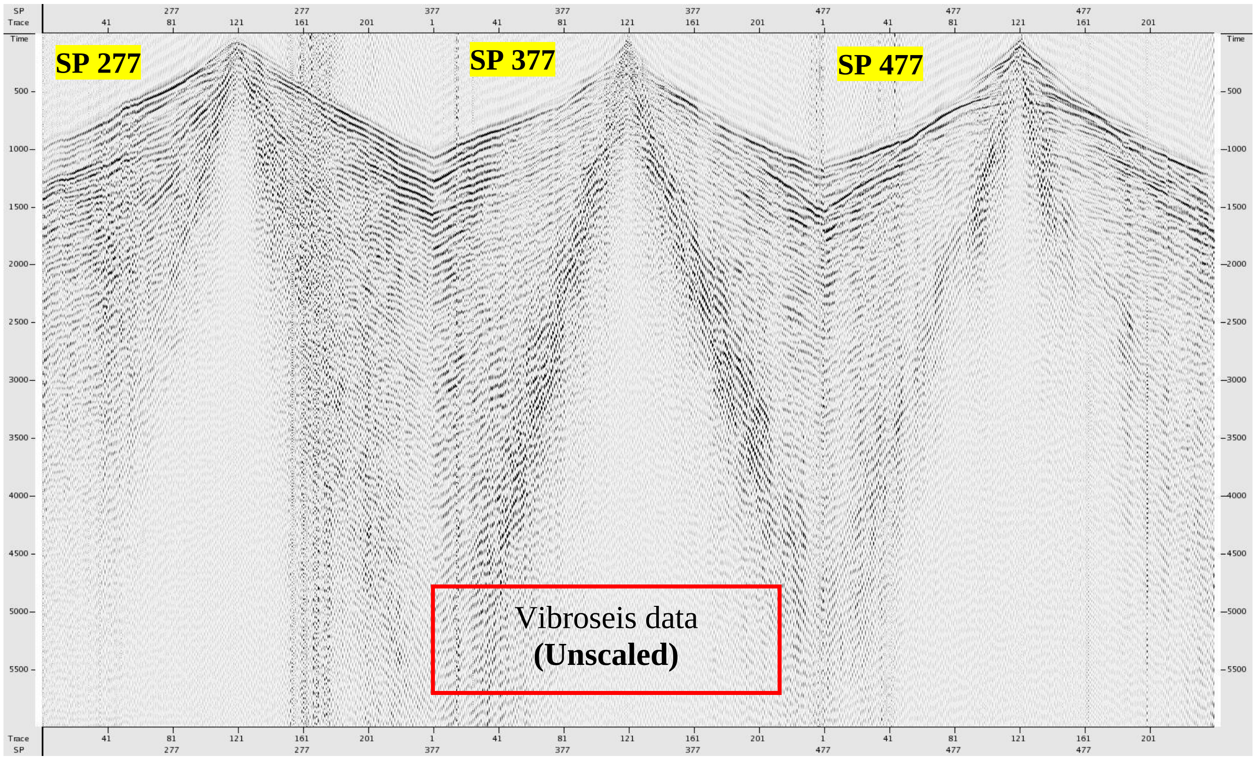


Figure 4.6: Vibroseis data (This is vibroseis data before the application of scaling)

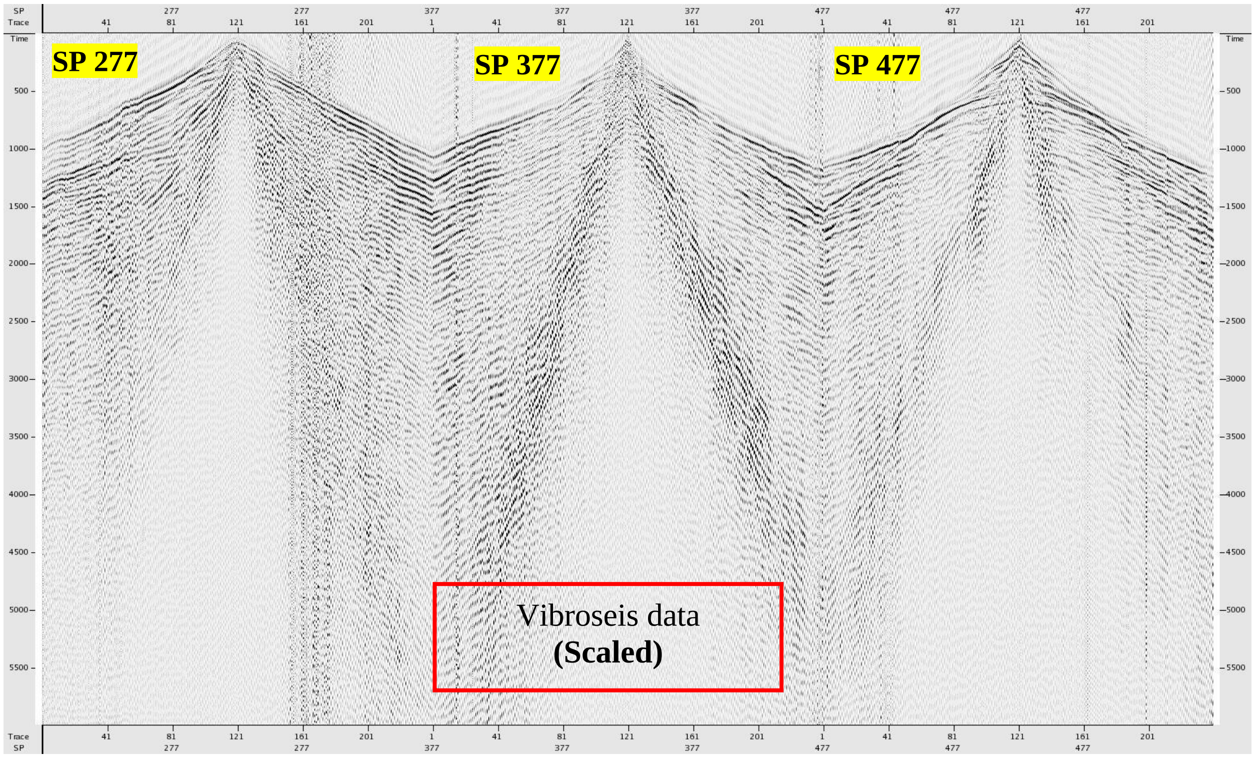


Figure 4.7: Vibroseis data (This is vibroseis data after the application of scaling. Scaling is applied for amplitude equalization)

2. Phase Conversion

Now, the scaled vibroseis data is converted from zero phase to minimum phase, shown in Figure 4.8. This conversion is important because deconvolution needs minimum phase data as an input.

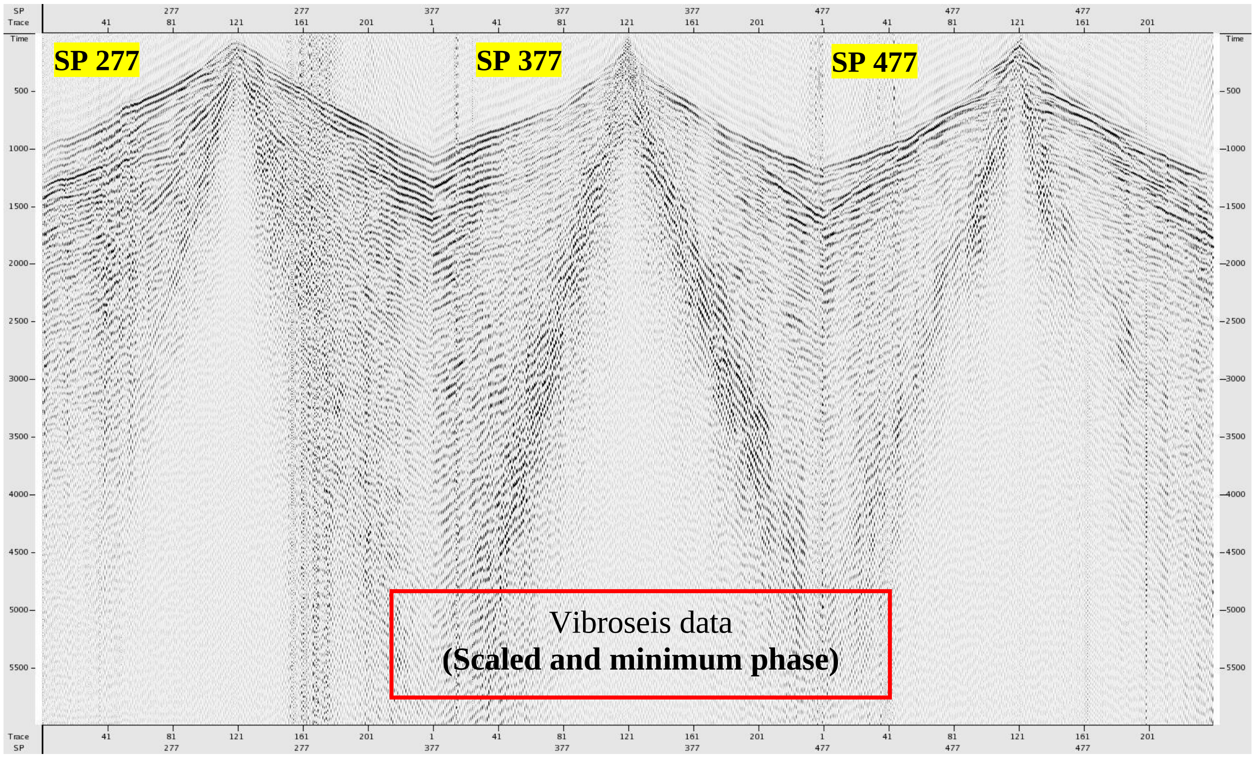


Figure 4.8. Vibroseis Data (This is minimum phase vibroseis data after the application of phase conversion)

Phase conversion technique was applied to bring the data into single phase and this step is important to ensure the compatibility between both vibroseis and dynamite data. The software utilizes a module, i.e. Minimum Phase Vibroseis Wavelet which automatically performs the minimum phasing of vibroseis data and converts the data into single phase.

After the vibroseis data has successfully gone through amplitude scaling and phase change, it is combined with the dynamite data, as shown in Figure 4.9. The images of shot gathers were taken at an interval of 100, in the figures 4.6, 4.7 and 4.8.

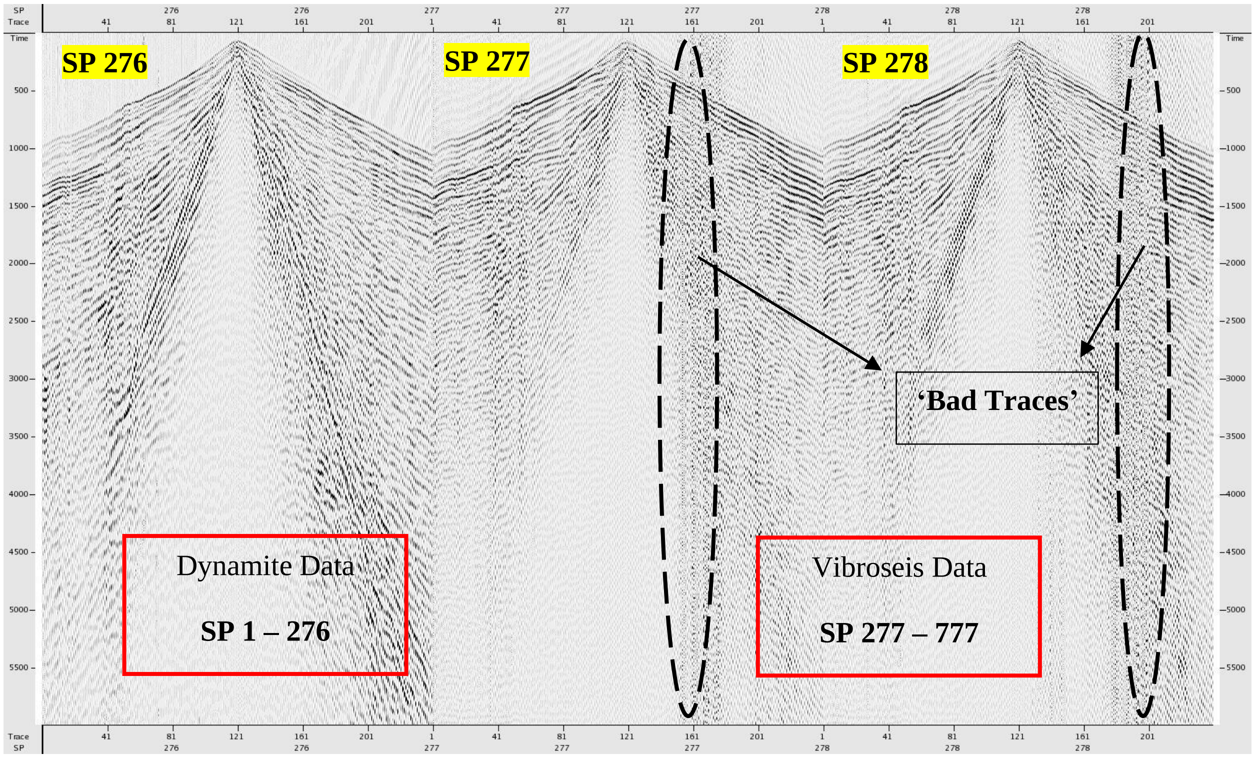


Figure 4.9: Combined geometry data (Minimum phase and scaled vibroseis data combined with dynamite data)

After the successful conversion of data into single phase i.e., minimum phase and equalizing the amplitudes of dataset by the application of amplitude scaling, the data is further prepared by the application of trace editing. There In figure 4.9, the presence of bad traces can be seen in the dataset. To resolve the issue, trace editing is applied to the data.

3. Trace Editing

In the final step, trace editing is applied to kill and remove all the faulty traces from the dataset, shown in Figure 4.10. The software utilizes a module 'Trace Edit' that edits the seismic traces by removing the bad traces from the dataset.

In the figure 4.10, the green highlighted part shows the traces that have been removed from the dataset by the application of 'Trace Edit'. The progressive improvement in data can be observed in figures 4.11, 4.12, and 4.13

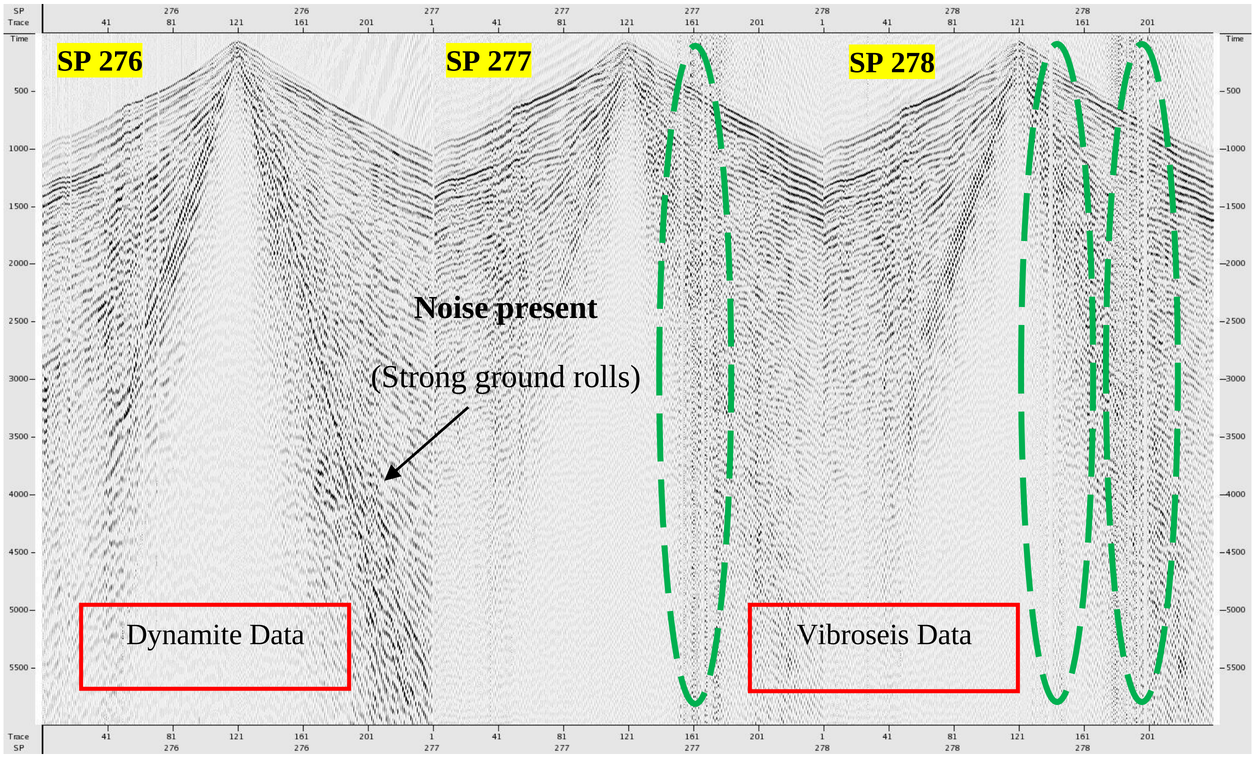


Figure 4.10: Trace Edit applied

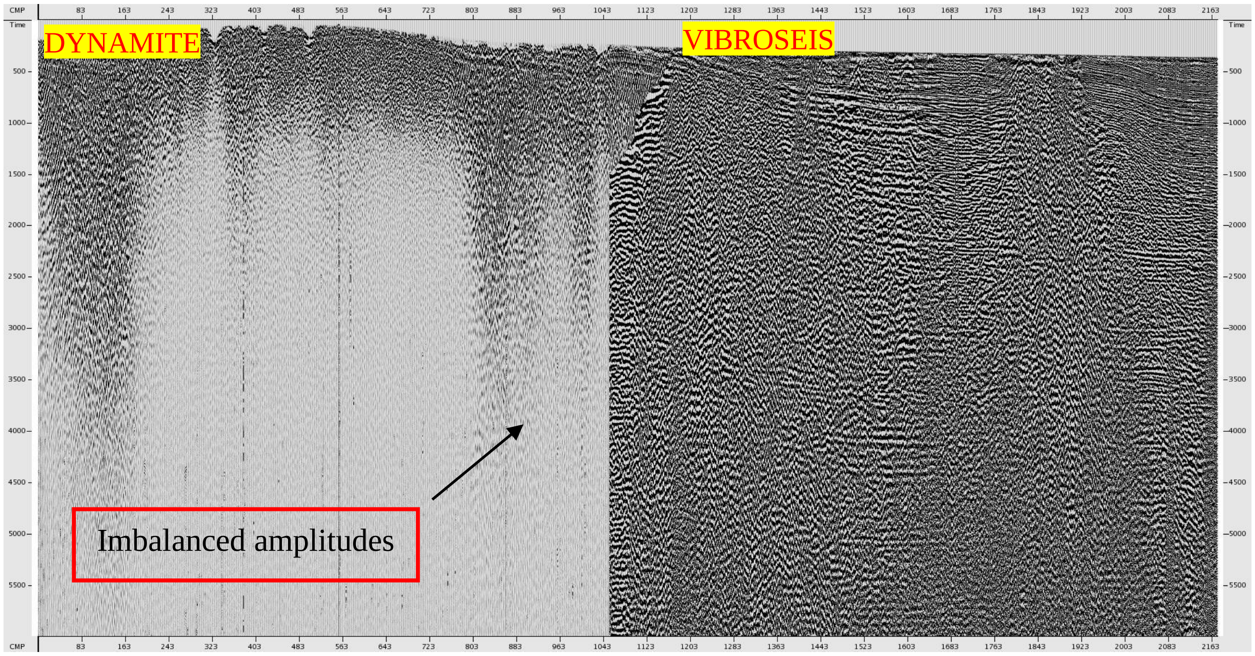


Figure 4.11: Geometry data stack (Stack clearly indicates difference in the amplitudes of both dynamite and vibroseis data)

