Technical University of Crete

Department of Mineral Resources & Engineering

MSc in Petroleum Engineering

Diploma Thesis: Analysis and Processing of Reflection Seismic Data

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CONTENTS

Preface

This thesis aims to provide the necessary industrial background of seismic data processing using MATLAB, starting from data input, displaying, quality control of the data up to obtaining a seismic image. Concepts, definitions, and methods are essential in analysis and processing of seismic reflection data, following on chapters bellow.

Firstly, the main concepts of seismic data processing are explained in Chapter 1. In Chapter 2, a two-dimensional (2-D) real seismic dataset is examined and useful processing information is extracted. Then, Chapter 3 includes various quality control techniques which are used aiming to correct the amplitude losses in real seismic data sets. Chapter 4 explains the concepts of the main signals and data are analyzed in the spectrum domain. Moreover, at the same chapter, frequency-filtering techniques are presented in order to attenuate ground roll noise contaminating the real data. Further up, in Chapter 5, the seismic convolution model is analyzed and how the deconvolution is used in order to strengthen the vertical resolution of the data. After that, a number of significant parameters for the seismic data processing are explained in chapter 6. Firstly, data classification (shot gathers into common mid-point gathers) takes part, stacking velocities are computed, thirdly, the application of normal moveout (NMO) correction follows and, finally, the data are stacked. In addition, for further enhancement of seismic data, Chapter 7 includes residual static correction to the NMO-corrected data and stacking the data again. The Chapter 8 includes the seismic migration in order to enhance the horizontal resolution of data. Finally, in Chapter 9 there are some concluding remarks.

1. A Brief Overview of Seismic Data Processing

1.1 Introduction

There are many geophysical techniques but the most widely used and well known is the seismic reflection. An important advantage of seismic reflection is the fact that can be processed to reveal details of geological structures on scales from a few meters to many kilometers. The main success of this method has to do with the fact that the primary seismic data is processed to produce seismic sections of the subsurface structure. The analysis of seismic data is mostly performed for petroleum exploration and deep crustal studies.

A source (explosion, air guns, vibroseis, e.t.c.) is needed for the generation and further propagation of the seismic signals through earth layers.. These seismic signals are reflected by the layers into the earth and they are recorded by receivers. How strong and clean will be the reflected signal depends on the acoustic impendence of the layers. In other words, a reflection seismic survey involves three main topics, collection of data by the geophones (on land) or hydrophones (marine surveys), transmission of signal through a channel and storage of data for the subsequent processing and interpretation.

The creation of a seismogram demands the collection of one or more seismic traces. A seismic trace represents the response of the elastic wavefield to velocity and density contrasts across interfaces of layers (rock or sediments) as energy travels from a source through the subsurface to a receiver or receiver array. An easy assumption that be made is the pulse shape remains unchanged as it spreading through the layers. This means that the new seismic trace can be considered as the anticipated convolution of the input impulse compared with a time series which are well known as a reflectivity function and that function is composed of spikes. Examining each spike is obviously that has an amplitude, which has to do with the reflection coefficient and a traveltime. It is very important to mention that traveltime is the time difference between primary time, which usually is zero, and the arrival time of seismic event. There are two cases, one-way time for the direct waves and two-way time for the reflected waves

Another important factor, which affects the quality of a seismogram, is the noise, an unwanted energy that corrupts the seismic records. More especially, in geology and other similar sciences, considered that a seismic noise is a continuous vibration of the ground, which comes from many causes. The most frequent cause is the ground roll. In other words, the seismic noise is a series of undesirable signals that are recorded by the seismometers. Consequently, suitable processing techniques are obligatory in order to recognize seismic traces, which have a complex appearance. The main goal and purpose is the reception of signal without noise. For that reason, the purpose of processing these data is considered as a process through which noise attenuates. After that, should be determined and removed the input pulse in order to provide the reflectivity that subsequently images the subsurface layers.

1.2 Seismic Data Processing

The computational analysis of recorded data to create a subsurface image and estimate the distribution of properties is called data processing. Processing of seismic data usually includes common mid-point (CMP or CDP) sorting, filtering, normal move-out (NMO) correction, velocity analysis, and stacking. Filtering and normal move-out (NMO) corrections are two very significant parameters in the processing. The nature of each seismic trace is determined by three significant geometrical factors. These factors are the shot position, receiver position and the position of the subsurface reflection point. The last one is the most critical factor because this point, before processing, is unknown but a good approximation can be made by common mid-point (CMP) or common depth-point (CDP).

Common mid-point is the point on the surface halfway between the source and receiver that is shared by numerous source-receiver pairs. Such redundancy among source-receiver pairs enhances the quality of seismic data when the data are stacked. The common midpoint is vertically above the common depth point, or common reflection point (fig. 1.1). A common midpoint gather is a display of seismic traces that share an acquisition parameter, which contains traces having a common midpoint (Schlumberger Oilfield Glossary). Given the fact that the subsurface velocity is possible to decrease, the CMP gather is very important for seismic data processing. Usually, the reflection seismic energy is weak; therefore, an increase of signal-to-noise ratio is crucial and essential. Signal-to-noise ratio is the ratio of desirable to undesirable energy. The next step is the calculation of velocity. When that happened, then the traces in common mid-point can be fixed for normal moveout, which is a process at which the time differences arising due to offset in a common mid-point, are corrected, in order to get a zero offset trace. It is significant to mention that offset is the distance from the source point to a geophone. This means that all traces are going to have the same reflected pulses with the same time, but with different noise. By combining all the traces in a common mid-point gather, exports an average noise and increases the signal-to-noise ratio. This procedure is the process of stacking.

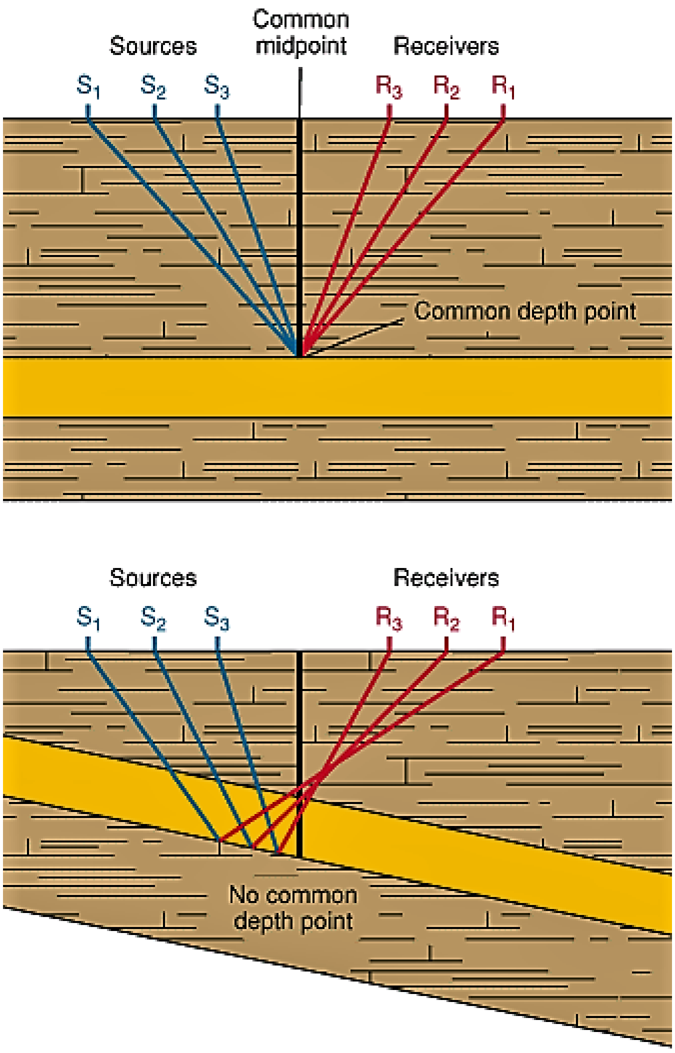

Figure 1.1: Schematic representation of CMP and CDP. The common depth point is the halfway point in the travel of a wave from a source to a flat-lying reflector to a receiver (Schlumberger, "Oilfield Glossary," *SLB*, 2017.[1])

The main goal of seismic data processing is the improvement of seismic resolution and the increase of signal to noise ratio (SNR). This can be done through three primary stages. The first stage is the deconvolution, which increases the vertical resolution. The second stage is the stacking, which increases the (SNR) and the third stage is the migration, which increases the horizontal resolution. In addition, there are also some secondary processes, which can be implemented at certain stages to condition the data and improve the performance of these three processes.

Based on the book of Mousa and Al-Shuhail (2011) [Processing of Seismic Reflection Data Using Matlab] the most important processing steps which are general and depending on the data type, land or marine, the accompanying noise types, and/or the acquisition conditions, are Mousa and Al-Shuhail (2011):

1. Preprocessing: This process involves a series of steps to condition the data and prepare it for further quality control and processing including: demultiplexing, reformatting, trace editing, gain application, setup of field geometry, application of field statics.

2. Filtering is used to attenuate components of the seismic signals based on some measurable property. It is an important step in order to proceed further with the other seismic data processing steps that will help geophysicists to better analyze and interpret the acquired data.

3. Deconvolution is performed along the time axis to increase vertical resolution by compressing the source wavelet to approximately a spike and attenuating noise and unwanted coherent energy such as multi-path signals (multiples).

4. CMP sorting transforms the data from shot-receiver (shot gather) to midpoint-offset (CMP gather) coordinates using the field geometry information.

5. Velocity analysis is performed on selected CMP gathers to estimate the stacking, root-mean squared (RMS), or NMO velocities to each reflector. Velocities are interpolated between the analyzed CMPs.

6. Residual static correction is usually needed mostly for land data. It corrects for lateral variations in the velocity and thickness of the weathering layer.

7. NMO correction and muting: The stacking velocities are used to flatten the reflections in each CMP gather (NMO correction). Muting zeros out the parts of NMO-corrected traces that have been excessively stretched due to NMO correction.

8. Stacking: The NMO-corrected and muted traces in each CMP gather are summed over the offset (stacked) to produce a single trace. Stacking M traces in a CMP increases the SNR of this CMP by SQRT(M).

9. Poststack processing includes time-variant band-pass filtering, dip filtering, and other processes to enhance the stacked section.

10. Migration: Dipping reflections are moved to their true subsurface positions and diffractions are collapsed by migrating the stacked section.

2. Examination of a Real Seismic Data Set

2.1 Introduction

For the examination of a real seismic data, the seismic data itself and its header include plenty of information and records of parameters used to obtain the data. Geologists take into account all these information, exporting significant findings through processing. Usually all this information is stored in hard disks. SEG-Y or Seismic Unix formats is an alternative way to save these information. However, the aim of this thesis is to examine all these information and data using MATLAB. Consequently, the conversion from SEG-Y to MATLAB is needed.

2.2 The Seismic Reflection Real Data Set

The data used for this reflection processing steps implementation are from east Texas, US and found into the book entitled "Processing of Seismic Reflection Data Using Matlab" by Wail Mousa and Abdullatif Al Shuhail (2011). The processing codes found into the aforementioned book, applied in a two-dimensional (2-D) mode and the main experimental geometry data are shown below,

- Number of shots = 18
- Source type = dynamite in approximately 100 ft depth holes
- Number of channels per shot = 33
- Receiver type = vertical component geophones
- Array type = 12 element in line
- Number of traces in line = 594
- Receiver interval = 220 ft
- Shot interval is variable
- Time sampling interval = 2 ms
- Number of time samples per trace = 1501
- Data format = SEG-Y
- Byte swap type = big endian
- Data file name = data.sgy
- Geometry has already been set up and recorded in the trace headers
- Uphole times at shot locations have been recorded in the trace headers
- An 8-64 Hz bandpass filter has been applied to the data in the field.

2.3 Examination of Data Set

The first step is the examination of the 2-D seismic dataset and its header information. That can be happen by loading the file Book_Seismic_Data.m (figs 2.1, 2.2). Running this command in the MATLAB workspace can be found two variables. These variables are header and traces.

```
%%$ Chapter 2 Header information %%%
%%% Examining the real seismic data set headers%%
clear,clc,close all
%Loading the raw seismic data and its header
load('Book_Seismic_Data.mat','H')
```

Figure 2.1: Part of Matlab code which gives the Header.

```
%Extracting a certain or a group of shot gathers from the data matrix D and H
[sx,sy,gx,gy,shot_gathers,num_trace_per_sg,sz,gz]=extracting_geometry(H);
```

Figure 2.2: Part of Matlab code which gives all the variables that are needed.

2.3.1 Header Information

After loading the data, it is observed that the variable H is a 1×594 structure array with many fields such as: the number of time samples per trace (ns), the shot gather numbers (fldr), the time sampling interval (dt), the offset (offset), the trace numbers (tracl). Below, the plots (figs. 2.3-2.7) of the shot gathers versus the traces is shown in order to present the geometry of the seismic line.

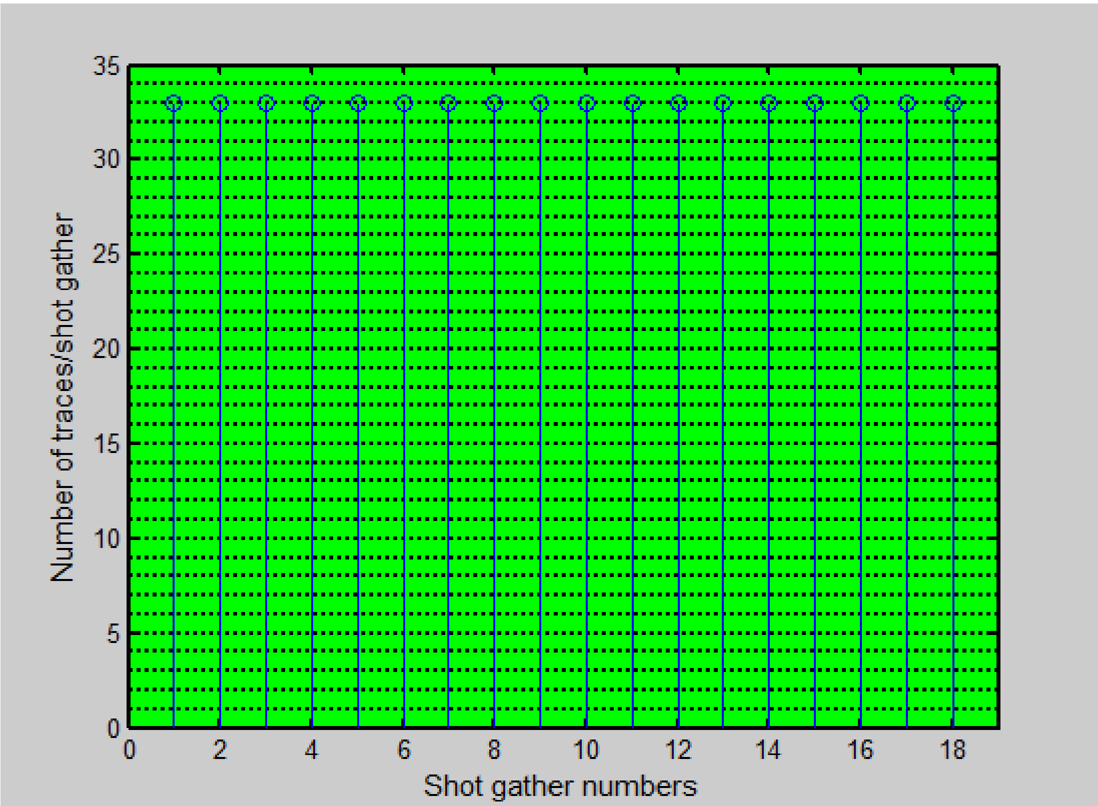

Figure 2.3: The number of seismic traces (33) versus the number of shot gathers (18).

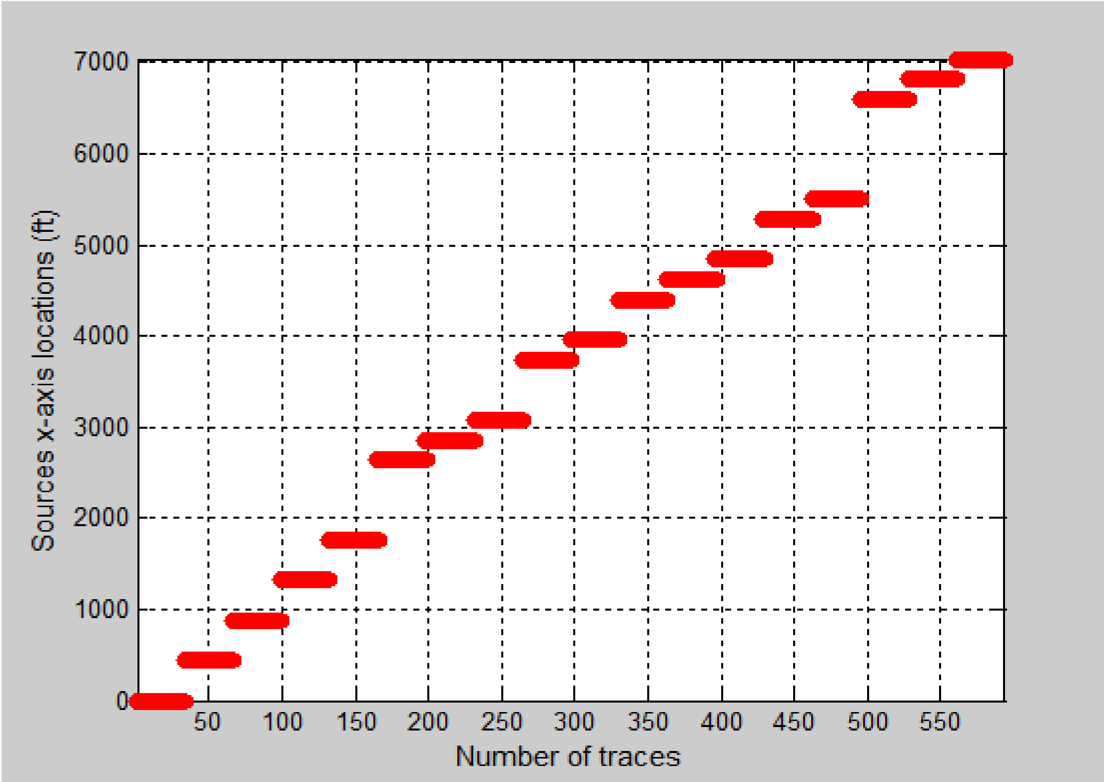

Figure 2.4: The number of sources x-axis locations versus the number of traces (594).

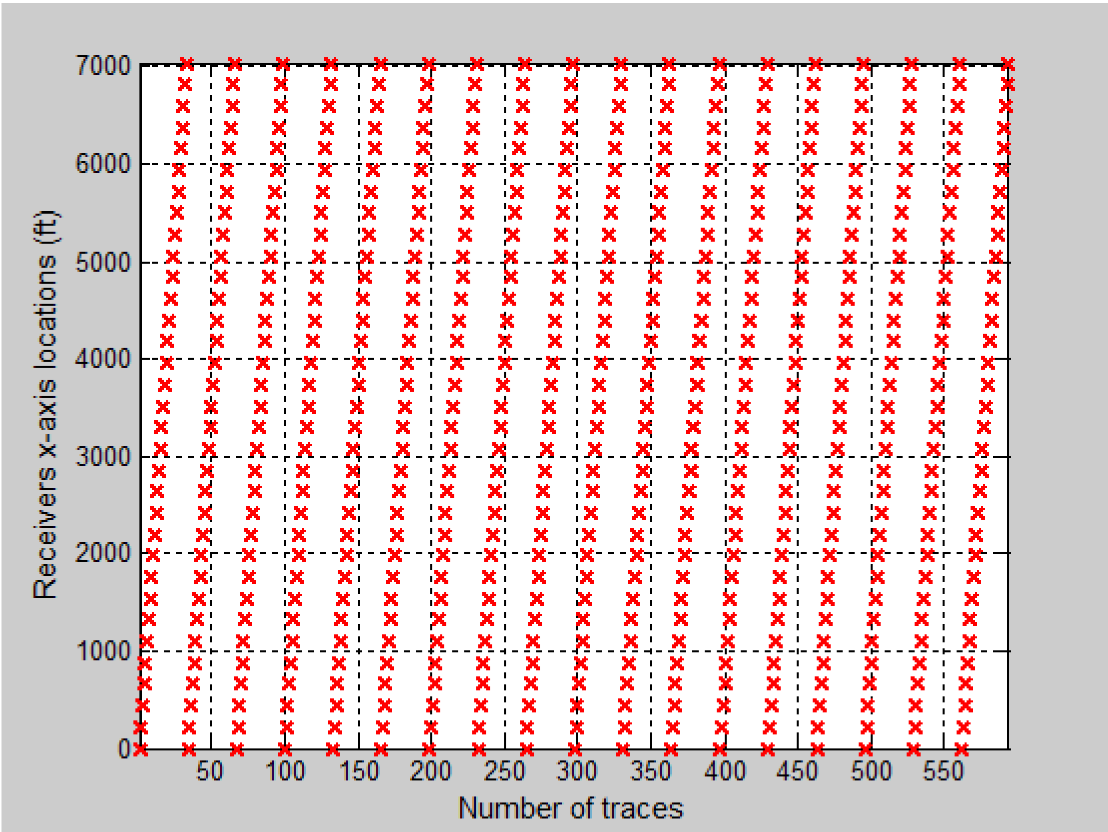

Figure 2.5: The number of receivers x-axis locations versus the number of traces (594).

