

**PARALLAX-BASED APPROACH TO REMOVE SAND
DUNE EFFECTS FROM SEISMIC DATA**

BY

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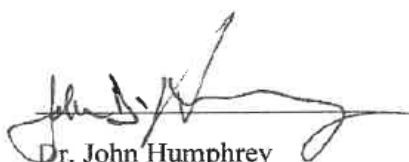
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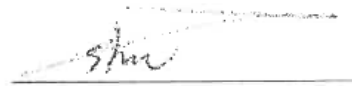
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To my father, mother, wife, brothers, sister, children, and friends.

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ABSTRACT

Full Name : Mohammed A. Bin Jahlan

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Removing an occlusion or an unwanted object from a photographic picture is a challenging problem in the image processing field. Extensive research has been done on this topic, which has led to many object-removal methods using single or multiple images as input. One class of these methods takes advantage of the parallax phenomenon, which uses multiple images to detect and remove the occlusion and then aligns the sequence of images to accurately fill the missing information in the original image by transferring it from the other images.

Seismic data acquired in a desert are impacted by the presence of sand dunes that alter the travel times and the amplitudes of the seismic waves passing through them. Using an analogy of taking a sequence of images for a distant object and recording seismic data over a deep target, I introduced four parallax-based approaches to remove the adverse effects of sand dunes on seismic data. The main steps of the proposed approaches are muting all traces affected by the sand dune, flattening the events by NMO correction, and filling the missing traces by either replacing these traces with other traces from the adjacent CDPs or by stacking. This method was tested on 2D synthetic elastic seismic data generated from a model composed of two horizontal layers overlain by a dune that has realistic barchan dune topography and vertical velocity profile. The results show that the stacked sections of the

target reflection below the dune are enhanced compared to the stacked section produced by a conventional seismic data processing workflow.

ملخص الرسالة

الاسم الكامل: محمد عبد الحميد محمد بن جحلان

عنوان الرسالة: النهج القائم على اختلاف المنظر لإزالة آثار الكتلان الرملية من البيانات الاهتزازية

التخصص: الجيوفيزياء

تاريخ الدرجة العلمية: ديسمبر 2023

تعد إزالة الأجسام غير المرغوب فيه في الصورة الفوتوغرافية مشكلة صعبة في مجال معالجة الصور. حيث انه قد تم إجراء ابحاث كثيرة حول هذا الموضوع، مما أدى إلى اكتشاف العديد من الطرق لإزالة هذه الاجسام باستخدام صور مفردة أو متعددة كمدخلات. تستخدم إحدى هذه الأساليب ظاهرة اختلاف المنظر، والتي تستخدم صورًا متعددة للكشف عن الاجسام غير المرغوبة وإزالتها ثم يتم محاذاة مجموعة متسلسلة من الصور لملء المعلومات المفقودة بدقة في الصورة الأصلية عن طريق نقلها من تلك المجموعة من الصور الأخرى.

تتأثر البيانات السيزمية (الاهتزازية) التي يتم الحصول عليها في الصحاري نتيجة لوجود الكتلان الرملية، التي تغير زمن الوصول وسعة الموجات السيزمية التي خلال هذه الكتلان الرملية. بما انا التصوير الفوتوغرافي مشابه للتصوير باستخدام الموجات السيزمية لطبقات الارض العميقة، لقد قدمت أربعة أساليب مبنية على ظاهرة اختلاف المنظر لإزالة الآثار الضارة للكتلان الرملية على البيانات السيزمية. تتمثل الخطوات الرئيسية للنهج المقترح في ازالة جميع التسجيلات (البيانات) المتأثرة بالكتلان الرملية، وتسوية (محاذاة) الأحداث السيزمية عن طريق تعديل الزمن باستخدام فرق زمن الوصول الطبيعي، ثم ملء التسجيلات المزالة لكل نقطة عمق مشتركة إما عن طريق استبدالها بتسجيلات أخرى من نقطة عمق مشترك قريبة أو تسجيل مجمع. لقد تم اختبار هذه الطريقة على بيانات سيزمية اصطناعية مرنة ثنائية الأبعاد تم إنشاؤها من نموذج يتكون من طبقتين أفقيتين يعلوهما كتائب رملي. وقد أظهرت النتائج أن المقاطع السيزمية للانعكاس المستهدف أسفل الكتائب الرمي قد تم تحسينها مقارنة المقطع السيزمي الناتج عن طريق استخدام الطريقة التقليدية لمعالجة البيانات السيزمية.

CHAPTER 1

INTRODUCTION

Science develops rapidly every day. New innovative ideas are generated in every scientific field. Some ideas were developed uniquely within the same field, while others were created through cooperation from different fields, such as geophysics and photography. In this study, I have tried to borrow a well-established and successful approach to remove localized noise from an image and apply it to seismic data to produce a better subsurface image. This approach uses the parallax phenomenon to replace the information between a group of images taken from different positions. Before diving deeper into this approach, let us talk about the photography field first.

1.1 Parallax Phenomenon

In the photography field, many great ideas have been developed to solve different issues. One of these issues is removing an occlusion or unwanted reflection from an image. An occlusion can be an object, such as a streetlamp, that covers part of a scene behind it in the image. This is a well-known issue in the photography field that can be solved through different methods. Most of these methods divide the image into two layers: the first layer (background) consists of the scene or the target I want to preserve, and the second layer

consists of the occlusion (foreground) or the noise I wish to remove. The relationship between the background (L_b) and the foreground (L_f) layers of an image (I_{image}) can be written mathematically as:

$$I_{image} = L_b + L_f \quad (1.1)$$

The solutions used to remove an occlusion from an image can be divided into two types of methods depending on the needed input: single-image and multiple-image methods. The single-image methods utilize the information in the image itself to separate the background and foreground layers, hence removing the occlusion from the image. On the other hand, multiple-image methods utilize a sequence of images to separate the background and foreground layers from an image. In other words, the original image's missing information can be transferred or replaced from other images. The single-image and multiple-image methods will be discussed thoroughly in Chapter 2. This study focuses on parallax vision (Xue et al., 2015; Du et al., 2018; Liu et al., 2020), an approach in multiple-image methods to separate the background and foreground layers. The parallax phenomenon is known as the apparent change in the position of an object based on the position or the angle of the observation. By looking at a scene from different viewpoints, I notice that the occlusion (the object) covers different parts of the scene depending on the viewpoint. This means that the information hidden by an occlusion in one image can be obtained from the other images that have been taken from different viewpoints. By combining the images taken from different viewpoints of the same scene, I can reconstruct the scene and remove the occlusion (Figures 1). More detail on the parallax phenomenon and its application in seismic data will be shared in Chapters 2 and 3.

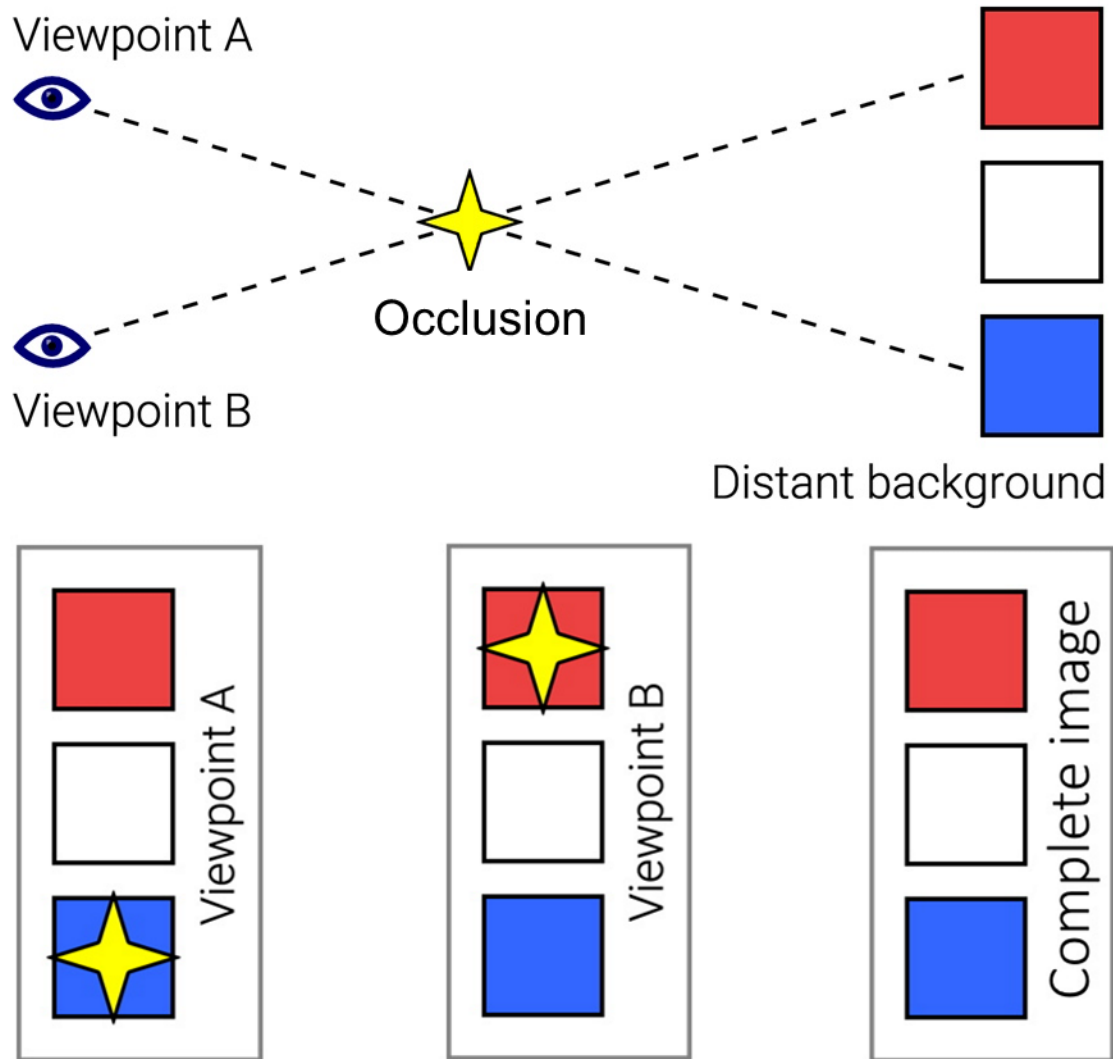


Figure 1: An explanation of the parallax phenomenon in photography: Looking at a distant background from different viewpoints A and B, the occlusion covers different parts of the background. The lower complete image is constructed by removing the blue box in viewpoint A and replacing it with the blue box from viewpoint B. (Modified after <https://en.wikipedia.org/wiki/Parallax>; Originally created by JustinWick in 2004 and was updated in 2021. This image is available under the Creative Commons Attribution-Share Alike License 3.0).

1.2 Parallax Seismic Analogy

1.2.1 The Seismic Challenge

The seismic method is a geophysical tool to image the subsurface. Like photography, seismic photography has many localized issues and noise, most of which are generated in the near-surface. One of the challenging localized issues of the seismic method is sand dunes. Sand dunes (Figures 2) are a geological feature formed in desert environments, such as the Rub Al-Khali Desert in the Kingdom of Saudi Arabia. The sand dune consists of unconsolidated sand and is usually separated by less rugged features such as sabkhas. Acquiring seismic data over a sand dune can lower the quality of the seismic image due to its severe effects on the seismic data. (Diallo & Chen, 2018) summarized the effects of sand dunes on seismic data as follows:

1. Time delays: Due to the sand dune's low velocity, the seismic wave will propagate more slowly inside the dune, delaying the seismic response.
2. Reverberation: The high contrast in the acoustic impedance between the dune and the underlying layer will make this boundary a multiple generator. Therefore, the seismic energy will be trapped within the dune as it bounces back and forth between its top and bottom boundaries.
3. Amplitude amplification: Another effect of the high contrast in acoustic impedance is amplifying the seismic energy under the dune. This produces an unbalanced seismic section, as the traces below the dune will have a higher amplitude than those away from the dune.

These effects are localized under the dune. In this case, the dune will behave as an occlusion in photographic images that masks and alters the signal reflected from the deep layers in the subsurface, preventing us from producing a high-resolution image of these targets. The current solutions to these three effects will be discussed thoroughly in Chapter 2.