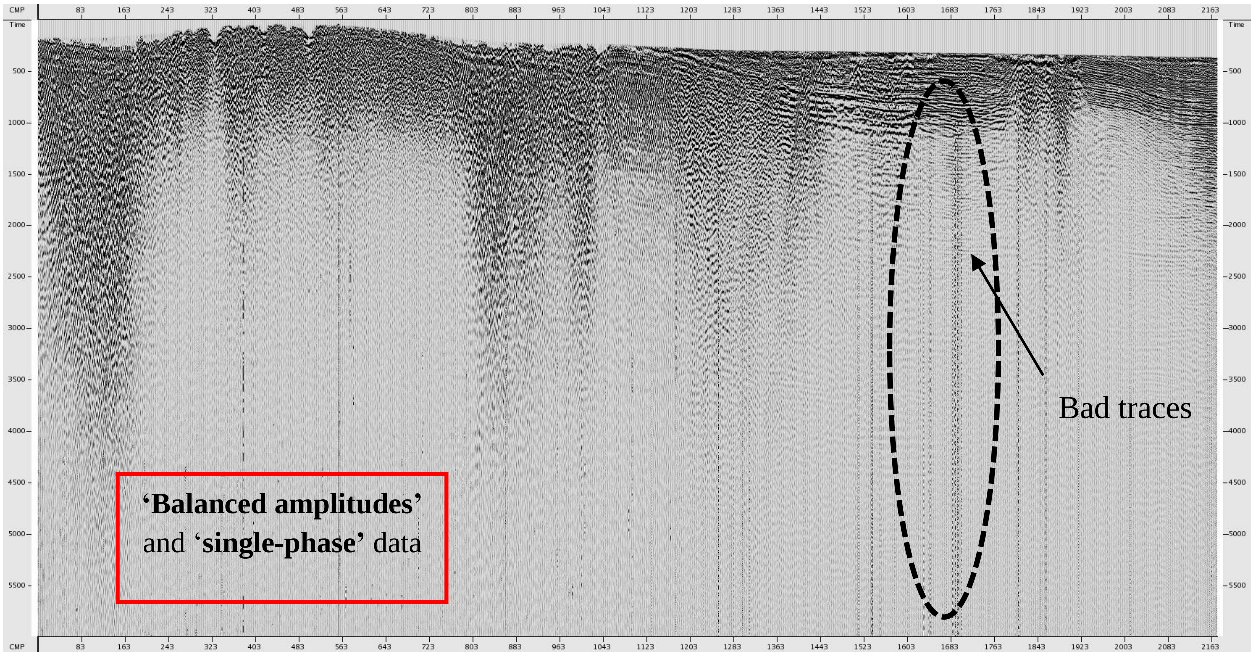


Figure 4.12: Geometry data stack (The data is scaled and converted to minimum phase to ensure compatibility)

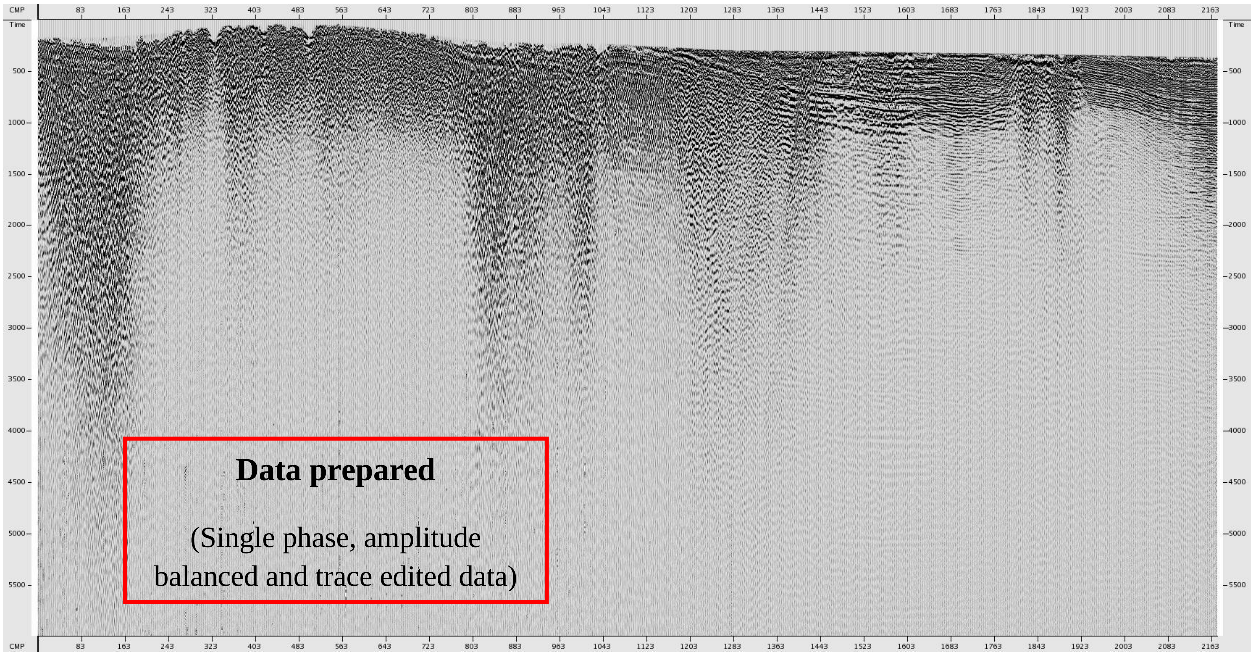


Figure 4.13: Geometry data stack (After the application of trace edit)

4.1.3. Noise Attenuation Results

4.1.3.1. Ground Rolls Attenuation

The attenuation of ground roll is dependent on both ***frequency*** and ***velocity***. Ground roll (GR) is commonly categorized as low frequency, high amplitude, and low velocity noise. Although it can also transcend this range, its velocities normally range from 300 to 700 m/s. Ground rolls usually occur at a frequency of 5 to 20 Hz (Lawrence et al., 2020).

In figure 4.10, strong ground rolls can be observed on every shot gather. A noise attenuation algorithm is used to remove data points that fall inside specified velocity and frequency bands to reduce the noise. In this study, the analysis showed that the frequency range of ground rolls to be 5 to 20 Hz, and the highest ground roll velocity was 1000 m/s, which was then utilized by the ground roll attenuation algorithm to successfully attenuate the ground rolls.

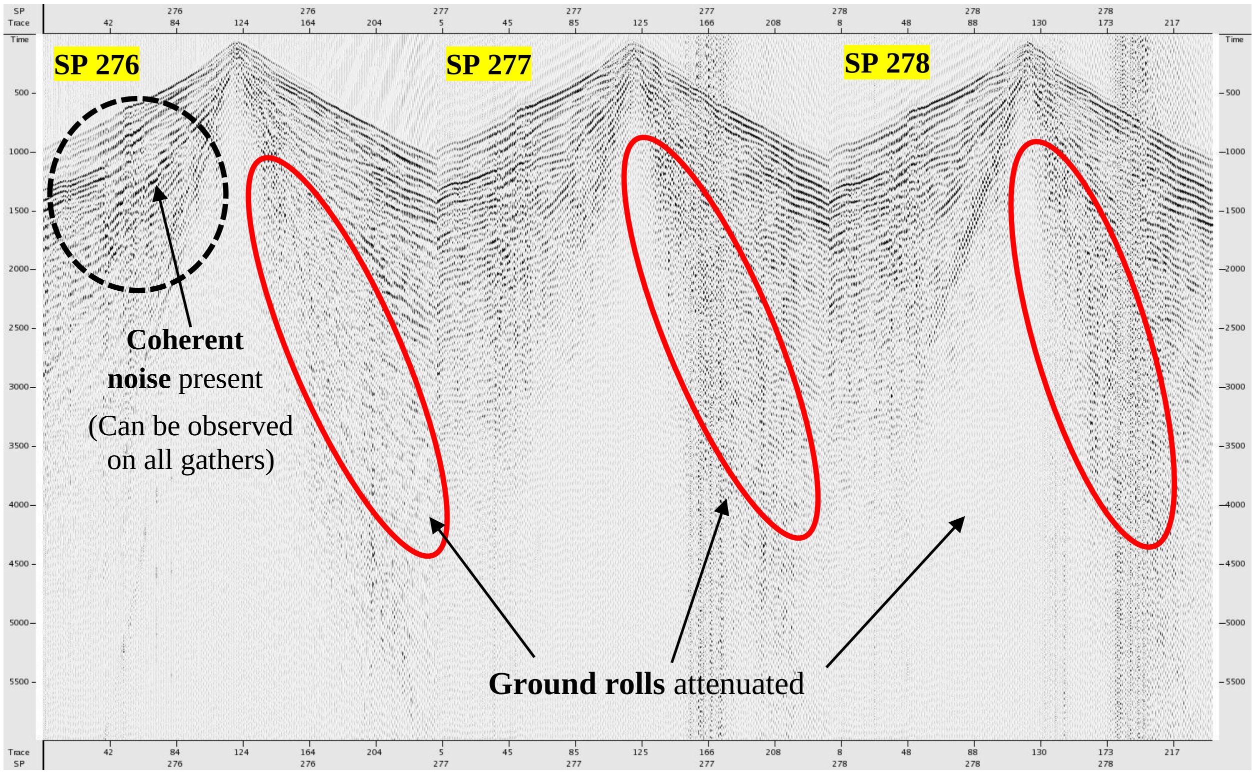


Figure 4.14: Ground rolls attenuation

If the above figure is compared with the figure 4.10, it shows the ground rolls are clearly eliminated from the data after the application of ground roll attenuation algorithm.

4.1.3.2. Coherent Noise Attenuation

The remaining coherent noises were also reduced when the ground rolls were removed. Because noise comes from a variety of sources, each category has unique traits and behaviors. Depending on where they originate, coherent noises have distinct frequency ranges and velocities. Here, the frequency range of 5 to 15 Hz is assigned to the noise reduction process, and the velocity range is 300 to 2000 m/s.

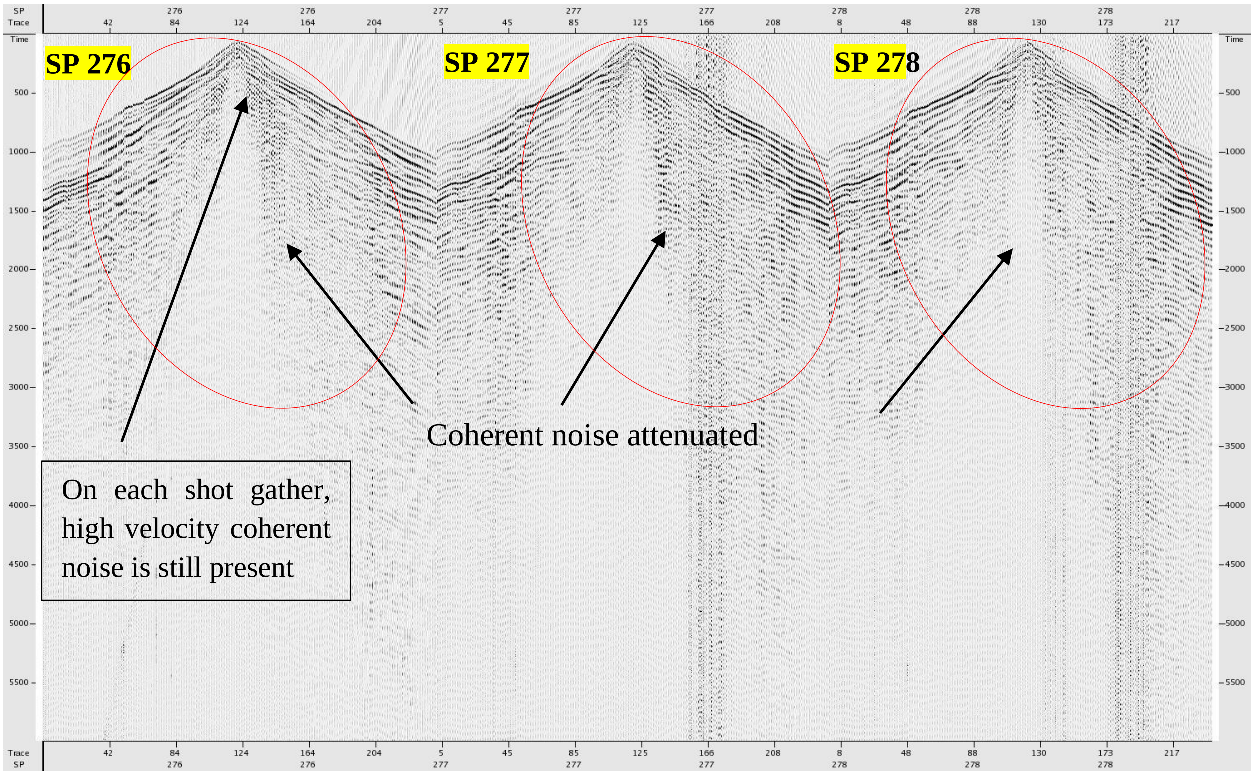


Figure 4.15: Coherent noise attenuation

4.1.3.3. Coherent Noise Attenuation by KL Transform

An additional technique to remove coherent noise is to use the Karhunen-Loève (K-L) Transform. By separating the ground roll from the reflector signal, this transform makes it possible to subtract it from the seismic data. When other methods are ineffective for eliminating high-velocity coherent noise, this technique proves to be quite helpful. In this study, the velocity range was defined as 100 to 3000 m/s, while the frequency range was set between 5 and 10 Hz.

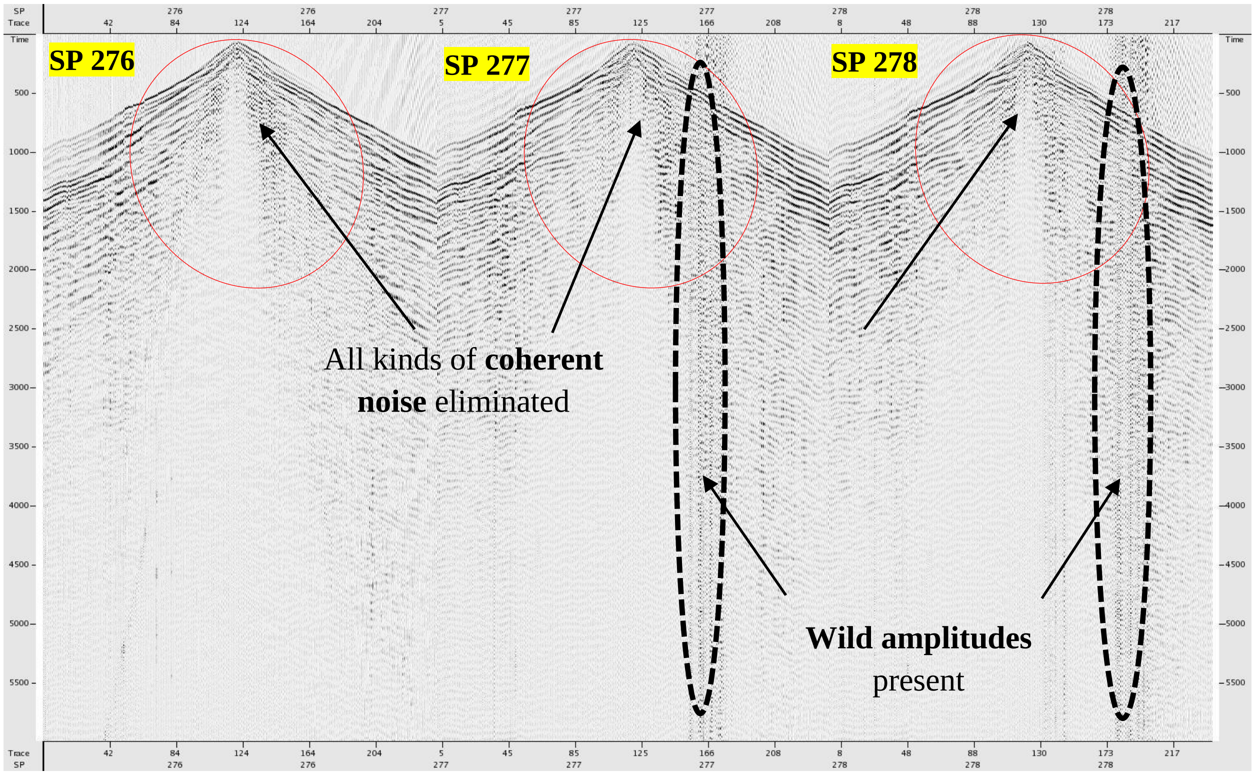


Figure 4.16: Coherent noise attenuation (Noise attenuation by the application of KL Transform)

4.1.3.4. Wild Amplitudes Attenuation

Abnormal or unusual amplitudes in seismic data, known as wild amplitudes, can be caused by loose receivers, moving cars, or high-tension cables in the area. The sources of these extreme amplitudes affect how frequently they occur; high-tension cables, for example, might cause spikes in the data. These amplitudes are typically captured on single traces. Through an analysis of the frequencies associated with these amplitudes within the dataset, the wild amplitudes attenuation technique reduces this noise.