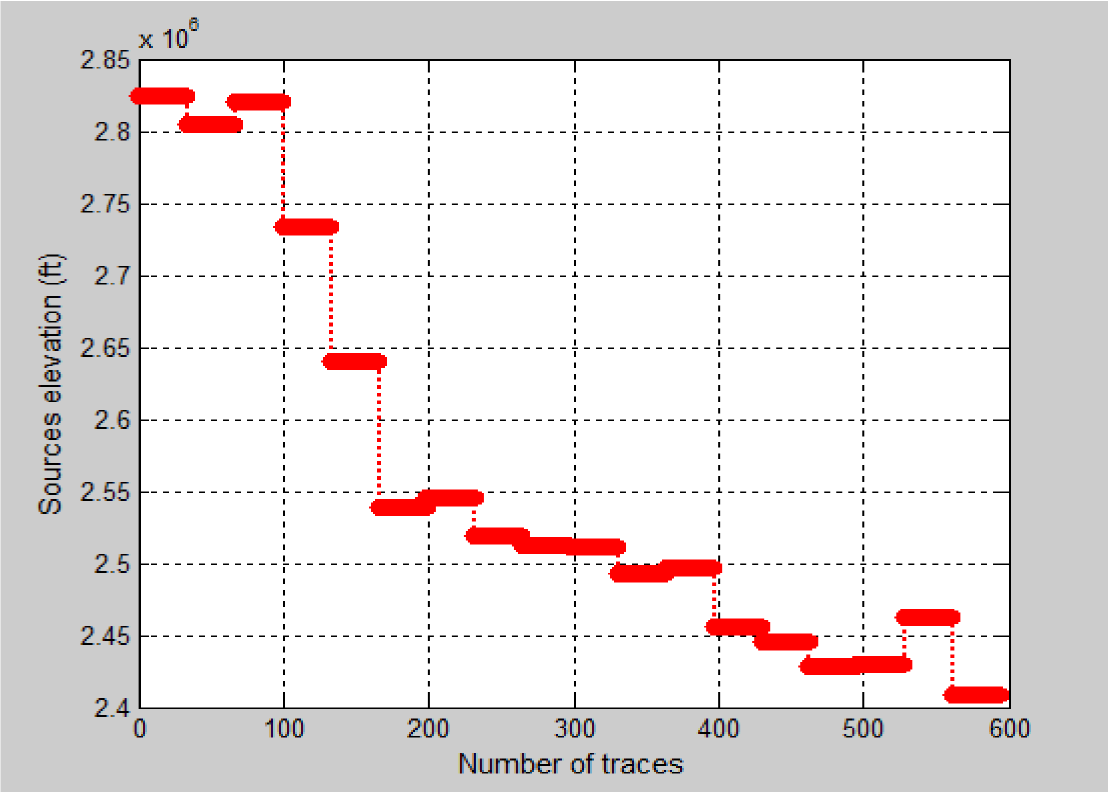

Figure 2.6: The sources elevation versus the number of traces (594).

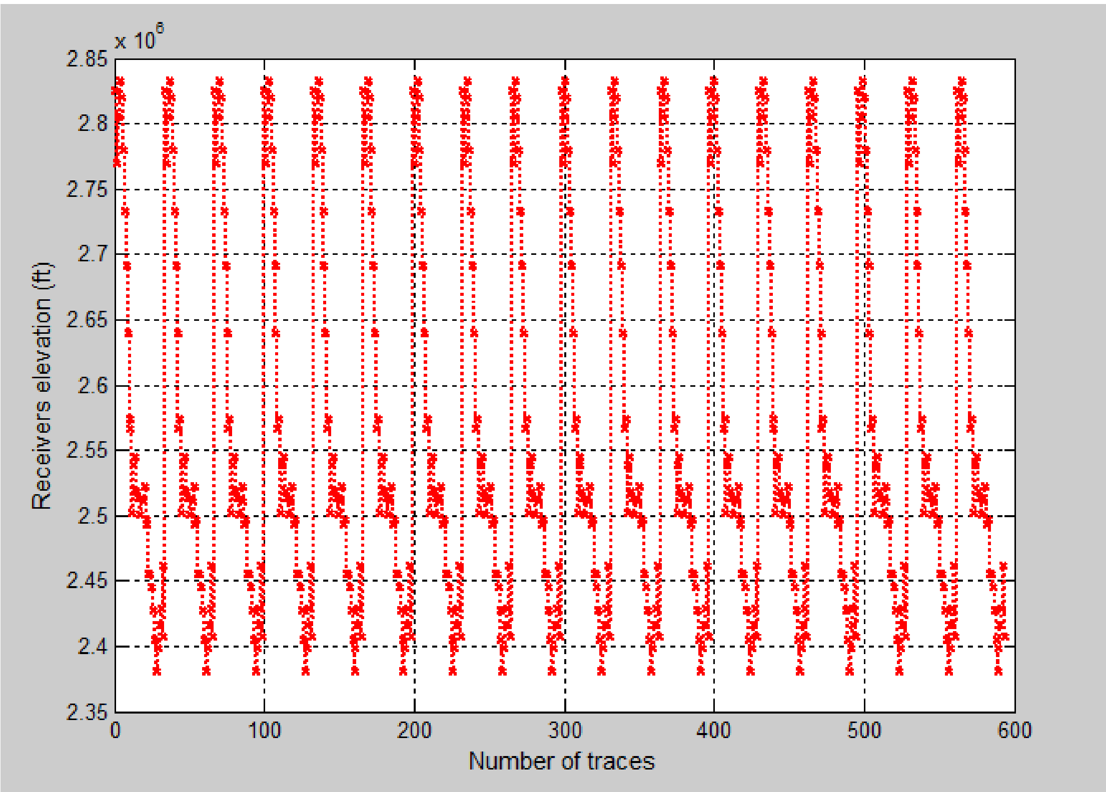

Figure 2.7: The receivers elevation versus the number of traces (594).

2.3.2 Different Kinds of Seismic Display

The appropriate choice of seismic display (fig. 2.8) is extremely important in order to check the number of the real reflections and further correctly interpret the data.. There are mainly three seismic displays, which are very used (Yilmaz, 1997). The wiggle display, the variable density display and the variable area display. Due to the fact that the seismic trace contains a huge number of information which has to do with changes in lithology and rock properties in the subsurface, the correct choice of the seismic display is vital. An appropriate seismic display should detect parameters like porosity, lithology and many others.

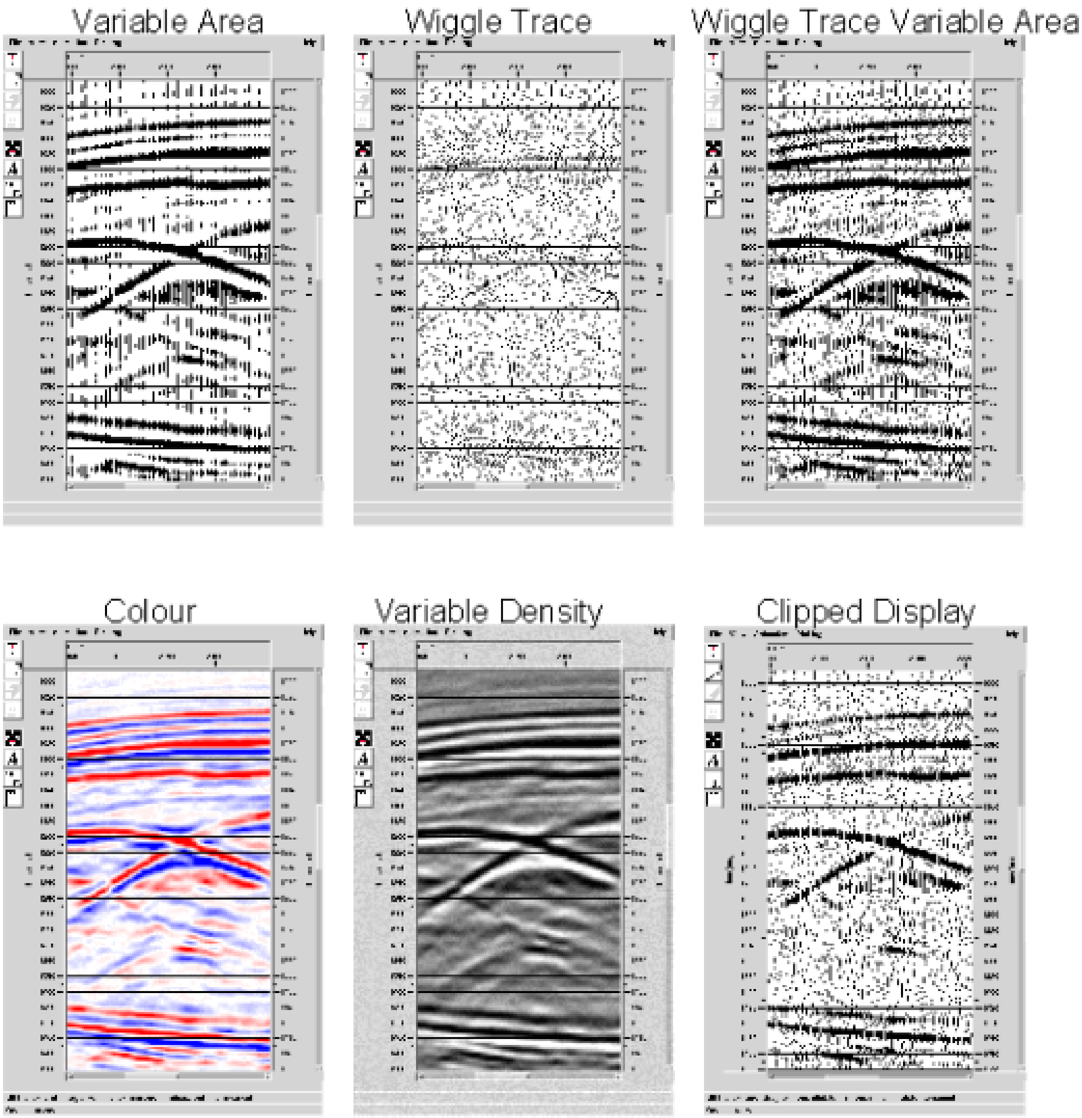

Figure 2.8: Types of seismic display. (Seismic Display - version 1.0 released 29/1/99 [2])

From the three displays which mentioned above, the wiggle display is commonly accepted in the petroleum exploration field. On the other hand, the variable area display conceals the region under the wiggle trace with the aim to make coherent seismic events. A seismic event characterizes a phase change or a change in amplitude on a seismic record. These changes correspond to reflection, refraction and diffraction.

Moreover, the creation of variable density display can be done by entrusting different density shades in different amplitude values. Darker shades for higher amplitudes and less dark for lower amplitudes. Nevertheless, many times different colors represent different amplitudes (figs 2.8, 2.9). The advantage of that procedure, colored amplitudes, permits better amplitude resolution, because geological changes in stratigraphic sequences can accurately identified. Additionally, there are significant and useful displays in stratigraphic studies for better detection of lateral variation. Different colors or shades of black are used in amplitude, frequency, velocity and all these parameters.

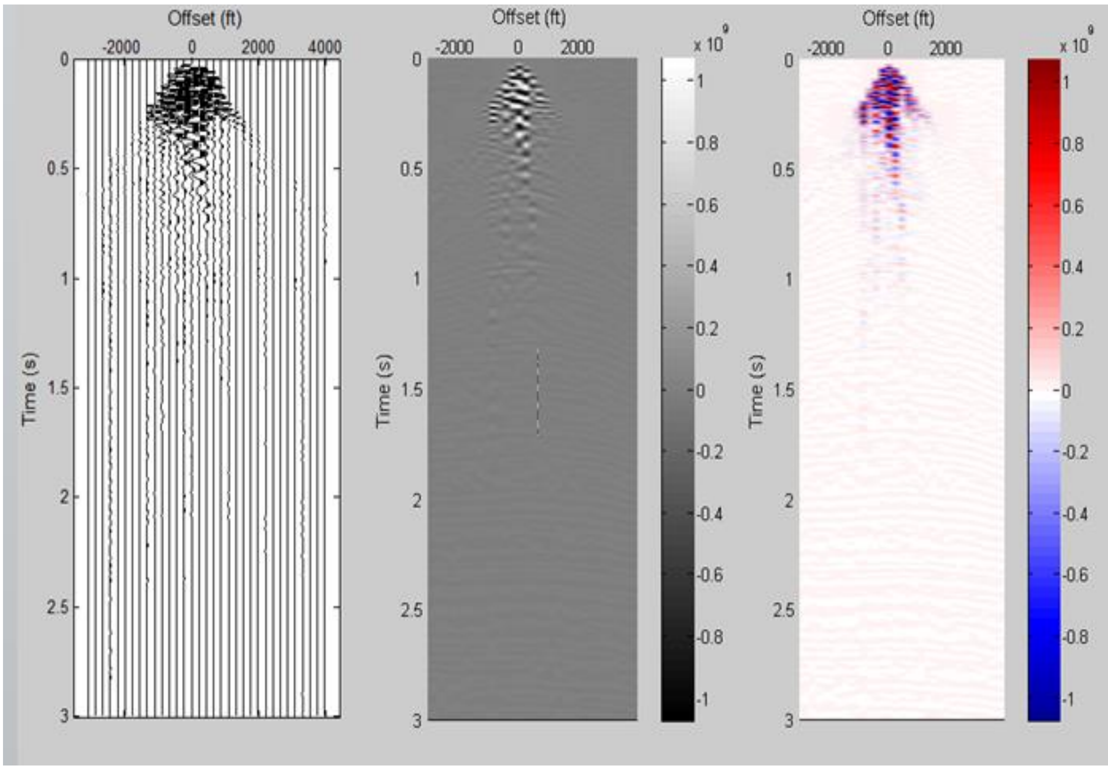

Figure 2.9: Types of seismic display. Wiggle display (left), gray-scaled variable density display (middle) and colored variable density display (right) (figure 2.3 from Mousa and Al-Shuhail, 2011).

2.4 The Steps of Processing

For the processing of seismic data are usually followed certain steps (fig. 2.10) (Processing of Seismic Reflection Data Using Matlab by Wail Mousa and Abdullatif Al Shuhail, 2011) such as:

- Preprocessing involving only the gain application using various methods
- Ground roll removal via bandpass filtering
- Spiking deconvolution
- CMP sorting
- Velocity analysis on several CMPs using the velocity spectrum method
- Residual static correction using the surface-consistent method
- NMO correction and muting
- Stacking

- Migration using Stolt (F-K) post-stack time migration

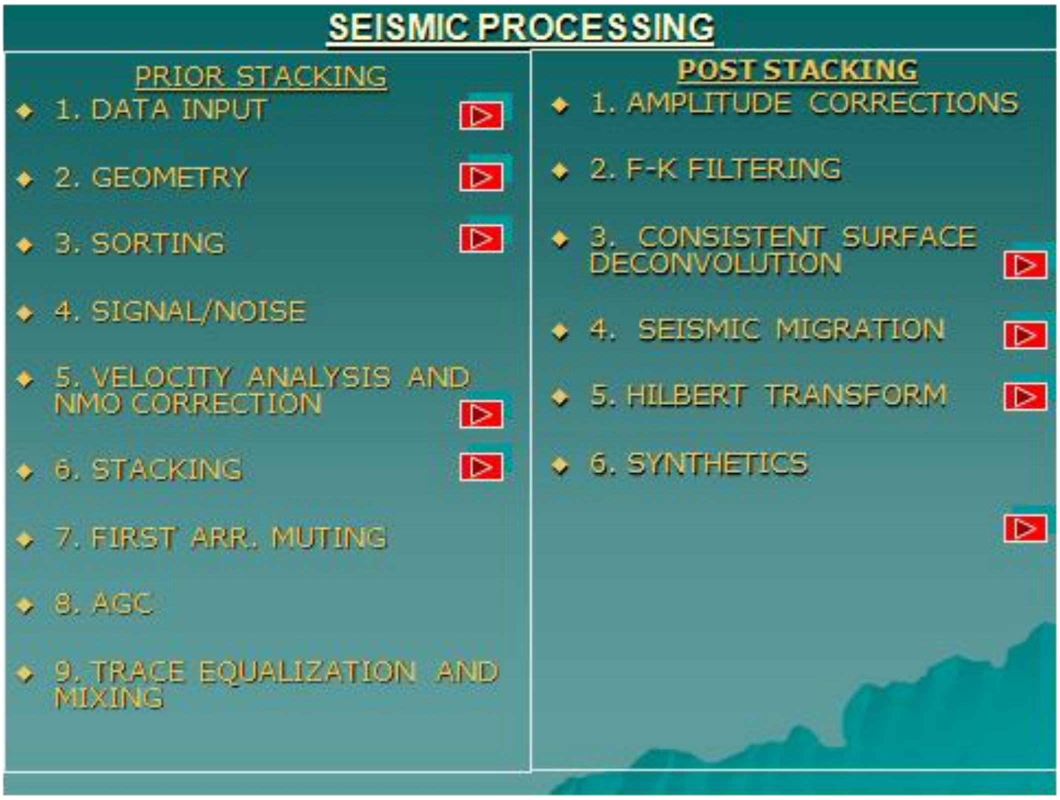

Figure 2.10: Steps of the pre- and post- stacking processing (Kokinou, 2002)

3. Quality Control of Real Seismic Data

3.1 Quality Control of Reflection Seismic Data

The process of quality control (QC) is necessary after the data collection and just before the processing. The steps that are following for the quality control are (a) the check of the survey geometry, and (b) the data format and coherence of components, which are different in a dataset. Furthermore, the QC must take into account that the quality and quantity of dataset must satisfy all the goals of survey. The QC usually is a pre-processing step. After that is following the full processing process with all the parameters, which are needed, like noise elimination from seismic image and better processing of data. Below are following all the steps that are necessary for QC and for better quality process.

1. Demultiplexing: referred to the classification (fig. 3.1) of traces from time listing (all receiver stations, the same time) to receiver ordered format (all times, the same receiver). This is usually happened in the field but many times data from the field are not clear. For that reason, SEG-Y formats are used.

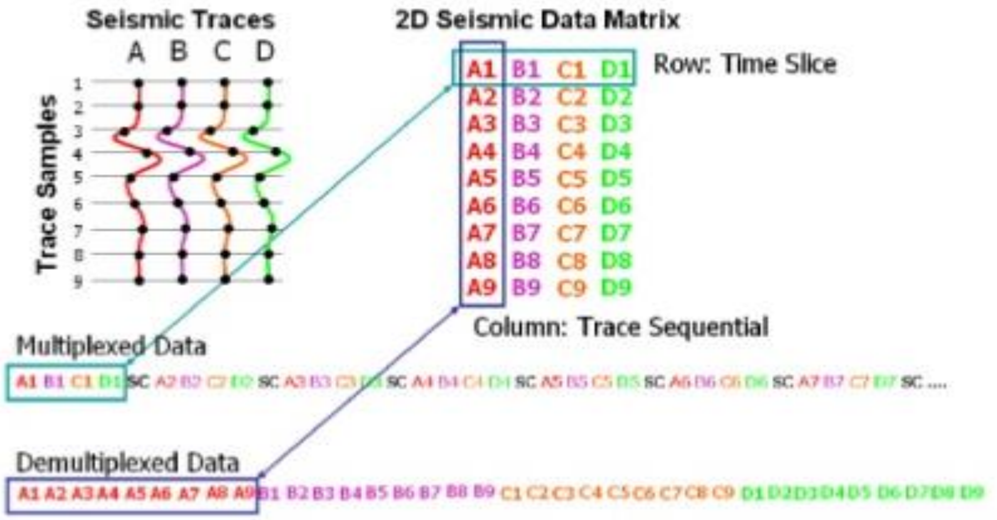

Figure 3.1: Demultiplexing. (seismic reflection data processing[3])

2. Reformatting: use of SEG-Y (fig. 3.2) format is the most common data format in seismic processing.

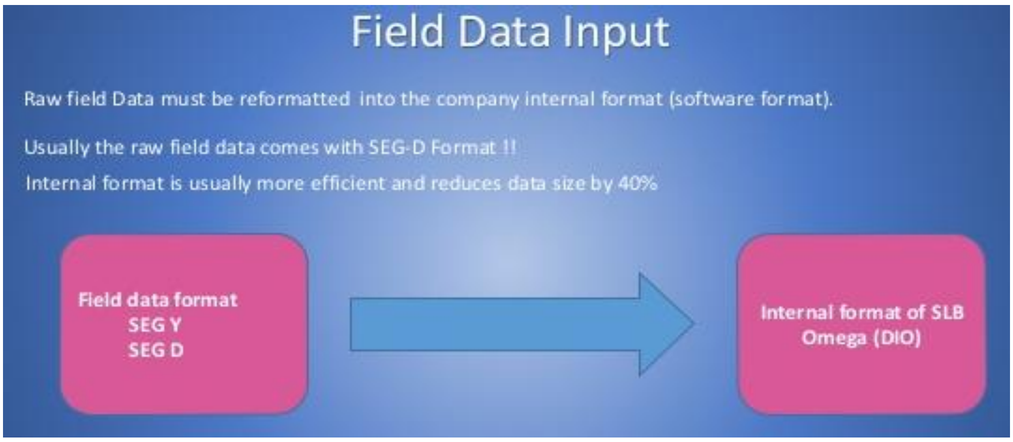

Figure 3.2: Reformatting. (Western Geco presentation - Seismic Data Processing Schlumberger Oilfield Service[4])

3. Setup of field geometry: the incorporation between field geometry (fig. 3.3) with seismic data processing. Regard to parameters like shot and receiver location, the coordinates and distance, and how the system can absorb them appropriately.