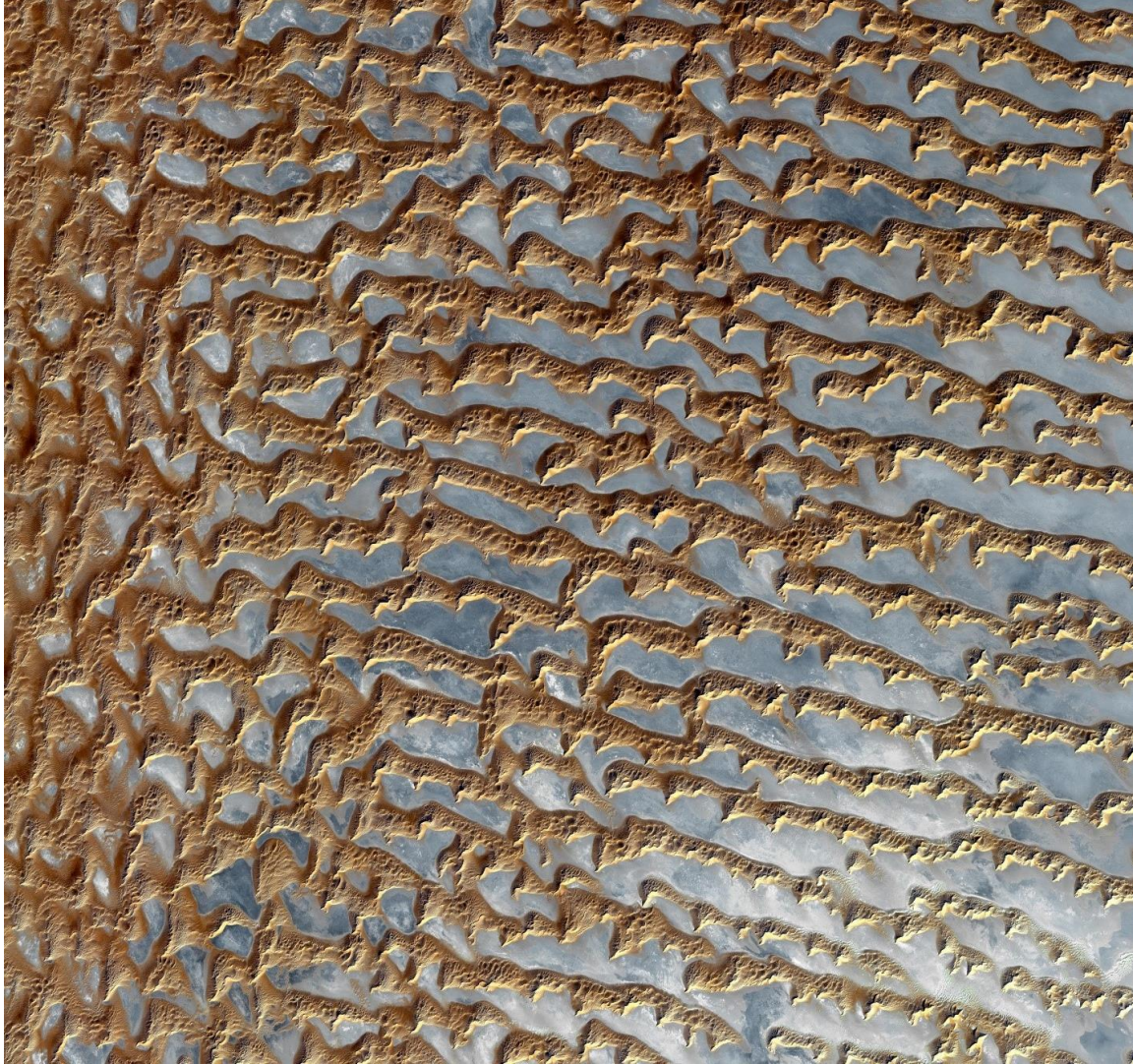


Figure 2: Shows an image of the abundant sand dunes in the Rub' al Khali Desert of the Kingdom of Saudi Arabia. Acquired by the Advanced Spaceborne Thermal Emission and Reflection Radiometer, or ASTER, aboard NASA's Terra Earth-orbiting satellite. (Created by NASA, 2005, https://en.wikipedia.org/wiki/Rub%27_al_Khali; from the public domain.).

1.2.2 Seismic Data Acquisition

Let us briefly introduce the seismic acquisition before linking the seismic with parallax phenomena. Acquiring seismic data requires having a seismic source and receiver. The seismic source emits seismic energy in the form of seismic waves. These waves propagate into the subsurface. Once they hit any boundary between two layers, they will be refracted, reflected, diffracted, and transmuted to the next layer. In the end, the seismic waves will be reflected to the surface, where they will be detected by the receivers and recorded in the recorder. Every receiver represents one seismic trace. There are many types of seismic sources, such as vibroseis, airgun, dynamite, weight-drop, and hammer. Similarly, there are many types of receivers, such as geophones and hydrophones. Selecting the source and the receiver depends on the location, the target, and the allocated budget of the seismic acquisition. The seismic data can be sorted and viewed in many domains, such as shot, receiver, offset, and CDP domains (Figures 3). Each domain has advantages in processing, visualizing, and QCing the seismic data. This study focuses mainly on the CDP domain (the common midpoint gather), as this domain images the same point in the subsurface through multiple source-receiver pairs placed in different locations on the surface. The (Chaouch & Mari, 2006) paper gives more details on the 3D land seismic data acquisition.

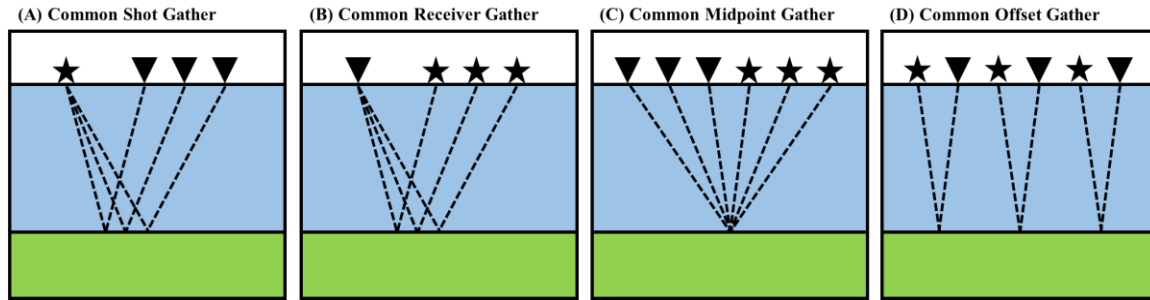
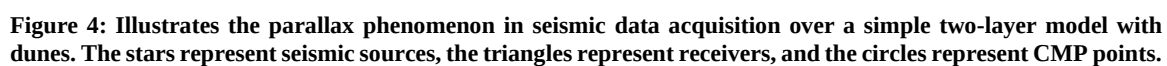


Figure 3: shows different source and receiver configurations. (A) Common shot gather, (B) common receiver gather, (C) common midpoint gather, and (D) common offset gather. The stars represent seismic sources, and the triangles represent receivers.



1.2.3 The Implantation and The Objective of This Study

The sources and receivers of any seismic survey should cover the entire study area based on the acquisition parameters. This includes locating the sources and receivers on challenging terrains such as sand dunes. Let us look at (Figures 4) the simple two-layer model with a sand dune on top. If I aim to image the boundary between the two layers (target or background), our challenge (occlusion or foreground) will be the sand dune. As stated earlier, acquiring seismic data over a dune will produce noisy traces below it, while acquiring seismic data over a flat homogenous layer should produce clean traces. Therefore, the three source-receiver pairs in this figure produce three traces from CMP₂. The (S_1R_1 and S_2R_2) source-receiver pairs are outside the dune, so they should produce clean traces with the information I want (the background). On the other hand, the (S_3R_3) source-receiver pair is located on top of the dune, so it should produce a noisy trace as the dune's noise masks the information I want (the foreground). In this sense, the parallax approach can be implemented in seismic data by removing the traces affected by the dune and replacing them with the other traces outside the dune. More detail is given in Chapter 3.

The objective of this study was to apply and evaluate the proposed parallax approach on 2D synthetic seismic data generated from a two-layer model with a sand dune on top of it.

CHAPTER 2

LITERATURE REVIEW

2.1 Occlusion Removal Methods in Photography

As stated in Chapter 1, this study focuses on removing the localized noise in the seismic data generated from the near-surface due to the presence of sand dunes by applying a parallax-based approach to the seismic data. Removing an occlusion from an image is a well-known issue in photography, and many methods have been developed to successfully remove an occlusion or an unwanted reflection from an image. Generally, the object removal methods in photography can be categorized into two groups based on the inputs: single-image methods and multiple-image methods. This chapter gives an overview of some of these methods.

2.1.1 Single-Image Methods

The single-image methods separate the background and foreground layers by using the information in the image itself. Many methods were developed under this category, such as the (Shih et al., 2015) approach, which takes advantage of a double reflection layer to remove it from the image. Other approaches assume that the target or background layer is in focus while the foreground layer is not (Li & Brown, 2014; Wan et al., 2016). A semiautomatic approach (Springer & Weiss, 2017) relies on users manually labeling the two layers to guide an optimization-based layer separation algorithm. The single-image methods improve quickly, yet removing an occlusion from a single image remains an ill-posed problem. Note that this category is out of the scope of this study.

2.1.2 Multiple-Image Methods

Multiple-image methods use a sequence of images to separate the background and foreground layers from an image. This can be done by transferring and replacing the information from different images of the same scene into the original image. Many methods have been developed under this category. Some methods in this category rely on linear relationships to separate the two layers (Sarel & Irani, 2004; Diamantaras & Papadimitriou, 2005). Other methods use motion cues (Bhavsar & Rajagopalan, 2010; Li & Brown, 2013; Han & Sim, 2017). Moreover, parallax vision (Xue et al., 2015; Du et al., 2018; Liu et al., 2020) was used to separate the two layers and then identify and remove the occlusion. This study is focused on the parallax vision approach of multiple-image methods to remove the effect of sand dunes on seismic data.

2.2 Removing the Effects of Sand Dunes in Seismic Data

The effect of sand dunes on seismic data can be summarized as time delay, reverberation, and amplitude amplification. There are some solutions to remove these adverse effects from seismic data. Time delays can be removed by applying specialized static correction methods such as those employing the sand curve of Saudi Aramco (Robinson & Al-Husseini, 1982). On the other hand, the reverberation and amplitude amplification of sand dunes can be suppressed using various surface-consistent methods (Cambois & Stoffa, 1992; Taner & Koehler, 1981; Cary & Lorentz, 1992). A more recent solution (Al-Marzooq et al., 2019) applies a spectral ratio technique based on a deterministic approach to sources and receivers placed on sand dunes rather than on sabkhas. Another solution (Colombo et al., 2020) applies a combination of both amplitude scalar correction and deconvolution using refraction waveforms.

CHAPTER 3

METHODOLOGY

3.1 Seismic Data

To test and evaluate the proposed parallax-based approaches, they must be applied to seismic data, and then the results before and after applying them must be compared. Therefore, I allocated two datasets for this study (synthetic and real datasets). The synthetic data were generated from a model composed of two horizontal layers overlain by a dune. The real data were acquired over a sand dune in the Eastern Province of the Kingdom of Saudi Arabia over a sand dune that is near the Dammam Airport. Unfortunately, after processing the real seismic data, I found that it is not suitable for this study, as it has no reflection events. The objective of this study is to improve the resolution of the subsurface layer by applying the parallax-based approach. Therefore, I cannot apply this method to real seismic data. For the synthetic seismic data, I applied a general 2D processing workflow and used the results as a benchmark. More details on how the synthetic seismic data were generated and processed are presented in this chapter. Then, I applied the parallax-based approaches to the synthetic data. Last, I evaluated the parallax-based approach results and then compared them with the results generated without applying the parallax-based approaches. The parallax-based approach steps are presented in this chapter, while their results are presented in Chapter 4.

3.1.1 Synthetic Data

The synthetic data were generated using a 2D elastic model of two layers and a sand dune on top (Figures 5). The length of this model is 10 km, and the sand dune is between 2 and 3 km. The source spacing is 20 m, and the receiver spacing is 1 m. The sources and receivers were located at $H = 15$ m below the surface to avoid the adverse effects of surface-related ghost reflections. The acquisition geometry is illustrated in Figures 6. The dune exhibits the following P-wave velocity-depth function $v(z)$:

$$V(z) = v_0 \sqrt{1 + kz^{1/3}} \quad (2)$$

where z is the depth of the dune's surface, the surface P-wave velocity $v_0 = 15$ m/s, and the velocity-depth gradient $k = 1500 \text{ m}^{-1/3}$ are constants selected for a typical quartz-rich, almost dry sand dune (Al-Shuhail, 2006). For simulation purposes, the minimum P-wave velocity is assumed to equal the average P-wave velocity from the dune's surface to the source and receiver depth (H). It is calculated by dividing the depth of the source and receiver by the vertical one-way time from the surface to this depth. Based on equation (3), the one-way time is equal to 0.0197 s (Al-Shuhail et al., 2018) and the calculated minimum P-wave velocity is approximately 761 m/s, rounded down to 700 m/s. Assuming the S-wave velocity is half the P-wave velocity in general (Thomsen, 1986), the corresponding minimum S-wave velocity will be 350 m/s.

$$T = \frac{2 \left[-8 + \sqrt{1 + H^{1/3}k} (8 - 4H^{1/3}k + 3H^{2/3}k^2) \right]}{5k^3v_0} \quad (3)$$

The maximum usable frequency is when the amplitude spectrum value becomes less than 1% of its value at the peak frequency (Thorbecke, 2016). A zero-phase Ricker wavelet (Figures 7) was used for the simulation with a peak frequency of 10 Hz and a maximum frequency of 25 Hz. The simulation accuracy condition requires at least five grid cells per wavelength (Thorbecke, 2016). Using the minimum model velocity and maximum usable frequency, the grid cell size becomes 2.8 m, rounded to 2.5 m along the X and Z axes. To meet the requirement of the Courant-Fredricks-Levy stability criterion, the simulation time step was calculated from the grid size and the maximum model velocity, and it is equal to 0.000355 s. It was rounded to 0.0003 s (Thorbecke, 2016). Tables 1, 2, and 3 summarize the parameters of the velocity model, simulation, and acquisition geometry.