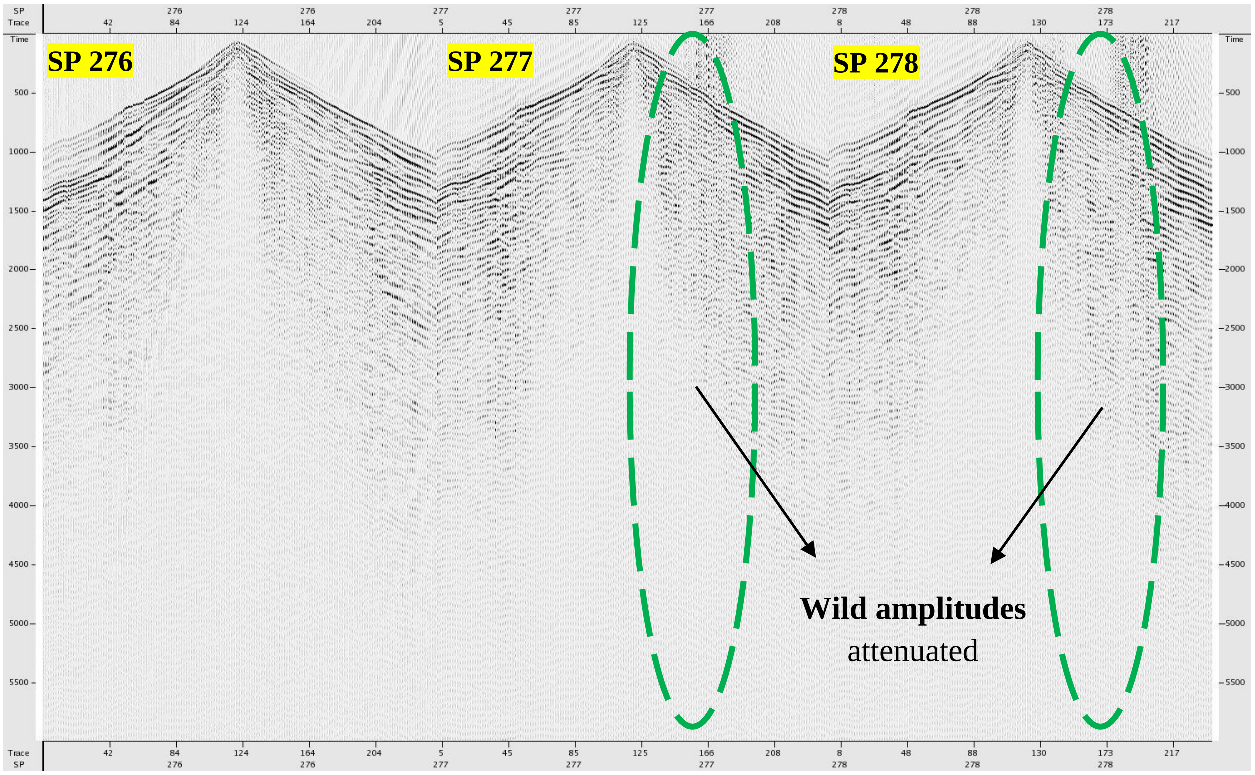


Figure 4.17: Wild amplitudes attenuated

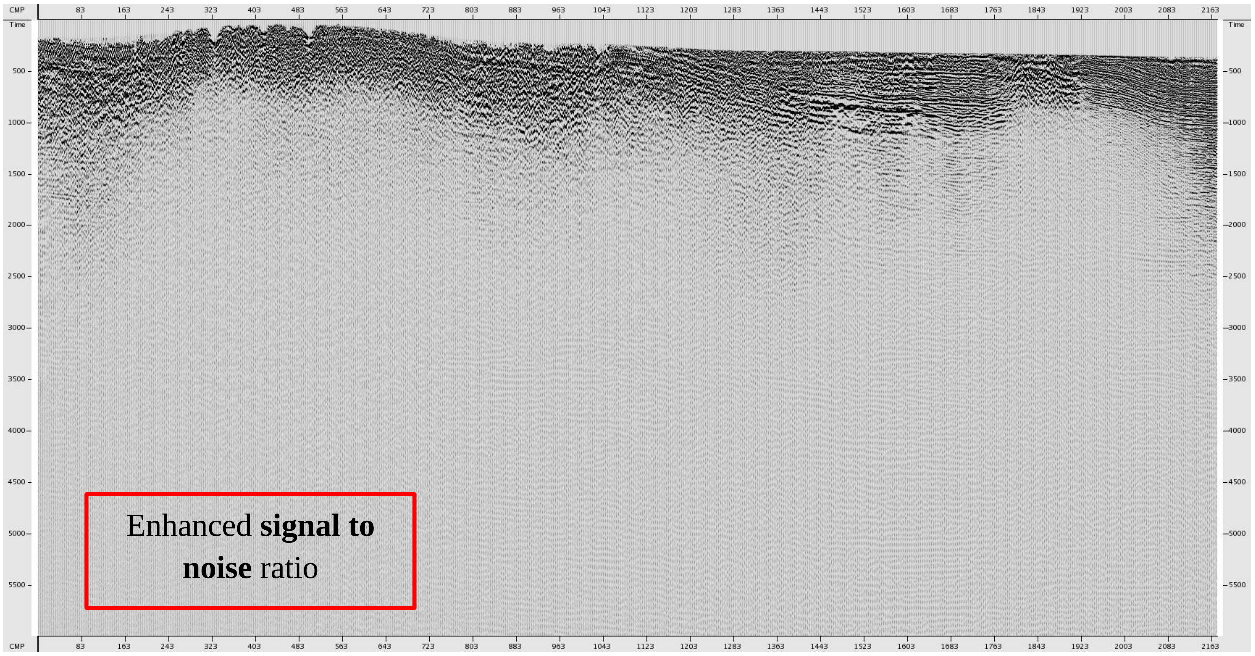


Figure 4.18: Denoised stack

After the successful completion of noise attenuation process, the refined data reveals considerable improvement with respect to signal to noise ratio. Whereas the eliminated noise from the data can be seen in figure 4.19 and 4.20.

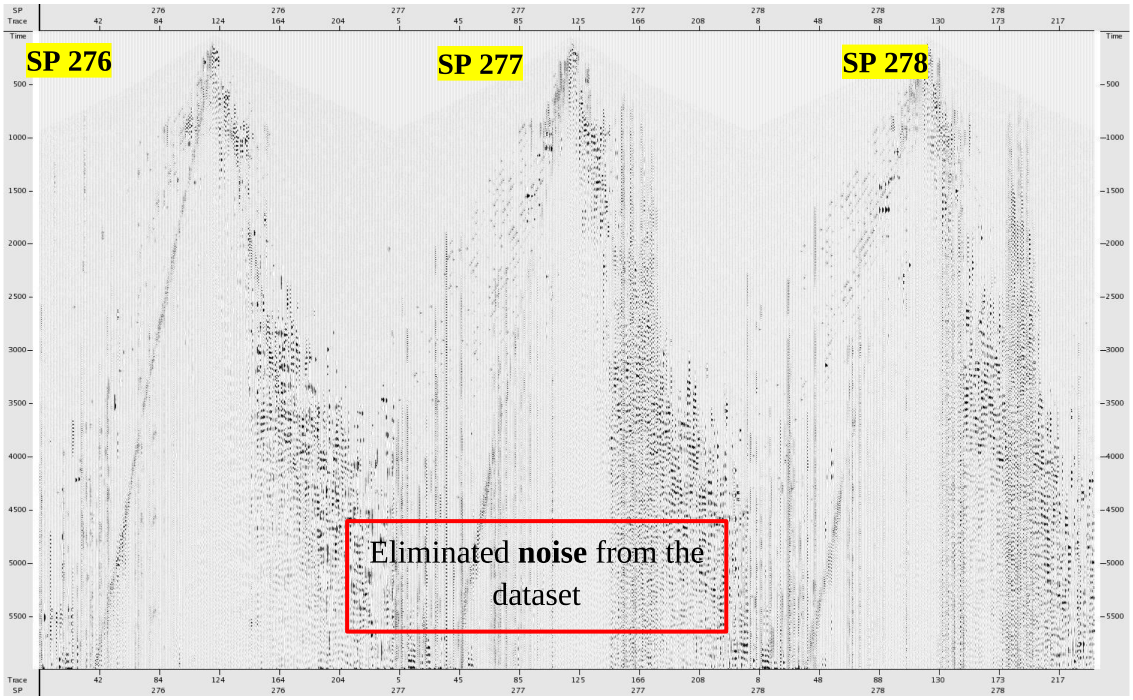


Figure 4.19: Removed noise from the data set (Ground rolls, coherent noise and wild amplitudes)

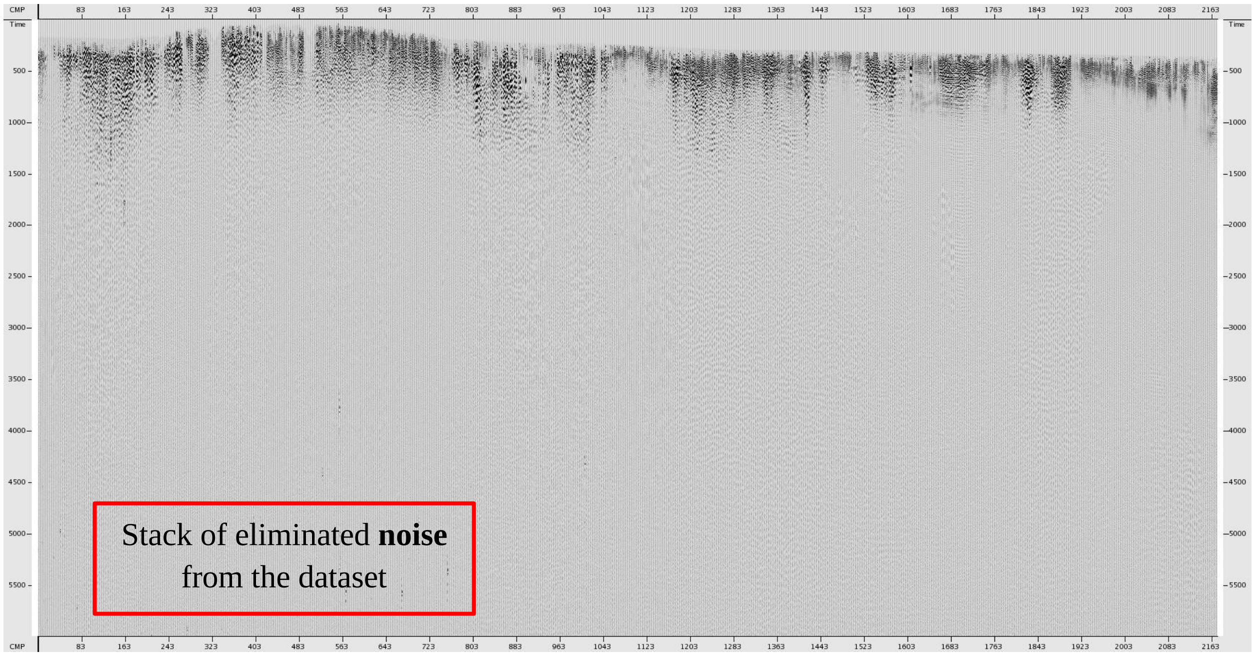


Figure 4.20: Stack of removed noise

4.1.4. True Amplitude Recovery (TAR) Results

As the seismic wave radiates outward into the subsurface, its energy spreads over a larger area. The amplitude of a wave decreases with increasing distance from the source. It is necessary to compensate for this amplitude decay and recover the true amplitudes. If not recovered, this can make deeper reflections appear weaker, causing misinterpretations in geological studies. To recover the lost amplitudes due to geometric spreading, a processing algorithm i.e., TAR is applied on the dataset.

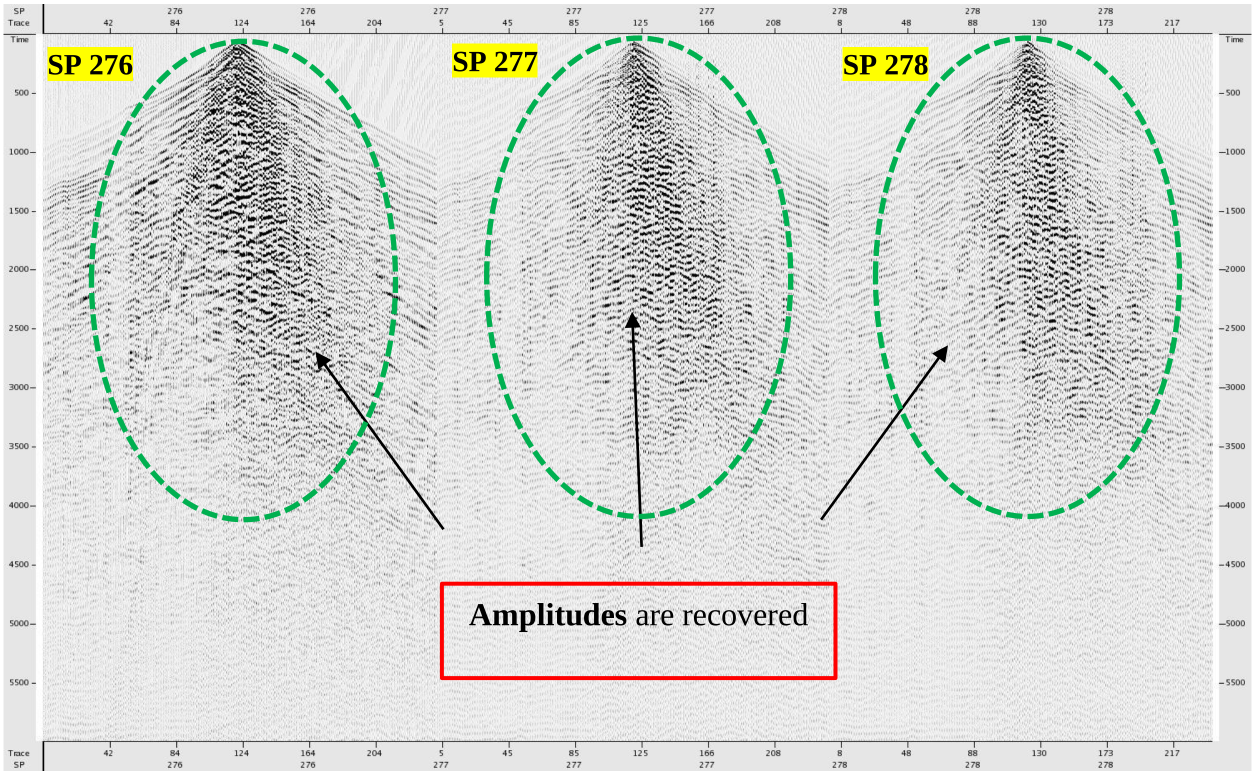


Figure 4.21: True amplitude recovery applied (The application of TAR enhanced the overall amplitudes in the dataset)

As shown in figure 4.21 and figure 4.22, it is apparent that the signal in the dataset is significantly improved as compared to the data shown in figure 4.17, with the application of TAR and amplitudes that had lost previously due to attenuation and geometric spreading are being restored adequately.

Figure 4.22: Stack after the application of True Amplitude Recovery (TAR)

4.1.5. Surface Consistent Amplitude Compensation (SCAC) Results

A three-step procedure called Surface Consistent Amplitude Compensation (SCAC) is intended to increase the accuracy of amplitude in seismic data.

1. **Amplitude Analysis:** The amplitudes of each seismic trace are examined in relation to different contributing elements in this first step.
2. **Amplitude Decomposition:** To determine which particular components contributed most significantly to the amplitude decay, the amplitude is first broken down in the second step. In this step, every possible component is extensively evaluated.
3. **Amplitude Application:** The last stage involves applying the elements found to be in charge of the maximum amplitude decay in order to make up for the amplitudes that were lost and improve the overall amplitude fidelity.

SCAC was tested for the analysis of five components:

1. Source
2. Receiver
3. Offset

4. Geology and
5. Trace

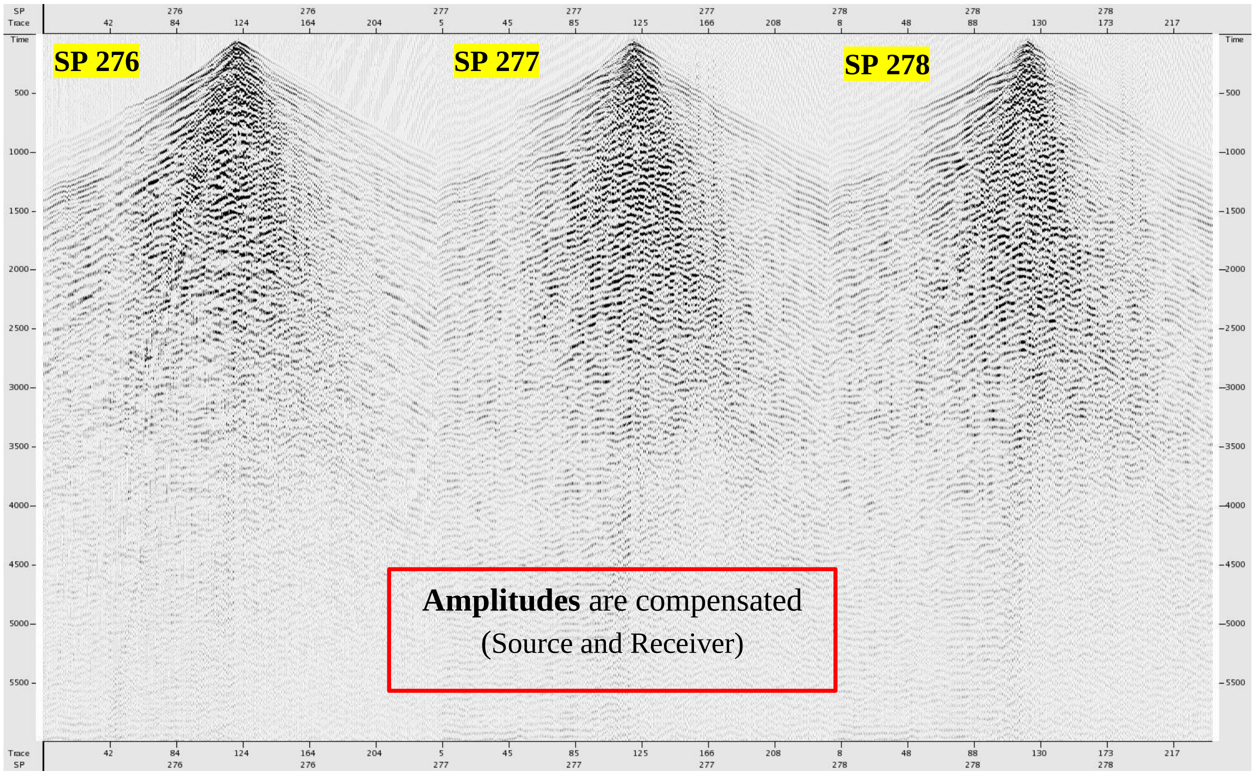


Figure 4.23: SCAC (Source and Receiver component)