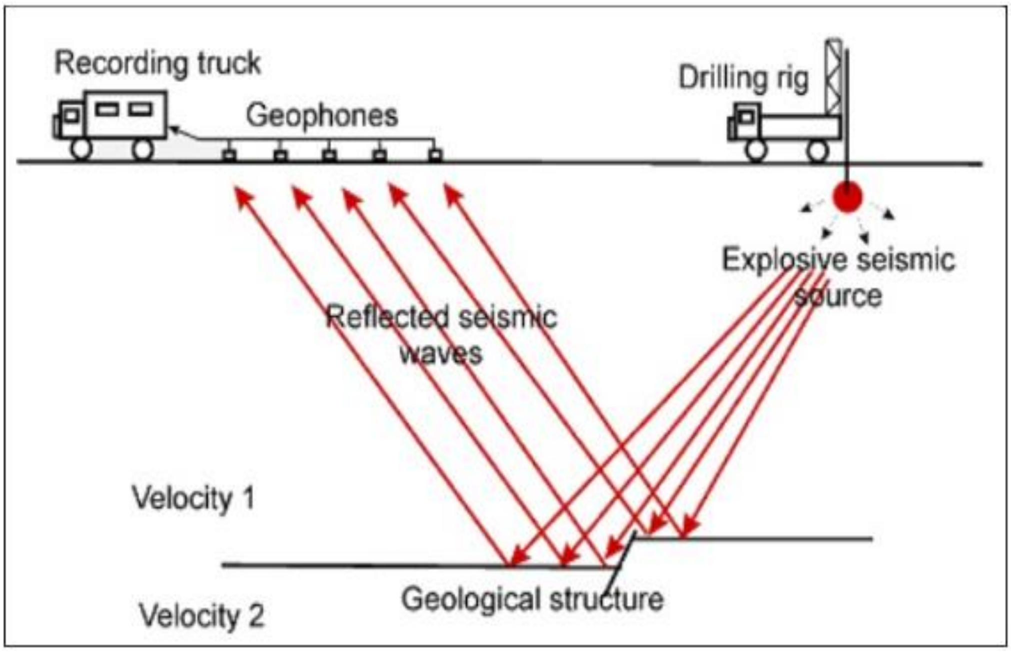

Figure 3.3: Setup of field geometry. (In field optimization of seismic data acquisition by real-time subsurface imaging using a remote grid computing environment[5])

4. Trace editing: all the activities that are needed for the removal of noise, mono frequency traces as well as incorrect polarities.
5. Gain application: the correction of amplitude (fig. 3.4) is essential for a stronger signal, due to the fact that far away from the source, the signal becomes very weak.

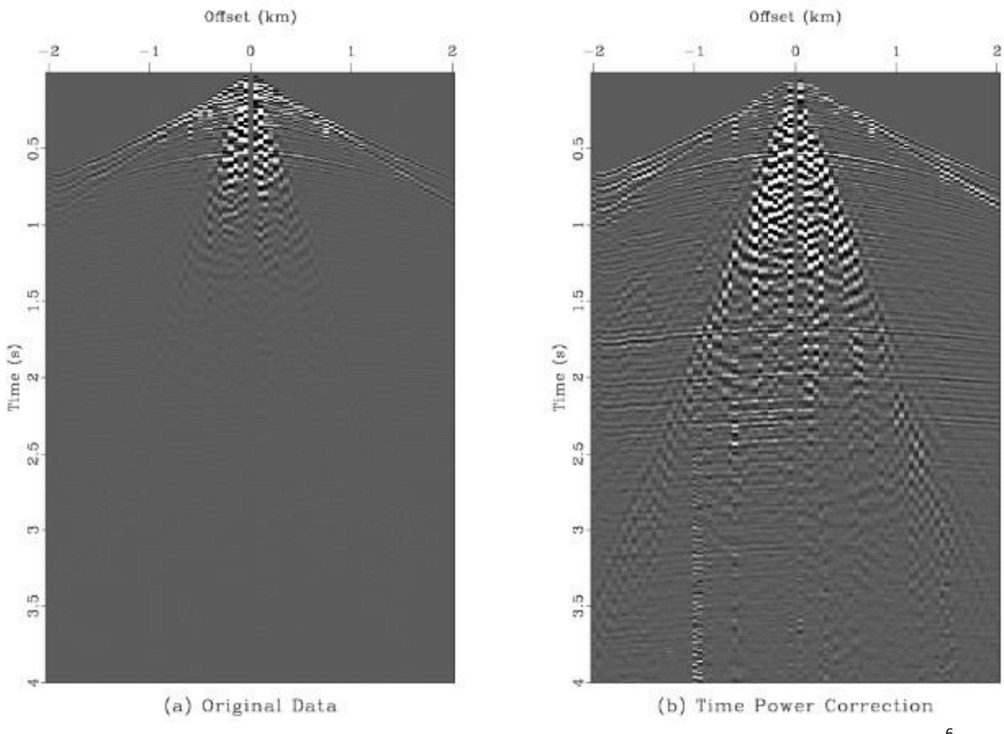

Figure 3.4: Gain application. Seismic shot record before and after time-power gain correction[6].

6. Application of field statics: the existence of a datum level is necessary for non-flat areas in order to reduce the travel time. This datum level can be the sea level (fig. 3.5).

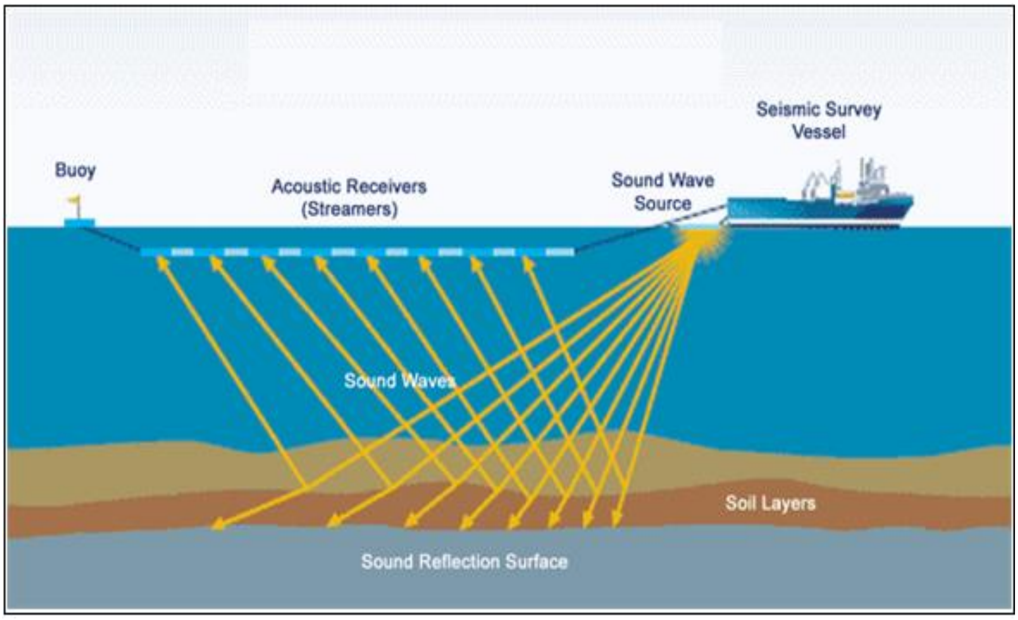

Figure 3.5: Application of field studies (Seismic Surveys[7]).

3.2 Trace Editing

The existence of a bad geophone can cause several problems in recordings. For that reason the replacement or the muted is needed. Below are shown two figures (processed using Matlab) which correspond to a shot gather, before and after trace editing and muting.

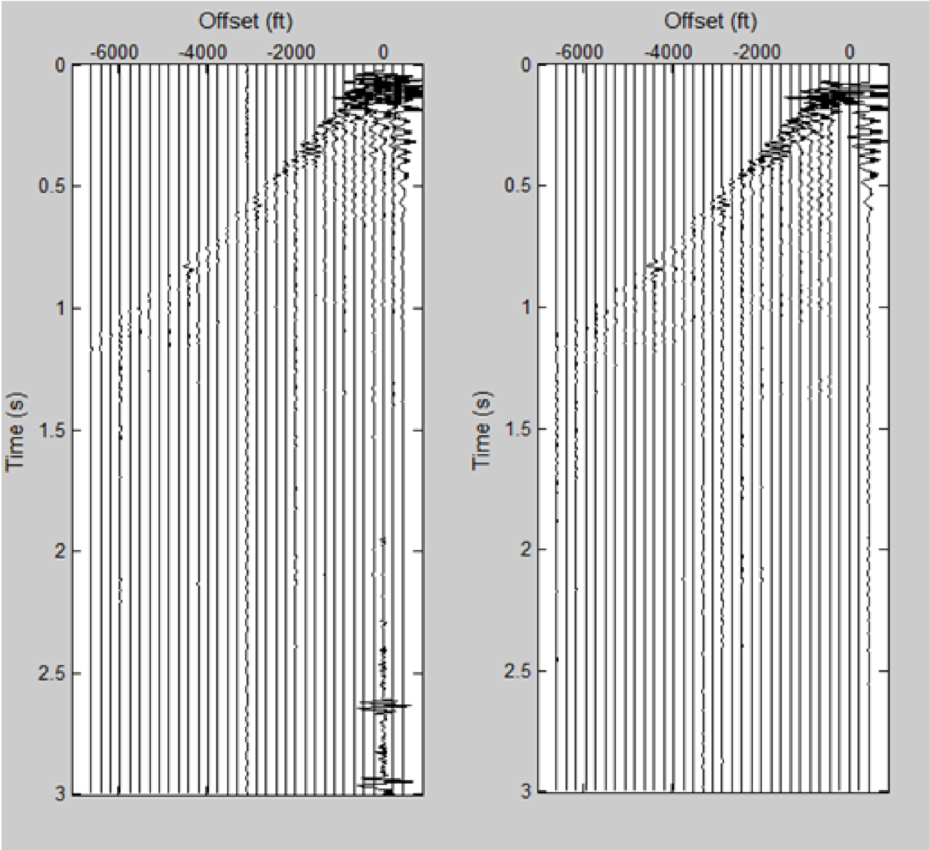

Figure 3.6: Seismic data before (left) and after (right) trace editing and muting (modified by Mousa and Al-Shuhail, 2011).

3.3 Losses and Correction of Amplitude

An exact seismic image of the subsurface structure is necessary. For this reason an appropriate quality control step for the correction of amplitude losses is needed. Heat and transmission losses by conversion of seismic energy are factors which affect and decrease the amplitude with time. The three main factors that affect the amplitudes are:

- Transmission loss: any loss which is able to occur when seismic waves are reflected refracted and scattered. The lost energy does not disappear which means there is no loss energy from mechanical view.
- Geometric divergence: the decrease of amplitude of signal in proportion to the distance between source and propagating seismic wave.
- Absorption: the loss of seismic energy by converting into heat energy. This conversion is a result of frictions. The loss is proportional to the exponential of the distance from the source.

As mentioned before, there are amplitude losses due to geometric divergence and absorption. All these losses must be addressed with amplitude corrections at the preprocessing stage. For the amplitude correction there are dependent and independent systems. The amplitude correction (fig. 3.7) of independent scheme becomes by multiplying the seismic trace amplitude with the time independent variable which has power of time.

$f_{corrected}(t)= f(t)t^a$ eq. 3.1

Where:

f(t)= seismic trace amplitude

t= time independent variable

a= the power of time

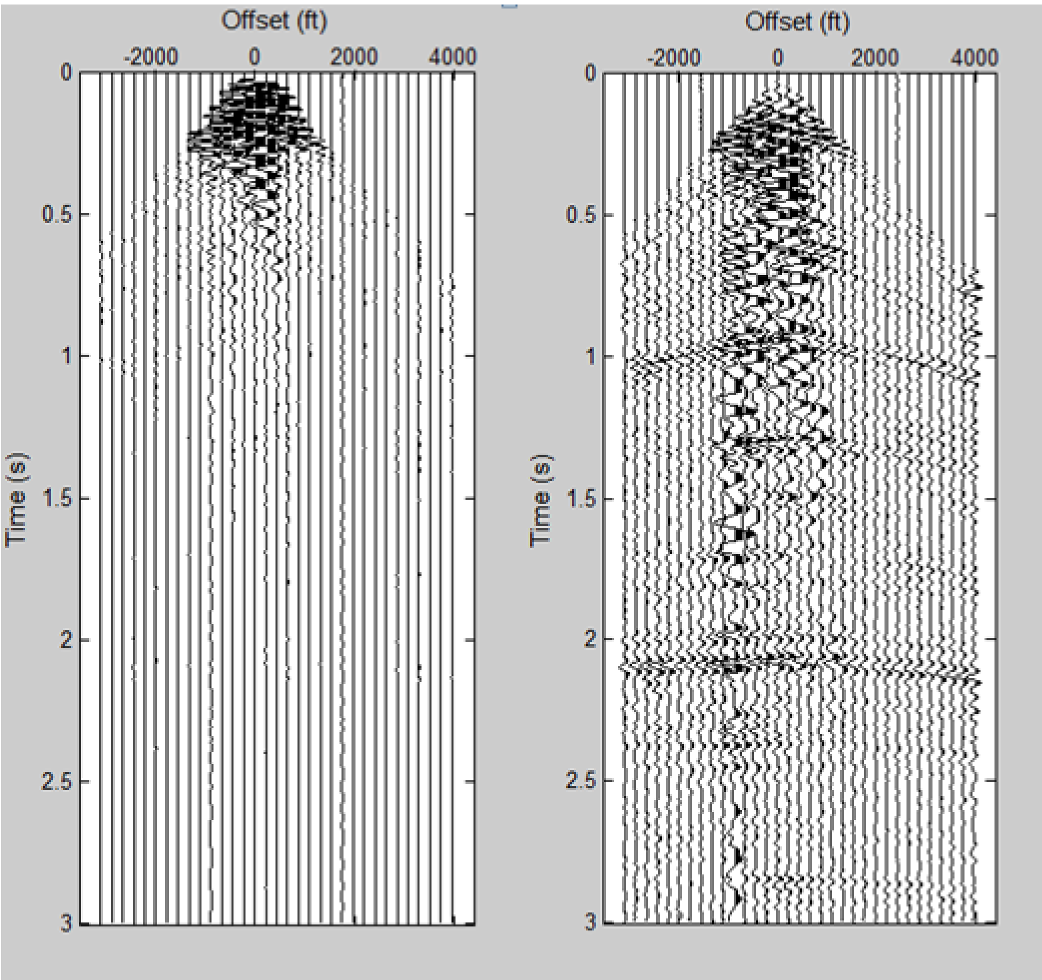

Figure 3.7: Seismic data before (left) and after (right) applying amplitude correction gain method of eq. 3.1 (modified by Mousa and Al-Shuhail, 2011).

On the other hand there is the automatic gain control (AGC) which is a system to control the gain, or the increase in the amplitude of an electrical signal from the original input to the amplified output, automatically. AGC is commonly used in seismic processing to improve visibility of late-arriving events in which attenuation or wavefront divergence has caused amplitude decay (Schlumberger Oilfield Glossary). Some of the famous AGC techniques (figs. 3.8-3.11) include:

a) The rms amplitude AGC gain function is calculated as follows. For an input trace there is a defined time gate. Each input trace is splitted into steady time gates and each one of these parts is squared. Subsequently, the average of the values is calculated and then the square root is taken. This is the whole procedure that should someone follow in order to take the rms amplitude over that gate. A step forward is the calculation of the value of the gain function at the center of the gate. This can be done by dividing the desired rms amplitude to the actual rms value. The corresponding function is:

$$g(t) = \frac{\text{desired rms}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}},$$

eq. 3.2

Where x_i is the trace amplitude and N is the number of samples within the gate. (Seismic Data Analysis –volume II- Öz Yilmaz).

b) The second AGC technique is the instantaneous one. The procedure which is followed for the calculation of the gain is as follows. Firstly, for a defined time gate, the average value of the trace amplitudes is computed. Secondly, the values of the gain function arising by dividing the desired rms level to this mean value. The difference between the rms amplitude AGC and instantaneous AGC is that the value of gain has been assigned at any time sample of the gain function, and not at the center of the gate. Subsequently, we have to move the time gate one sample down the trace and compute the value of the gain function. This must be done repeatedly The gain function is computed by the following formula:

$$g(t) = \frac{\text{desired rms}}{\frac{1}{N}\sum_{i=1}^{N} |x_i|},$$

eq. 3.3

Where x_i is the trace amplitude and N is the number of samples within the gate.

(Seismic Data Analysis –volume II- Öz Yilmaz)

A significant note is that someone must be very careful when applying amplitude corrections techniques since they may destroy the signals character.

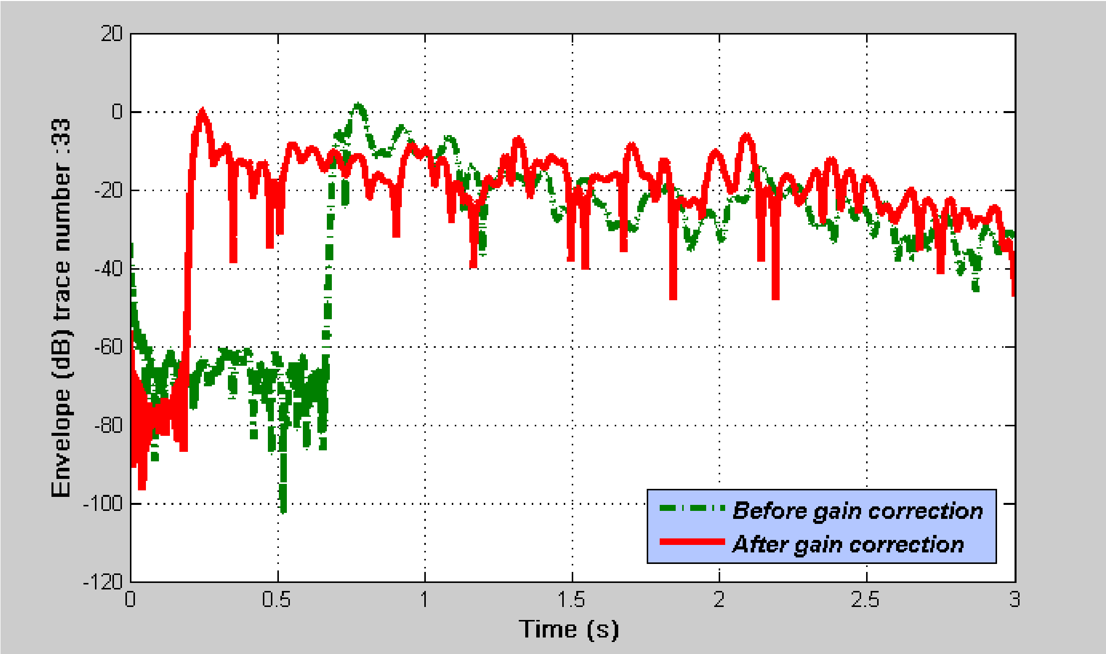

Figure 3.8: The amplitude envelope gain in dB for trace 33 (modified by Mousa and Al-Shuhail, 2011).

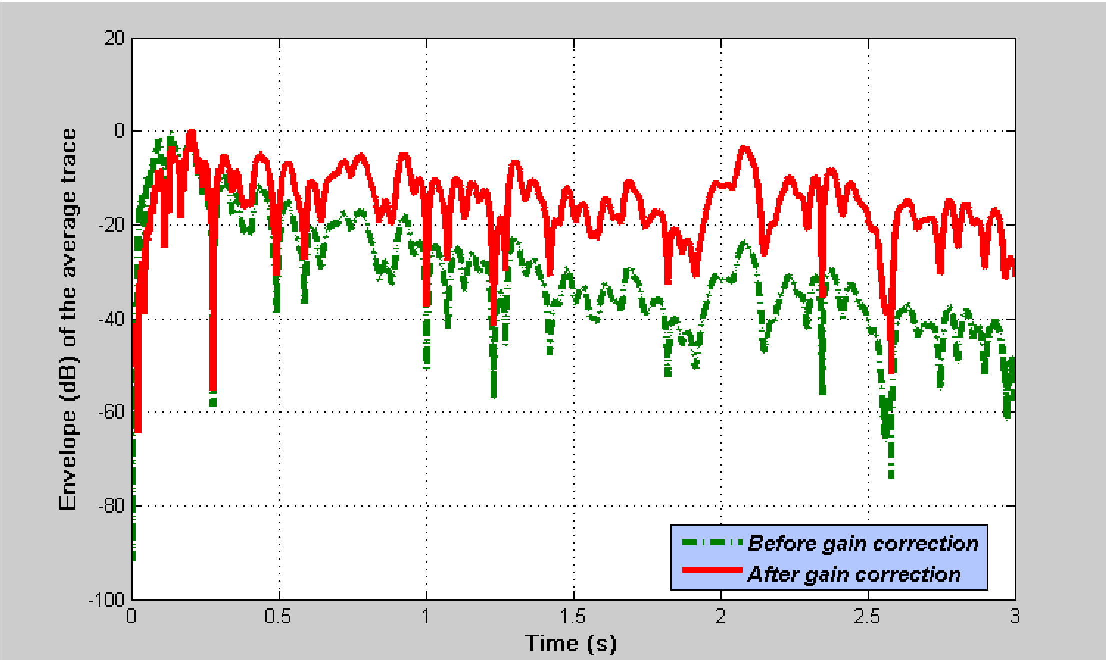

Figure 3.9: The amplitude envelope gain in dB for the average trace (modified by Mousa and Al-Shuhail, 2011).