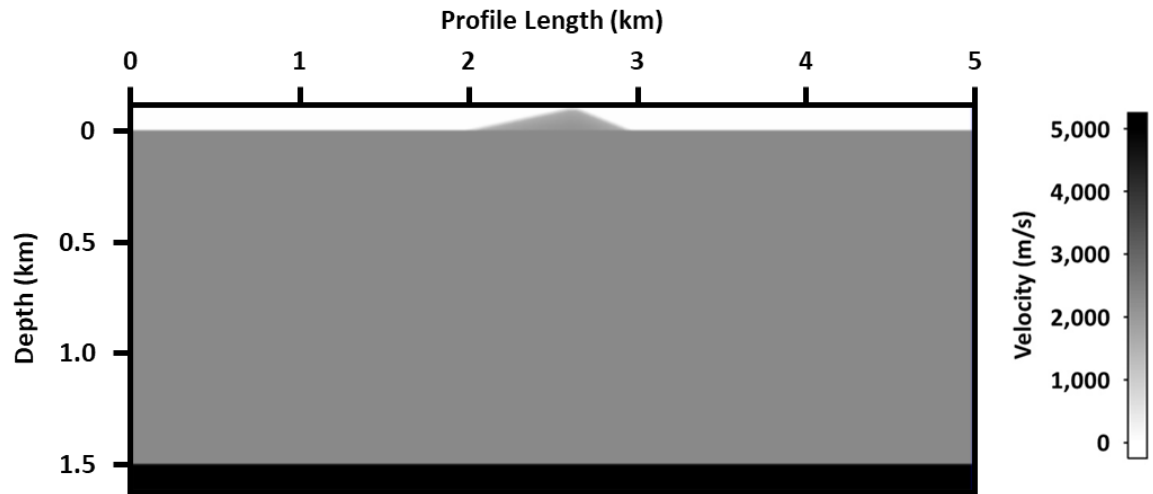


Figure 5: A schematic shows the two-layer velocity model used to generate the synthetic data.



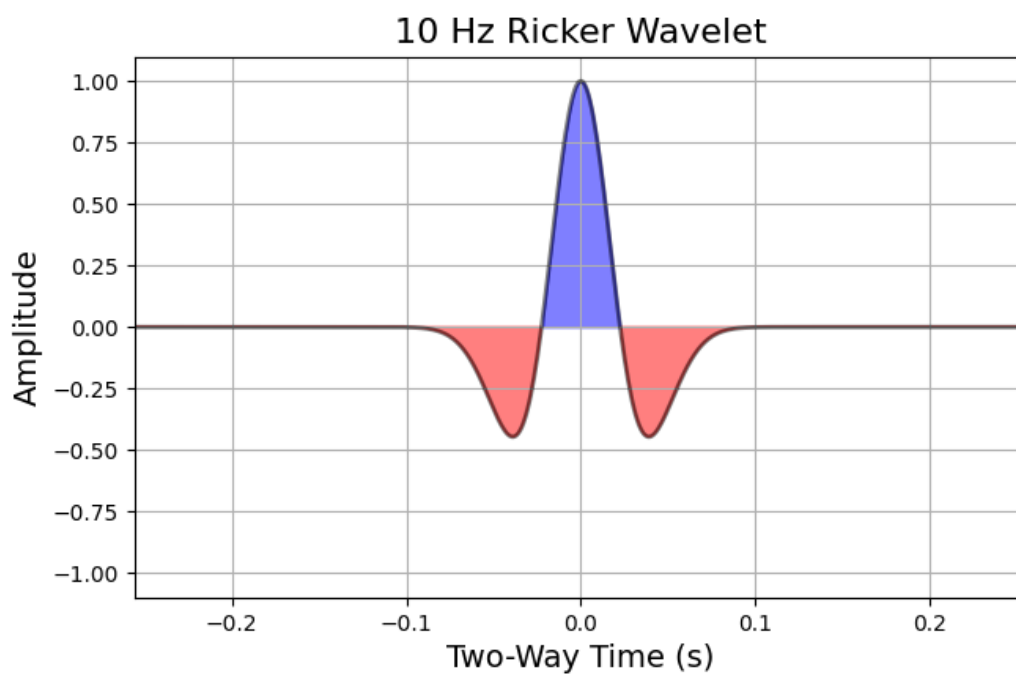


Figure 7: A 10 Hz Ricker wavelet used in generating the synthetic seismic data.

Table 3.1 Layer parameters of the synthetic data

Layers	V_P (m/s)	V_S (m/s)	Density (kg/m³)	Depth Range (m)
Layer-0 (Sand Dune)	15-1252	7.5-626	2000	0 to +100
Layer-1	3000	1500	2000	0 to -1500
Layer-2	5000	2500	2000	-1500 to -1600

Table 3.2 Simulation parameters of the synthetic data

Parameter	Value
Spatial sampling	$dx = dz = 2.5 \text{ m}$
Temporal sampling	$dt = 0.0003 \text{ s}$
Minimum velocity	$v_{\min} = 350 \text{ m/s}$
Maximum velocity	$v_{\max} = 5000 \text{ m/s}$
Maximum frequency	$f_{\max} = 25 \text{ Hz}$

Table 3.3 Acquisition parameters of the synthetic data

Parameter	Value
Receiver spacing	1 m
Shot spacing	20 m
Receiver depth	-15 m
Shot depth	-15 m
Number of receivers	5001
Number of shots	251
Minimum offset	-5000 m
Maximum offset	5000 m
Source wavelet	Zero-phase Ricker with 10 Hz peak frequency
Recording time	2.5 s
Sampling interval	2.1 ms

3.2 Processing Workflow

The synthetic seismic data were processed using a general 2D land seismic data processing workflow. This processing workflow consists of the following steps (Figures 8):

1. Gain application using automatic gain control (AGC) with a window = 0.1 s to boost the amplitude of the raw shot gathers.
2. Frequency-wavenumber (F-K) filtering to remove prominent linear events that have velocities below 1500 m/s.
3. Spiking deconvolution using a prediction lag = 2.1 ms, operator length = 0.125 s, prewhitening noise = 0.1%, and an autocorrelation window = 0 – 2.5 s to improve the resolution and sharpen the seismic wavelet.
4. CDP sorting to convert the data from the shot domain to the CDP domain.
5. Normal-moveout correction (NMO) with a velocity function was used to generate the synthetic data (i.e., $V_{\text{NMO}} = 3000$ m/s and $T_0 = 1.0$ s). This step is equivalent to the alignment step in parallax-based multiple-image processing methods.
6. Static correction was used to remove the variable elevation and the velocity effects within the dune location at distances between 2000 and 3000 m. This step was not applied to the parallax-based approach data because all the traces affected by the dune were muted.
7. CDP stacking by using the straight mean stacking technique (Sheriff and Geldart, 1995). There are many stacking techniques (Rashed, M., & Nakagawa, K., 2006),

and some of these techniques have been reviewed. This step is equivalent to the summation step in the parallax-based multiple-image processing methods.

8. Post-stack enhancement using a mild F-K filter to remove the artifact linear noise in the stack section.

The results of this workflow will be a reference point, as they show the effect of the sand dune and will be used to evaluate the parallax-based approaches. Note that this processing workflow has no migration step as the target reflector is horizontal, and I do not expect any improvement on the final stacked section. The three main parallax steps are muting, NMO correction (alignment), replacing, and stacking (summing). Note that the muting and replacing steps should be applied before the CDP stacking step. In this study, I used Seismic Un*x (Cohen and Stockwell, 2023) and MATLAB with the SeisLab package (Rietsch, 2023) to process and visualize the seismic data.

Processing Workflow

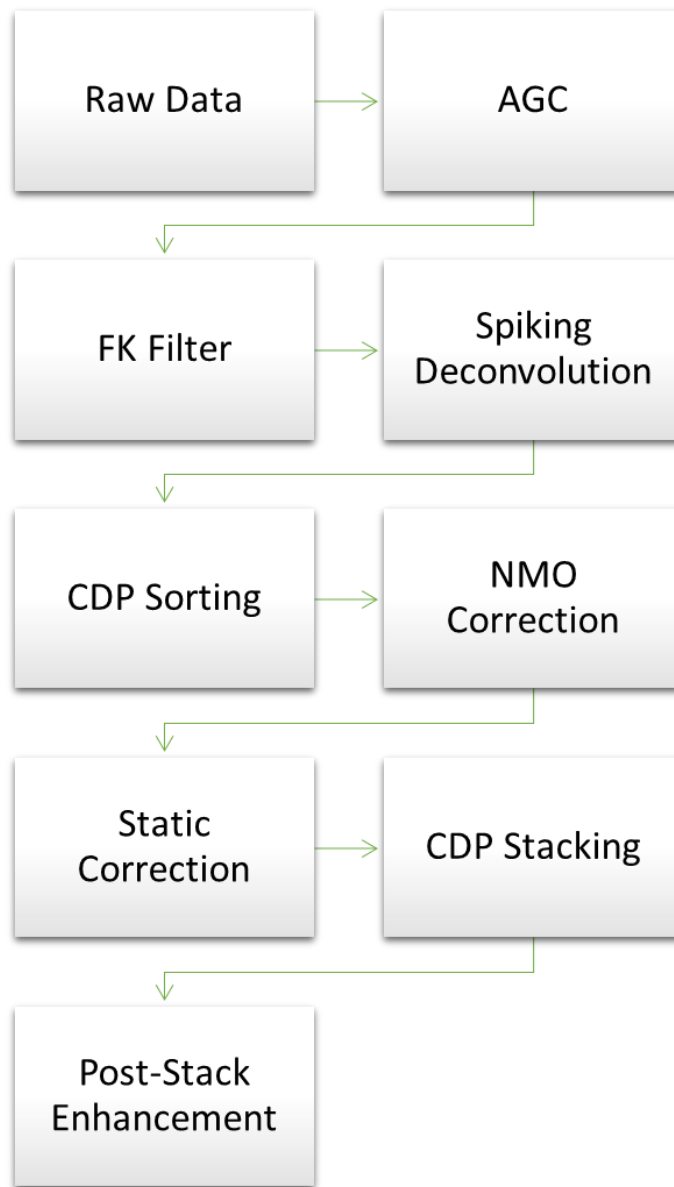


Figure 8: A general 2D land seismic data processing workflow used to process the 2D synthetic data.

3.3 Parallax-Based Approaches

The idea of parallax in photography (Figures 9) is to remove the affected pixels by the occlusion of an image and replace them with other pixels from the other images (You, Shaodi, et al., 2014). With the assumption that the image is divided into the background layer, which is our target, and the foreground layer, which is the occlusion, which is the noise. This can be achieved by removing the affected parts of the images, aligning the images, and replacing the affected pixels with other pixels from other images or summing all the aligned images. Note that the removed pixels will be replaced in the summing step. Each parallax step has an equivalent in the seismic data processing. Removing the affected pixels is equivalent to muting the noisy traces affected by the sand dune. This muting step includes all the traces generated from the sources or received from the receivers above the dune. Aligning the images is equivalent to the NMO correction, as it flattens the primary events. Summing the images is equal to CDP stacking. Every trace in a CDP can be considered an image by itself, as they are reflected from the same point in the subsurface but generated from different source-receiver pair offsets. Therefore, the missing information can be obtained from the traces within the CDP through stacking it. Hence, this concept can be applied to seismic data. Based on this analogy, I have introduced, tested, and evaluated four different approaches to implement the parallax concept to remove the sand dune effects on the seismic data in this study.