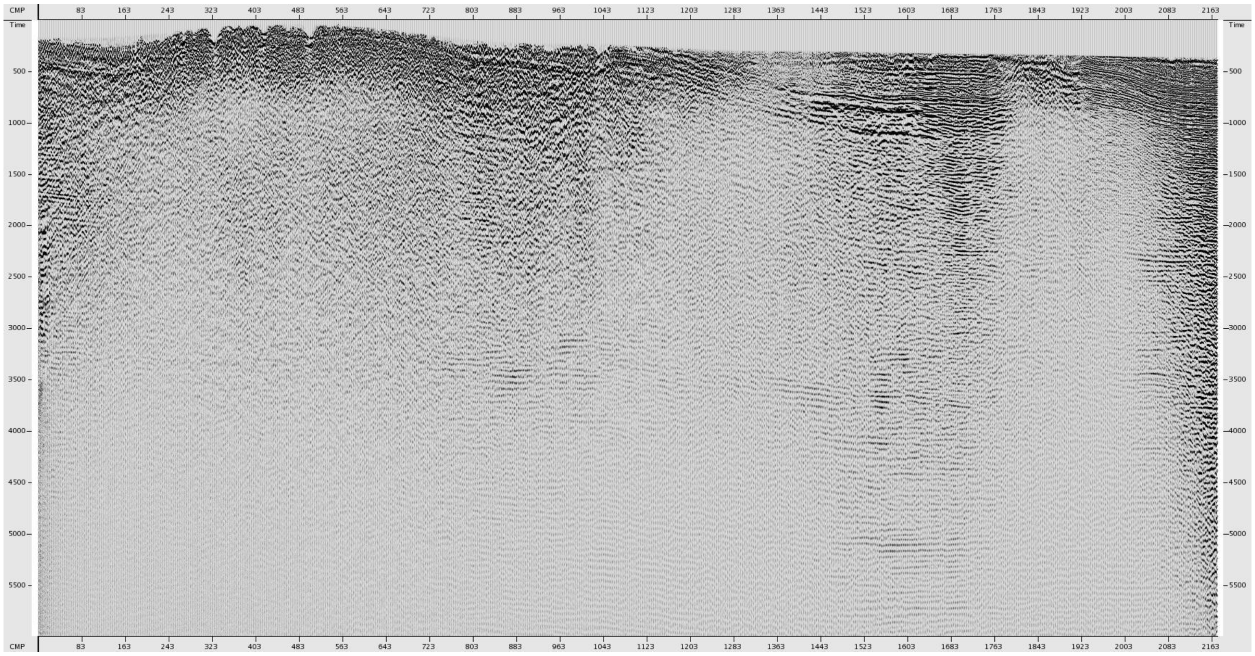
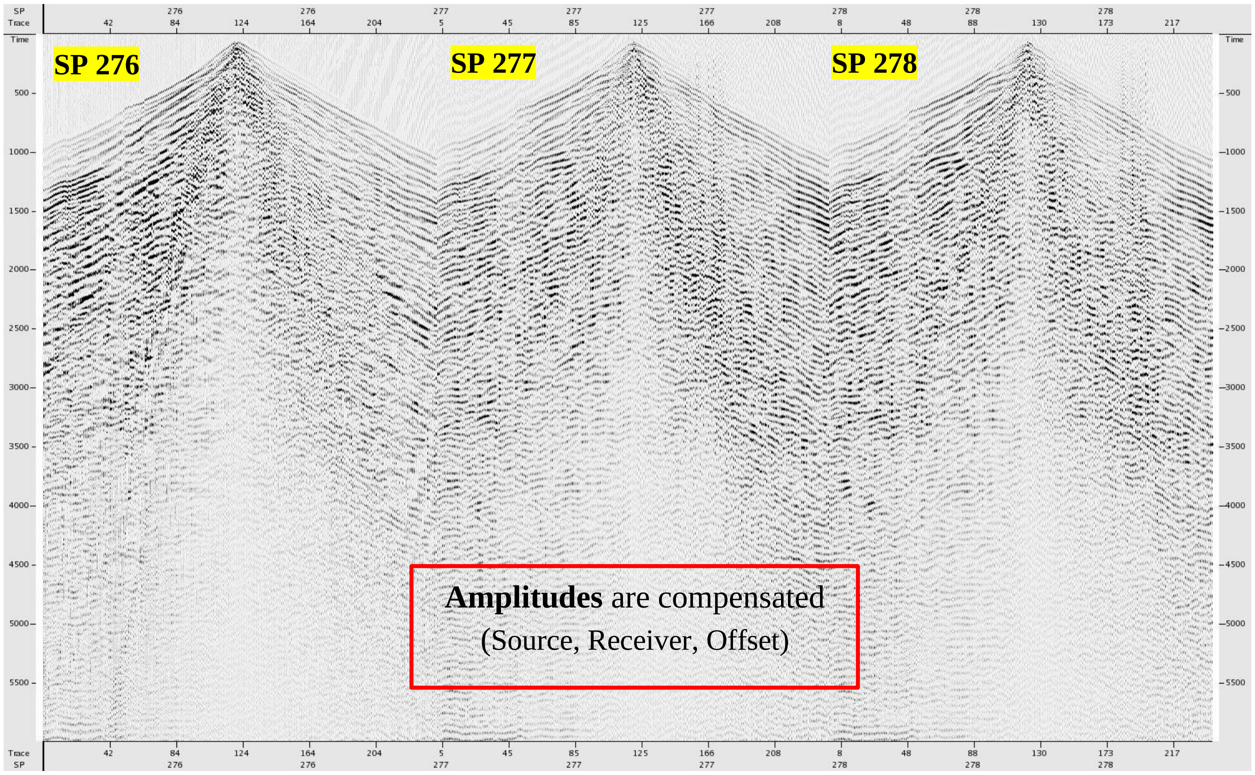


Figure 4.24: SCAC Stack (Source and Receiver component)



Amplitudes are compensated
(Source, Receiver, Offset)

Figure 4.25: SCAC (Source, Receiver & Offset component)

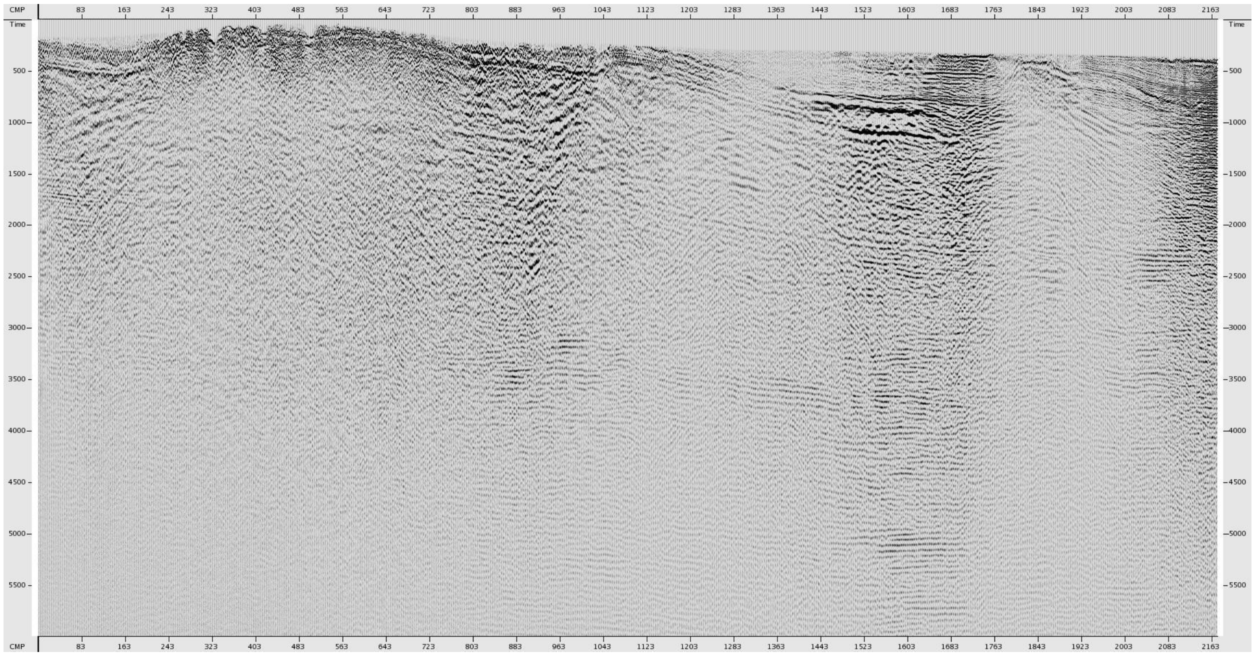
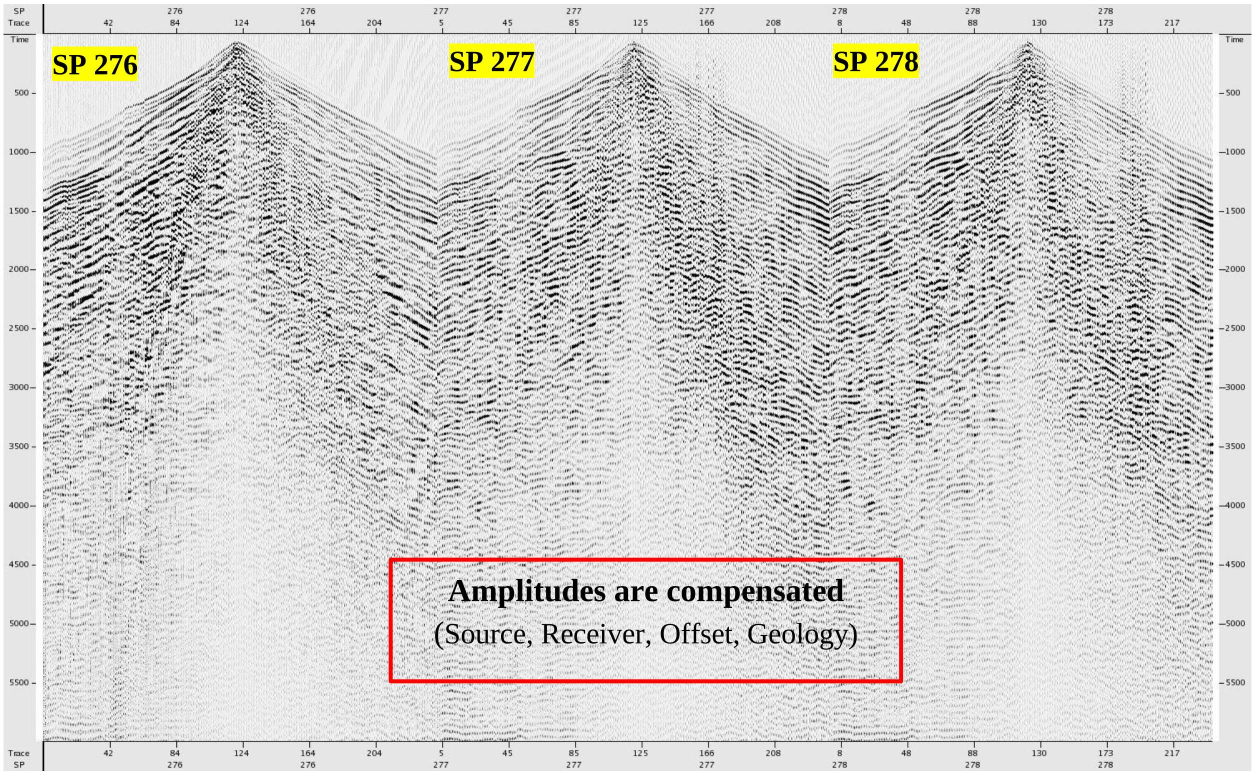


Figure 4.26: SCAC Stack (Source, Receiver & Offset component)



Amplitudes are compensated

(Source, Receiver, Offset, Geology)

Figure 4.27: SCAC (Source, Receiver, Offset & Geology component)

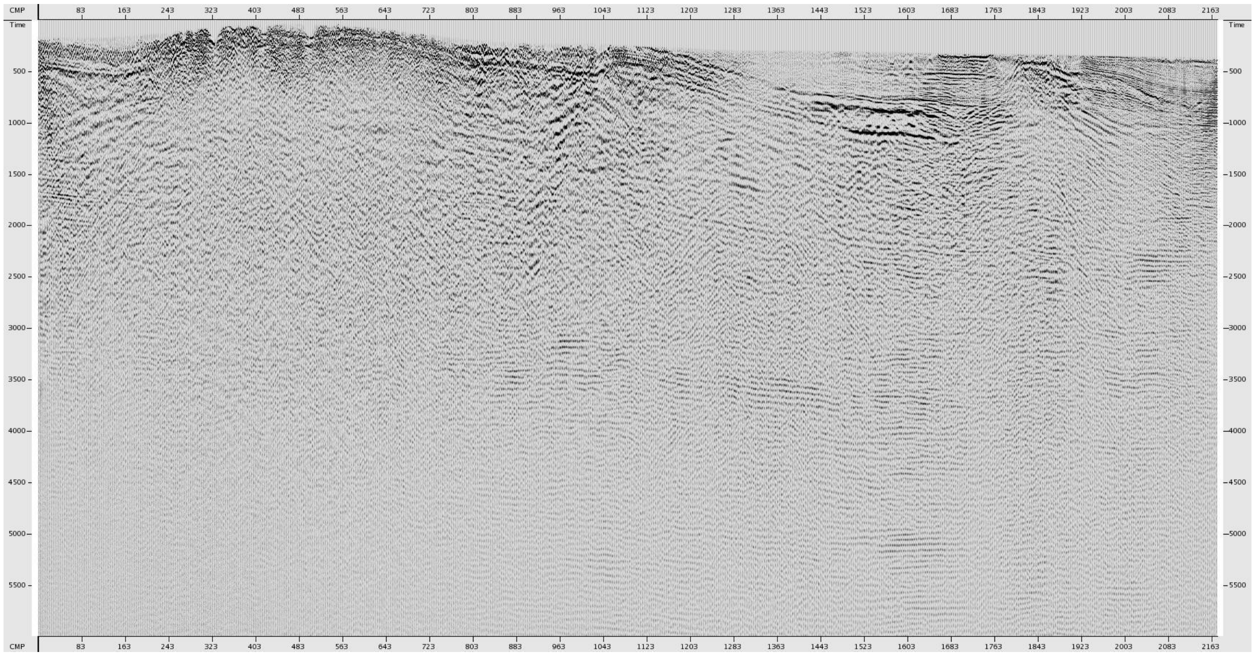
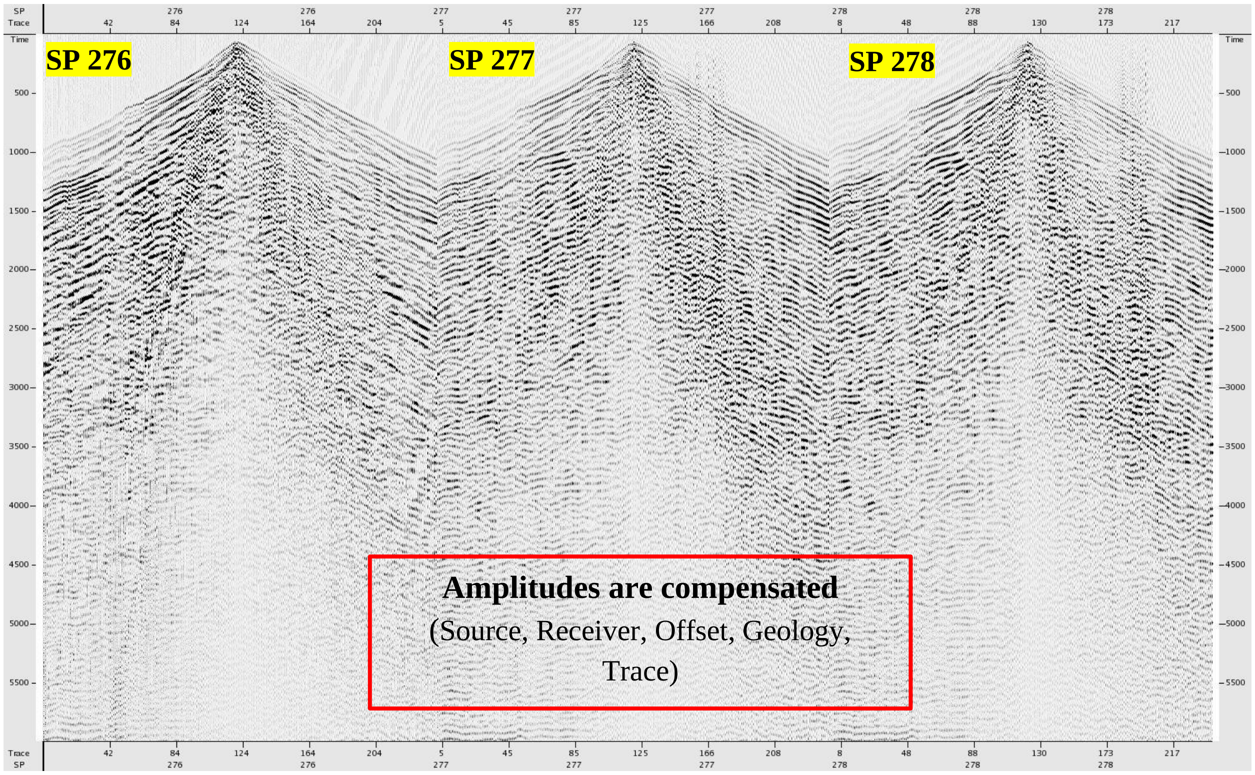


Figure 4.28: SCAC Stack (Source, Receiver, Offset & Geology component)



Amplitudes are compensated

(Source, Receiver, Offset, Geology, Trace)

Figure 4.29: SCAC (Source, Receiver, Offset, Geology & Trace component)

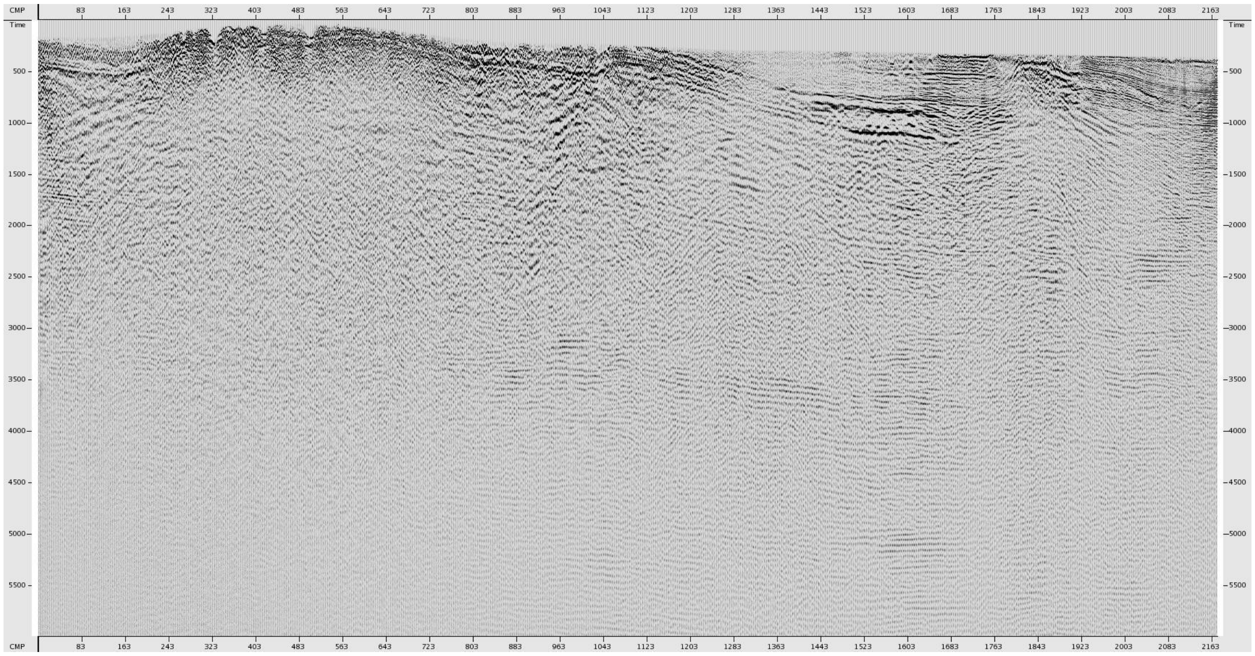


Figure 4.30: SCAC Stack (Source, Receiver, Offset, Geology & Trace component)

After testing all the components, the ones responsible for maximum amplitude decay will be applied to restore the lost amplitude. The tests showed the components responsible for the maximum amplitude attenuation are:

1. Source
2. Receiver
3. Offset
4. Geology

Therefore, these components were then utilized in the compensation process to bring back the lost amplitudes. The results of compensation process for every component could be compared both in both shot gathers and stacks.