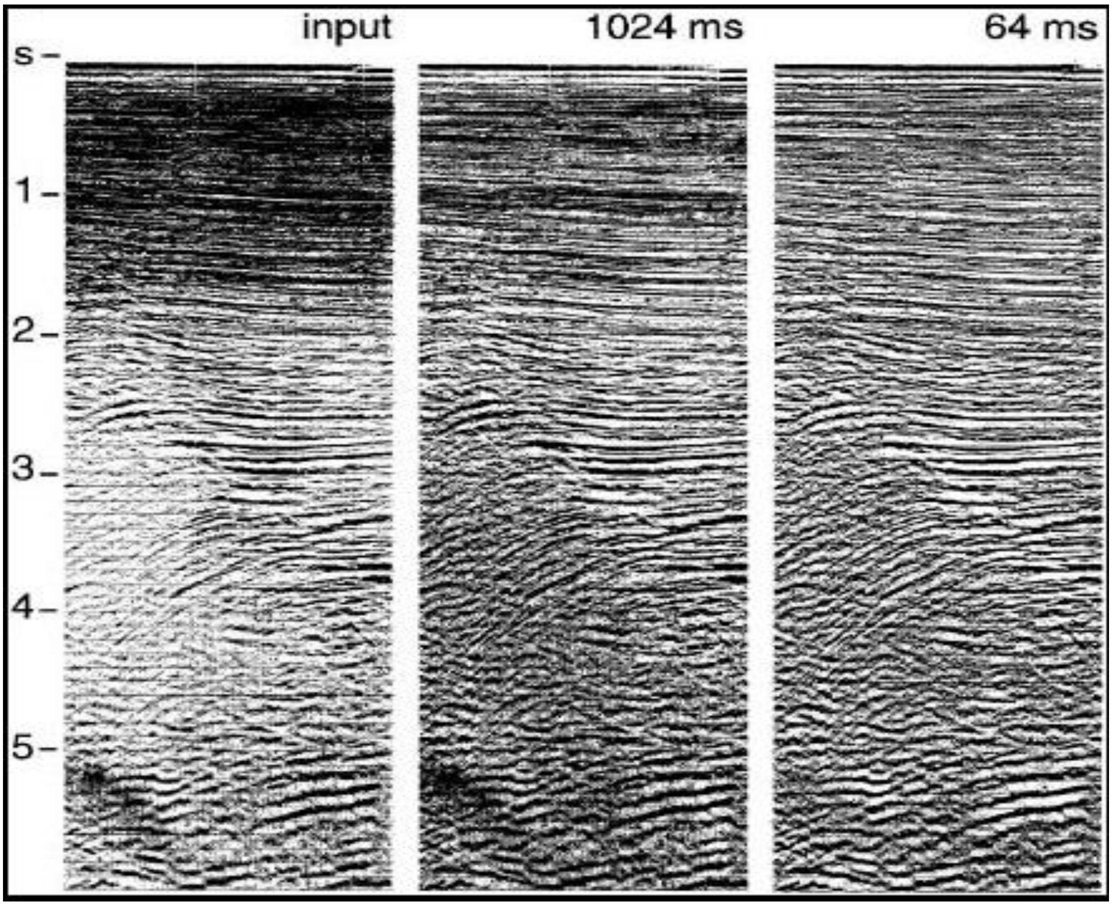

Figure 3.10: A portion of a CMP stack before and after application of two different rms AGC functions[8]. (Yilmaz, O., 1994, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.)

4. Seismic Noise Attenuation

4.1 Introduction

In the oil industry the seismic interpretation is the most significant parameter. More and more companies spend much money in order to have modern and efficient technology for better exploitation of reserves and to maximize their profits. For this purpose, a good interpretation of seismic data is extremely considerable. In this direction, a clean signal without noise is required. There are many factors which can affect the seismic signal and destroy the seismic data. This noise which in other words is an unwanted energy can be classified in two categories. The random noise and the coherent noise. It is easily understood that each noise must be eliminated for better results. This can be done by improving as much as possible of signal-to-noise ratio (SNR).

4.2 The Importance of Noise Attenuation

The noise attenuation (figs. 4.1 4.2) is very important for seismic recording, because it contributes to better seismic interpretation. Some significant issues concerning the noise attenuation are the following:

- The quality of input data is very important for each deterministic process due to the fact that is derived by surface amplitude correction. Hence, the removal of noise is necessary.
- For the pre-stack imaging the removal of noise is obligatory. The Common Depth Point (CDP) is a tool of noise attenuation but it cannot be used for pre-stack imaging, because the noise must be faced prior to imaging.
- The correct treatment of the noise provides the opportunity to avoid amplitude losses.
- A clean signal without noise which gives perfect seismic interpretation is able to offer much better understand of subsurface structures and reservoirs.

It is very important to know the source of the noise as well as the noise characteristics in order to efficiently attenuate the noise. However, beyond the source of noise, the characteristics come under two main categories, random and coherent noise, as mentioned before(Seismic Processing – Noise Attenuation Techniques. For Relative Amplitude Processing. By Carolyn Dingus Center Manager, ION/GXT-Guide[9])

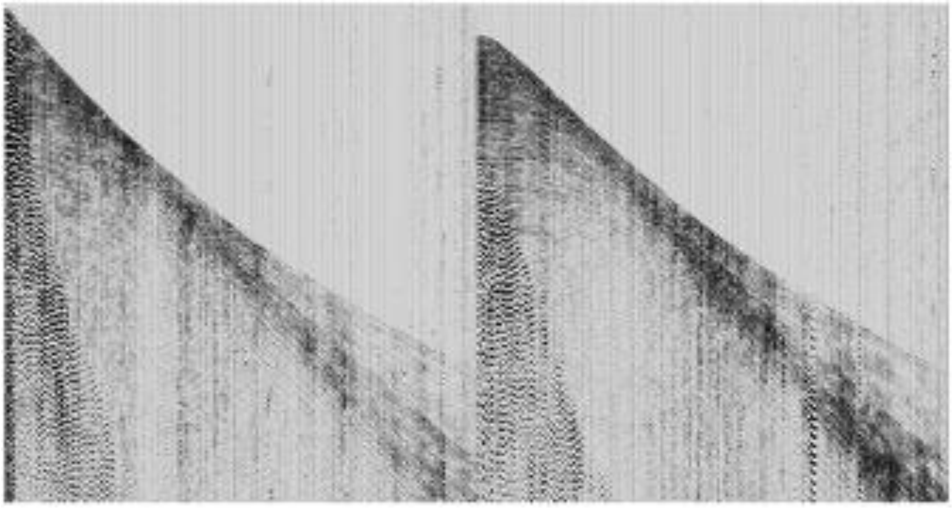

Figure 4.1: Before noise attenuation (Seimax Technologies[10])

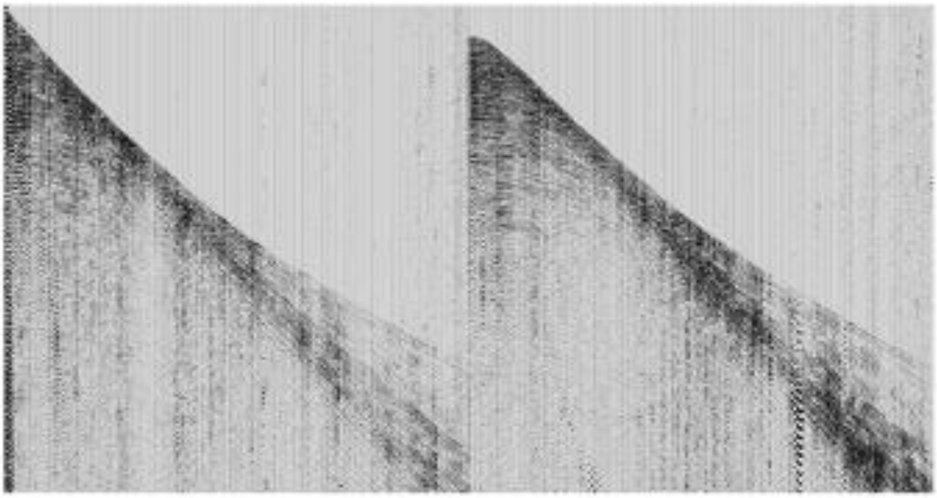

Figure 4.2: After noise attenuation (Seimax Technologies)

4.2.1 Random Noise

Noise presents different characteristics in frequency and amplitude depending on the area where the data are collected,. In case the noise is not coherent, it is called random noise (fig. 4.3). This type of noise can be faced by isolating. There are also some other ways to attenuate noise such as deconvolution, frequency filtering, stacking and many other methods.

Figure 4.3: Example of ''Photographer'' with 40% random noise[11].

4.2.2 Coherent Noise and Ground Roll Noise

Coherent noise as well as random noise is undesirable seismic energy. These two types of noise differ in fact that the coherent noise shows continuous phase from trace to trace. The ground roll (figs 4.4, 4.5), coherent scattered waves and multiples (?) constitute examples of coherent noise. For the attenuation and suppression of coherent noise there are several techniques. Due to the fact that the ground roll coherent noise is the main noise in a real seismic data, it must be described.

Signal and noise components are always parts of the seismic data and an effective method, in order to eliminate noise, is an algorithm which removes the noise and improves the time-frequency. This algorithm can be set up using matlab. The main type of coherent noise is the ground roll noise which is characterized by high amplitudes and low frequencies. This type of noise can be faced by frequency filtering, wavelet transforms and many other methods.

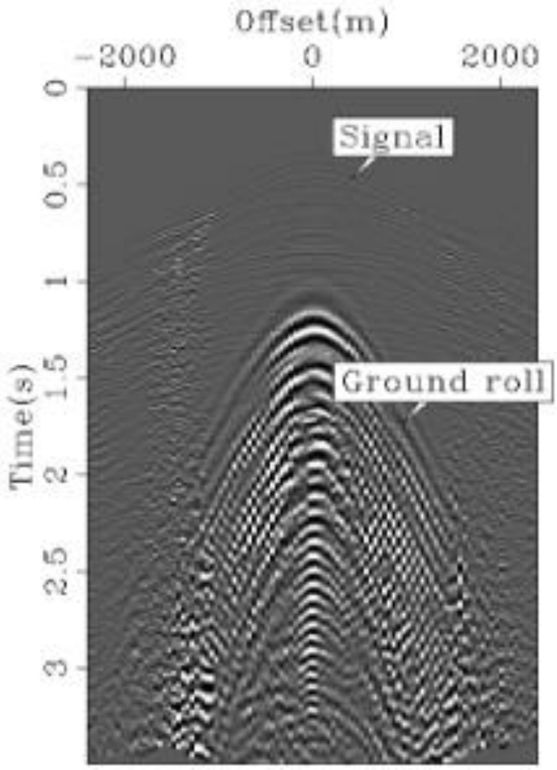

Figure 4.4: Shot record from a land acquisition in Saudi Arabia[12]. (Ground roll noise).

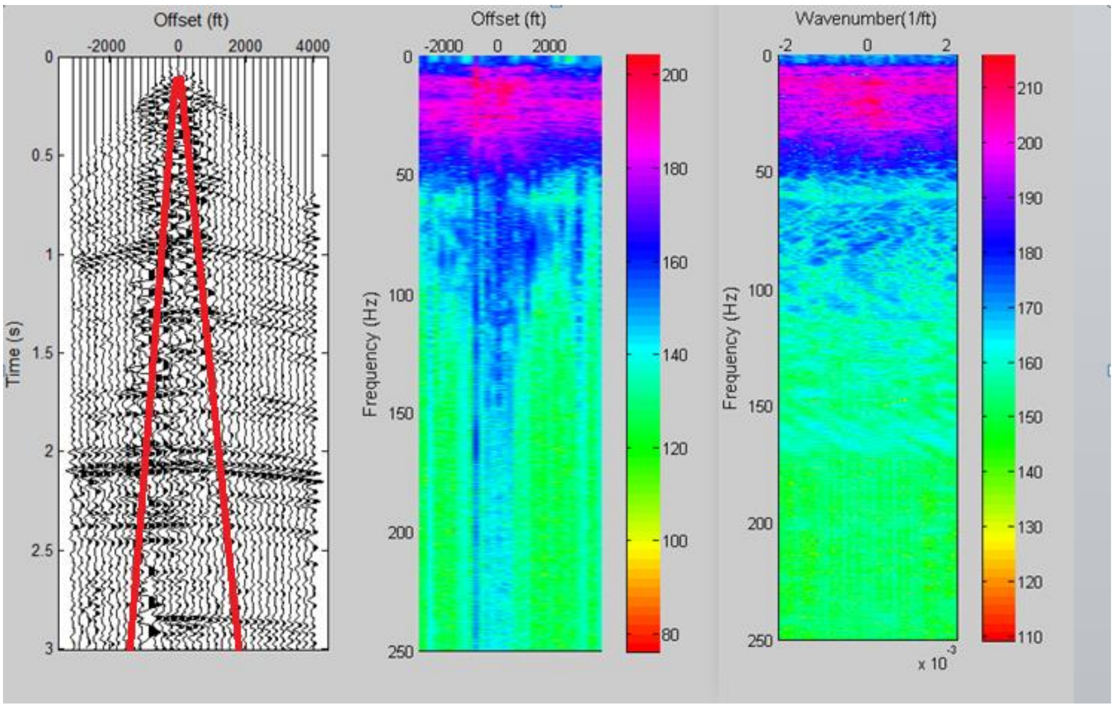

Figure 4.5: Seismic data containing ground roll noise, marked with red lines (left). Frequency vs Offset magnitude spectra (middle). Frequency vs Wavenumber magnitude spectra (modified by Mousa and Al-Shuhail, 2011).

4.3 Spectrum Analysis and Filtering of Seismic Data

A good seismic data processing is vital for a reliable seismic interpretation and the filtering process is mostly the most significant step to this direction. Filtering process includes all the steps which are needed in order to remove each unwanted frequency component, and that can be happen through bandpass frequency filtering (BPF). The bandpass filtering (BDF) aims to increase the total gain of each seismic shot gather and furthermore to correct high and low frequency noise records by increasing the signal-to-noise ratio. Although the more filters can be used in several domains, the bandpass filters (figs. 4.6 - 4.8) can be used mostly in the frequency domain. Another important characteristic of BPF is the fact that it is applied in post migrated data. Moreover, the bandpass filters can be applied in the time or in the frequency domain by convolution or multiplication respectively. However, the most important issue is to understand the analysis of seismic data in the spectrum domain by using MATLAB. For that analysis there are several means. Firstly, there is the frequency content of 1-D time or space signal. Secondly, there is 2-D which can be frequency-space or frequency-wavenumber. Each one of these two can be used to obtain the best possible filtering technique with the aim to export the better interpretation. The plots which are going to arise of these interpretations are very significant and vital, especially, applying linear filtering to 1-D and 2-D seismic data sets(Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail)

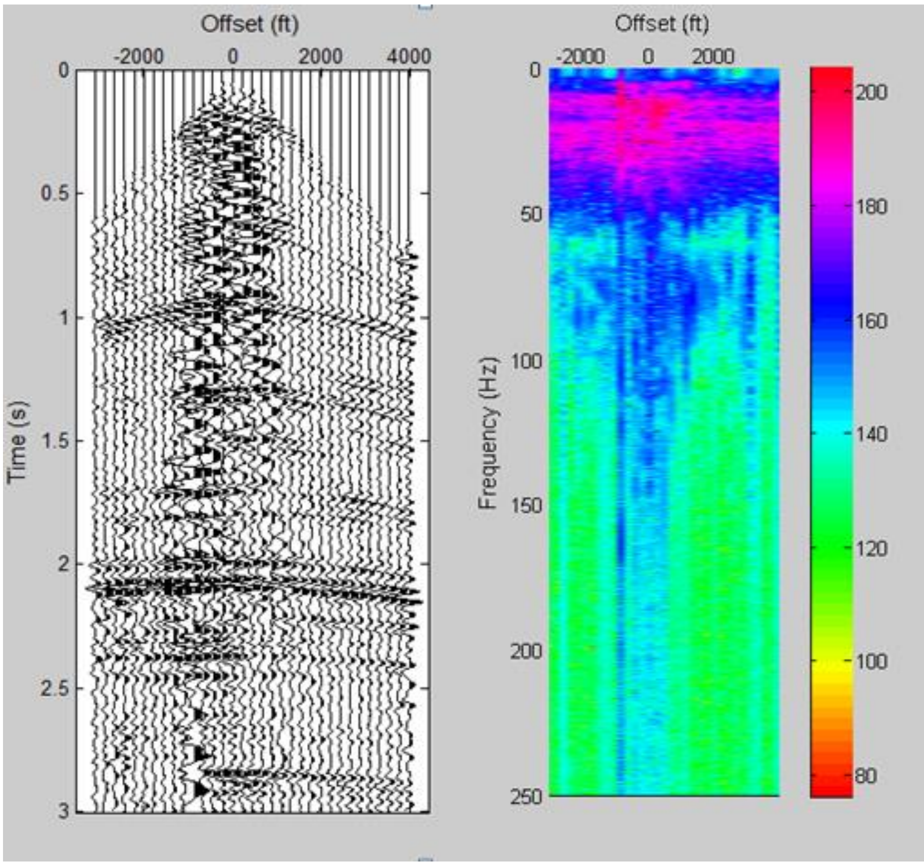

Figure 4.6: Seismic data containing ground roll noise before BPF filtering (modified by Mousa and Al-Shuhail, 2011).

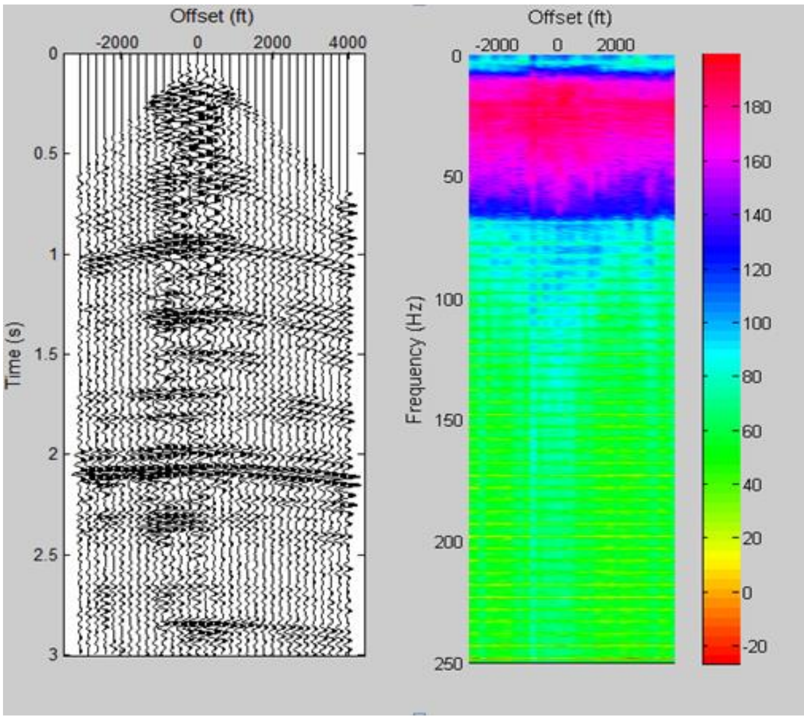

Figure 4.7: Seismic data containing ground roll noise after BPF filtering (modified by Mousa and Al-Shuhail, 2011).

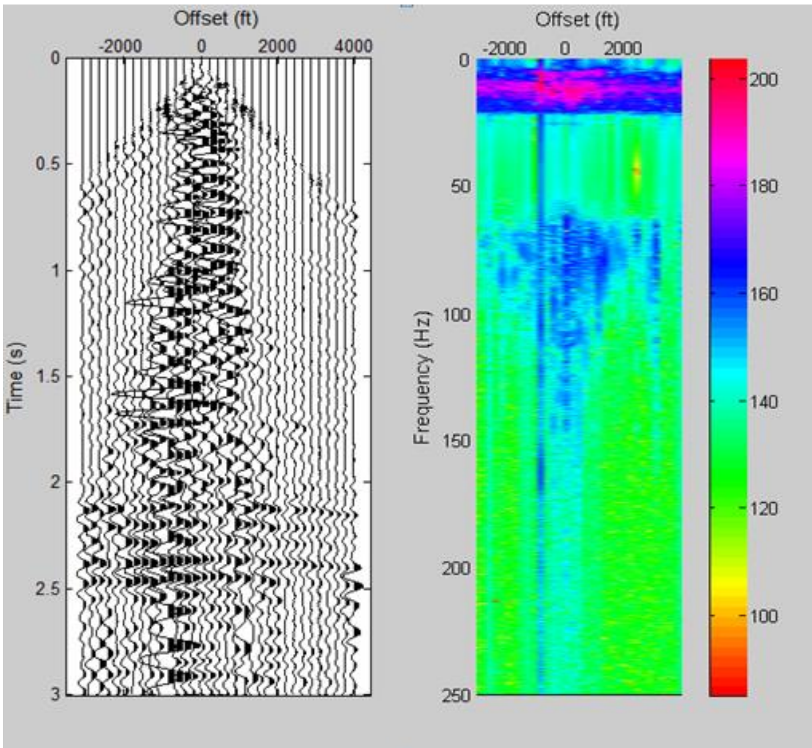

Figure 4.8: The difference between before and after BFP filtering (modified by Mousa and Al-Shuhail, 2011).