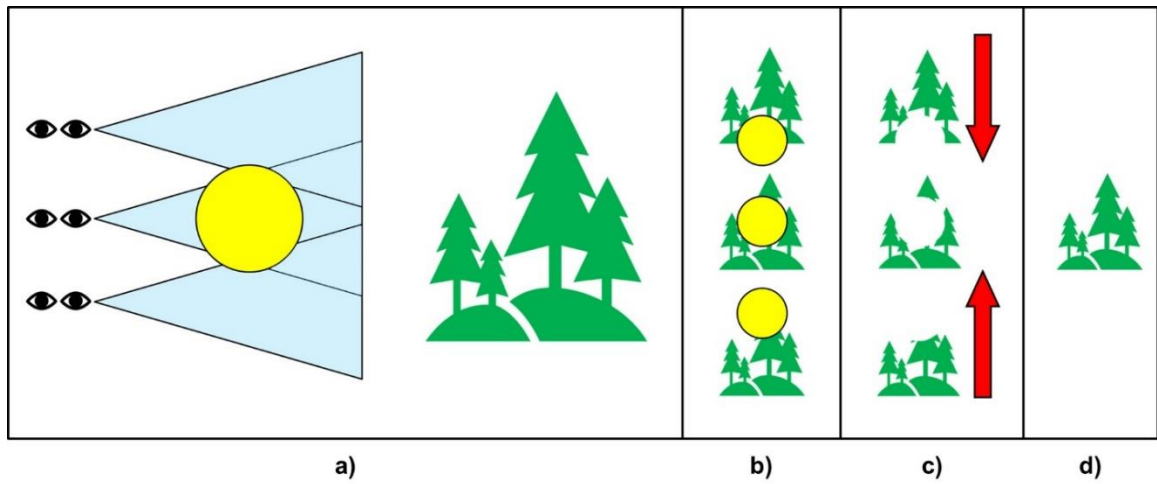


Figure 9: A schematic shows parallax steps in photography. a) shows a scene captured from three locations where an obstacle blocks part of the scene. b) The three images of the scene; note that the location of the obstacle is changed in each image. c) the parallax steps, removing, alignment, and summing of the images. d) The results after applying parallax steps.

3.3.1 Approach One

This is the first and simplest approach to apply the parallax-based method to seismic data, and it is the basis of all proposed approaches in this study. It consists of three steps: muting, NMO correction, and CDP stacking. In the muting step, all the traces that were affected by the sand dune will be removed. This includes all the traces generated or received from a source or receiver located above the dune. Then, the NMO correction is applied to flatten the seismic events. Note that this step can be performed before or after muting. Last step is to stack the remaining CDP traces. As there are muted traces in these CDPs, I tested two methods of straight mean stacking. First, the mean of the total traces, including the muted and unmuted traces, was taken. Second, the mean of only the fold number (the unmuted traces) was taken. The results of this approach are presented in Chapter 4.

3.3.2 Approach Two

This approach consists of five steps:

- a. muting,
- b. NMO correction,
- c. CDP stacking the unmuted traces,
- d. replacing the muted traces with the stacked trace generated from the unmuted traces of the CDP itself, and
- e. stacking the filled CDP.

The first three steps are the same as approach one, while steps 4 and 5 are extra. The results of this approach are presented in Chapter 4.

3.3.3 Approach Three

This approach consists of four steps:

- a. muting,
- b. NMO correction,
- c. trace replacement, and
- d. CDP stacking.

Therefore, after muting the affected traces by the sand dune and flattening the CDP gathers, the muted traces will be replaced with other traces from the adjacent CDPs that share the same offset or the same sequence number (Figures 10). This will fill the gap in the CDP. Last step is to stack the filled CDP. The replacement step here was performed by scanning all the CDPs that had at least one trace that was affected by the sand dune. Then, flag the muted traces and replace them with other traces that have the same offset from the adjacent CDPs (Figures 10).

The dataset has 5001 CDPs where 3001 CDPs of them were affected by the dune. These 3001 CDPs are located between 1000 to 4000 m and they have at least one trace that was generated from a source or a receiver located on the dune. The trace replacement method will scan all of these 3001 CDPs first and flag their muted traces. Then, for each muted trace the code will scan the 3001 CDPs searching for the first available trace that has the same offset or the trace sequence number, this trace should be the nearest possible trace. Once the code finds a trace that met these criteria for that muted trace then it will be used

to replace the muted trace. This process will be done for each muted trace. Note that, each trace can be used for replacement only once. In case where the code cannot find a trace that met the replacement criteria or if all the possible traces were used in previous replacements, then there will be no replacement and that muted trace will not be replaced. If we look at (Figure 11) we can see CMP 1000 (on the left) is donating traces to CMP 1200 (in the middle), the highlighted traces by the yellow dashed boxes in CMP 1000 are used to replace the muted traces in CMP 1200 (on the right).

The replacement step requires having the same number of traces for all the CDPs. Unfortunately, the number of the traces of the CDPs in our data is not fixed. Therefore, I used the `imresize()` function in MATLAB to increase the number of traces for all the CDPs that had muted traces to match the CDP that had the maximum number of traces. Now, I can apply the replacement step in the resized CDPs. After the completion of the replacement step, I reused the `imresize()` function to decrease the number of traces for all the resized CDPs to their original number of traces. To avoid artifacts due to the resizing process, I took only the replaced traces from these new CDPs and used them to fill the muted traces of the original CDPs. Now, the muted traces in the original CDPs are filled by traces from the adjacent CDPs. Then, I can generate a stack section from these CDPs. Note that the resizing step is only needed if the number of traces of the CDPs is not fixed. The results of this approach are presented in Chapter 4.

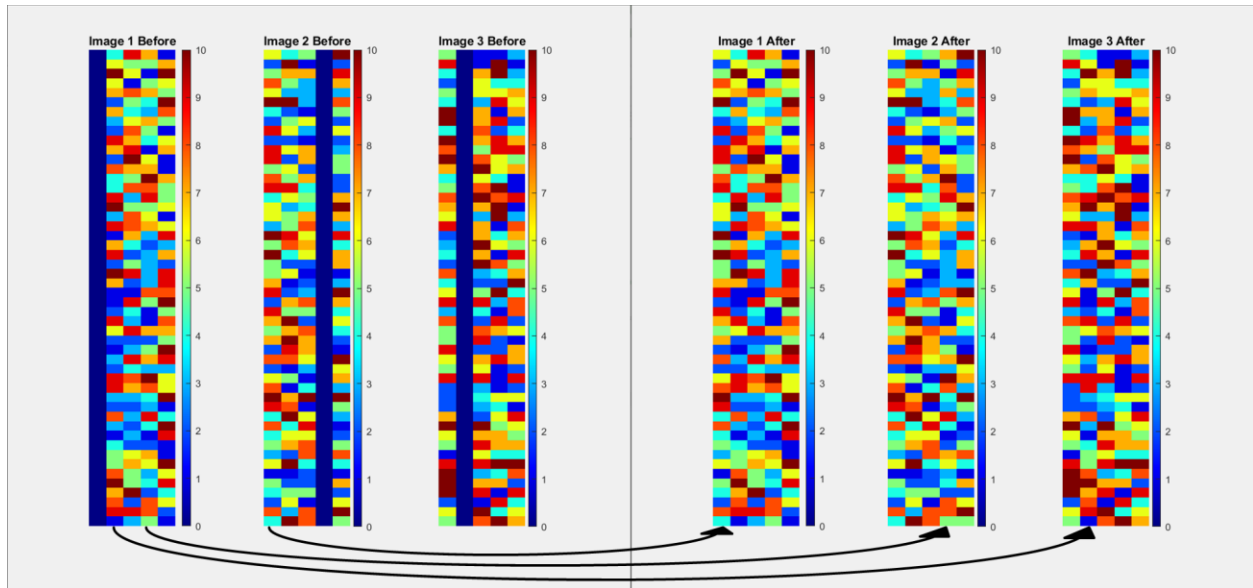


Figure 10: A schematic shows three images before and after applying the replacement step of the third parallax approach. The black arrows represent the movement of the traces before and after replacement.

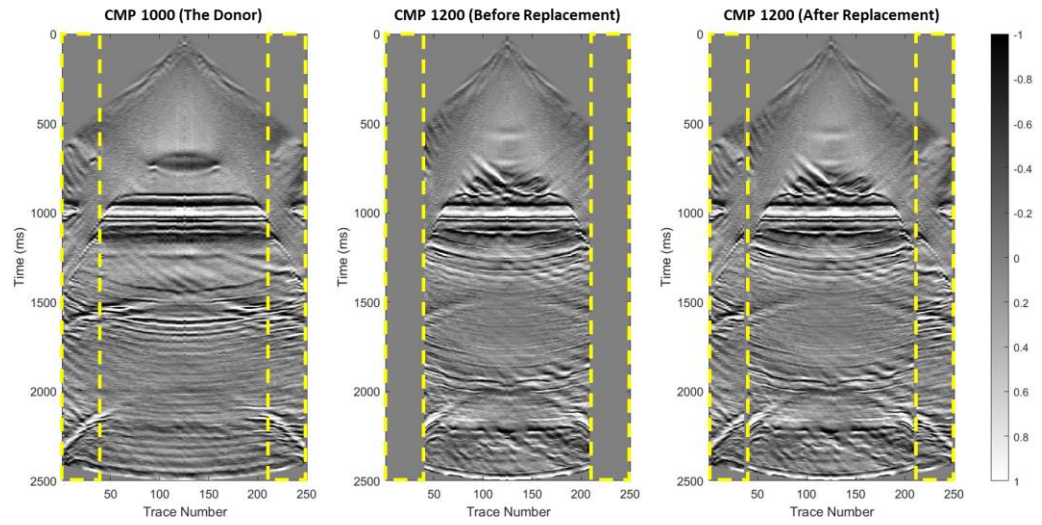


Figure 11: CMP 1000 is the donor for CMP 1200, the highlighted traces by the yellow dashed box in CMP 1000 are used to replace the muted traces (highlighted by the dashed yellow boxes) in CMP 1200.

3.3.4 Approach Four

This approach consists of five steps:

- a. muting,
- b. NMO correction,
- c. creating a supergather,
- d. trace replacement, and
- e. CDP stacking.

Therefore, after muting the affected traces by the sand dune and flattening the CDP gathers, I will create a supergather by stacking all the CDPs that have at least one trace that is affected by the sand dune. Because the number of the traces of the CDPs in my data is not fixed, I had to resize all the CDPs that were affected by the sand dune by using the `imresize()` function in MATLAB. Like approach three, I increase the number of traces in all the CDPs to match the number of traces in the CDP that have the maximum number of traces. Note that the supergather will act as the background layer that I want to preserve. Now, replace the muted traces in the resized CDPs with other traces from the supergather. After the completion of the replacement step, I reused the `imresize()` function to decrease the number of traces for all the resized CDPs to their original number of traces. To avoid artifacts due to the resizing process, I took only the replaced traces from these new CDPs and used them to fill the muted traces of the original CDPs. Now, the muted traces in the original CDPs are filled by traces from the supergather. Then, I can generate a stack section

from these CDPs. Note that the resizing step is only needed if the number of traces of the CDPs is not fixed. The results of this approach are presented in Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Processing Workflow Results

The linear noise dominates the raw synthetic data, while the primary events are weak (Figures 12). Therefore, the first step in processing these data was to boost the amplitude by applying automatic gain control (AGC) with a window of 100 ms (Figures 13). After applying AGC, the amplitude of the seismic data becomes homogenous and balanced, which makes seismic events appear. The seismic events in these data are the first arrival (direct wave), the P-wave primary reflection observed at 1 s, the PS-wave primary reflection observed at 1.5 s, the S-wave primary reflection observed at 2 s, and the multiple P-waves observed at 2 s. The linear noise is still present, and the effect of the sand dune (time delay and the amplification of the amplitude) on the traces below it between 2000 and 3000 distances is clear. Additionally, the linear noise generated from the sand dune affects the traces away from it, as shown in (Figures 13). To remove linear noise, an F-K filter was applied to these data. The F-K filter removed most of the linear noise with a velocity below 1500 m/s. This filter did not remove the effect of the sand dune on the traces under it (Figures 14). To improve the resolution, spiking deconvolution with a prediction lag = 2.1 ms, operator length = 0.125 s, prewhitening noise = 0.1%, and an autocorrelation window = 0 – 2.5 s was applied to these data. Now, the seismic events are sharper, yet the effect of the sand dune is still present in the data (Figures 15).

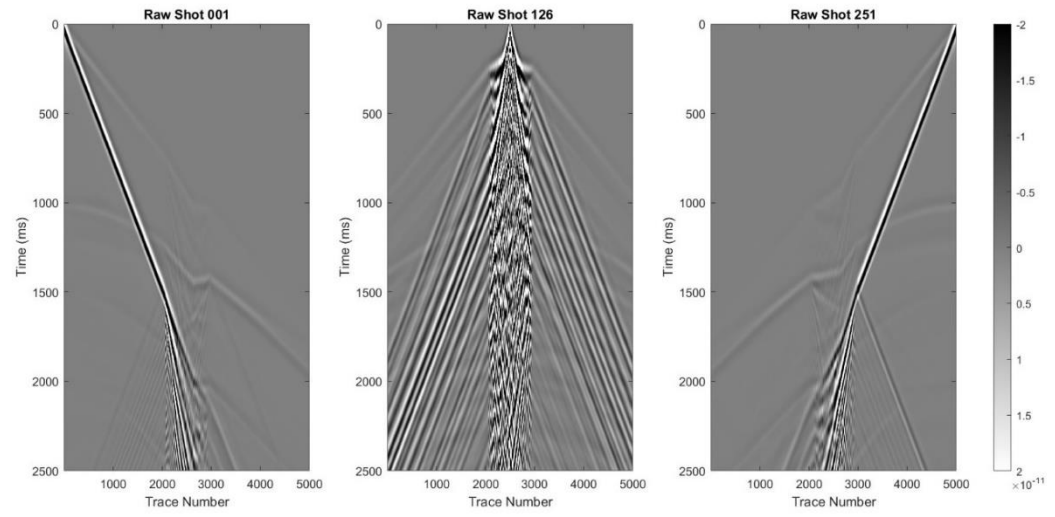


Figure 12: Three raw shot gathers. Shot001 is located at 0 m, shot126 at 2500 m, and shot251 at 5000 m.