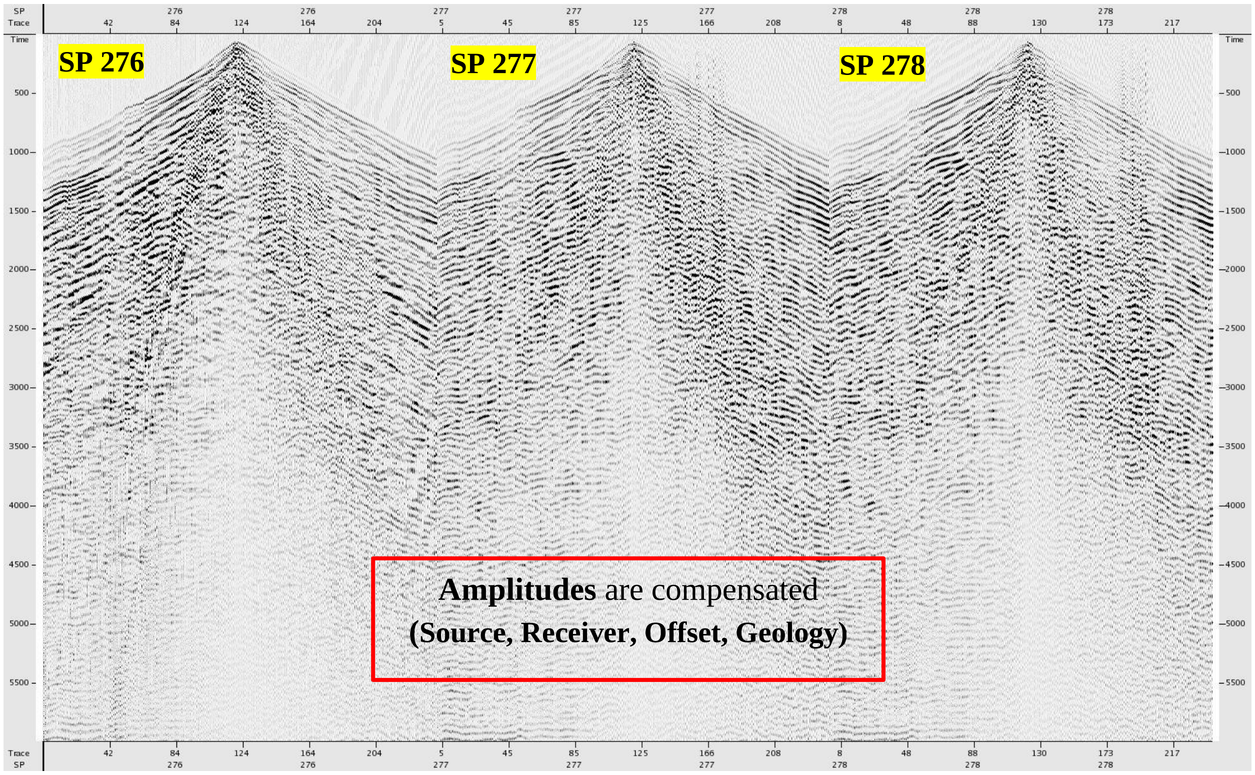


Figure 4.31: SCAC Data (This data incorporates source, receiver, offset and geology component)

The figure 4.31 shows the amplitude compensation effect and this is the combined effect of source, receiver, offset and geology.

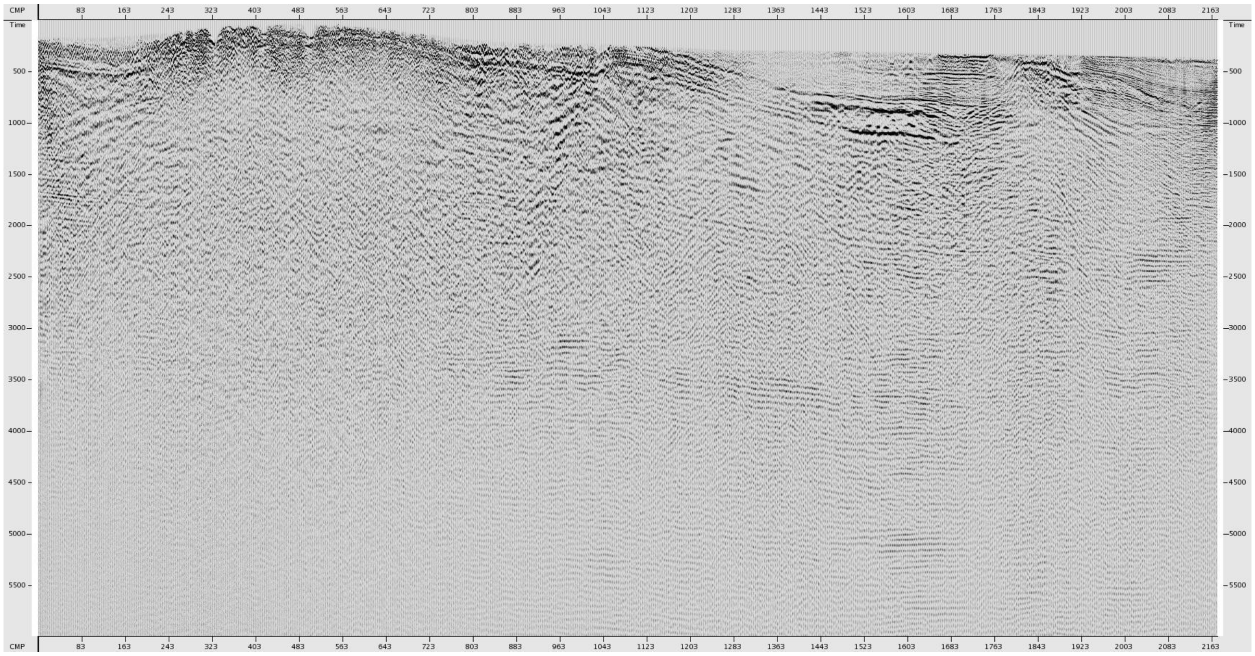


Figure 4.32: SCAC Final Stack

4.1.6. Deconvolution Results

Deconvolution is an inverse filter, which is used to eliminate noise and the source signature from the received data to get real reflectivity. Here, the impacts of the wavelet are predicted and eliminated by the application of ***predictive deconvolution***, which makes use of data from seismic traces to improve the clarity of reflections.

The two important steps involved in the analysis are;

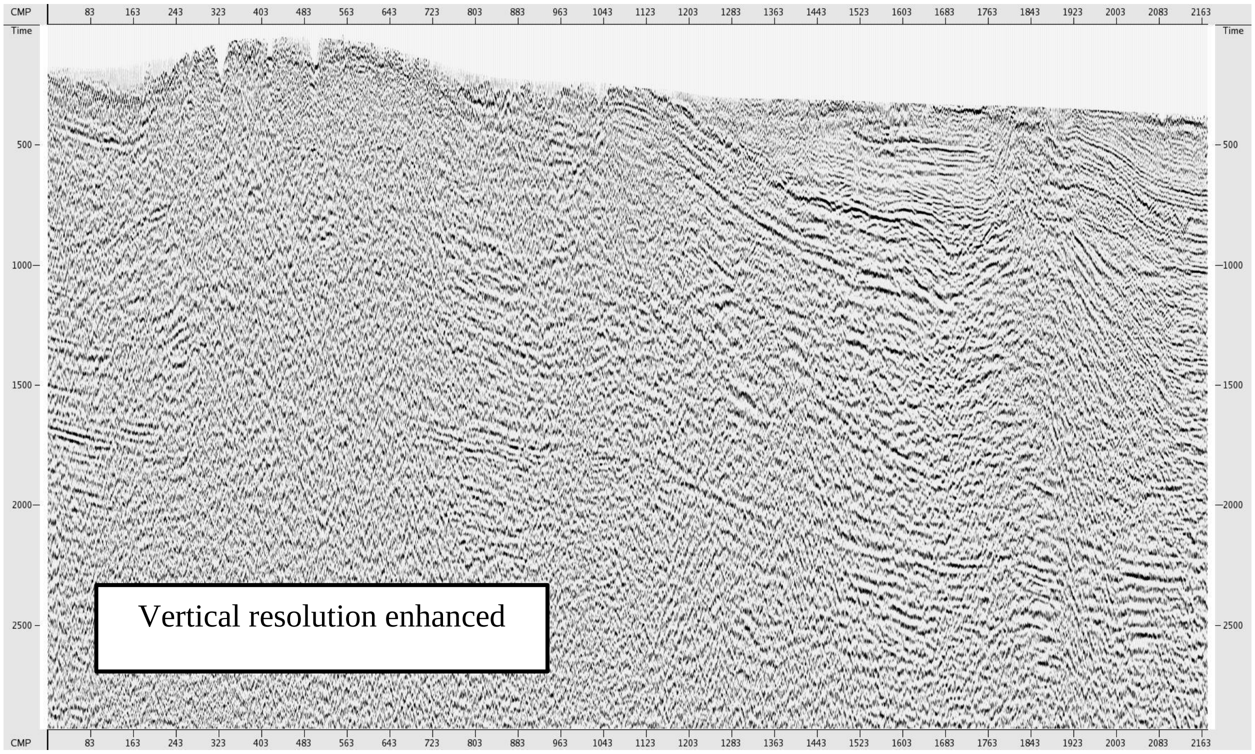
i. Operator Length
ii. Predictive Distance

i. Operator Length

During the autocorrelation strong multiples were found at 160 ms, and real reflections were shown at zero time, hence the operator length was set to 160 ms in this case.

ii. Predictive Distance

Following testing of several gaps, a prediction distance of **16 ms** and an operator length of **160 ms** were chosen for this study.



Vertical resolution enhanced

Figure 4.33: Deconvolution stack (Result of deconvolution with predictive distance 16 milliseconds and operator length 160 milliseconds)

So, operator length is removing the short path multiples, and gap is improving the resolution of data by removing the source signature.

As deconvolution enhances the resolution of data, it also introduces wild amplitudes in the data as shown in figure 4.34. This issue was addressed by the application of noise attenuation technique. ***Wild amplitudes attenuation filter*** was applied to remove the wild amplitudes while a ***low-cut filter*** was also designed of **4 to 8 Hz** frequency range to eliminate the low frequency noise from the dataset as shown in figure 4.35. The final deconvolution data is shown in figure 4.36. While the eliminated noise from the data can be observed in figure 4.37 and figure 4.38.

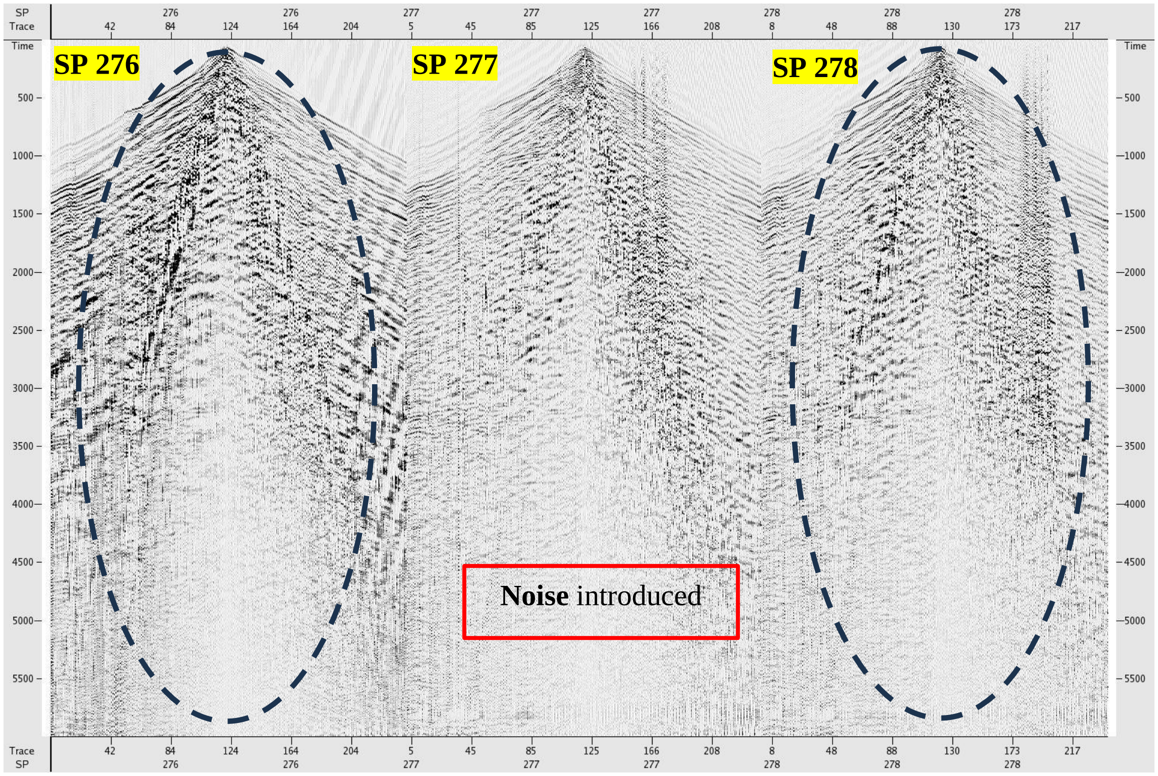


Figure 4.34: Deconvolution initial data

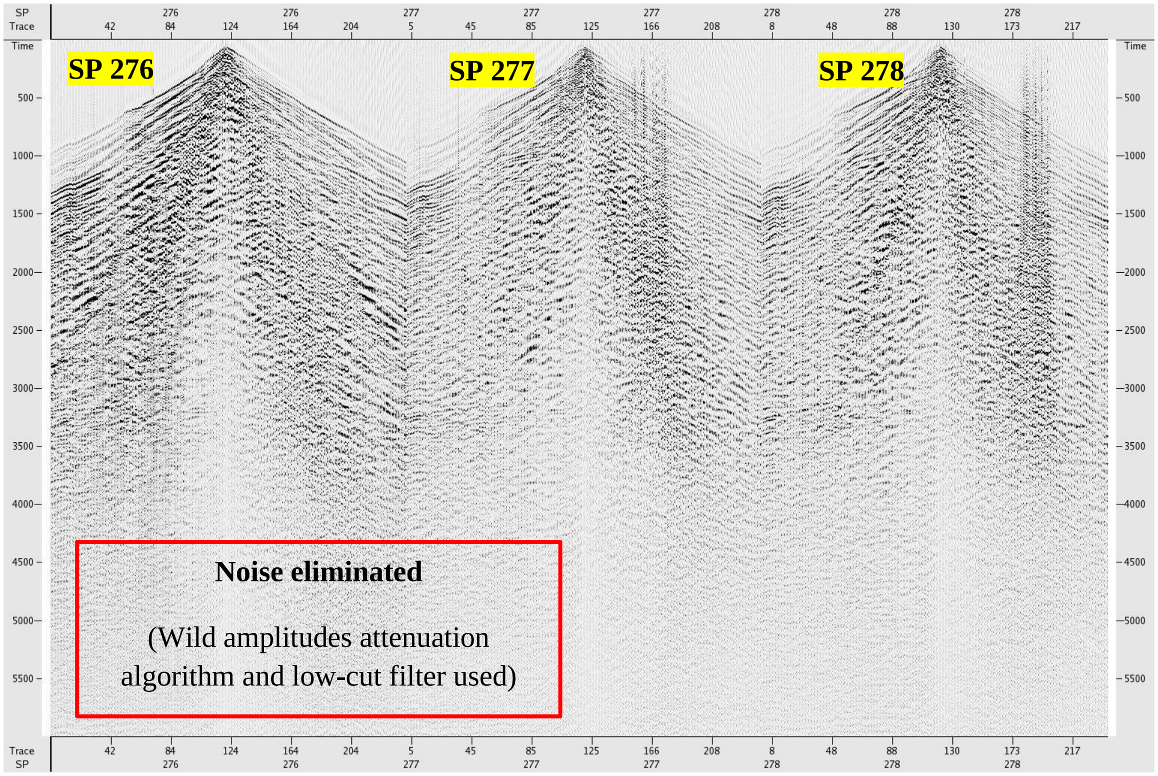


Figure 4.35: Deconvolution data (After wild amplitudes attenuation)

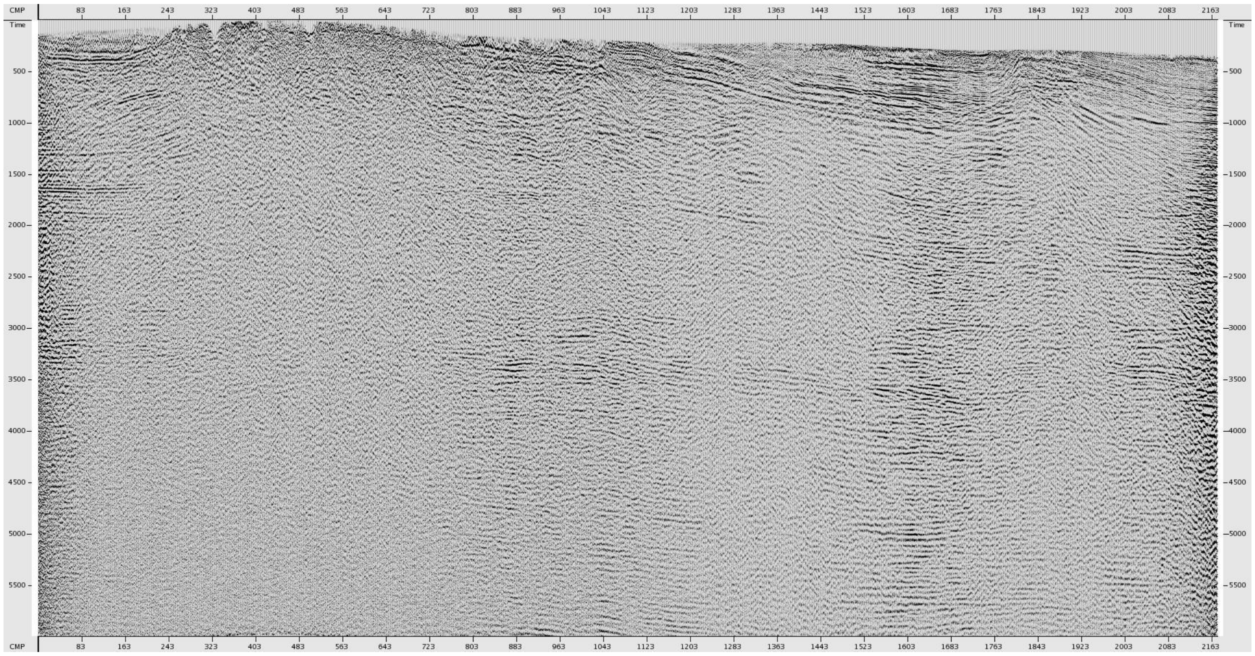


Figure 4.36: Deconvolution stack (After wild amplitudes attenuation)