5. Seismic Deconvolution

5.1 Introduction

Deconvolution is a very important process which is applied to seismic data and the main topic of that process is the compression of the basic wavelet in the recorded seismogram and the attenuation of reverberations and short-period multiples. As a result, deconvolution increases resolution and yields a more interpretable seismic section (fig. 5.1). Seismic deconvolution can use as well for noise attenuation such as multiples. Moreover, there are many stages of deconvolution and each one has different type and objective.

Different kinds of deconvolution are generally described by the different adjectives. They usually designate the type of assumptions made in the process. a) Deterministic deconvolution: can be used to remove the effects of the recording system, if the system characteristics are known. This type of deconvolution can also be used to remove the ringing that results from waves undergoing multiple bounces in the water layer, if the travel time in the water layer and the reflectivity of the seafloor are known. b) Spiking deconvolution: shortens the embedded wavelet and attempts to make it as close as possible to a spike. c) Predictive deconvolution: uses the later portions of the autocorrelation to remove the effects of some multiples. d) Sparse-spike deconvolution attempts to minimize the number of reflections, thus emphasizing large amplitudes. However, before deconvolution, must be defined the seismic convolutional model. ("What Is Deconvolution" - By Robert E. Sheriff, Professor, University of Huston - Search and Discovery Article - 40131 (2004))[13].

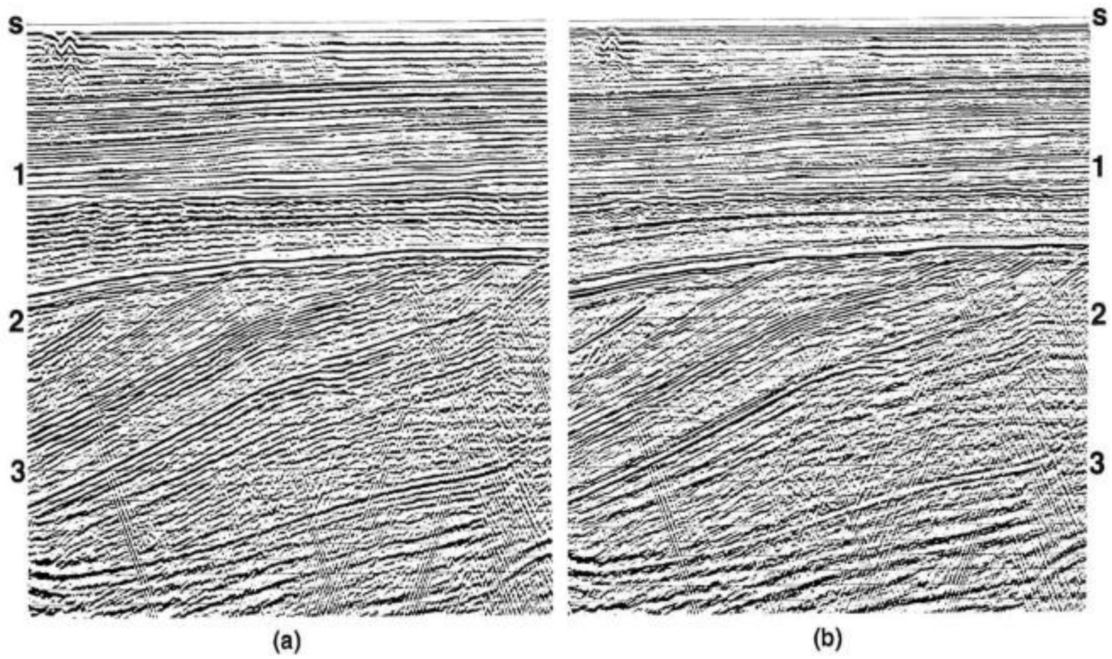

Figure 5.1: Seismic line without deconvolution (a) and with deconvolution (b). (Yilmaz, O., 1994, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.)

5.2 The Seismic Convolution Model

In order to explain how the seismic trace is formed, the seismic convolution model is necessary. Convolution is a mathematical way of combining two signals to take another modified signal. The process of convolution is the reversal of the deconvolution process. Convolution is represented in the frequency domain by multiplying the amplitude spectra and adding the phase spectra. In addition, the earth's reflectivity could be obtained by deconvolving the source wavelet, however, noise and some other features are also present in the recorded trace and in the most cases, the source wavelet is unknown or rarely known with any accuracy. In other words, the seismic trace as a function of time is equal with the production of wavelet vector multiplying by reflectivity series and adding some noise.

Mathematically expressed as: $s_n(t) = w(t)*e(t)+\gamma(t)$ eq. 5.1

Where $s_n(t)$ is the seismic trace as a function of time t, w is the wavelet vector, e is the reflectivity series and γ is noise.

As it mentioned above, the process of convolution is the reversal of the deconvolution process. The deconvolution is used for two reasons. The first and main reason is the computation of earth reflectivity. It is important to be mentioned that depending if it is known or unknown the source wavelet, the convolution becomes deterministic and statistical respectively. The second reason is the computation of source wavelet w(t) given the seismic trace s(t) and the earth's reflectivity e(t).

The following rules are necessary in order to be valid the seismic convolutional model: a) the source wavelet is stationary, b) the Earth's velocity is constant and the layers are horizontal, c) the Earth's reflectivity e(t) is a random series of impulses, d) the source generates only a primary wave, e) the noise component is zero, f) The seismic wavelet is a minimum - phase wavelet. If one or more of the above rules are not satisfied then the process of deconvolution is needed (Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail).

5.3 Spiking Deconvolution

The spiking deconvolution (figs. 5.2, 5.3) is the process at which the effect of source wavelet is removed and the effect of the Earth's reflectivity is the only one remained in the seismogram. This can be happen by the compression of the source wavelet into a zero-phase spike of zero width. The convolution of the inverse filter h(t) with the seismic trace s(t) provides the spiking deconvolution (figs. 5.4, 5.5, 5.6, 5.7):

$h(t)*s(t) = h(t)*[w(t)*e(t)] = [h(t)*w(t)]*e(t) = \delta(t)*e(t) = e(t)$ eq. 5.2

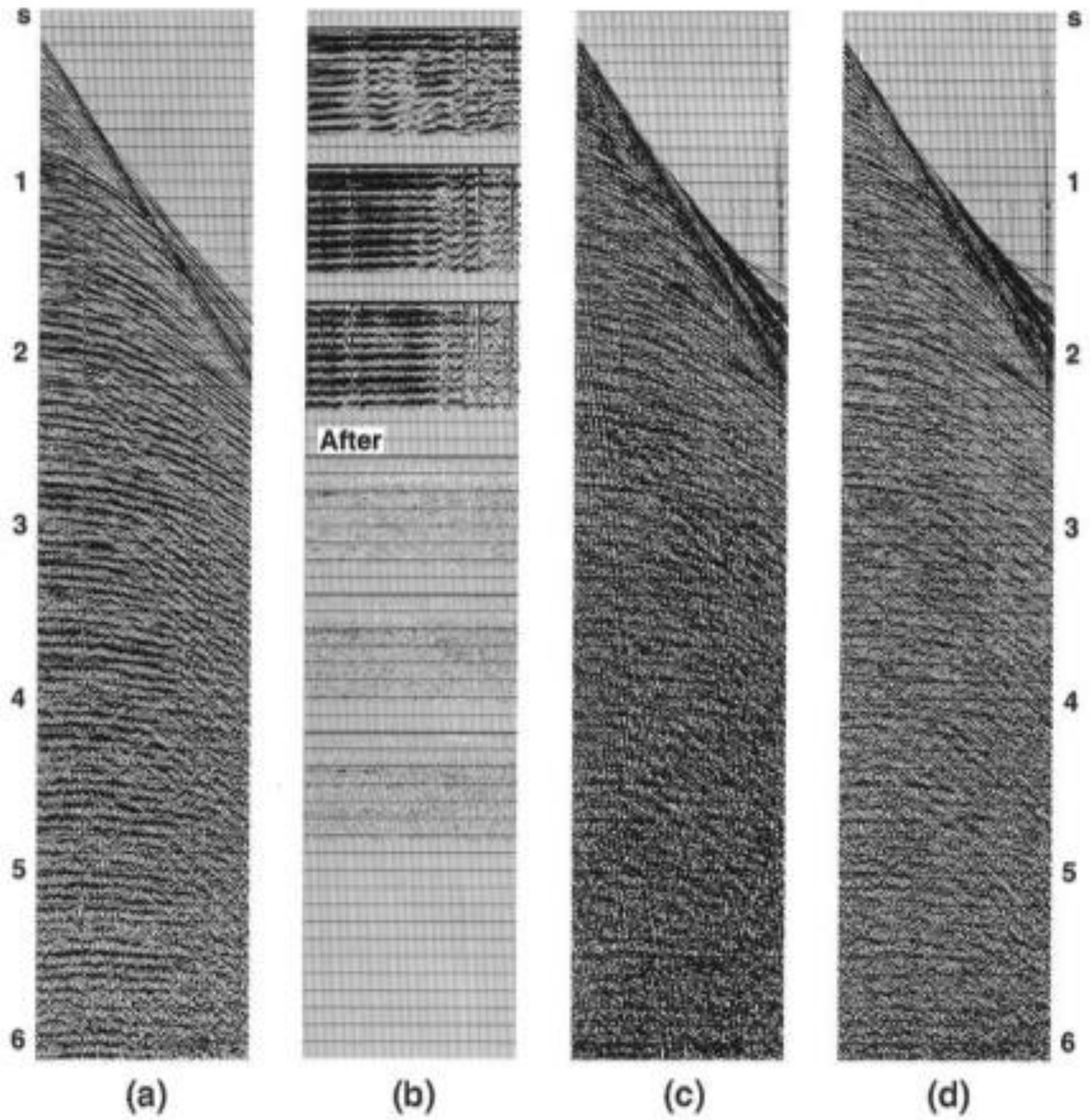

Figure 5.2: Three-window deconvolution on the same shot record. (a) Input gather, (b) autocorrelograms before and after spiking deconvolution, (c) three-window spiking deconvolution on (a), (d) band-pass filtering on (c). (Yilmaz, O., 1994, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.)

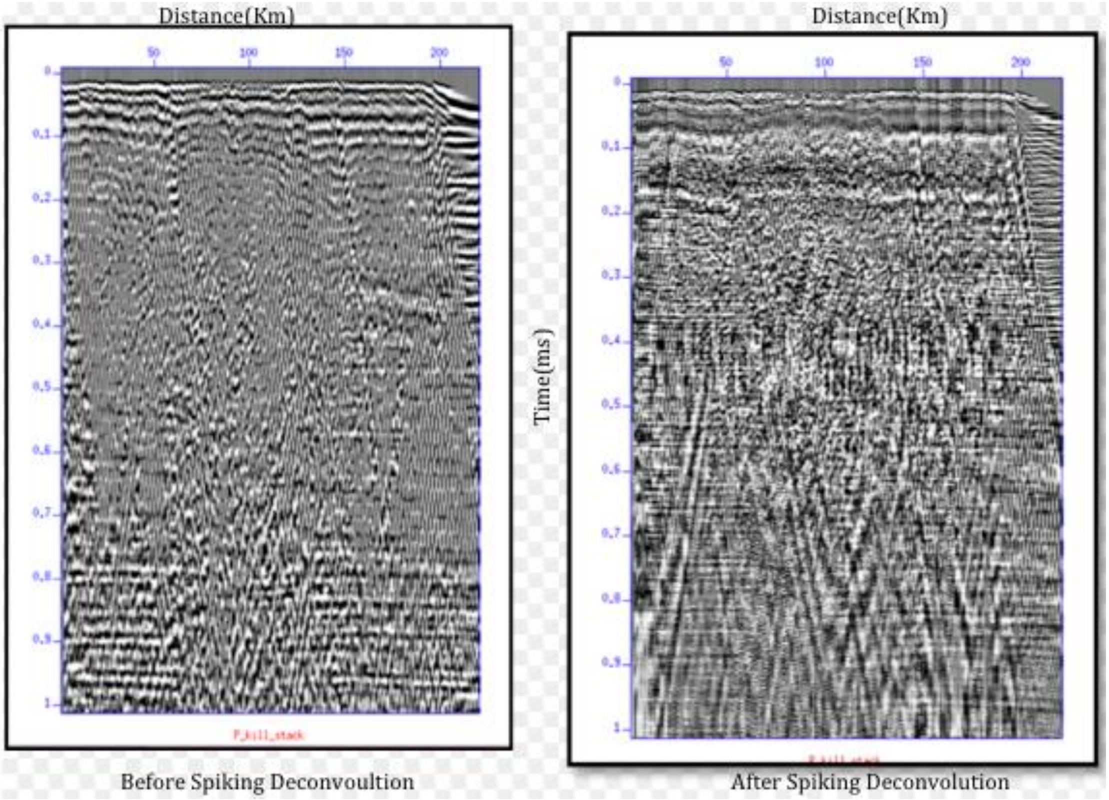

Figure 5.3: Spiking Deconvolution, before and after. (Wikimedia Commons[14])

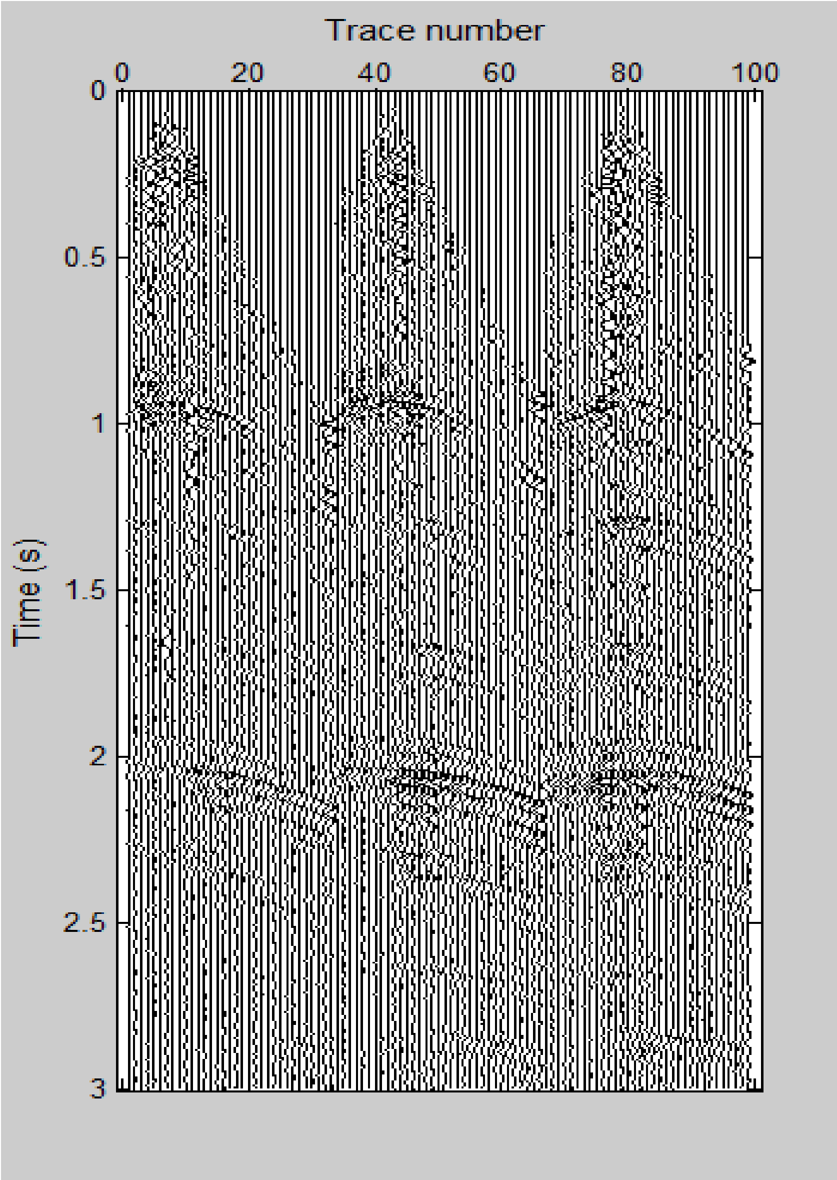

Figure 5.4: Shot gathers before applying spiking deconvolution (modified by Mousa and Al-Shuhail, 2011).

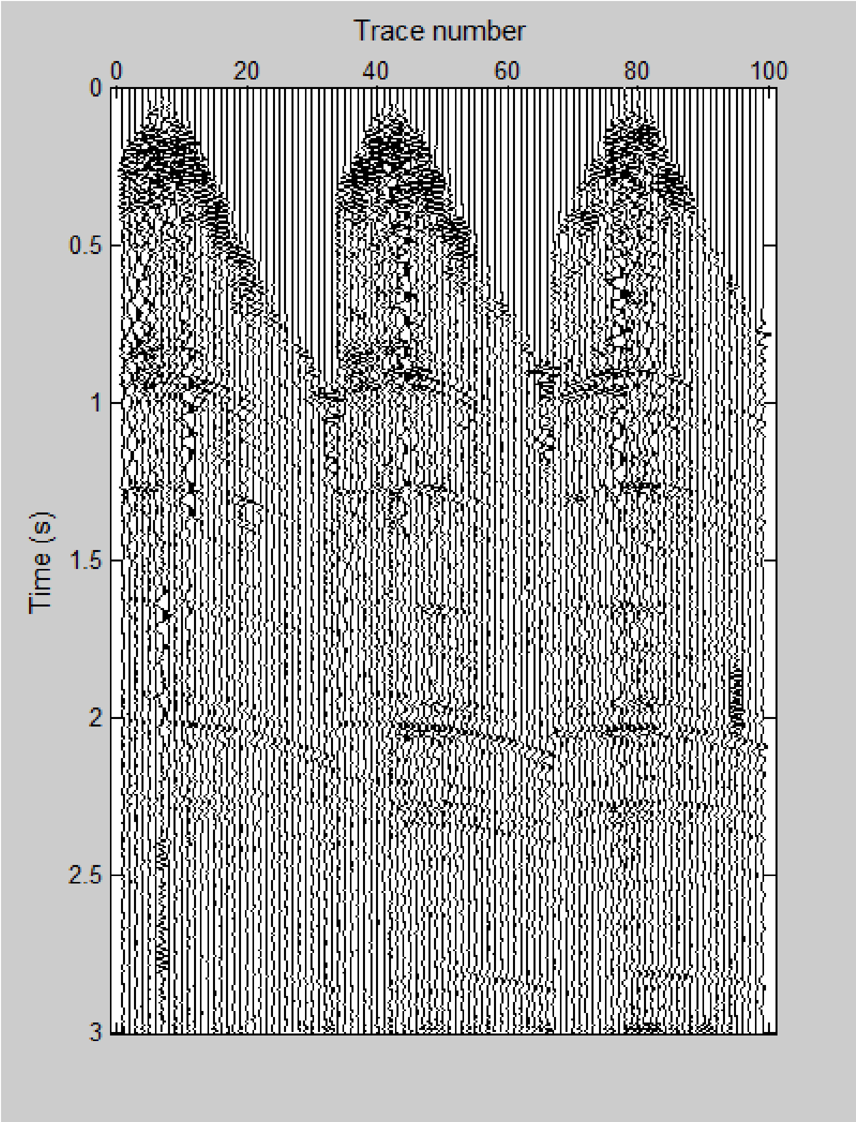

Figure 5.5: Shot gathers after applying spiking deconvolution (modified by Mousa and Al-Shuhail, 2011).