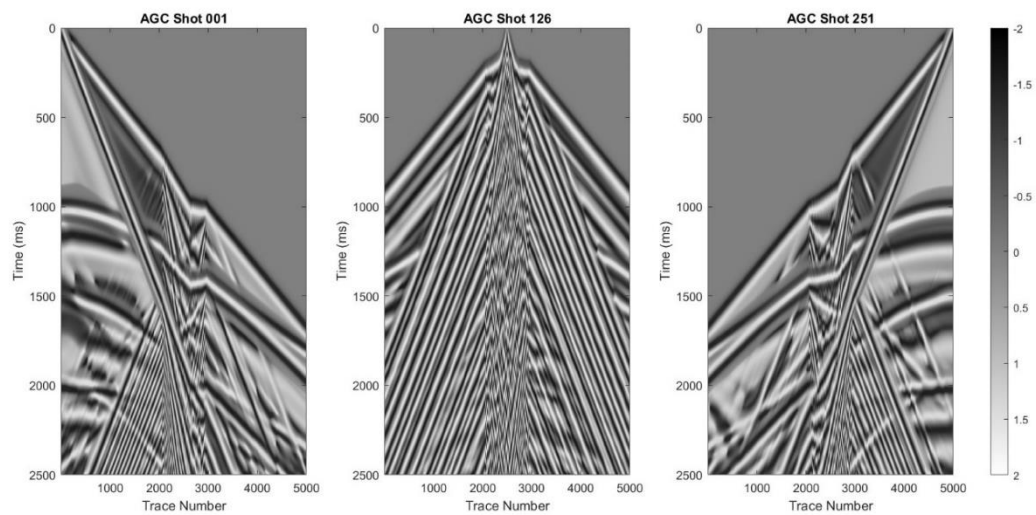


Figure 13: Three shot gathers after applying AGC only. Shot001 is located at 0 m, shot126 at 2500 m, and shot251 at 5000 m. The effect of the sand dune is clear at distances between 2,000 and 3,000 m.

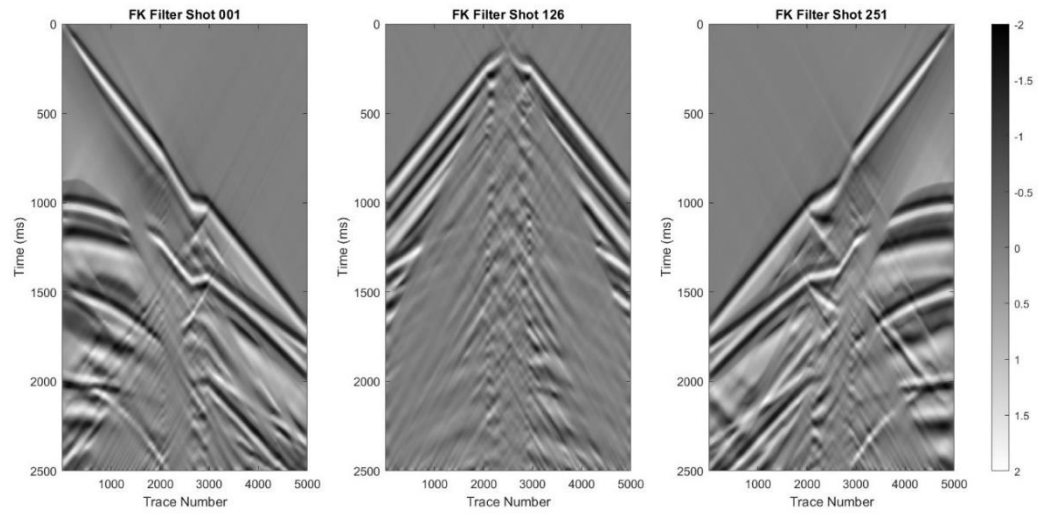


Figure 14: Three shot gathers after applying the AGC and F-K filters. Shot001 is located at 0 m, shot126 at 2500 m, and shot251 at 5000 m. Much of the liner noise was removed, yet the effect of the sand dune is still clear.

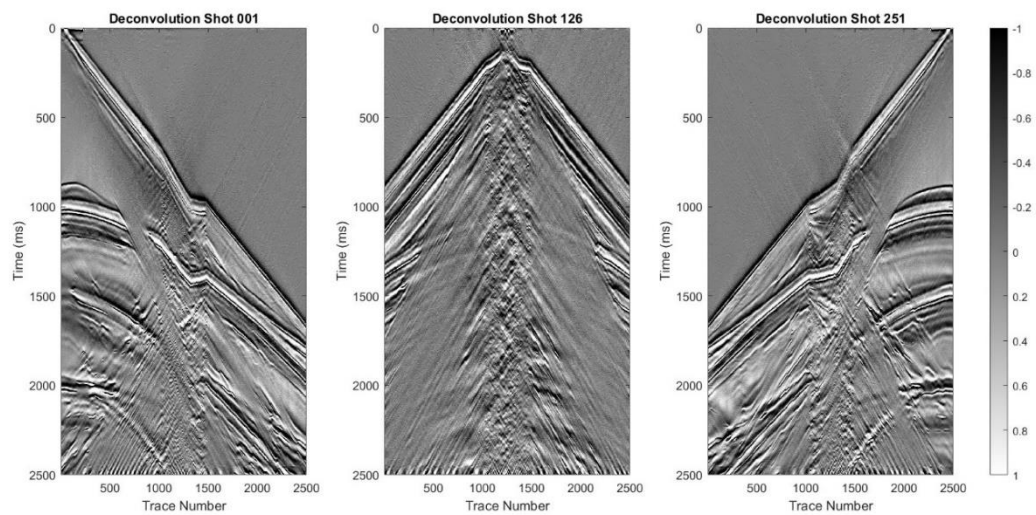


Figure 15: Three shot gathers after applying AGC, F-K filter, and deconvolution. Shot001 is located at 0 m, shot126 at 2500 m, and shot251 at 5000 m. The events became sharper after applying the speckle deconvolution.

After that, these data are sorted to the CDP domain, which represents all the traces that are reflected from the same point in the subsurface (Figures 16). Then, the NMO correction was applied to these data using a velocity function of $T_0 = 1$ s and $V_{\text{nmo}} = 3000$ m/s. This flattened the P-wave primary reflection observed at 1 s, as shown in (Figures 17). However, the area under the sand dune is unflattened due to the time delay caused by the sand dune. To account for the time delay issue, static correction was applied to these data (Figures 18). This step partially compensates for the time delay caused by the sand dune, as some traces are still affected by the sand dune. To enhance the signal-to-noise ratio further, the CDP stack was performed on these data, which generated the stack section (Figures 19). The primary P-wave reflection is well illuminated away from the sand dune, and it becomes dimmer under the sand dune. All the noisy traces in all the CDPs were included in the stacking process, which reduced the quality of the stack section away from the sand dune boundary. The sand dune is located between 2000 and 3000 m, while the affected traces are between 1000 and 4000 m. After stacking, there was an artifact liner noise, which was removed by applying a mild F-K filter. This filter did not affect the primary P-wave reflection, as shown in the difference section (Figures 19).

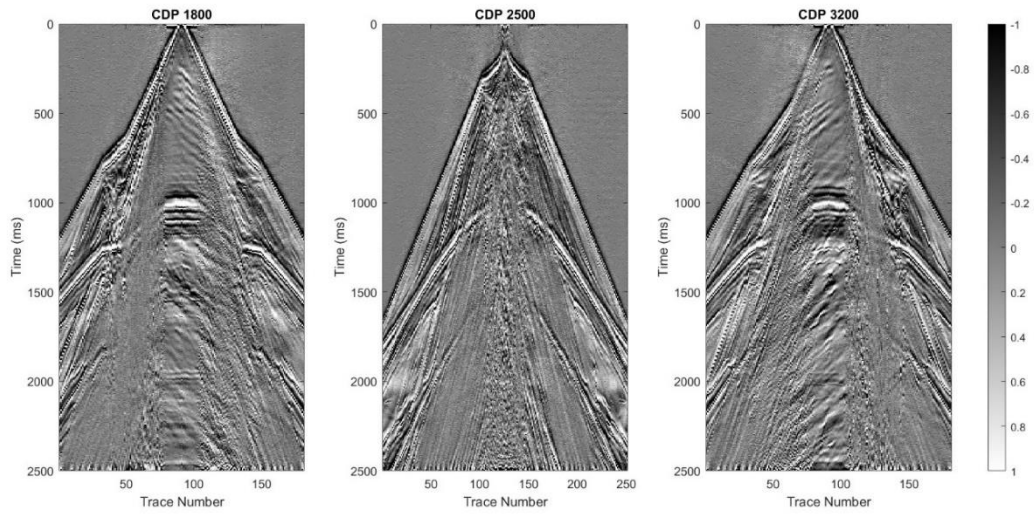


Figure 16: Three CDP gathers after sorting to CDP domain application. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m.

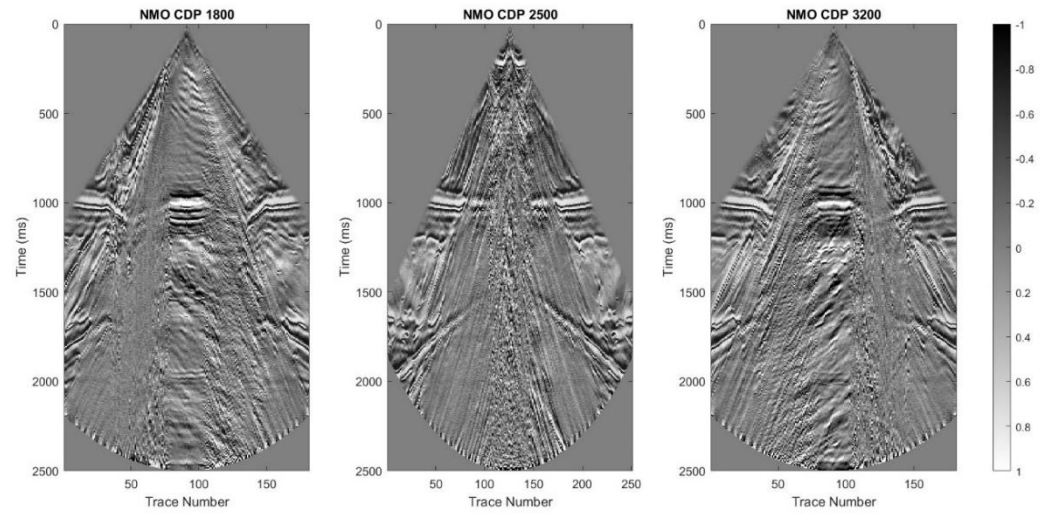


Figure 17: Three CDP gathers after applying NMO correction. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m. The events become flatter except for the area under the sand dune.

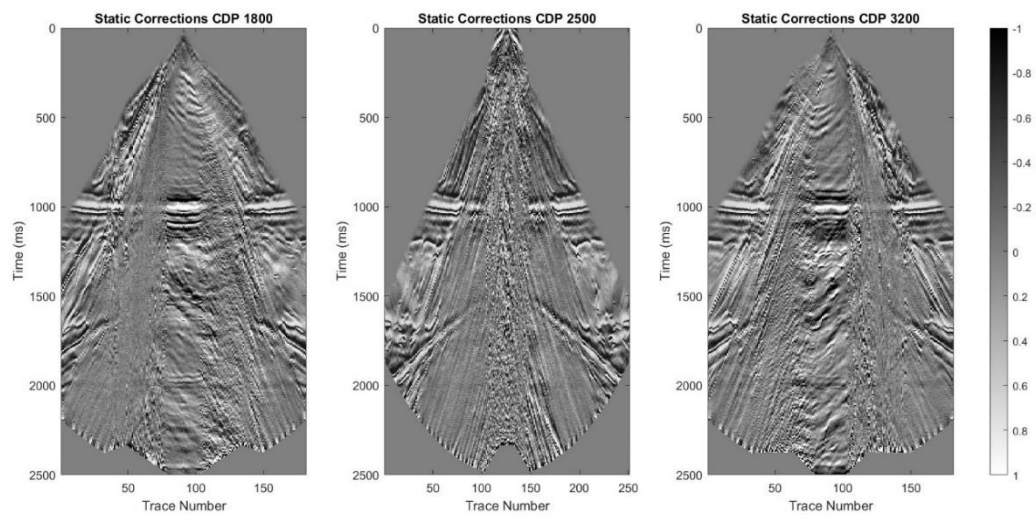


Figure 18: Three CDP gathers after applying NMO and static corrections. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m. The events away from the sand dune become flatter, and some of the area under the sand dune is corrected. However, the effect of the sand dune is still clear.