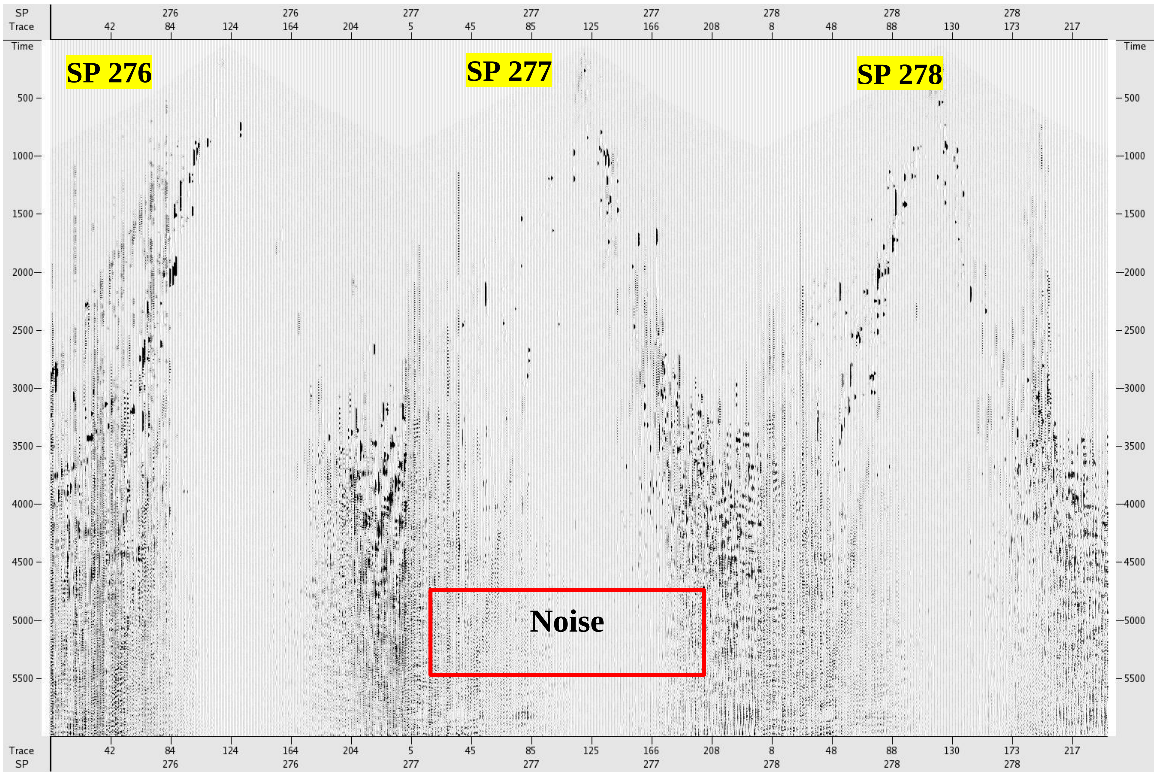


Figure 4.37: Removed noise after wild amplitude attenuation filter

Figure 4.38: Noise Stack (Removed noise after wild amplitude attenuation filter)

4.2. Data Refinement Results

4.2.1. First Breaks and Refraction Statics

The formula:

$$S = VT$$

Where S denotes thickness, V denotes velocity within the weathered layer, and T is the time derived from first breaks picking (figure 4.36), which is used to compute the thickness of the weathered layer (LVL) in refraction statics.

We ascertain the arrival times for each trace by locating the initial breaks. A substitute velocity for the velocity input can be used; it is commonly replacement velocity or the regional velocity (Vo). Next, we multiply the selected first break time by the velocity to find the thickness of the weathered layer at each source and receiver point. Then, refraction statics are applied using this computed thickness.

After the application of refraction statics corrections, an upward shift in the seismic traces is observed. The adjustments provided by refraction statics usually make the seismic trace shift upward. This shift compensates for the time delays related to the faster or slower near-surface layers. This aligned the reflected waveforms to their true locations within their corresponding positions in time.

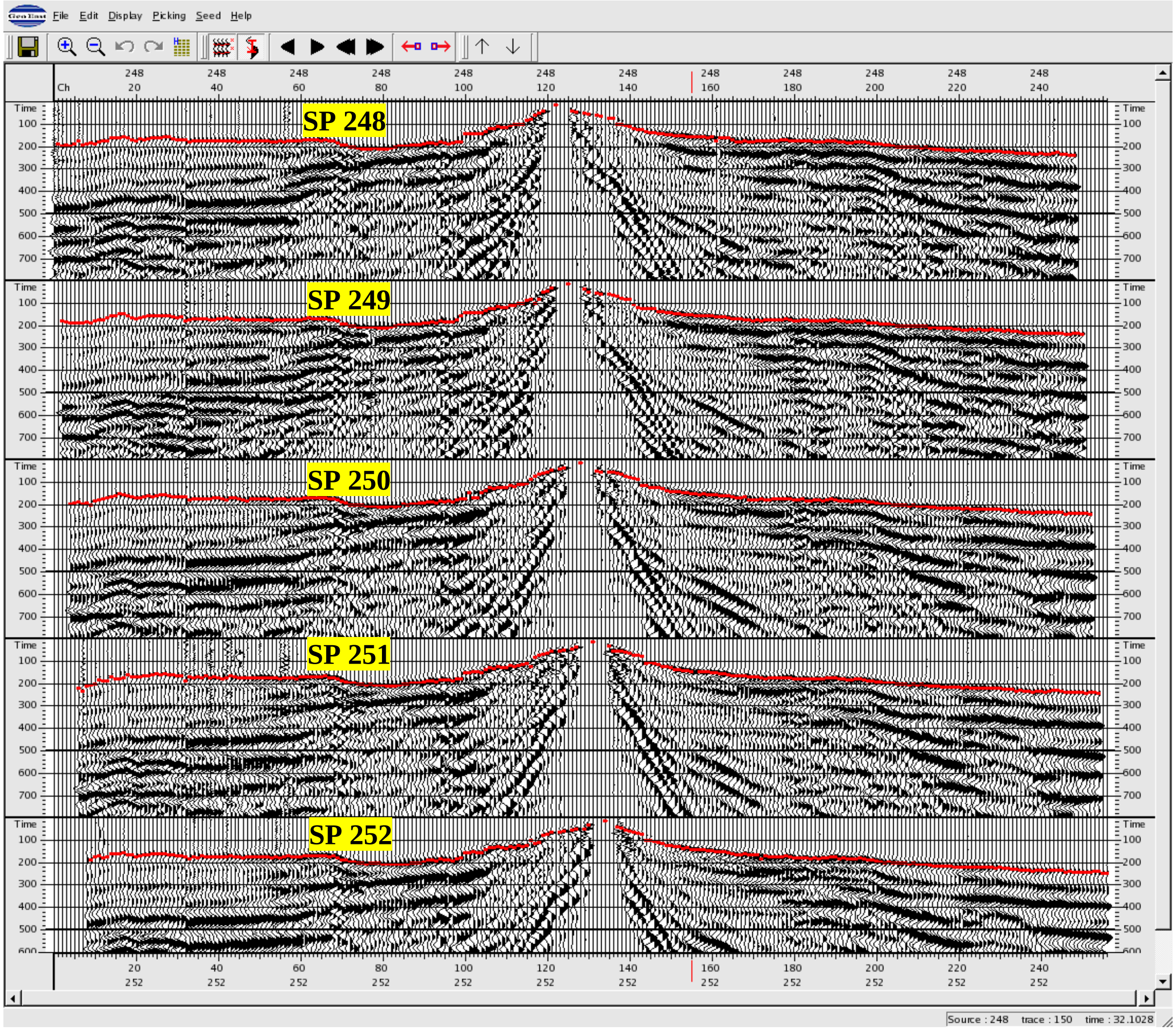


Figure 4.39: First break picking

The figure 4.39 shows the first break picking done at SPs 248, 249, 250, 251 and 252. This is how the first breaks were picked at every SP within the dataset.

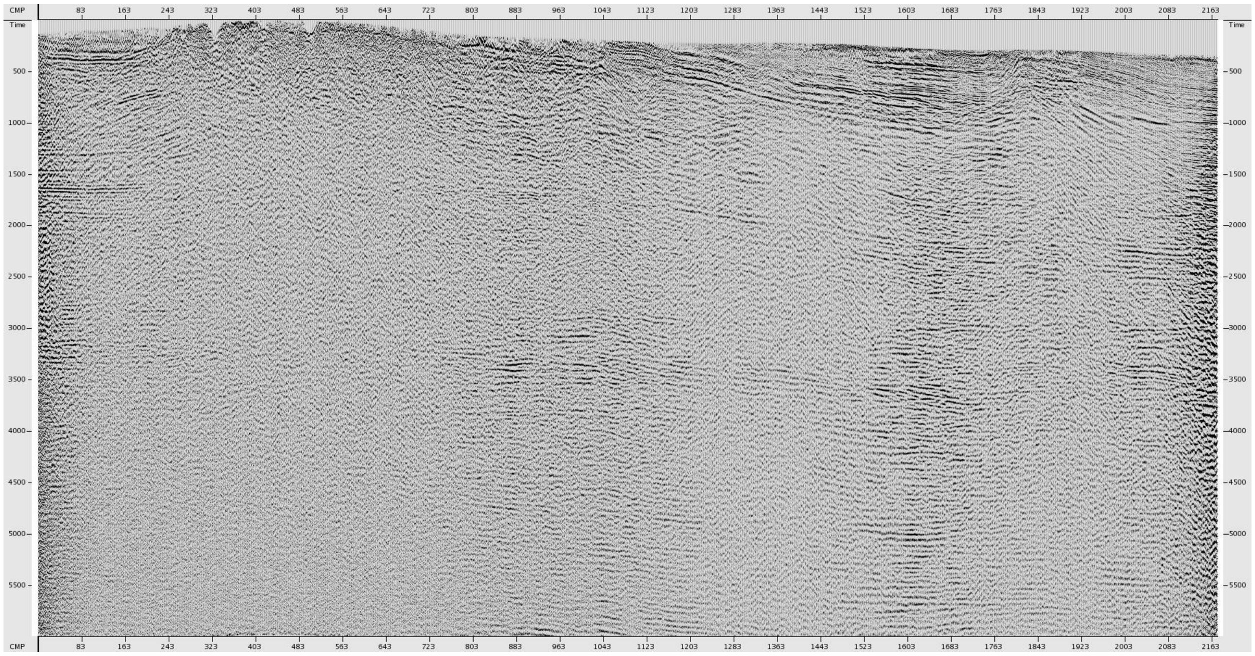


Figure 4.40: Refraction statics stack

4.2.2. Velocity Modeling and Residual Statics Results

Since precise migration results are produced by accurate velocity modeling, velocity analysis is an essential step in the processing of seismic data. From the beginning to the end of the processing sequence, this analysis is done several times. Regional velocity analysis is carried out while building a brute stack during the pre-processing stage. ***Regional velocity analysis*** was performed at **4 km** interval.

Multiple iterations of velocity analysis are carried out during data refinement. There are two passes, during ***first pass velocity analysis*** was performed at every **1 kilometer**, as shown in figure 4.41. And the ***second pass velocity analysis*** was performed at **500 meters**, interval as shown in figure 4.43. During the data conditioning and migration phases, additional passes of velocity were performed. The first and second velocity passes are applied in conjunction with alternating applications of residual statics (figure 4.42 and figure 4.44).

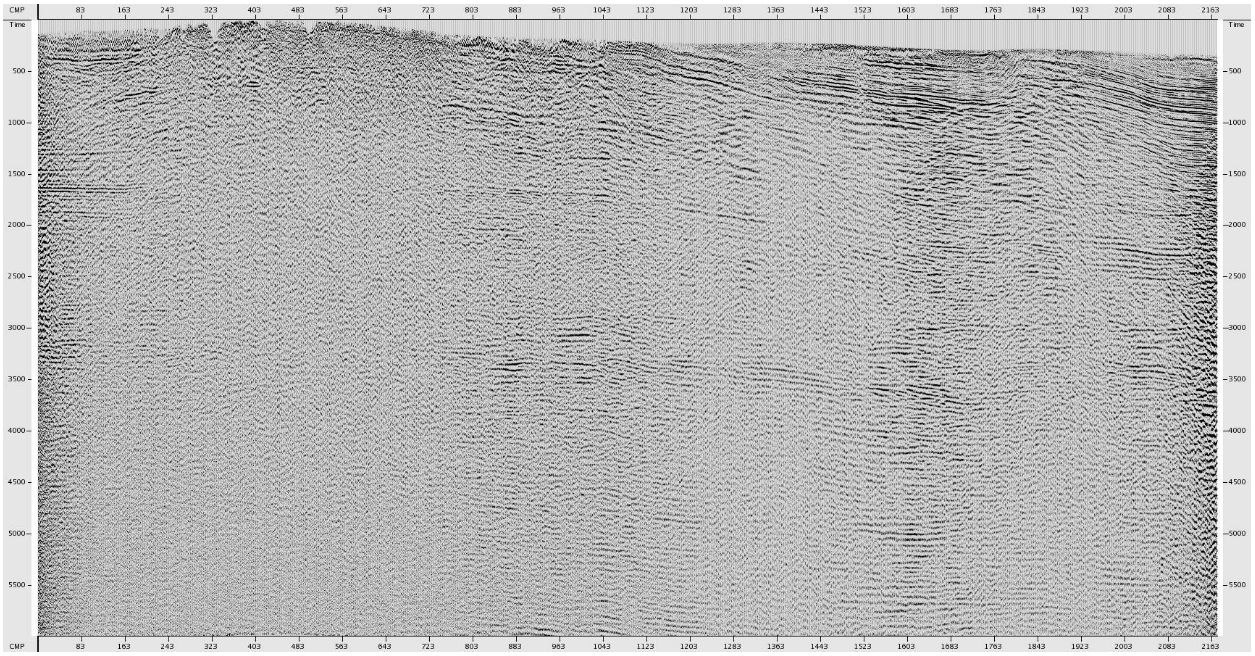


Figure 4.41: 1st pass velocity Analysis (The 1st pass velocity analysis was performed at 1km interval)

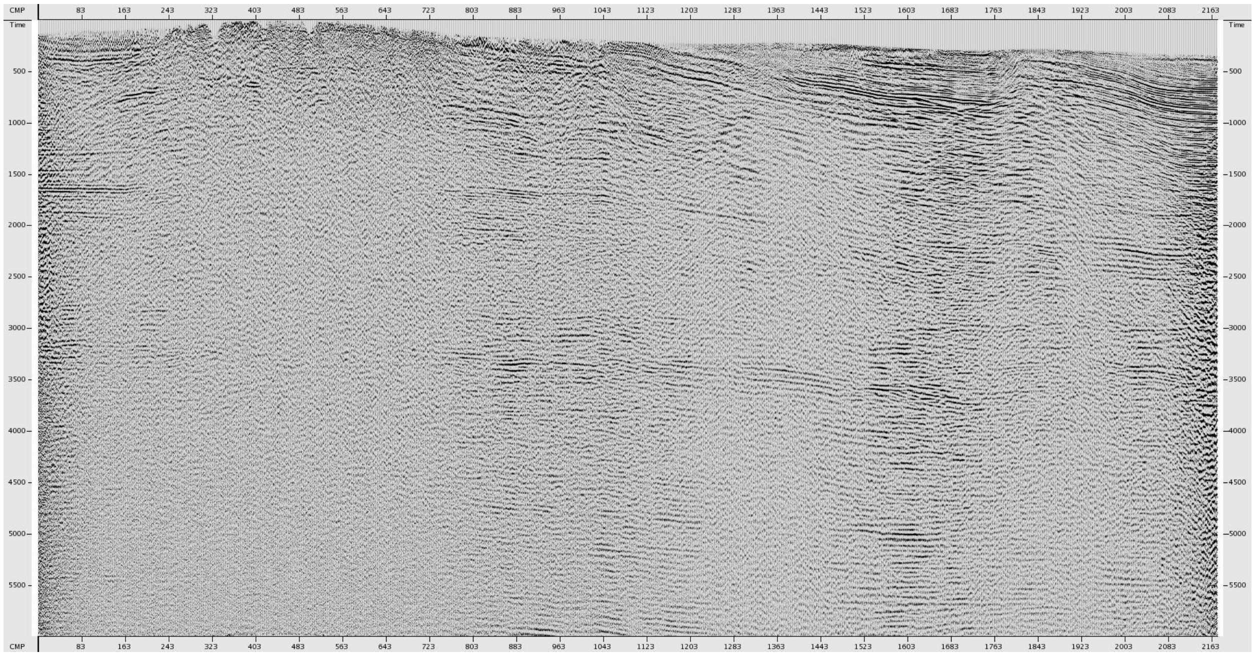


Figure 4.42: 1st pass residual statics (To resolve any static issues in the data)

To precisely map subsurface structures, velocity analysis is carried out at different intervals, and any residual static problems in the data are remedied by applying residual statics. In addition, this procedure aids in correcting any mistakes made during the velocity analysis itself.