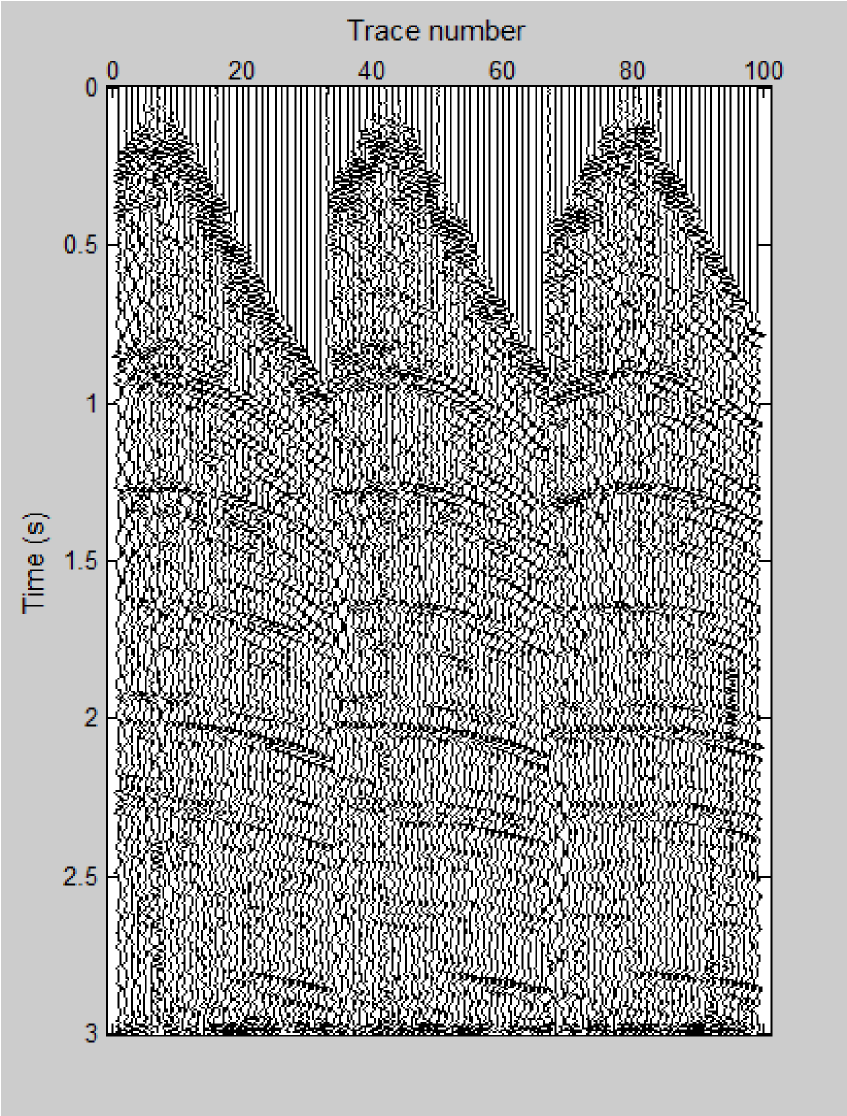

Figure 5.6: Shot gather after applying spiking deconvolution and Instantaneous AGC (modified by Mousa and Al-Shuhail, 2011).

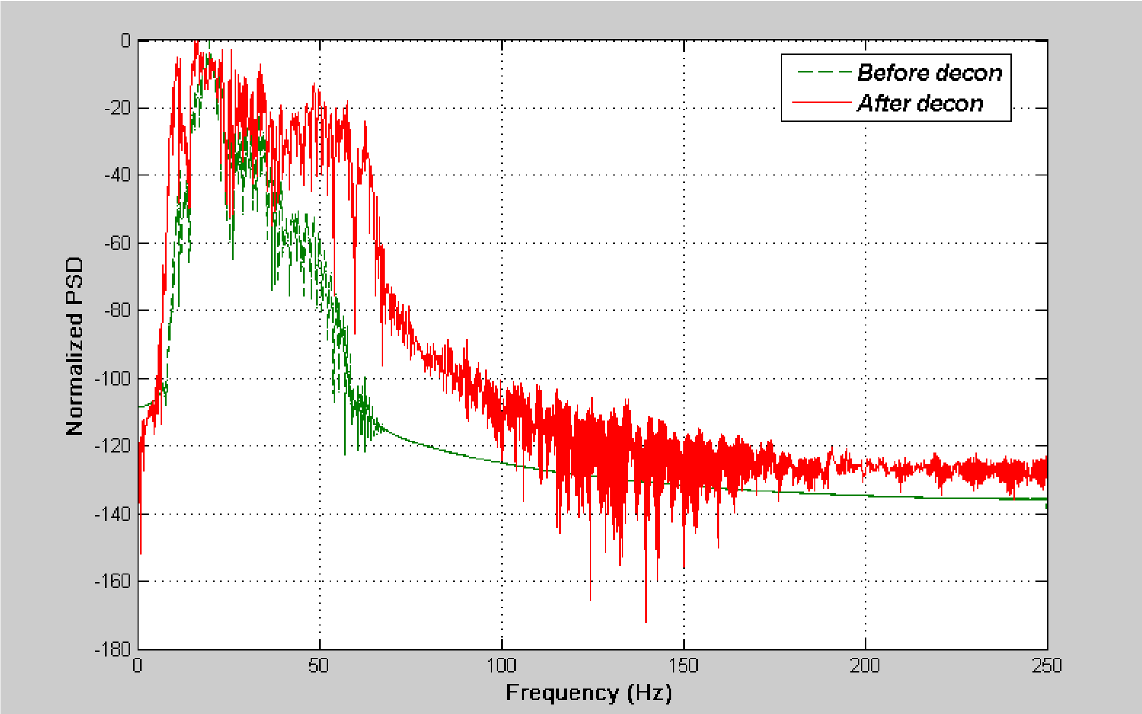

Figure 5.7: PSD of the average trace of shot gathers before and after spiking deconvolution (modified by Mousa and Al-Shuhail, 2011).

5.4 Spiking Deconvolution Using Wiener Optimum Filters

An optimum filter differs from the classical filters such as bandpass which mentioned above, in the fact that is used for the best possible estimation of desired signal from noise measurements. Optimal filters do an optimization with the aim to eliminate or to minimize the average square error between a processed and desired signal. Wiener filters are linear optimum filters.

5.5 The Trace – Wavelet Relation

As mentioned in the previous chapters, the knowledge of the autocorrelation of the source wavelet (fig. 5.8) is necessary in order to perform the process of spiking deconvolution. However, there is a drawback in this direction because the source wavelet for several sources which are mainly impulsive is unknown and there is a difficulty in performing deconvolution or filtering. Hence, the estimation of source wavelet or on the other hand, each relation that can be exist between autocorrelations of seismic trace and source wavelet is necessary for that purpose.

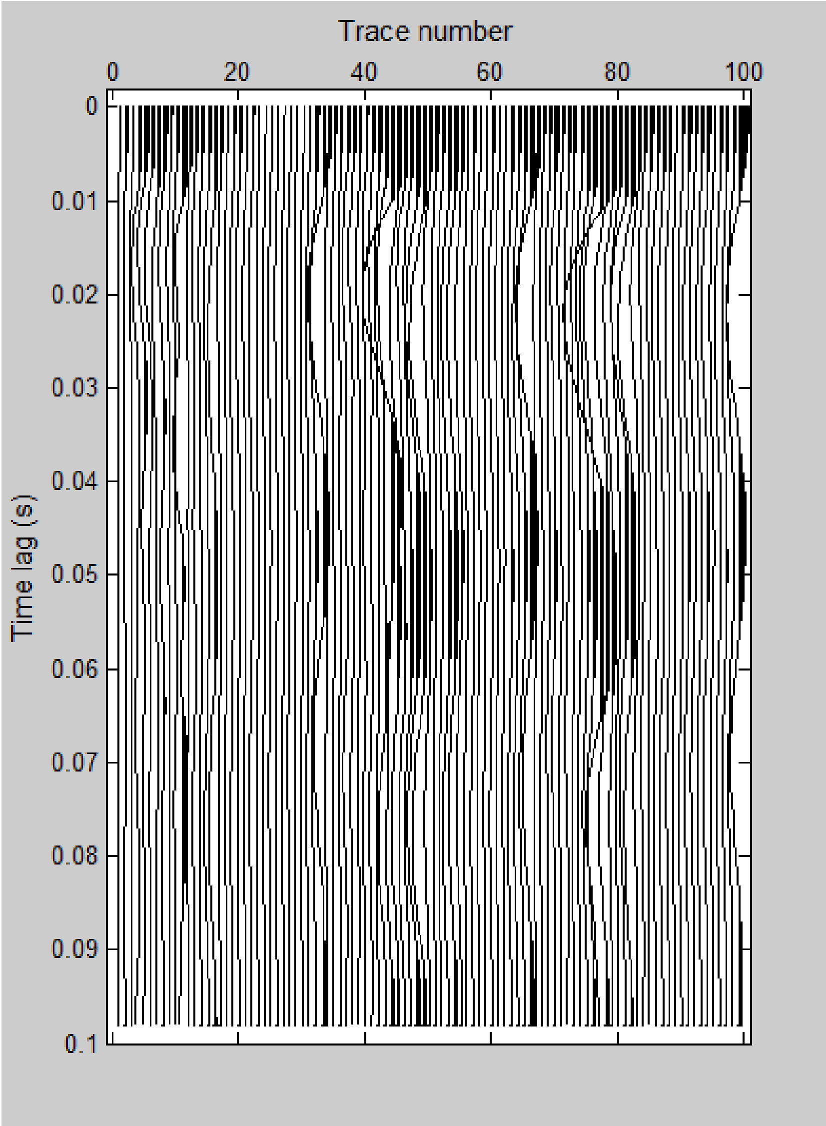

Figure 5.8: Autocorrelogram of shot gathers (modified by Mousa and Al-Shuhail, 2011)

5.6 Spiking Deconvolution in Practice

The parameters of Autocorrelation window, Filter length and Percent pre-whitening are necessary in order to perform the spiking deconvolution. In more detail:

- Autocorrelation window (w): This sets up the part of seismic trace from which we will select the elements of the autocorrelation matrix in the normal equations.
- Filter length (N): This sets up the length of the spiking filter h(n).
- Percent pre-whitening (ε): This sets up the amount of white random noise we want to include into our autocorrelation matrix to stabilize the solution of the normal equations(Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail)

5.6.1 Autocorrelation Window

The whole characteristics of the autocorrelation (fig. 5.9) of the seismic trace affect the appropriate choice of deconvolution parameters, which mean that the choice of autocorrelation window is extremely significant for the calculation of deconvolution parameters. Moreover, the autocorrelation window must include all these parts which contain practical reflection signals and not whichever noise, like coherent or incoherent noise.

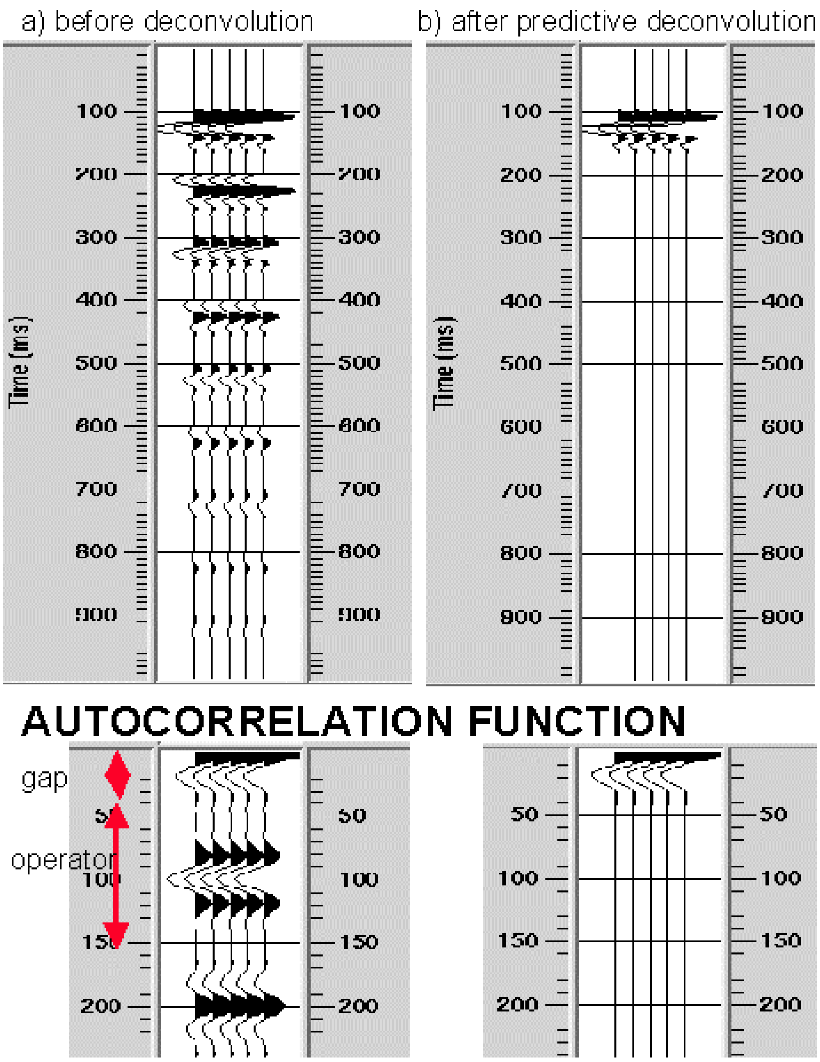

Figure 5.9: Autocorrelation function[15].

5.6.2 Filter Length

For spiking deconvolution, the kind of the filter (operator) length used, must have the same length with the wavelet length. Due to the fact that the first transient zone of the trace autocorrelation has all the characteristics of the wavelet autocorrelation and contains high amplitudes, it should be selected in order to be almost equal to the operator length, as mentioned before. Moreover, the amount of energy in the trace autocorrelogram which comes from the optimum filter length should be as less as possible.

5.6.3 Percent Pre-whitening

The amplitude spectrum of the source wavelet is the inverse of the amplitude spectrum of the spiking deconvolution operator. The phenomenon which has been observed is the difference at the frequency values between these two amplitude spectrums. More specifically, when the amplitude spectrum of the source wavelet is zero at some frequencies, then, at the same frequencies the amplitude spectrum of the spiking deconvolution operator will be infinite. Similar to the previous difference, is the inversion of the trace autocorrelation matrix when the determinant of the autocorrelation matrix is zero. In this case is used a procedure known as pre-whitening.

Pre-whitening (fig. 5.10) is a process where a white random noise is added. This noise has a fairly small variance with respect to the trace amplitudes at every time sample. This addition is equivalent to a very small positive constant to the zero - lag autocorrelation of the trace as well as to a very small positive constant to the amplitude spectrum of the trace at every frequency component. The extent of pre-whitening is mostly measured as a percentage of the zero-lag autocorrelation value (Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail).

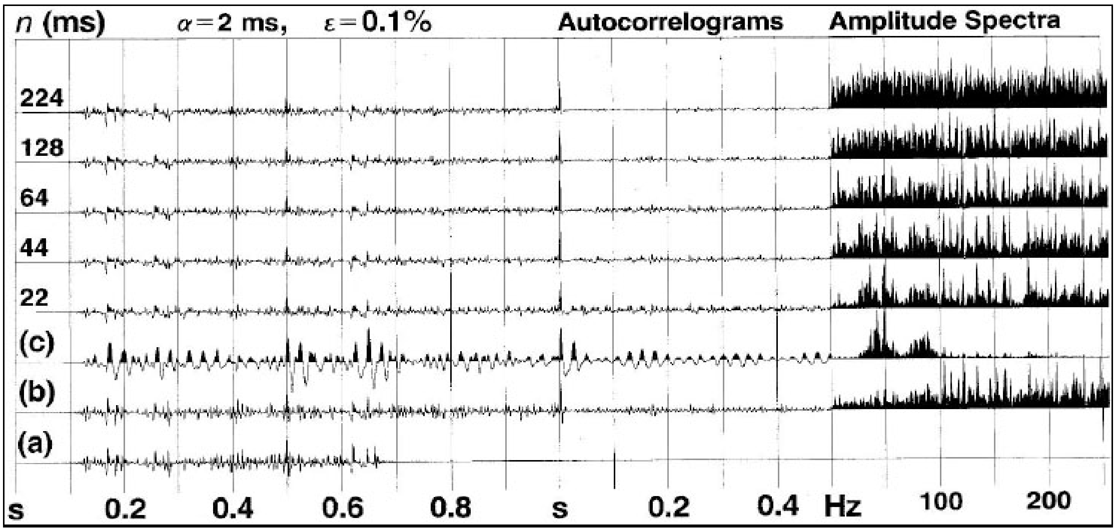

Figure 5.10: Test of operator length where *n* = operator length, *α* = prediction lag, and ***ε*** = **percent prewhitening** (Yilmaz, O., 1997, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.).

6. Carrying the Processing Forward

6.1 Introduction

Data quality control, frequency filters and deconvolution are seismic processing steps which were mentioned in the previous chapters. Understanding the mechanism of all these steps, it is quite easy afterward to reflect the real image of the subsurface. Stacked section is the term for the first possible subsurface image approximation, and that can be happen by examining separately the three main steps which are included in a compressed seismic data.

Sorting the shot gathered data into CMP (common mid-point) is the first step. Afterward, are selected the appropriate stacking velocities and accordingly are made the normal moveout corrections (NMO). The last step includes stacking of all common mid points.

6.2 Common Mid-Point (CMP) Sorting

Common depth point, common mid-point or common reflection points are sorting methods which are used in seismic reflection methods. In these methods, many and different source - receiver pairs are used in order to catch through reflection as many as possible points in the subsurface for more than one time. All the traces which are reflected from the same mid-point create a common mid-point gather. Moreover, the total number of all these traces in the gather represents the fold (fig. 6.1) of the gather.

The stacking charts were created from the need of sorting the traces between the shot gather mode and the common mid-point offset mode. These charts are composed from two axes, a horizontal x-axis (geophone location) and a y-axis (source location). Beyond the sort of traces into various modes, this chart is used to sort gathers such as shot, receiver or common mid-point. In a stacking chart (figs. 6.2, 6.3) are observed four lines. A vertical line at which the points have a common receiver, a horizontal line at which the points have a common source, a right diagonal line at which the points have a common mid-point and finally a left diagonal line at which the points have a common offset.

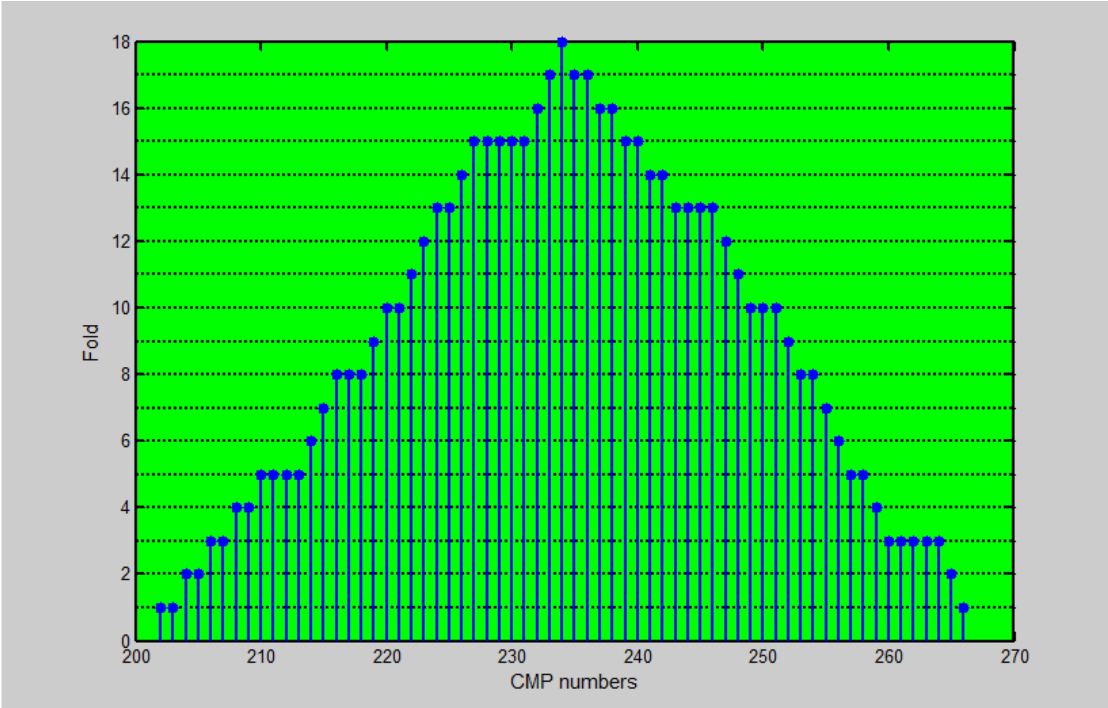

Figure 6.1: The fold vs the CMP numbers.