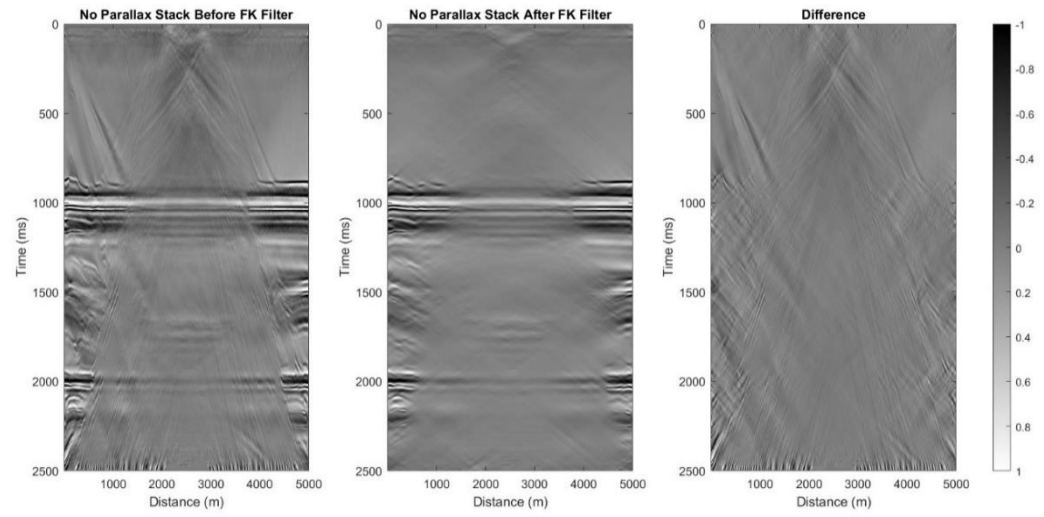


Figure 19: The stack data without parallax approach before and after applying the F-K filter.

4.2 Parallax Approaches Results

4.2.1 Results of Approach One

The proposed parallax-based approach consists of muting the noisy traces, flattening the seismic events by applying NMO correction, and finally summing or stacking the CDPs to solve the localized near-surface issue. In these data, the sand dune affects the traces that are generated or received from the sources or the receivers that are located on the sand dune. Therefore, these noisy traces were muted (Figures 20) before the CDP stacking step. Note that the NMO correction or the flattening step can be performed before muting, as I did in this case. The last step is summing the images or the CDP stacking. In seismic processing, there are many ways to stack CDPs. In this study, I am using straight mean stacking, which is the conventional stacking technique in seismic data processing that can be implemented in two ways. The first one (Figures 21), is by taking the mean of the total traces, including the muted and unmuted traces. The second one (Figures 22) is to take the mean of the fold number (the unmuted traces). I applied the mild F-K filter to remove the artifact liner noise on both stacks, and it did not affect the primary P-wave reflection. Stacking the CDP by taking the mean of the fold number produces a stack section as it illuminates the traces under the sand dune, as shown in (Figures 23), where the difference is only in the amplitude. I have compared the stack sections before and after applying the parallax-based approach. There is a slight improvement in the continuity of the P-wave primary reflection using a parallax-based approach that stacked the CDPs based on the total traces (Figures 24). However, stacking the CDP based on the fold number showed better results as the events were more illuminated (Figures 25).

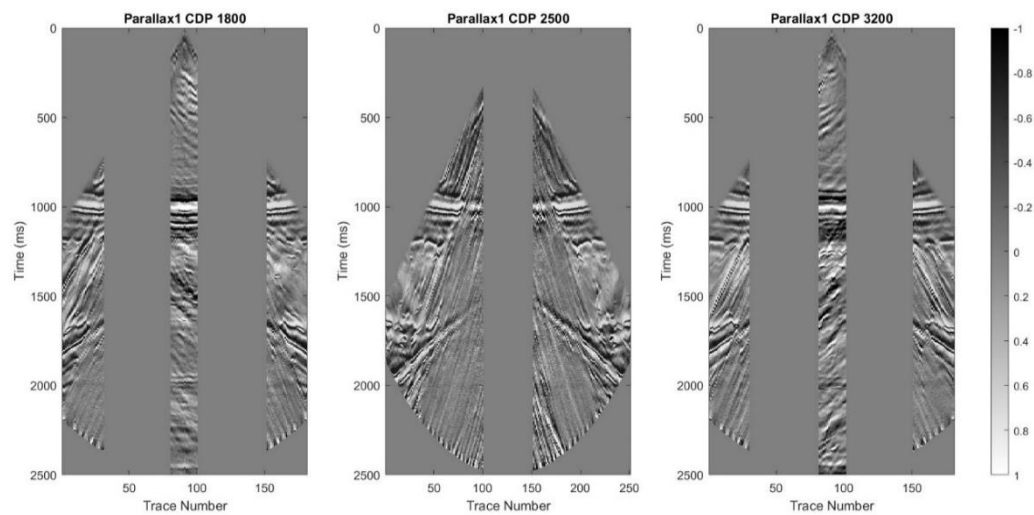


Figure 20: Three CDP gathers after applying the Parallax 1 approach. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m.

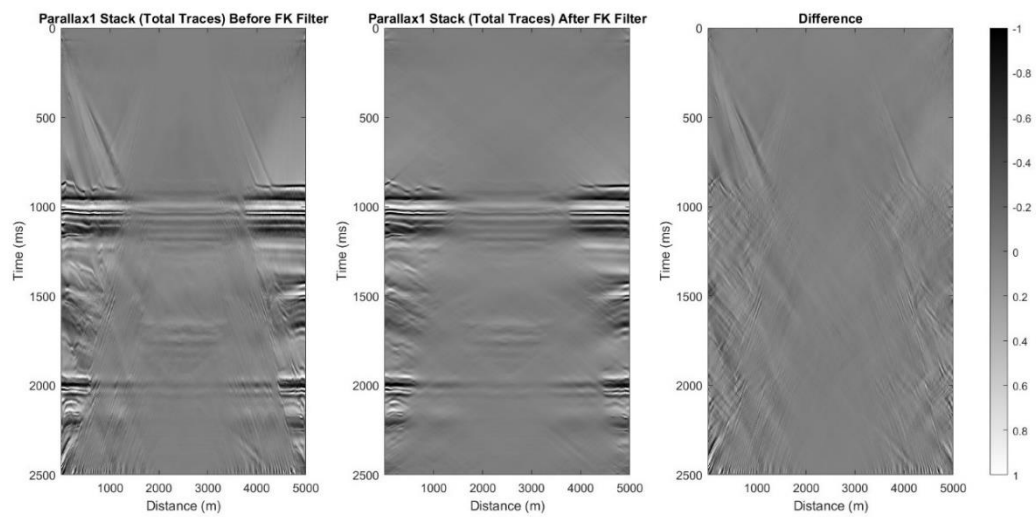


Figure 21: The parallax 1 stack using the total traces before and after applying the F-K filter.

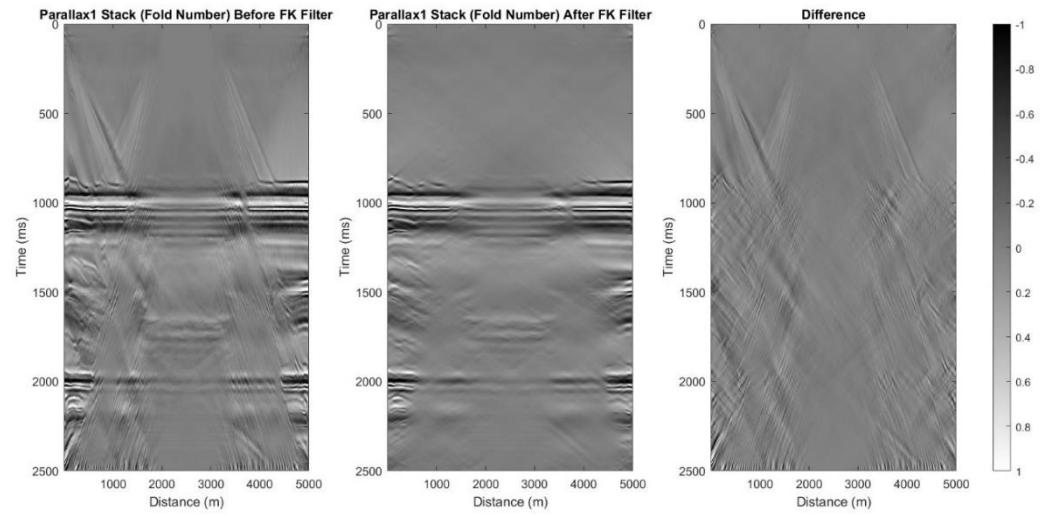


Figure 22: The parallax 1 stack using the fold number before and after applying the F-K filter.

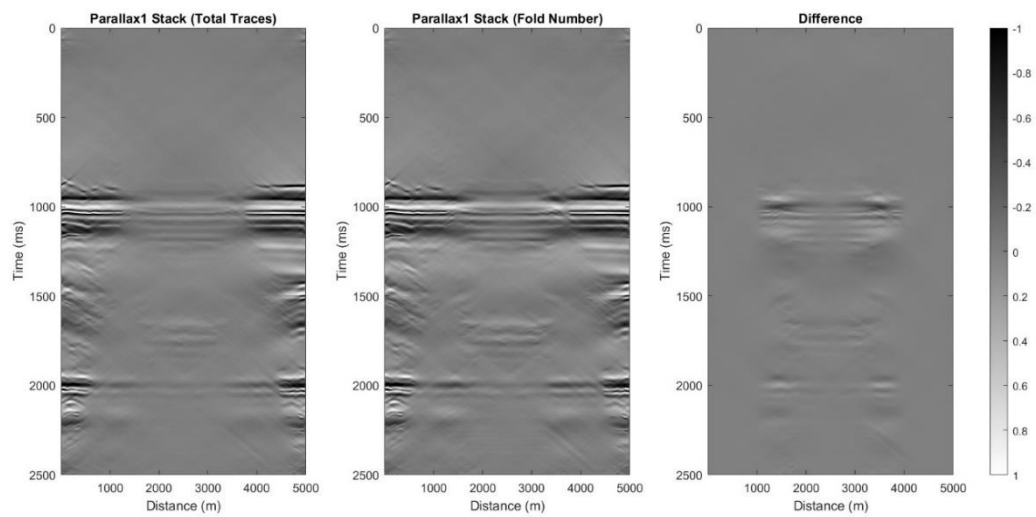


Figure 23: The parallax 1 stack using the total traces, the parallax 1 stack using the fold number, and their difference.

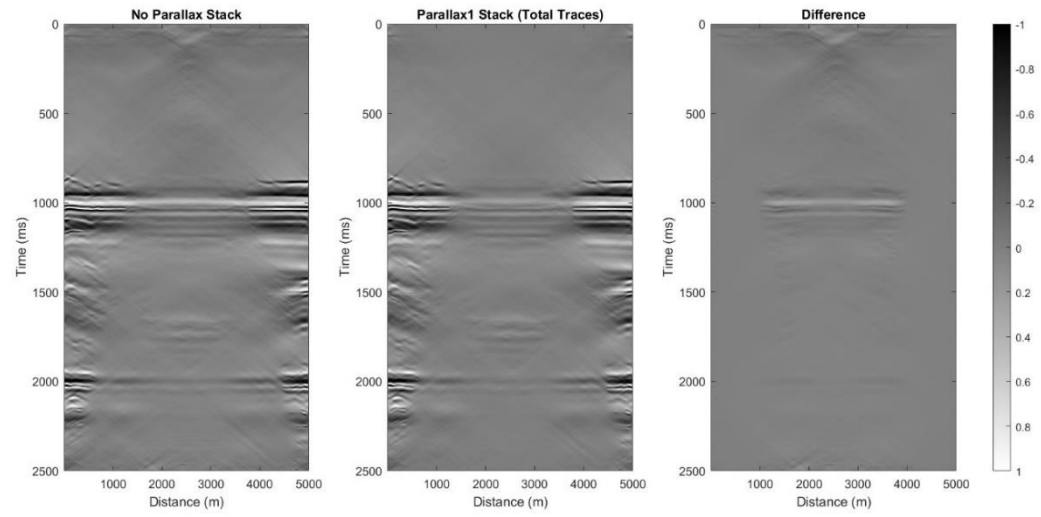


Figure 24: The stack data without parallax, the parallax 1 stack using the total traces, and their difference.