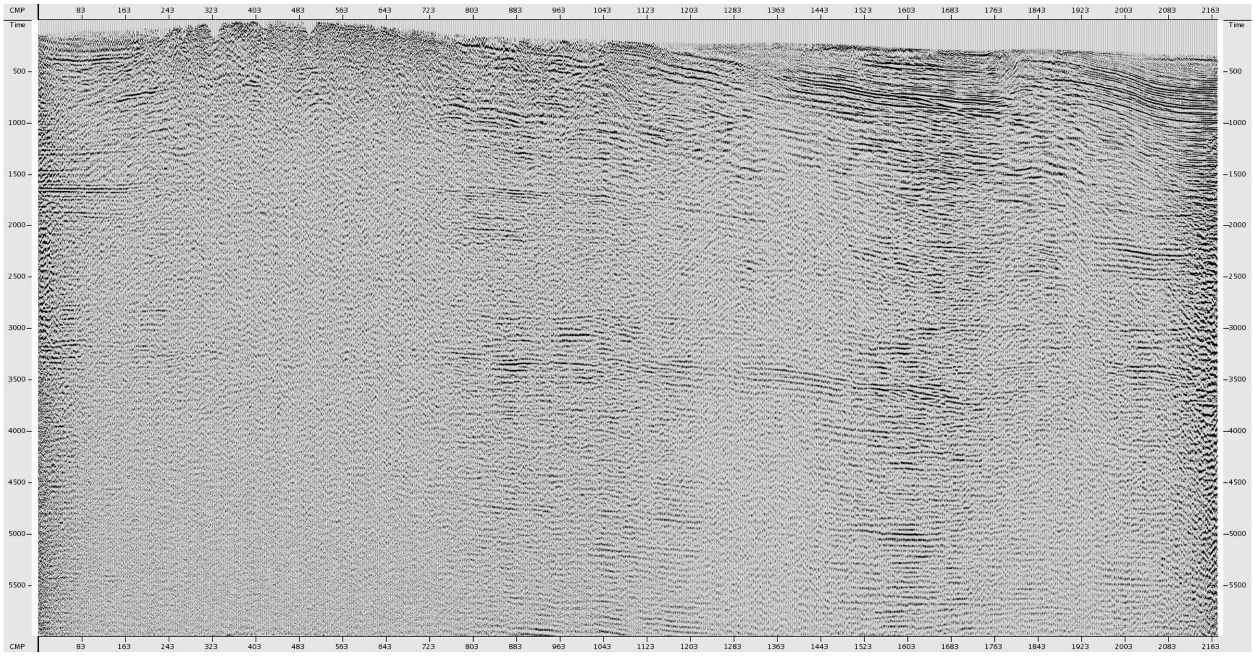


Figure 4.43: 2^{nd} pass velocity analysis (2^{nd} pass velocity analysis performed at 500 m interval i.e., finer velocity analysis)

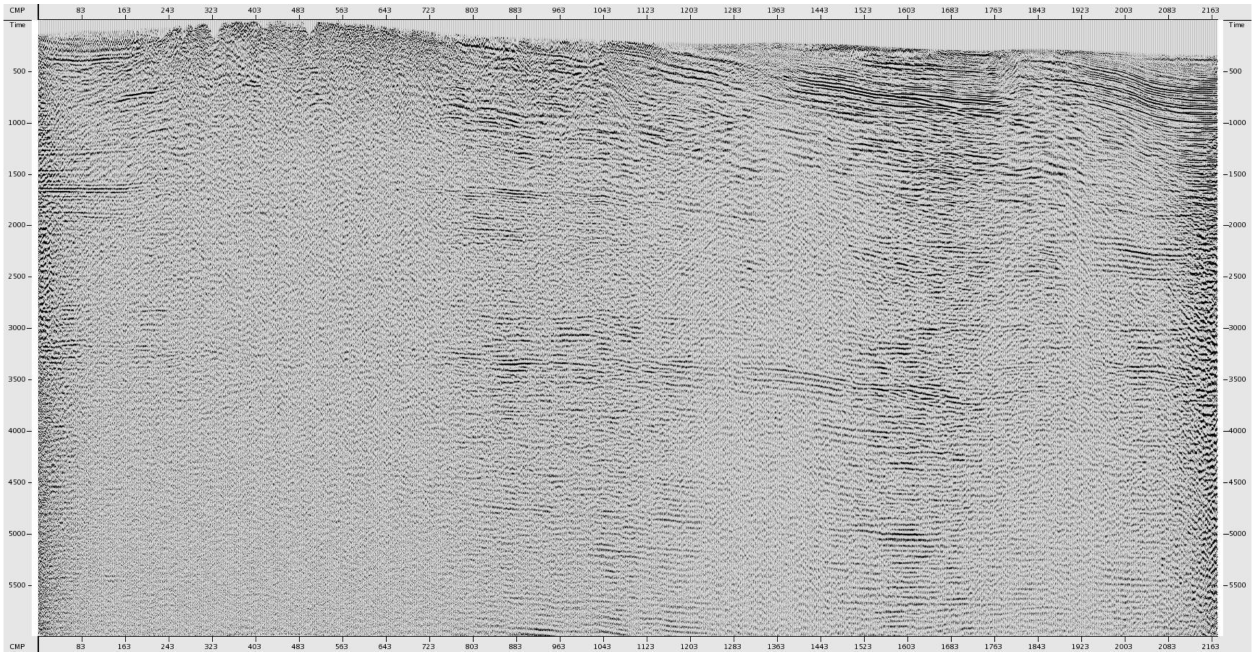


Figure 4.44: 2^{nd} pass residual statics (To resolve any static issues in the data)

This process is termed iterative because more detailed velocity models can bring out factors in the subsurface that warrant correction through further use of the residual statics. On the other hand, by applying the residual statics, the data can be improved and consequently, the better velocity model can be derived. By carrying out these sequences in an alternate manner, models related to velocity inaccuracy and ground effects are tackled in a well-adjusted way.

4.3. Data Conditioning and Migration Results

4.3.1. Pre-Stack Random Noise Attenuation

Noise attenuation during the pre-processing stage involves attenuation of coherent noise from the data. To remove the incoherent noise or random noise still present in the data, the application of Pre-stack Random Noise Attenuation (PreRNA) is utilized. The PreRNA module works in FX (Frequency – offset) domain. The random noise comes from different sources and exists in a random pattern where every random noise has its own frequency range. The application of PreRNA converts the data into FX domain and picks the frequency ranges which do not align with the signal frequency.

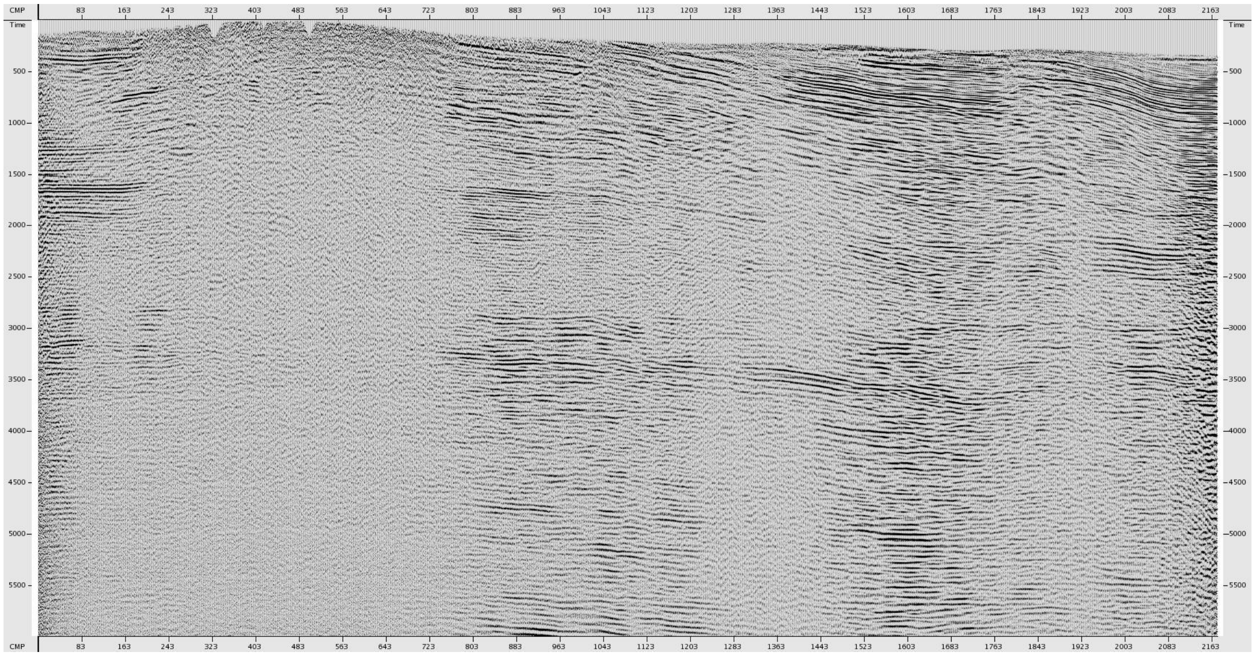


Figure 4.45: PreRNA Stack (Application of random noise attenuation yielded refined data)

The attenuation of random noise before migration preconditions the data and this step further enhances the resolution of data by enhancing the signal to noise ration.

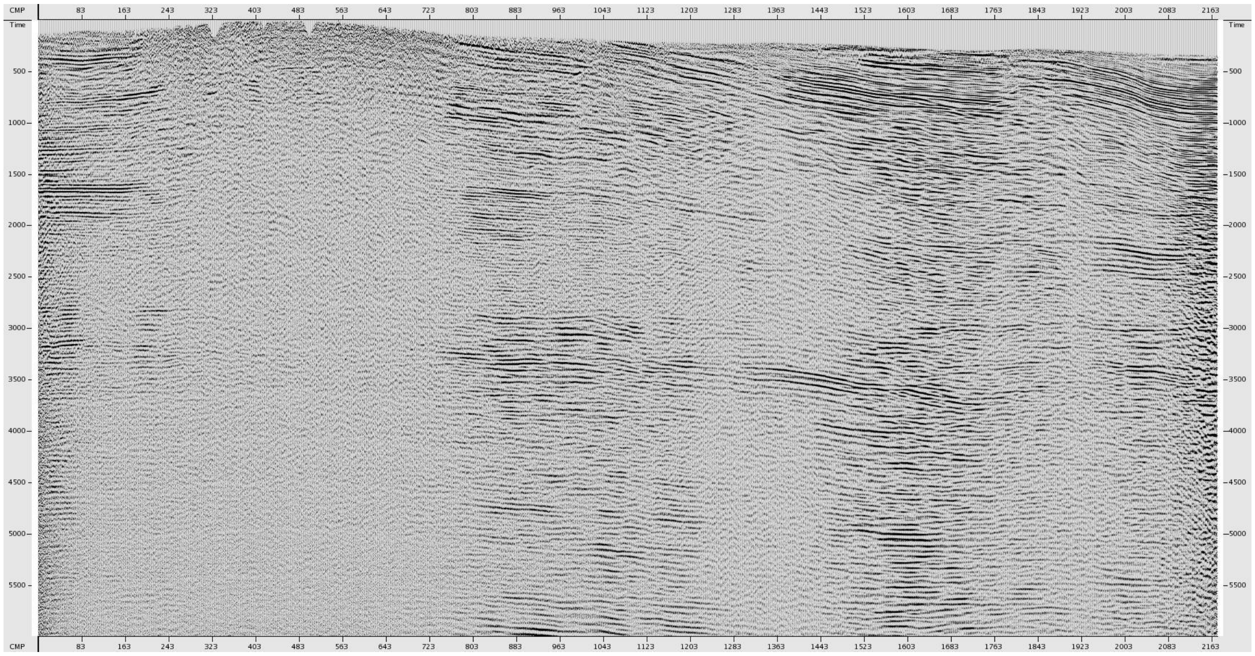


Figure 4.46: 3rd pass of velocity analysis data or Final Stack (3rd pass of velocity is performed to refine the velocity and to improve the visualization of subsurface structures)

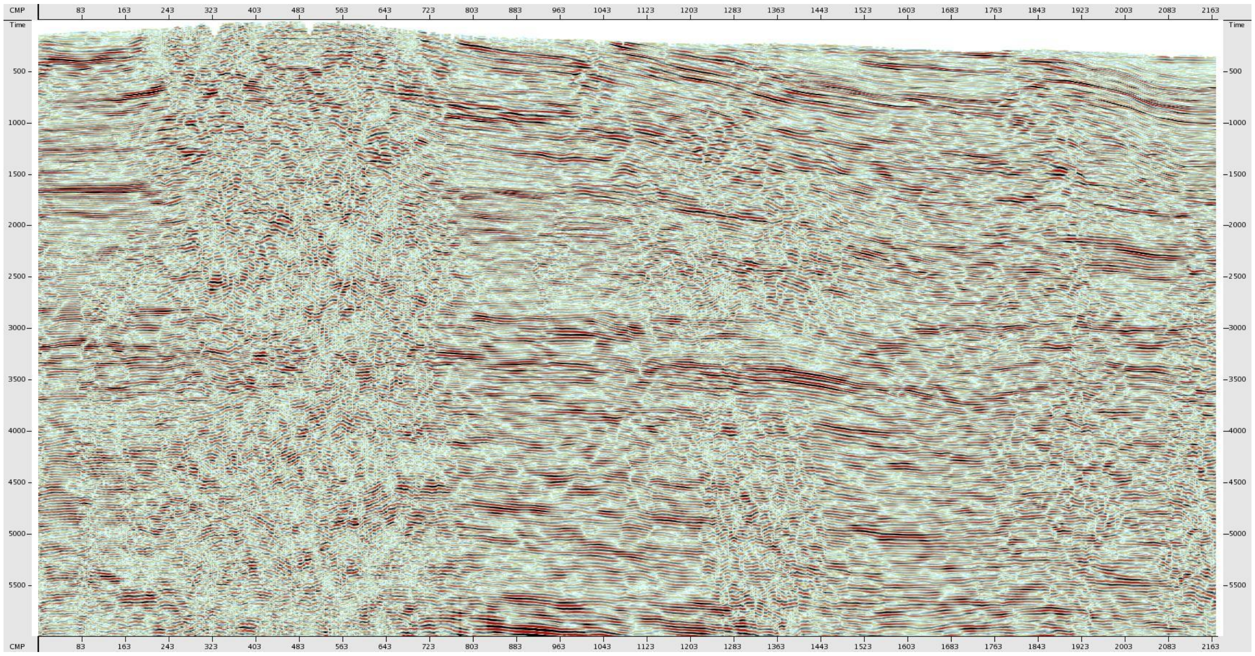


Figure 4.47: Final Stack (Final stack also known as Un-migrated data. RNA, Coherency filter and Time Variant filter is applied on the Final stack to improve the resolution of data)

Another pass of velocity analysis is performed i.e., 3rd pass velocity analysis (figure 4.46). This velocity analysis is the most accurate as compared to the previous two, as all types of noises have been eliminated and S/N has been increased, so the subsurface information provided by the 3rd pass velocity analysis is the most accurate. This data is further used for migration because for pre-stack time migration there should be an accurate velocity model and an ideal type of data with high S/N. The 3rd pass velocity analysis data is also termed as the 'Final Stack'.

Random Noise Attenuation (RNA), coherency filter and time variant filter is applied on the Final Stack to improve the resolution of seismic data by enhancing the S/N, the coherency of faults and reflectors and the overall visualization of structures in the data, as shown in figure 4.47.

4.3.2. Pre-Stack Time Migration (PSTM)

The objective of PSTM lies in bringing correct images of seismic events by shifting seismic reflections to their correct time level to have a better estimation of the subsurface events. This aids in proper delineation of subsurface faults and other geologic structures.

A time migration seismic image result is produced (figure 4.48) in which all the reflections have been time reset to the correct positions in time so that the depiction of the subsurface is clearer and more accurate. It must be noted that the success of PSTM depends on how accurate the velocity model is. An incorrect model will, in practice, give inaccurate results following migration.

This initial PSTM data will go through another round of velocity analysis (figure 4.49). The 4th pass velocity modeling is done on a 500 m interval. The purpose of velocity analysis after PSTM is to rectify any errors still present in the data. An updated velocity model will give a true subsurface image, where all the geologic structures and faults can be observed and marked with great accuracy.

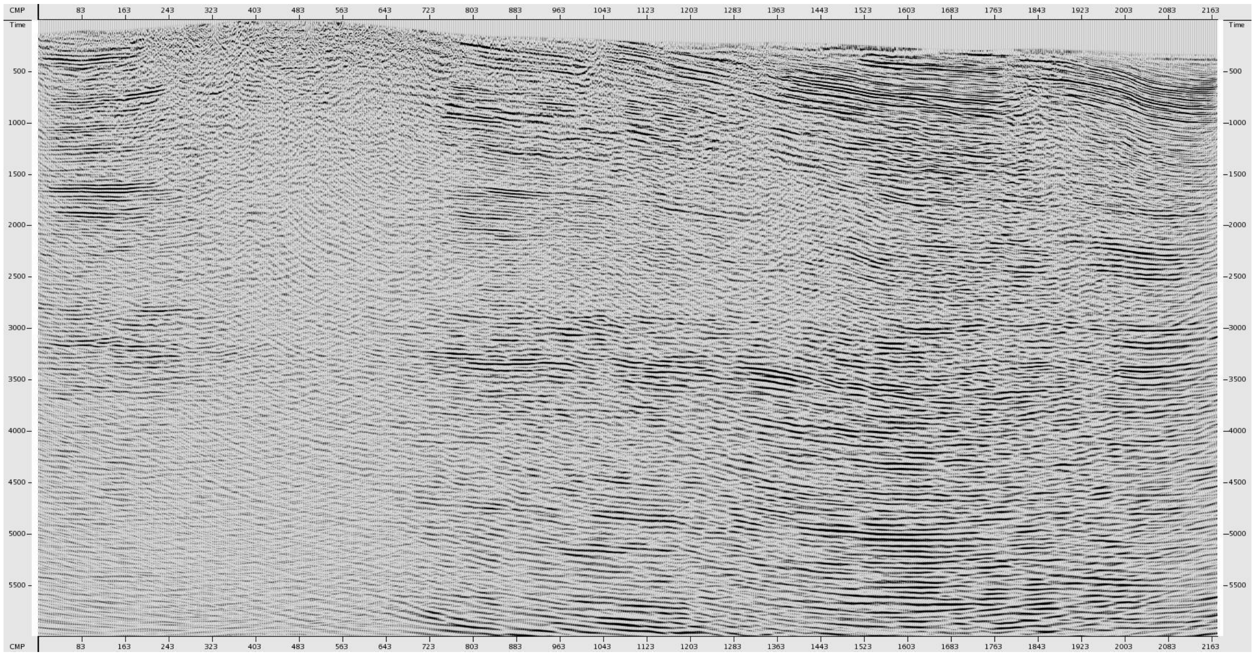


Figure 4.48: Pre-stack time migrated data (This is the initial Pre-stack time migrated data. PSTM improves the horizontal or lateral resolution of data)

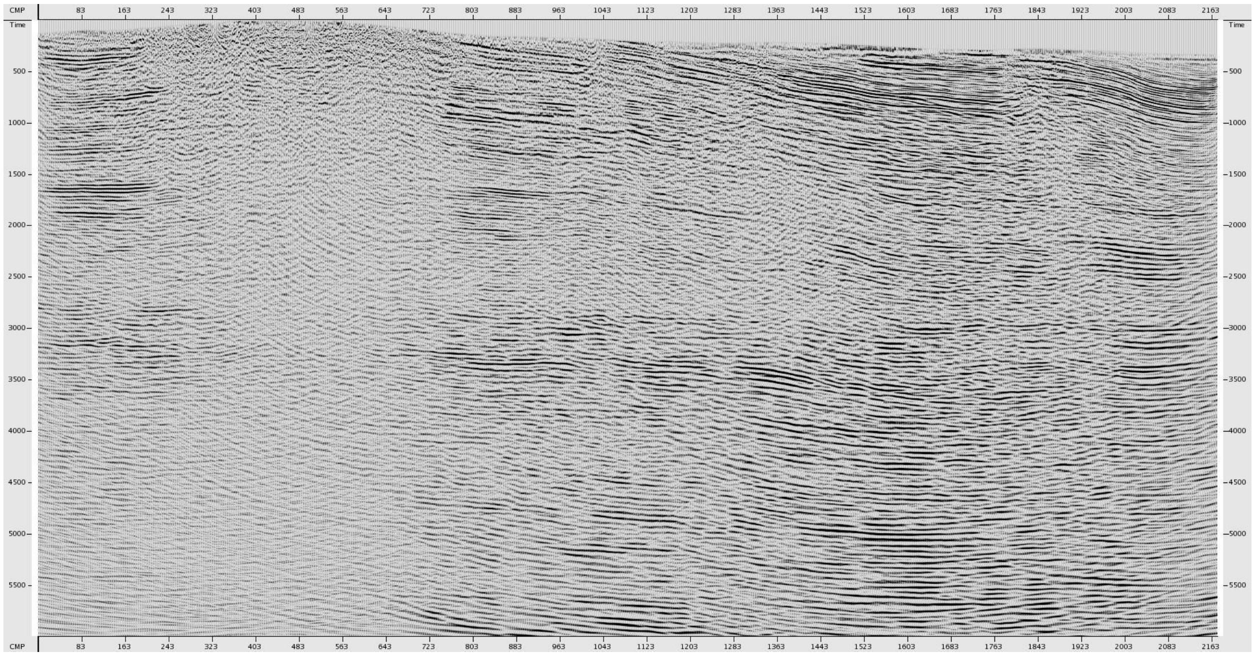


Figure 4.49: 4th pass velocity analysis (The stack clearly indicates an improvement in the resolution of seismic data. The appearance of faults and structures is improved)