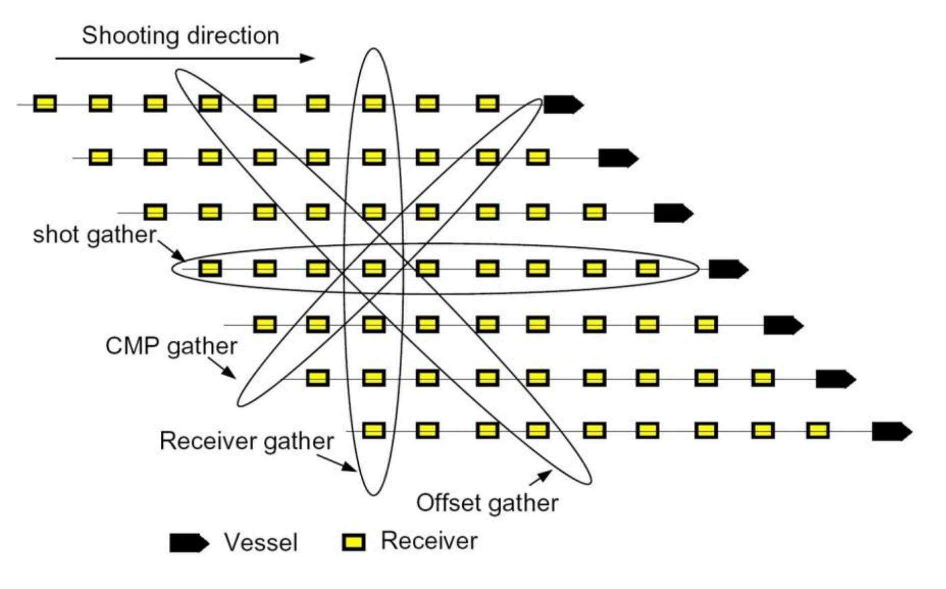

Figure 6.2: The stacking chart plot of the seismic data (Drs. Luc Ikelle & Lasse Amundsen's – Petroleum Seismology.com)

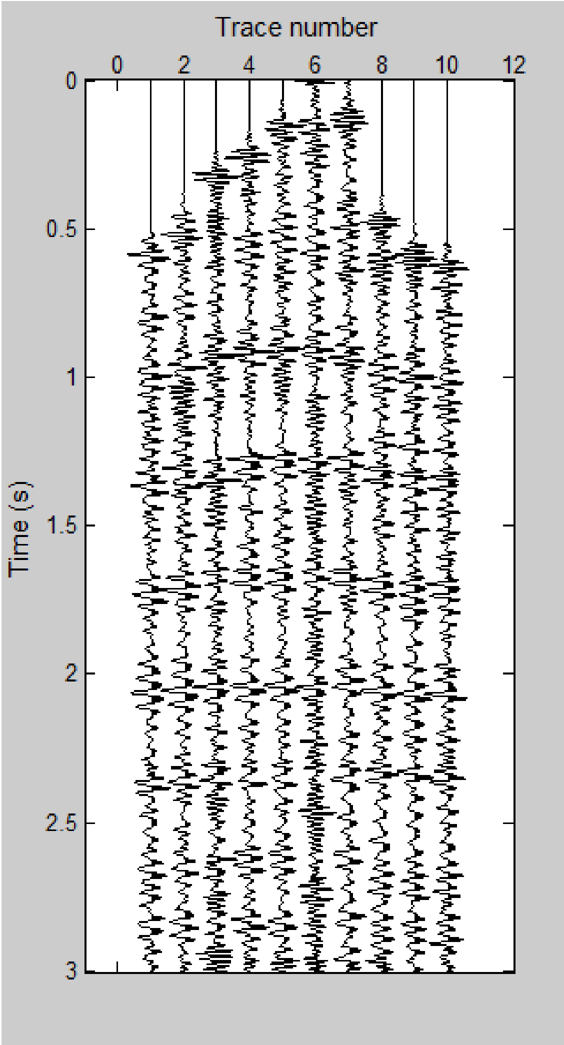

Figure 6.3: CMP – sorted seismic data (modified by Mousa and Al-Shuhail, 2011).

6.3 Velocity Analysis

Interpretation and several processing stages like normal moveout correction (NMO), stacking and velocity determination which are mentioned in the previous chapters, or migration which is going to be analyzed in the next chapter, use seismic velocities. The velocity analysis is very significant in this direction and determines the seismic velocities for the layers which are in the subsurface. Each one of the processing stages has different types of seismic velocities and different ways of analysis. For example, stacking velocities can be obtained by common mid-point (CMP) velocity analysis. However, there are also and other methods to compute the velocity. More specifically, stacking velocity can be calculated by the velocity spectrum technique. In other words, the velocity analysis is a very important method but this is not the only one.

6.4 Normal Moveout Correction (NMO)

Normal moveout correction (NMO) is a function of time and offset that can be used in seismic processing to compensate for the effects of normal moveout, or the delay in reflection arrival times when geophones and shotpoints are offset from each other (Schlumberger Oilfield Glossary). The aim of this correction is double. First, the estimation of NMO (figs. 6.4, 6.5) and second, the preparation of data for stacking.

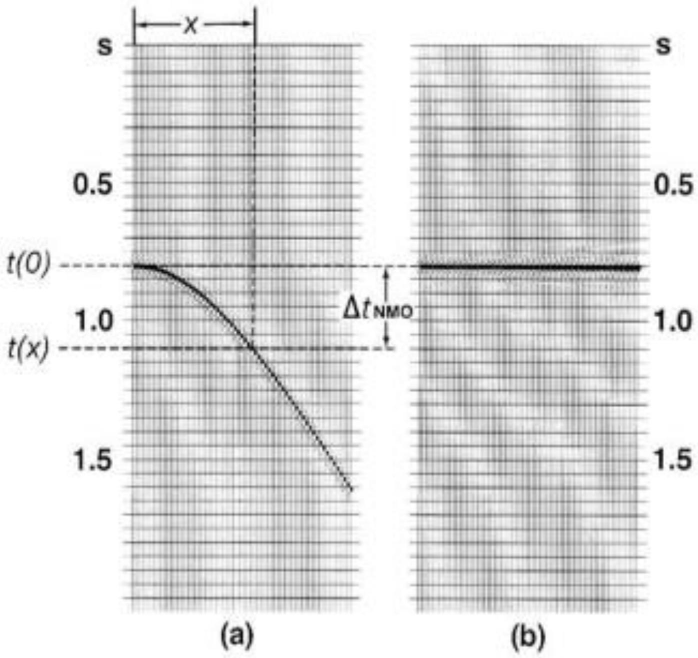

Figure 6.4: NMO correction involves mapping nonzero-offset traveltime t(x) onto zero-offset traveltime t(0). (a) Before and (b) after NMO correction. (Yilmaz, O., 1994, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.)

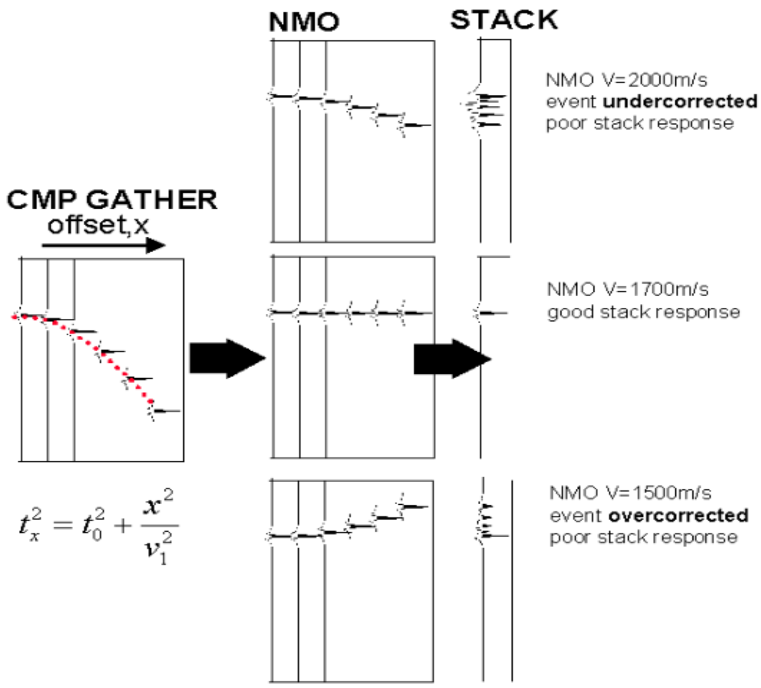

Figure 6.5: Normal Moveout Correction and Stacking.[16]

The time difference between the two-way travel time t(χ), when the offset χ is not zero, and the two-way travel time t_0, when the offset is equal to zero gives the definition of Normal moveout (NMO). The equation which gives this definition is:

$\Delta t_{NMO}(\chi) = t\chi - t_0$ eq. 6.1

When there is only one horizontal layer (fig. 6.6) with constant velocity, then the time-distance curve is hyperbola. The equation which gives the curve is the next:

$t^2(\chi)=t_0^2+\chi^2/u^2$ eq. 6.2

Where: χ is the distance between source and receiver, u is the velocity above the reflector, and t_0 is twice the traveltime of MD.

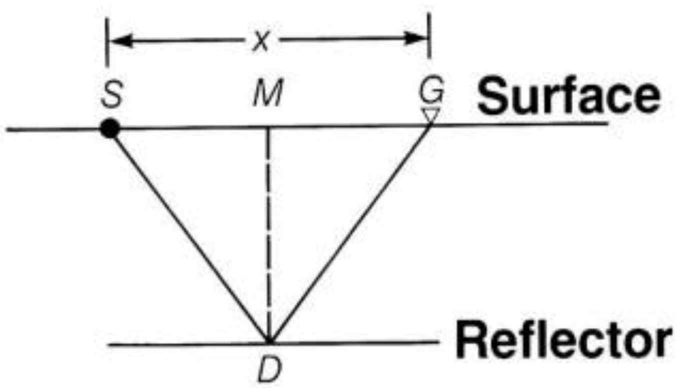

Figure 6.6: The NMO geometry for a single horizontal reflector (Yilmaz, O., 1997, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.)

For this case, the NMO correction will be:

$t_{NMO}(\chi)=\chi^2/2t_0u^2$ eq. 6.3

The above equation provides better results when the offsets are small or, when the quotient of maximum offset over the reflector depth gives values less than 2. Based on the above equation, the NMO correction increases when the offset increases. On the other hand, when the depth and velocity increase, then the NMO correction decreases. In addition, the two-way travel time t_0, when the offset is equal to zero, is approximately equal to $t_{NMO}(\chi)$, which is equal to the difference of the two-way travel time $t(\chi)$, when the offset χ is not zero minus the $\Delta t_{NMO}(\chi)$. The equation 6.4 gives the NMO correction (fig. 6.7).

$t_{NMO}(\chi)=t(\chi)-\Delta t_{NMO}(\chi)=t_0$ eq. 6.4

In the case of several horizontal constant - velocity layers the time-distance curve is not a hyperbola. For this reason, the best possible processes should become in order to approximate the hyperbola. The smaller the offset the better will be the approximation. Based on this scenario, all the other layers are replaced by one layer, which is closest to the hyperbola curve. This time-distance curve will arise by an average velocity (NMO velocity) of all the layers. For every dipping layer, it holds that the bigger the dip angle, the bigger the NMO velocity. On the other hand the NMO velocity is very small or negligible. The equation 6.4 can be used for the second case, while for the first case the process of Dip Moveout (DMO) is needed.

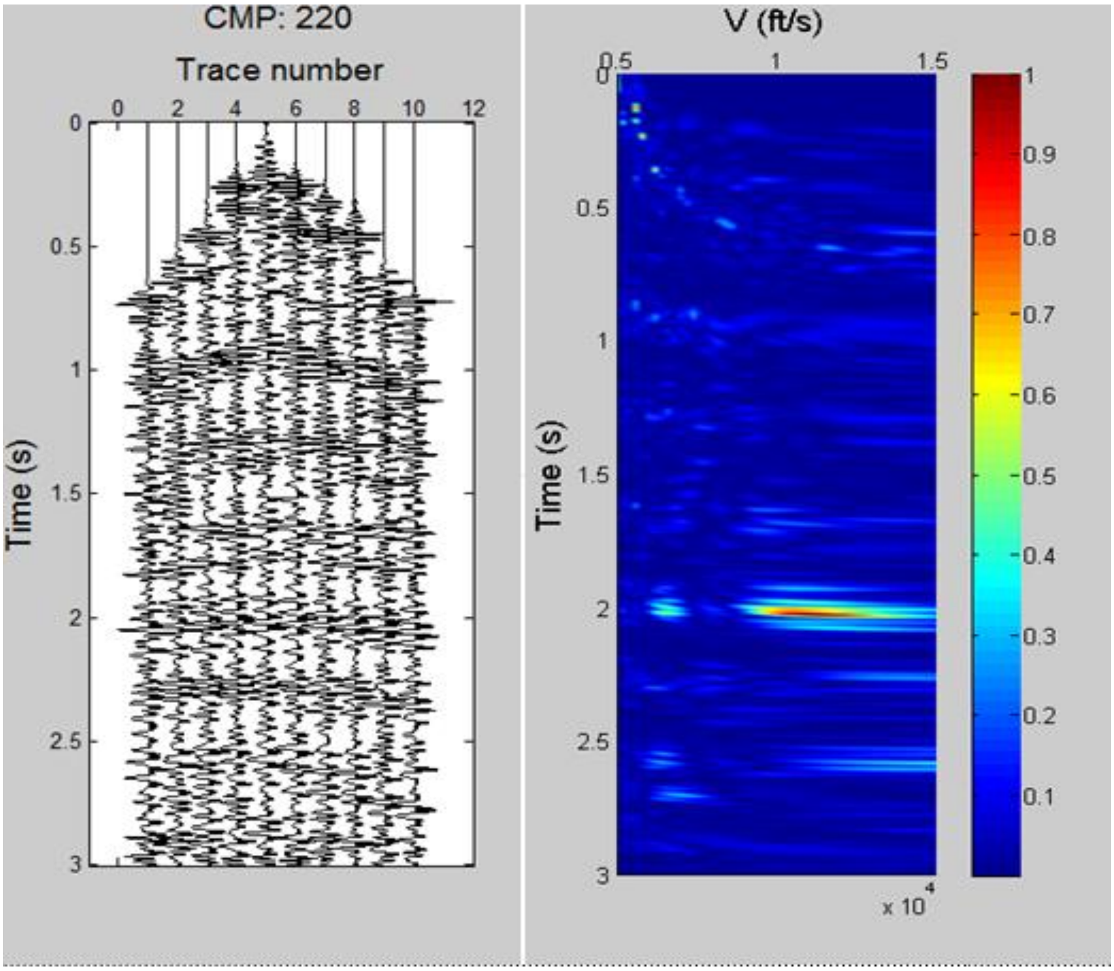

Figure 6.7: CMP gather 220 of sorted seismic data before NMO correction and its semblance (modified by Mousa and Al-Shuhail, 2011).

6.4.1 Normal Moveout (NMO) Stretching

NMO stretching (fig. 6.8) happens when there are two points belonging to the same event present a time difference (a) before NMO correction and a time difference (b) after NMO correction. The (b) will be bigger than (a) (b>a) due to the fact that the upper point will undergo bigger NMO correction than the other point which is lower. In other words, stretching is a frequency distortion in which events are shifted to lower frequencies (Seismic Data Processing - Ozdogan Yilmaz). The quantification of stretching expressed as:

$S_{NMO}(\chi) = \Delta t_{NMO}(\chi)/t_0$ eq. 6.5

Based on the equation 6.5, it is obvious that stretching is mostly confined to large offsets and shallow times. The shallow seismic events are usually affected by stacking NMO corrected and stretched points. Hence, the removal of stretching prior stacking is necessary. The solution to the NMO stretching s is the mute of the stretched zone from the gathers. Each zone which has S_{NMO} bigger than the lower limit should be muted. This limit takes values between 0.5 and 1.5. Choosing a value close to 0.5, the stretching is avoided but a significant loss of data may happen. Selecting a value close to 1.5, the loss of data is avoided, but the streching may be not eliminated.

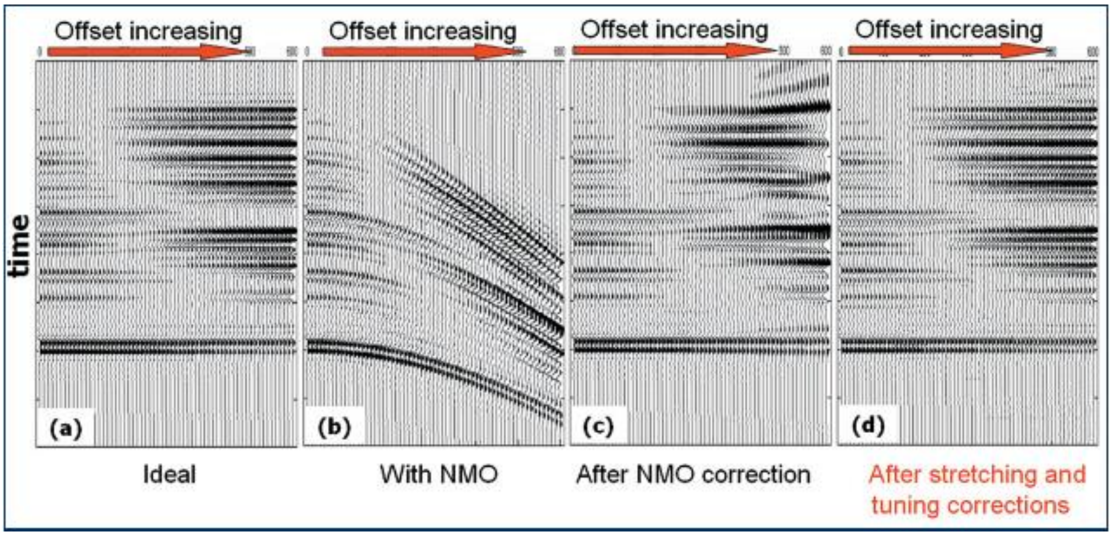

Figure 6.8: NMO stretching and tuning corrections for a synthetic offset gather with strong AVO effect. (Recorder – Official publication of Canadian Society of Exploration Geophysicists)[17]

6.5 Process of Stacking

The aim of stacking is the reduction or elimination of the noises, either these noises are coherent or incoherent, enhancing the signal-to-noise ratio (SNR) in order to extract a first possible subsurface image. All the traces in the NMO-corrected added together in order to create one stacked trace which represents a CMP gather (figs 6.9, 6.10). The average of the amplitudes of the traces gives the amplitude of the stacked trace in the CMP gather.

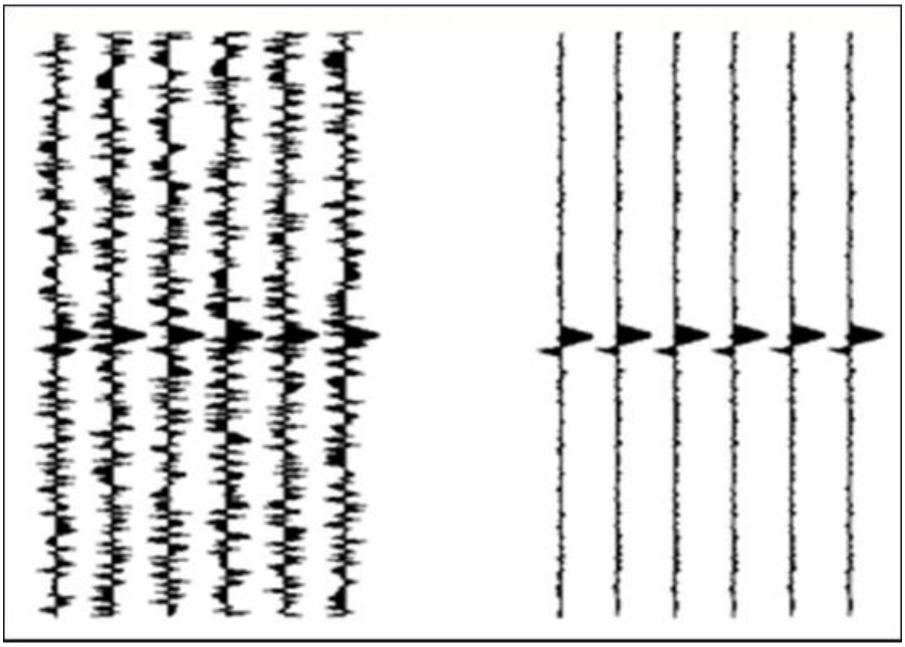

Figure 6.9: Stacking. Seismic traces from the same reflecting point are gathered together (CRP gather) and summed, or 'stacked'. (Veritas Caspian)

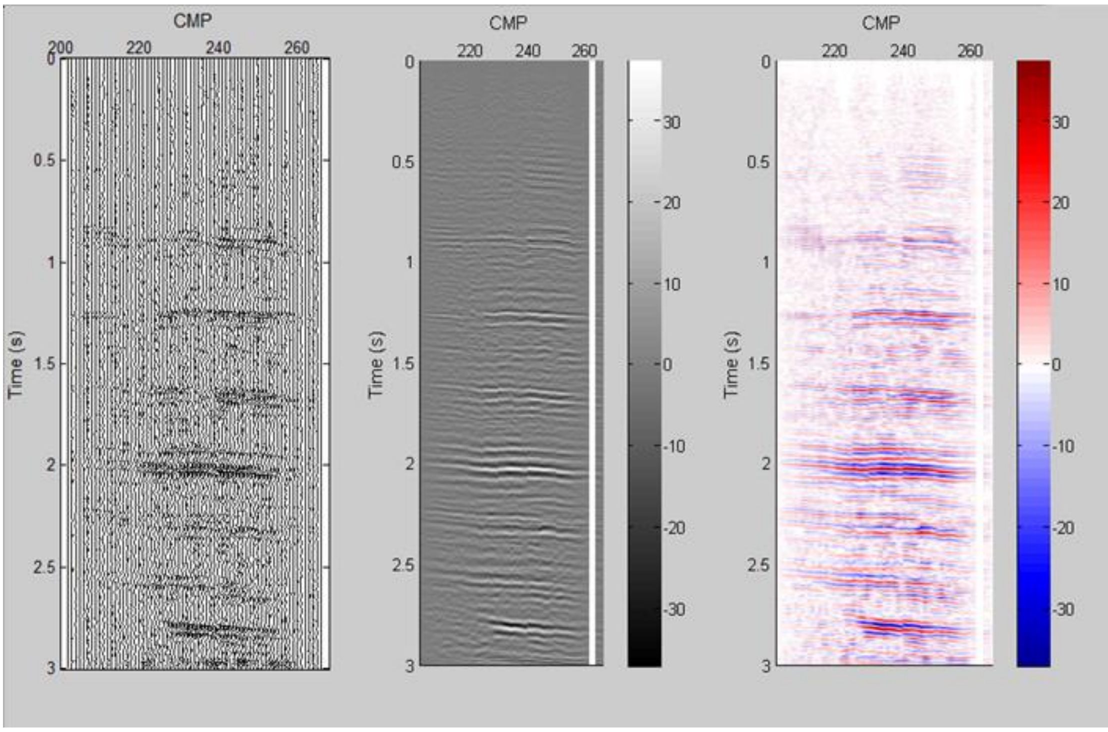

Figure 6.10: Seismic data stacked section in various displays: (a) variable area-wiggle, (b) variable density in gray and (c) variable density in colors. The two color bars refer to the amplitude dynamic range of the data (modified by Mousa and Al-Shuhail, 2011).