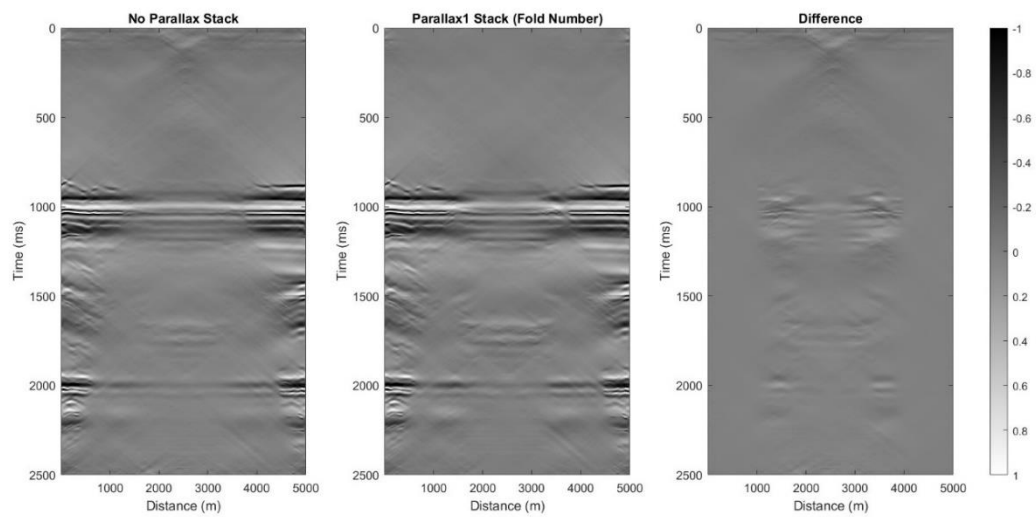


Figure 25: The stack data without parallax, the parallax 1 stack using the fold number, and their difference.

4.2.2 Results of Approach Two

The idea of parallax-based approach two is similar to approach one. This approach consists of muting the noisy traces, flattening the seismic events by applying the NMO correction, summing or stacking the CDPs, replacing the muted traces with the stacked traces generated from the same CDP (Figures 26), and finally stacking the CDP (Figures 27). I applied the mild F-K filter to remove the artifact liner noise from the stack section, and it did not affect the primary P-wave reflection (Figures 28). The resulting stack section is exactly the same as the parallax-based approach section. Since the replaced traces have the same amplitude values, they have the same mean. Hence, they produced the same stacked trace. By comparing the stacks before and after applying this approach, I obtained the same results as approach one, and parallax-based approach two showed better continuity and illumination of the P-wave reflection event.

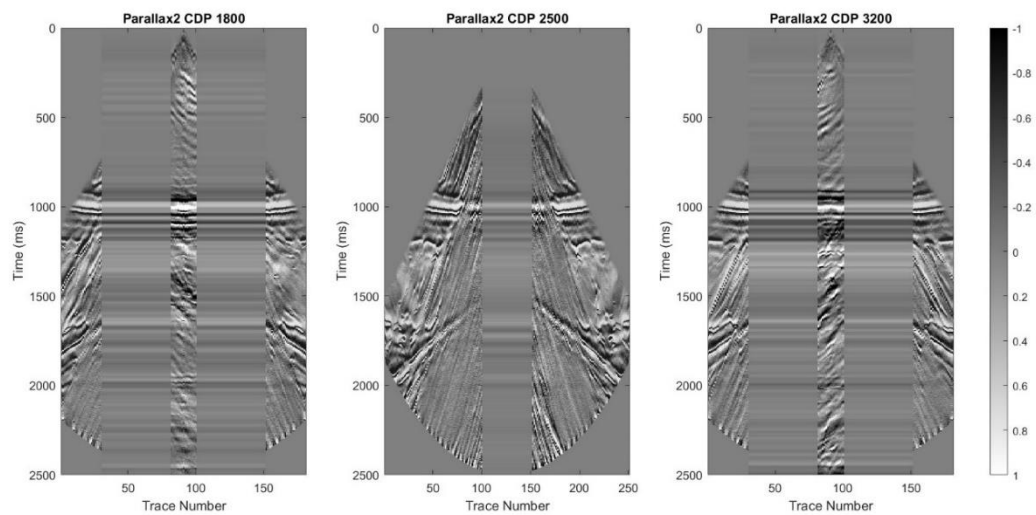


Figure 26: Three CDP gathers after applying the Parallax 2 approach. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m.

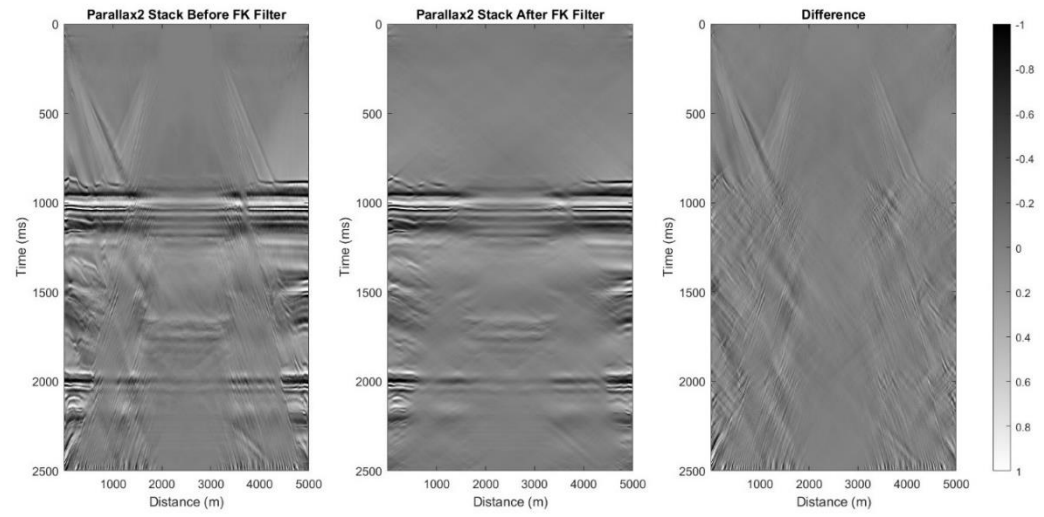


Figure 27: The parallax 2 stack before and after applying the F-K filter.

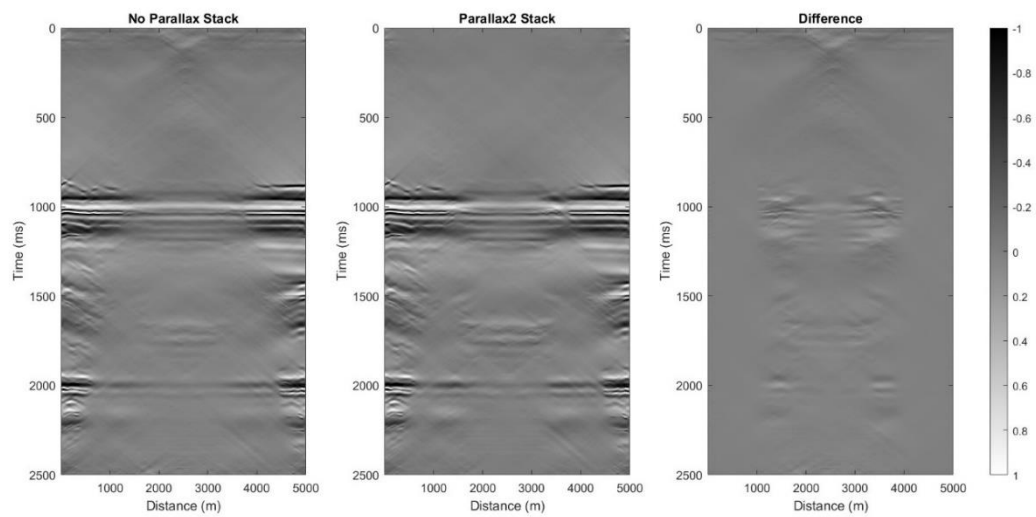


Figure 28: The stack data without applying parallax, the parallax 2 stack, and their difference.

4.2.3 Results of Approach Three

The parallax-based approach three is similar to approach one, yet here, there are a few extra steps. This approach consists of muting the noisy traces, flattening the seismic events by applying the NMO correction, and replacing the muted traces with other traces from the adjacent CDPs that share the same offset (or the trace sequence number) that will fill the gap in the CDP (Figures 29) finally, summing or stacking the CDPs (Figure 30). I applied the mild F-K filter to remove the artifact liner noise from the stack section, and it did not affect the primary P-wave reflection (Figures 31). By comparing the stacks before and after applying the parallax-based approach three, I can notice the significant improvement in the quality of the stack that was generated from applying the parallax-based approach three, as it illuminated the primary P-wave reflection event under the sand dune. In addition, it makes this event sharper and clearer, as shown in (Figures 4.31). Some noise is introduced in this stack section due to its presence in the donor CDPs.

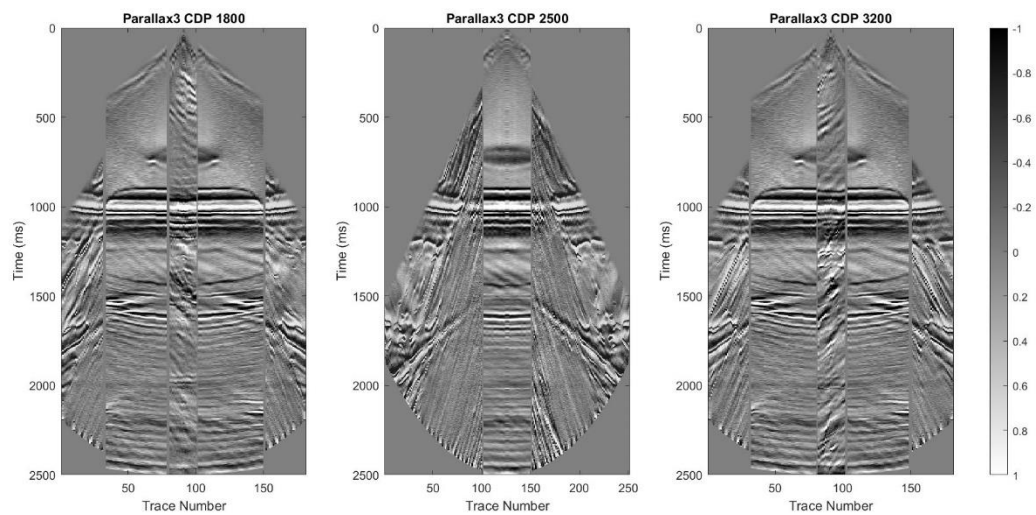


Figure 29: Three CDP gathers after applying the Parallax 3 approach. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m.

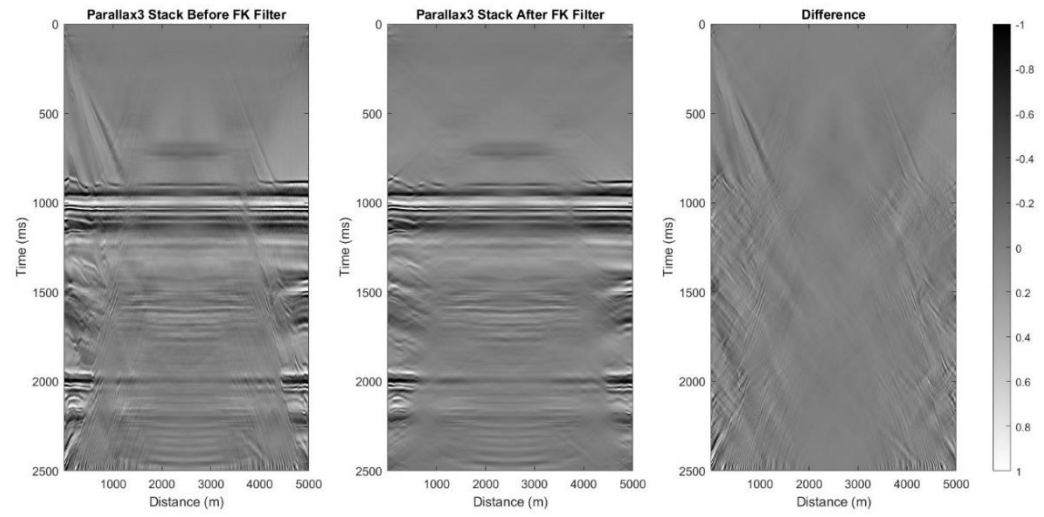


Figure 30: The parallax 3 stack before and after applying the F-K filter.