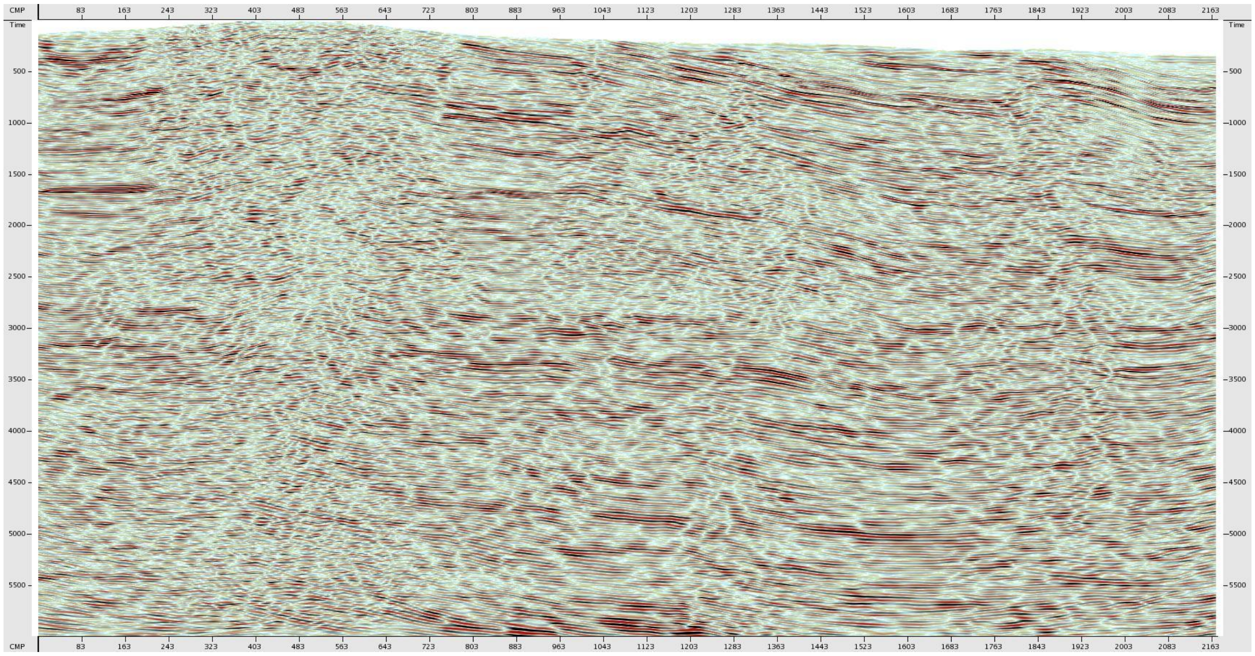


Figure 4.50: PSTM Data (Final pre-stack time migrated data)

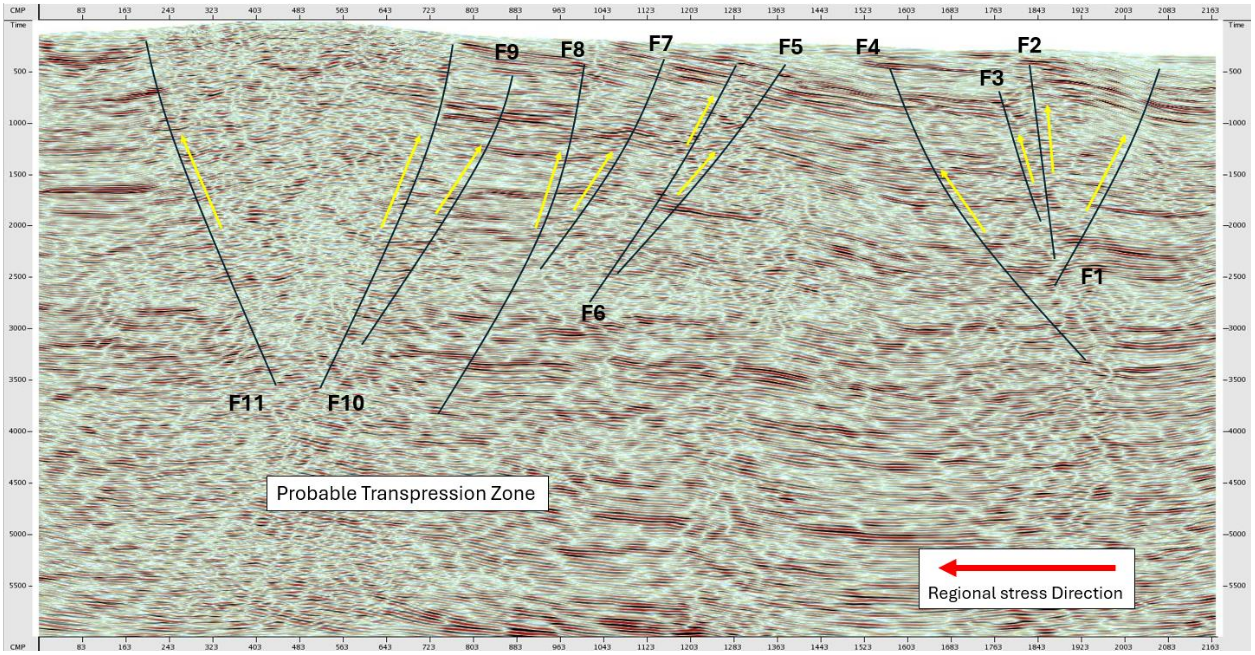


Figure 4.51: Resultant Processed File (Better identification of anticlinal structure, shallow information is much more preserved, better continuity of reflectors can be observed with much improved identification of faults).

The final PSTM stack has a high signal to noise ratio. All types of noise attenuation algorithms have been performed (for coherent and random noise), the data went through finer velocity analysis which reduced any artifacts in the velocity picking. Along with that the application of refraction and residual statics played a major role in refining the data and enhancing the seismic resolution.

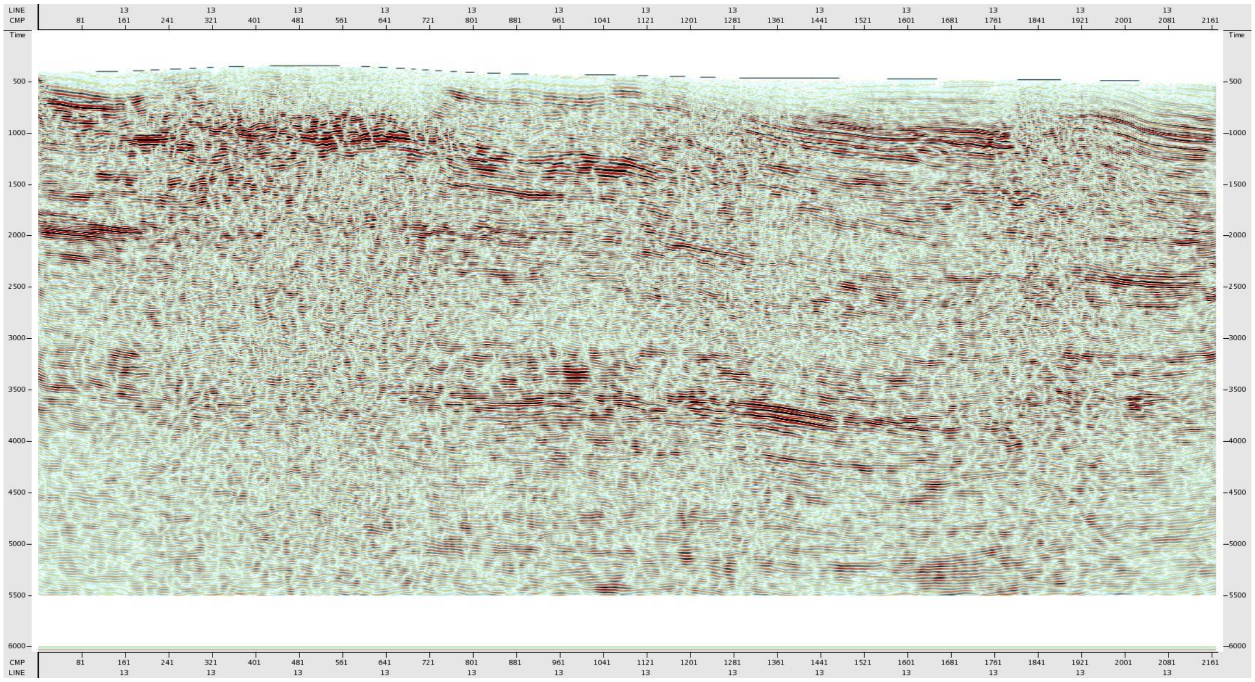


Figure 4.52: Legacy data (Previously processed file)

Compared to legacy data in which the continuity of reflectors and coherency of faults is compromised, faults and structures cannot be marked accurately, and the signal strength appears weak, in figure 4.51, it can be observed that the structures visualization is improved, there is better coherence of faults, the continuity of reflectors can be observed and there is an overall enhancement in the resolution of data.

So, in comparison with the legacy data (figure 4.52), the reprocessing results clearly indicated high resolution seismic data with better imaging of faults and subsurface structures.

CONCLUSION

The current study emphasizes the importance of seismic data reprocessing and how the adoption of adequate processing algorithms enhances the subsurface imaging of faults and other geologic structures.

By the application of appropriate processing algorithms, the study was able to produce;

i. A high-resolution seismic data that can help identify structural traps.
ii. A high-quality seismic data that can delineate the faults and fractures in the area, as well as their orientations and displacements.

Apparently, improved imaging allowed the reliable identification of subsurface structures and accurate delineating of faults. In general, the processing sequence adopted for the study has greatly enhanced the quality of seismic data and provided a more realistic and detailed picture of the area, as compared to the legacy data.

REFERENCES

A A Halepoto et al. (2023). Integrated study of structural styles and suitability for hydrocarbon entrapment, Southern Kirthar Belt, Pakistan

Aki, K., & Richards, P. G. (2002). Quantitative Seismology (2nd ed.). University Science Books.

Bannert, D., A. Cheema, A. Ahmed, and U. Sch-R., (1992) The structural development of the western fold belt, Pakistan: Geologisches Jahrbuch, Hannover, Reihe B, 80, p. 1-60 (with map in three sheets).

Claerbout, J. F. (1985). Imaging the Earth's Interior. Blackwell Scientific Publications.

D. Halliday et al. (2015). Scattered ground-roll attenuation using model-driven interferometry Geophysics Prospect.

Fowler, J.N., Graham, R., Sassi, W., Smewing, J.D. & Warburton, J. (2004). Two-dimensional kinematic modeling of the southern Kirthar fold belt, Pakistan. In Deformation, Fluid Flow, and Reservoir Appraisal in Foreland Fold and Thrust, edited by Swennen, R., Roure, F. & Granath, J.W. Belts

Powell, C.M.A. (1979). A speculative tectonic history of Pakistan and surroundings: Some constraints from the Indian Ocean. In Geodynamics of Pakistan, edited by Farah, A. & DeJong, K.A. Geological Survey of Pakistan. pp. 5-24.

H.A. Raza, S.M. Ali, R. Ahmed. (1990). Petroleum geology of the Kirthar sub-basin and part of the kuch basin, Pakistan

Hale, D. (2009). Seismic Amplitude Interpretation. Cambridge University Press.

Henin* (CGG), K. Garceran (CGG), D. Le Meur (CGG), F. Bertin (CGG) &A. Rollet (CGG). (2019). Surface-Consistent Amplitude Simultaneous JointInversion for PP and PS DataG.

Hinsch, R., Chloé, A., Nasim, M., Abbas, A.M. & Sultan, S. (2019). Linked thick-to thin-skinned inversion in the central Kirthar Fold Belt of Pakistan. Solid Earth 10(2): 425-446.

Kadri, I. B. (1995). Hydrocarbon prospectivity of Pakistan's sedimentary basins—Present status and future prospects. In Proceedings of the Pakistan Academy of Sciences (Vol. 32, No. 1, pp. 15-24).

Adnan Khalid, Sajjad Ahmad, Asghar Ali, Gohar Rehman & Muhammad Yaseen. (2022). Structural Analysis of Kirthar Fold Belt, Lower Indus Basin, Balochistan, Pakistan; Implications from Compression and Inversion Tectonics

Muhammad Kamal, Aamir Ali, Yawar Amin, Asam Farid, & Bakhtawar Sarosh. (2023). Advanced Data Processing as a Tool to Enhance the Vertical and Horizontal Resolution of Bottom Simulating Reflector (BSR): Implications for Gas Hydrates Exploitation.

Naeem, M., Akhtar, S., Mustafa, N., Jamil, T., & Hussain, M. (2016). Structural Analysis of Hydrocarbon Bearing Strata in Lower Indus Basin. Pakistan Journal of Science, 68(2).

Nanda, N.C. (2021). Seismic Interpretation Methods. In: Seismic Data Interpretation and Evaluation for Hydrocarbon Exploration and Production. Advances in Oil and Gas Exploration & Production.

O'Haver, T. (2008). "Intro to Signal Processing - Deconvolution". University of Maryland at College Park.

Olawale Olakunle OSINOWO. (2020). REPROCESSING OF REGIONAL 2D MARINE SEISMIC DATA OF PART OF TARANAKI BASIN, NEW ZEALAND USING LATEST PROCESSING TECHNIQUES

Quadri, K. R., & Shuaib, S. M. (1986). Stratigraphy of the Badin-Jhimpir region, Sindh: Geological Survey of Pakistan.

Raza, H. A., Tariq, M., & Amjad, M. N. (1990). Geological and engineering aspects of Sembar shale and seal in the Middle Indus Basin. In Annual Technical Conference and Exhibition of the Society of Petroleum Engineers.

S. Saha*, A. Mandal, B. Borah and M. Gupta, (2019). Oil India Ltd.

Schuster, G. T. (2022). Seismic Reflection Processing. Cambridge University Press.

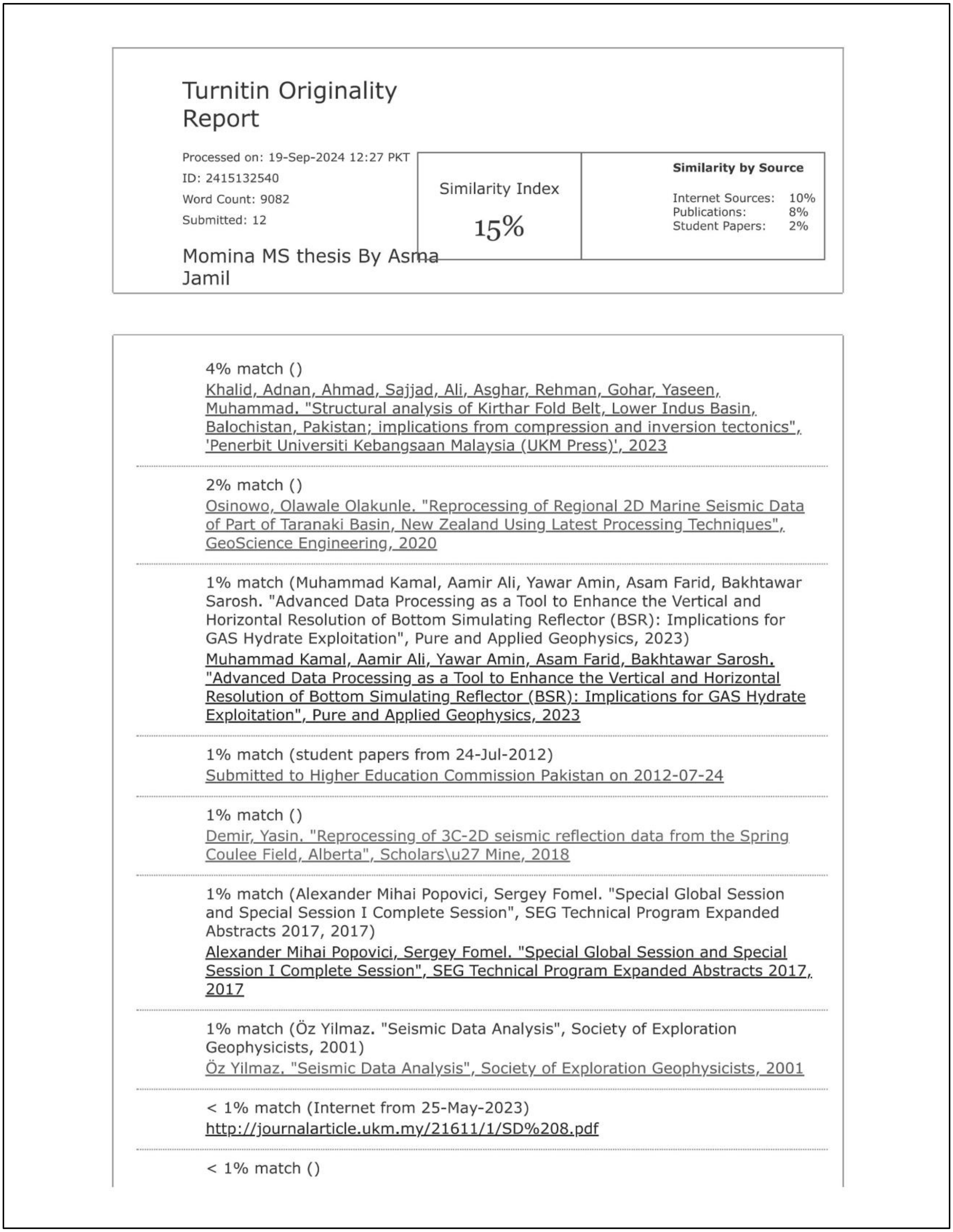
Sheriff, R. E., & Geldart, L. P. (1995). Exploration Seismology (2nd ed.). Cambridge University Press.

Yan Yan, Xianhuai Zhu, Junru Jiao, Pan Deng, Bin Yang and Lei Fu. (2017). Forland Geophysical Services (FGS) Ernesto V. Oropeza, Jianxiong Chen and Sarah Mueller, Anadarko Petroleum Corporation. Permian Basin Seismic Data Reprocessing – A Case Study

Yasin Demir. (2018). Reprocessing of 3C-2D seismic reflection data from the Spring Coulee Field, Alberta Coulee Field, Alberta.

Yilmaz, O. (2001). Seismic Data Analysis: Processing, Inversion, and Interpretation of Seismic Data. Society of Exploration Geophysicists.

Zhou H-W. (2014). Practical Seismic Data Analysis-CUP



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