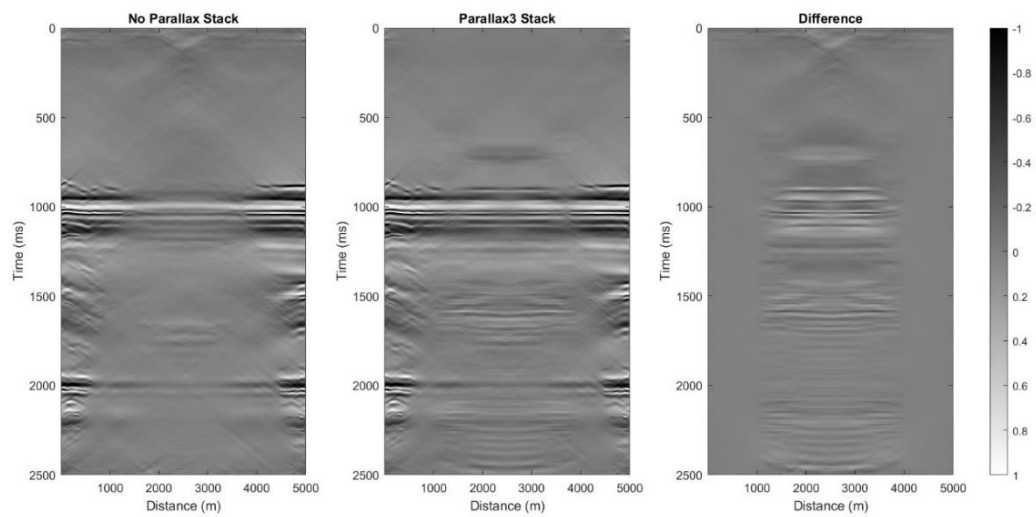


Figure 31: The stack data without applying parallax, the parallax 3 stack, and their difference.

4.2.4 Results of Approach Four

The parallax-based approach four is similar to approach one, with an extra few steps. This approach consists of muting the noisy traces, flattening the seismic events by applying the NMO correction, generating a super gather (Figures 32) of all the CDP that have at least one trace affected by the sand dune, and replacing the muted traces with other traces from the super gather CDPs that share the same offset (or the trace sequence number) that will fill the gap in the CDP (Figures 33) last, summing or stacking the CDPs (Figure 34). I applied the mild F-K filter to remove the artifact liner noise from the stack section, and it did not affect the primary P-wave reflection (Figures 35). If I look at the supergather (Figures 4.21), I can notice that the primary P-wave event is continuous and sharp. This indicates that this layer's boundary is flat along the stacked CDP range. This can help us when dealing with real data, where I do not have the real answer. Knowing that I have flat layers in the subsurface allows us to replace the traces from the super gather with the muted traces in the original CDPs. By comparing the stacks before and after applying parallax-based approach four, I can see that there is an improvement in the quality of the stack that was generated from applying parallax-based approach four as the event under sand dune illumination, and the continuity of the primary P-wave reflection event is better, as shown in (Figures 35).

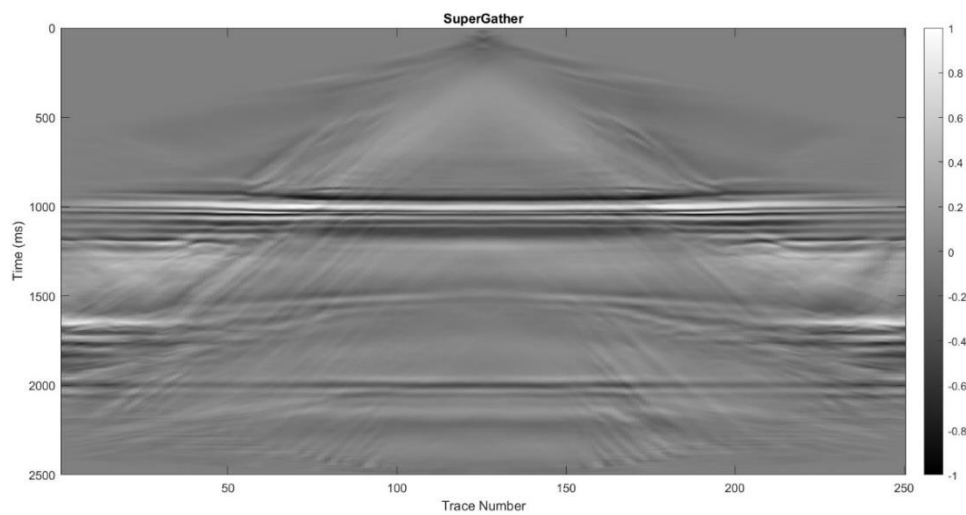


Figure 32: A supergather generated by stacking all the CDP with at least one trace affected by the sand dune.

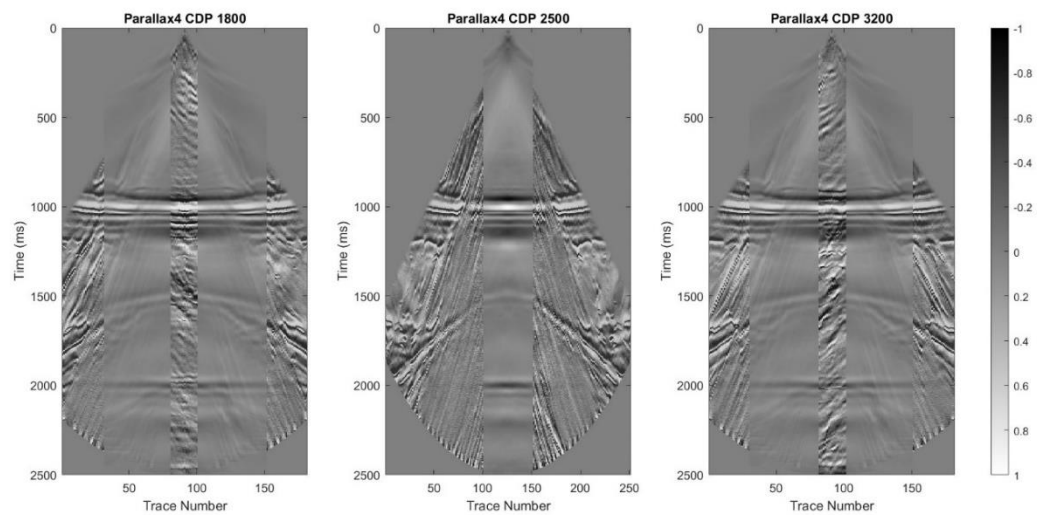


Figure 33: Three CDP gathers after applying the Parallax 4 approach. CDP1800 is located at 1800 m, CDP2500 at 2500 m, and CDP3200 at 3200 m.

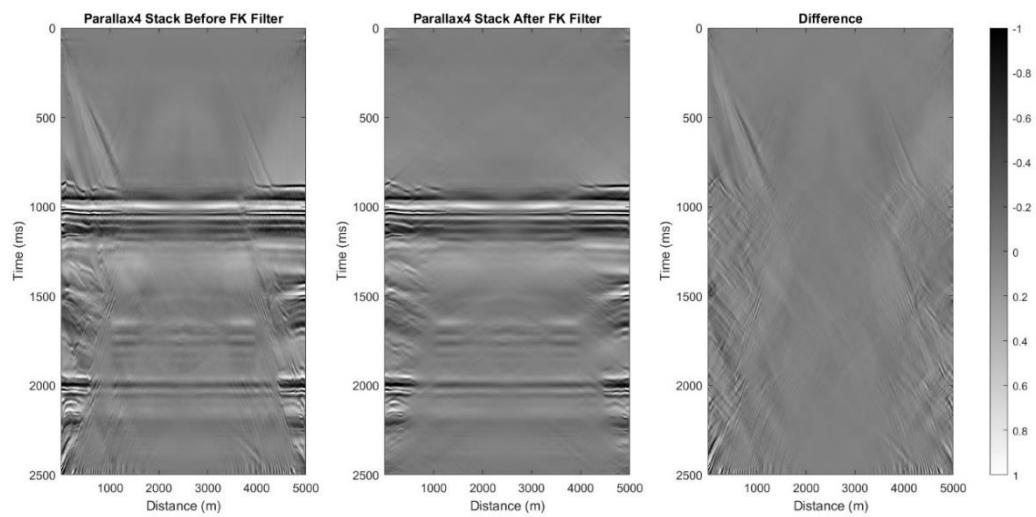


Figure 34: The parallax 4 stack before and after applying the F-K filter.

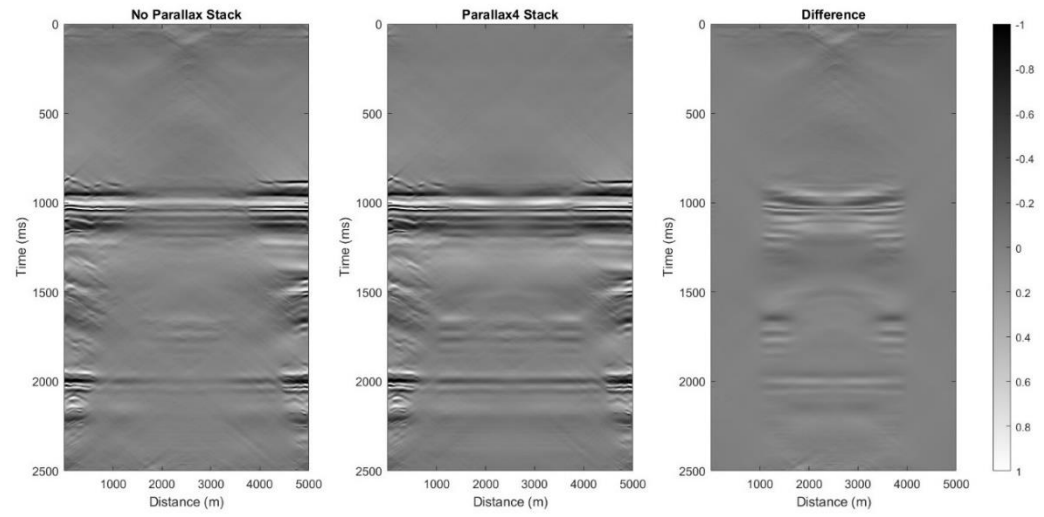


Figure 35: The stack data without parallax, the parallax 4 stack, and their difference.

CHAPTER 5

CONCLUSION

In this study, I have tested and evaluated a well-established and successful approach to remove localized noise from an image and apply it to seismic data to produce an enhanced subsurface image free of near-surface noise without noise generated by sand dunes. This method utilizes the parallax phenomenon, which is known as the apparent change in the position of an object based on the position or the angle of observation. Therefore, I have called it the parallax-based approach. The idea of this method is to divide the image into two layers: the background layer, the target, and the foreground layer, the occlusion or the noise. By utilizing a sequence of images of the same scene taken from different positions, I can detect and remove the obstacle to see what is behind it. This can be achieved by removing the affected part of the data by the localized obstacle and then aligning the images before summing them, replacing the missing data between the images.

In seismic data, I can apply parallax through muting, NMO correction, and CDP stacking. In this study, I introduced four approaches to implementing the parallax method on seismic data. The first approach consists of these steps: muting, NMO correction, and CDP stacking. The second approach consists of these steps: muting, NMO correction, CDP stacking, replacing the muted traces with the stacked traces generated from the same CDP, and stacking the new CDP. The third approach consists of these steps: muting, NMO correction, replacing the muted traces with other traces from the adjacent CDPs that share the same offset, and CDP stacking. The fourth approach consists of these steps: muting,

NMO correction, generating a supergather of all the CDPs that have at least one trace affected by the sand dune, and replacing the muted traces with other traces from the supergather CDPs that share the same offset, and CDP stacking.

I have implemented these four approaches on elastic synthetic 2D data. These data were processed using a 2D conventional land processing workflow. The results of this workflow were used to evaluate the four parallax-based approaches. The stack generated without a parallax-based approach has a dimmer and weak reflection below the sand dune. The first parallax approach illuminated the reflection below the sand dune as the noisy traces were muted and the CDP stacked by taking the mean of the fold number. Similarly, the second parallax approach produces the same result. Since the replaced traces have the same amplitude values, they have the same mean. Hence, they produced the same stacked trace. The third parallax approach improved the quality of the stack section significantly as the reflection event illuminated and became continuous and sharper. However, some noise was introduced to the stack section due to its presence in the replaced traces. The fourth parallax approach also improved the quality of the stack section as the traces below the sand dune illuminated, and the continuity of the reflection event improved.

In conclusion, the parallax-based approaches improved the quality of the stack section as it illuminated the event under the sand dune. Additionally, it enhanced the continuity of the reflection event and made it sharper. The third approach produced the best results. The fourth approach also produced excellent results. The first approach gives simple and decent results. The second approach can be avoided because it provides the same results as the first approach, yet it has extra steps.

For future research, I suggest the following:

- a. Creating a workflow for preconditioning the CDP gathers and improving the trace selection for the replacement step.
- b. Testing the proposed approaches on appropriate real seismic data sets from near-surface and exploration surveys.
- c. Extending the proposed approaches to refraction events.

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