7. Static Corrections

7.1 Introduction

Static correction is the procedure compensating the effects which affect the seismic data. Weathering, differences in topography and variations in the elevations are the most common phenomena which need correction. The aim of static correction is the creation of a smooth layer without weathering in order to determine the reflection time.

The weathering layer constitutes the shallowest low velocity layer. The sediments in this layer are mostly loosely consolidated and include dunes, karsts, gravels and valley fills. Due to the fact that the velocity of weathering layer is lower in comparison to the velocity of the deeper layers, it significantly contributes to the overall traveltime of the seismic rays.

7.2 Elevation Static Correction

Elevation static correction is a datum or topographic correction (fig. 7.1) which aims to smooth and correct different source and receiver elevations. The procedure that usually is followed is the creation of a common datum level for sources and receivers and this level is deeper than the lower elevation of source and receiver. Consequently, a new replacement velocity is necessary in order to cover the distance between the datum level and the lower elevation of source and receiver. The equation which provides the elevation static correction (T_D) is:

$T_D = ((E_S - Z_S - E_D) + (E_R - Z_R - E_D))/V_R$ eq. 7.1

Where: E_S: the ground elevation at shot location,

Z_S: the depth of shot,

E_D: the datum elevation,

E_R: the ground elevation at receiver location,

Z_R: the depth of receiver,

V_R: replacement velocity.

The elevation static correction is always subtracted from the two-way traveltime of the trace belonging to that particular source-receiver pair.

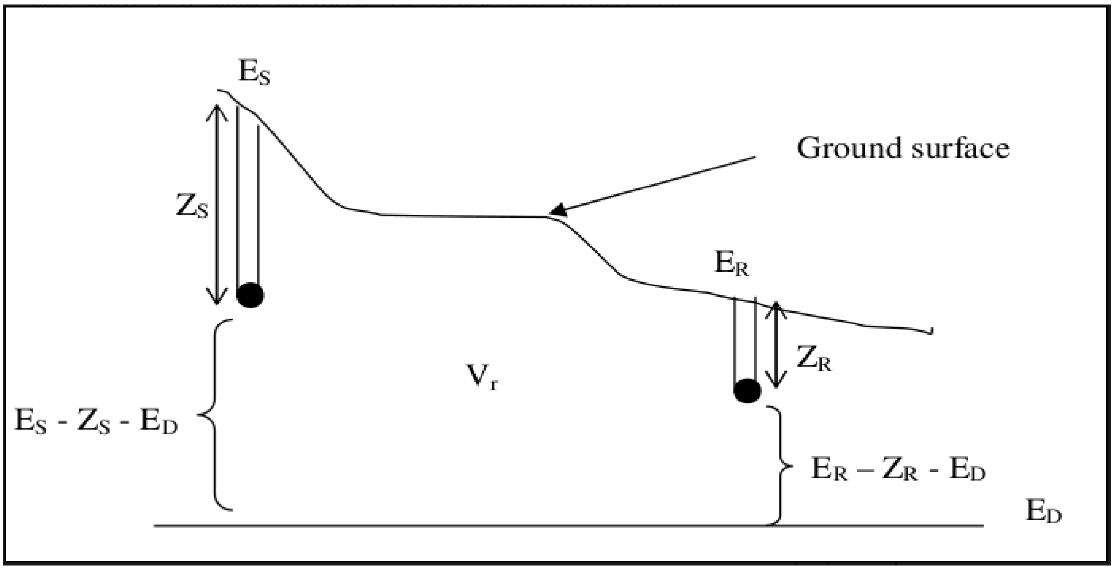

Figure 7.1: Elevation static correction[18].

7.3 Residual Static Correction

All the static corrections have mentioned in chapter 7.2. However, the lack of information close to surface creates inaccuracies for this model. A residual static correction is the model aiming to correct all these inaccuracies close to the surface. The application of this new model improves the final processed section in contrast with the previous model which implements only datum static corrections.

The three main methods, used to correct these effects, are the downhole surveys, the refraction statics and the surface - consistent statics.

7.3.1 Downhole Surveys

The downhole survey (fig. 7.2) is a method in which many geophones are placed in a borehole which has a depth between 100 and 200 meters. An explosion takes place at the surface close to the hole, and the arrival times recorded by the geophones. It is especially used to determine the velocity of the weathered layer as well as its thickness. Consequently, the aim of this method is the construction of a weathering layer (WL) model by estimating the velocity and thickness of WL, taking into account the location and the interaction between these locations. The downhole survey has a great advantage that offers extremely high accurate surface velocities and thicknesses. On the other hand the disadvantage of this method is the high cost as well as the fact that the lateral resolution is demanded. Hence, the downhole survey usually is used in estimating long wavelength statics.

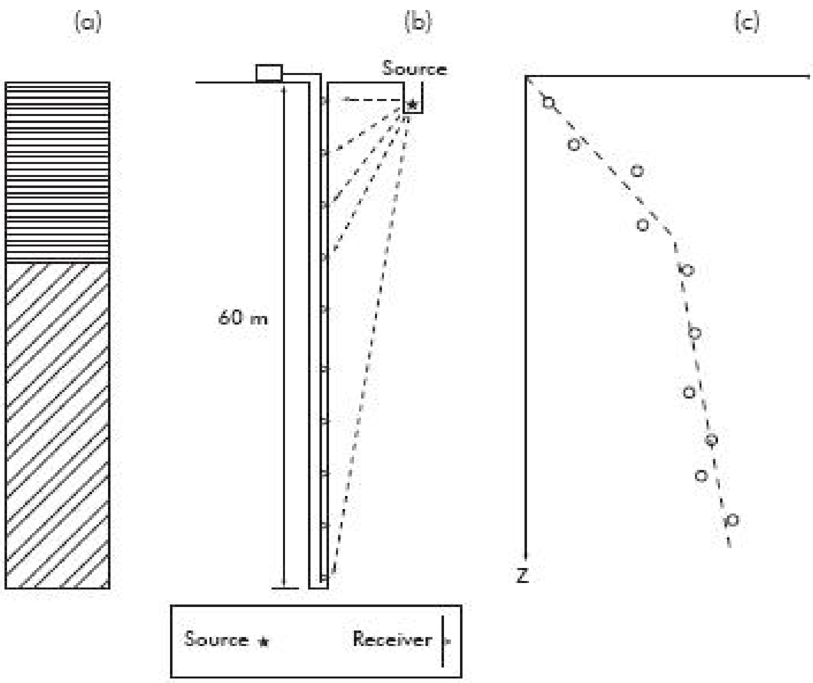

Figure 7.2: Principles of downhole survey. (a) lithologic profile, (b) Field deployment with a source in the surface and receivers into the well, (c) Time – Depth graph. (SEISMIC AND LITHOLOGICAL NEAR SURFACE CHARACTERISTICS OF AN AREA IN NORTH-EAST COLOMBIA)[19].

7.3.2 Refraction Statics

The method of refraction statics (fig. 7.3) is particularly used for the estimation of long wavelength statics and construction of a weathering layer (WL) model, taking into account the velocity and the thickness of that layer. For the refraction statics calculation the next methods are needed.

- Delay - time: It constitutes a method, used to map an irregular interface. Delay time represents the difference between the real traveltime and the time which needs a wave to travel in horizontal way from source to receiver. The depth of the irregular interface can be determined by the reverse and forward traveltime and from the velocities of the upper and lower layer. This velocity can be calculated by the difference of reverse and forward traveltimes with respect to the distance to a straight line.

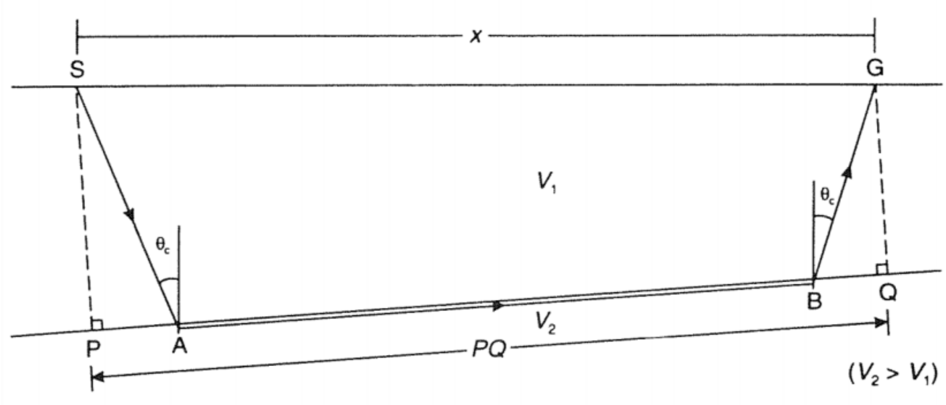

Figure 7.3: Delay time is the difference between SG along SABG and PQ. (Seismic Refraction - Jean Virieux from Anne Obermann – 2013/14 - ISTerre[20])

- The generalized reciprocal method (fig. 7.4) is a method which uses two geophones X and Y, recording refracted data which consist of forward and reverse traveltimes. The origin of these records comes from the same trace on the refractor.

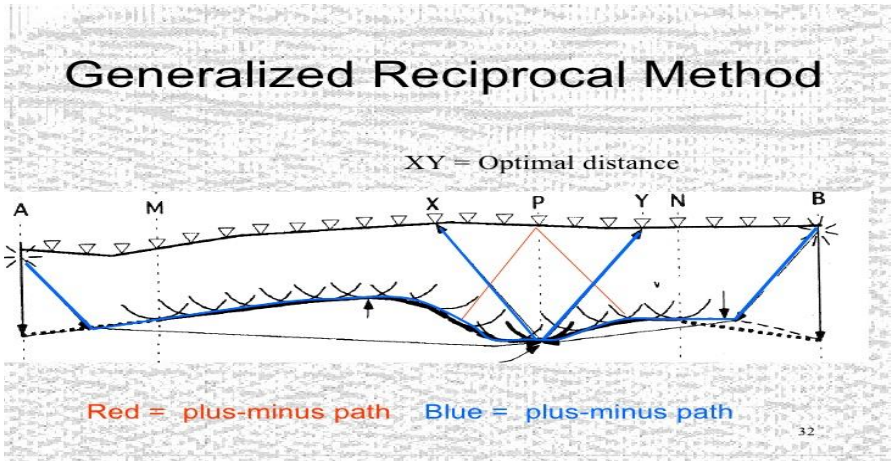

Figure 7.4: Generalized Reciprocal Method. (Seismic Refraction – Jacques Jenny – Geo2x Geneve)[21].

- The Least square method is a procedure to determine the best fit weathering layer (WL) velocity and thickness model by direct and head waves. The method of Least Square fairly uses similar techniques with the surface - consistent method.

7.3.3 Surface Consistent Statics

Long wavelength statics has been already described in a previous paragraph. The surface consistent statics (fig. 7.5) method is used to estimate the short wavelength statics. The main issue of this method has to do with the fact that the static shifts are temporal variations and delays, primarily dependent by the source and receiver locations on the surface and in no case from raypaths (lines which are perpendicular to the wavefront in isotropic media) in the subsurface. All raypaths must be vertical and close to the surface, irrespective of the source and receiver offset.

Based on the assumption at which the residual statics are surface and subsurface consistent, the total residual static time shift T_{ijk} on a particular trace can be expressed as the sum of four terms is calculated by the following formula:

$T_{ijk} = S_j + R_i + G_k + M_k X^2_{ij}$ eq. 7.2

Where: S_j is the static at the $_j$th source position. R_i is the static at the $_i$th receiver position. G_k is the structure term at the $_k$th CDP (common depth point) position. M_k is the residual NMO (normal moveout) component at the $_k$th CDP. X_{ij} is the source-to-receiver distance normalized by the maximum source-to-receiver distance of the survey.

Below are referred the basic steps in order to make clear in practice the terms of surface consistent residual static correction (Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail).

- A CMP with good SNR ratio is gained and it is NMO-corrected using a preliminary velocity function.
- The CMP gather is stacked to produce the first pilot trace.
- Each individual trace in this CMP gather is cross correlated with the first pilot trace.
- Time shifts T_{ijk}, corresponding to the maximum cross correlations, are picked.
- Shift each original trace by its corresponding time shift T_{ijk}.
- A second pilot trace is constructed by stacking the shifted traces in the gather.
- The second pilot trace is, cross correlated with the original traces in the gather and the new time shifts T_{ijk} are computed.
- Shift each original trace by its corresponding new time shift T_{ijk}
- The process is performed this way on all CMP gathers moving to left and/or right from the starting (reference) CMP gather.

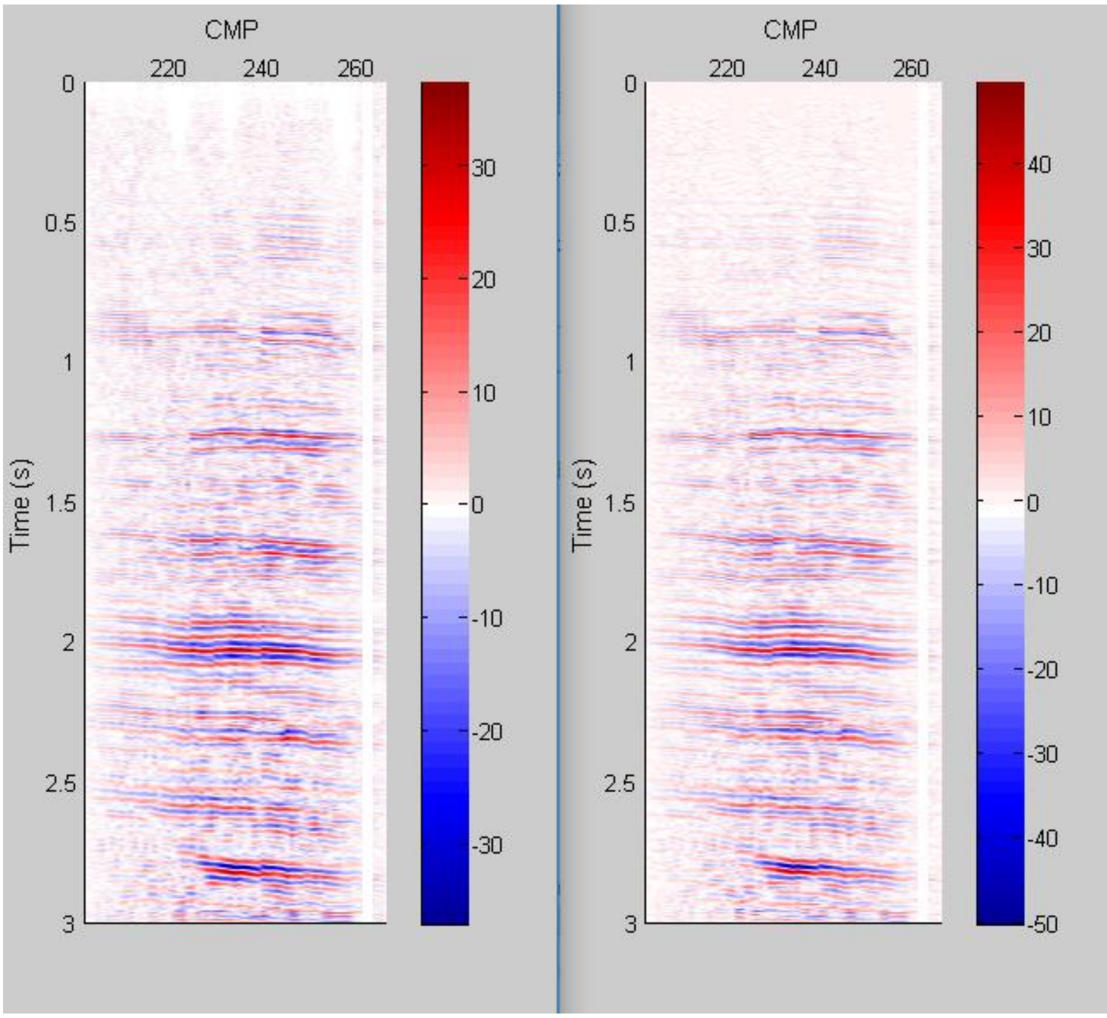

Figure 7.5: Stacked section. Before applying residual static correction (left) and after applying residual static correction (right) (modified by Mousa and Al-Shuhail, 2011).

8. Seismic Migration

8.1 Introduction

In the previous chapters all basic steps have been described in order to produce a reliable subsurface seismic image.. However, this image differs a lot from the actual subsurface image. The reason is that the real reflection points are not known. The Seismic Migration process is the key to have a more accurate image of the underground layers. This method takes into account each wave propagation effect to determine all the reflection points of the subsurface layers. This is very important in order to avoid undesirable geometrical effects which lead in a bad interpretation, and consequently at failures in drilling which can cost thousands of dollars to the petroleum industries. Taking into account all the above, Seismic Migration is a process which corrects the location of the reflection points, putting them at the right depth location, or in other words reconstructing a seismic section. This reconstruction of the seismic section is implemented by removing each distorting effect from the reflectors which are in large depths as well as by eliminating the diffracted arrivals by lateral discontinuities. The main migration methods are the pre-stack and post-stack migration.

8.2 Basic Migration Principles

According to the Huygens Principle, each point on a reflector produces another source and the other source produces another one and so on. This model is known as exploding reflector model. Taking into account the figure (8.1.a), a single point which operates as a scatterer is set at the medium, and the minimum traveltime is defined by the next equation:

$t_0 = \frac{2z}{c}$.   eq. 8.1

Where z is the scatter depth and c is the velocity of the propagating wave. It is very important to mention that the offset for source and receiver is zero.

For the calculation of traveltime as a function of distance, the next equation is used:

$t(\chi) = \frac{2\sqrt{x^2+z^2}}{c}$ eq. 8.2

Solving the equation 8.1 with respect to z and putting that in equation 8.2 then, arising a third equation (8.3) which has the next form:

$\frac{t(x)^2}{t0^2} - \frac{4x^2}{c^2 t0^2} = 1$ eq. 8.3

The form of equation is hyperbola as it shown in figure (8.1.b). This form represents the traveltime curve for the scattered arrival.

Considering a horizontal reflector that consists of several point scatterers and each scatterer creates a diffraction hyperbola in a zero offset. However, if one point stops working, then a diffracted arrival is going to be created and it will show up in the zero offset data. This malfunction creates a wrong image which is going to be corrected by the migration process.

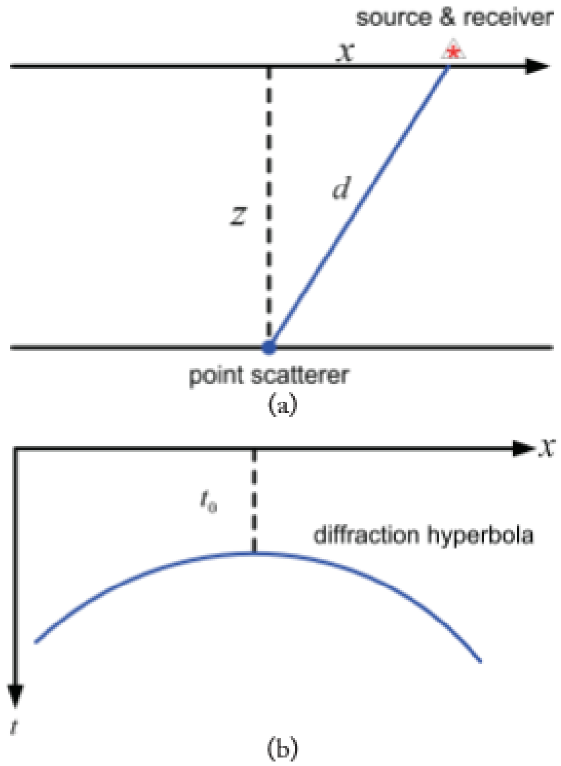

Figure 8.1: (a) A point scatterer. (b) A curved reflector which is produced based on the point scatterer (modified by Mousa and Al-Shuhail, 2011).

A second significant goal of the migration principle is the comparison of the apparent and the true dip. Between them, the apparent dip is always smaller than the true dip angle. Taking into account the figure (8.2), it is more easily to understand the migration principle for the comparison of the angles. The figure (8.2.a) represents a profile 0x with a depth section and the figure (8.2.b), a profile 0x with a time section. In the first figure, a dipping reflector of depth section (CD) is considered. The point A is the first normal - incidence arrival from dipping reflector, arising by a source - receiver pair (s,g) on the 0x axis. Similarly, B is the last normal - incidence arrival from dipping reflector, arising by the last source - receiver pair (s,g) on the 0x profile. In figure (8.2.b), C' represents the reflection arrival at location A, on the zero offset. Similarly, D' is the reflection arrival at location B, on the zero offset. Comparing the CD in depth section with C'D' in time section it is obvious that are different. The C'D' reflection must be migrated to the CD position and this can be done only by the migration method. In the above description should be included two notes. First, the velocity is considered constant and equal to 1, and second, diffractions are not included at all.

Observing the figures (8.2.a) and (8.2.b) it is clearly that the dip angle of the reflector in depth section is larger in comparison to that in the time section and the length of the reflector in depth section is shorter than the length of time section. Consequently, in the first case the migration steepens and in the second case the migration shortens reflectors. Finally, reflectors are moved in the updip direction constituting the main procedure of the migration.

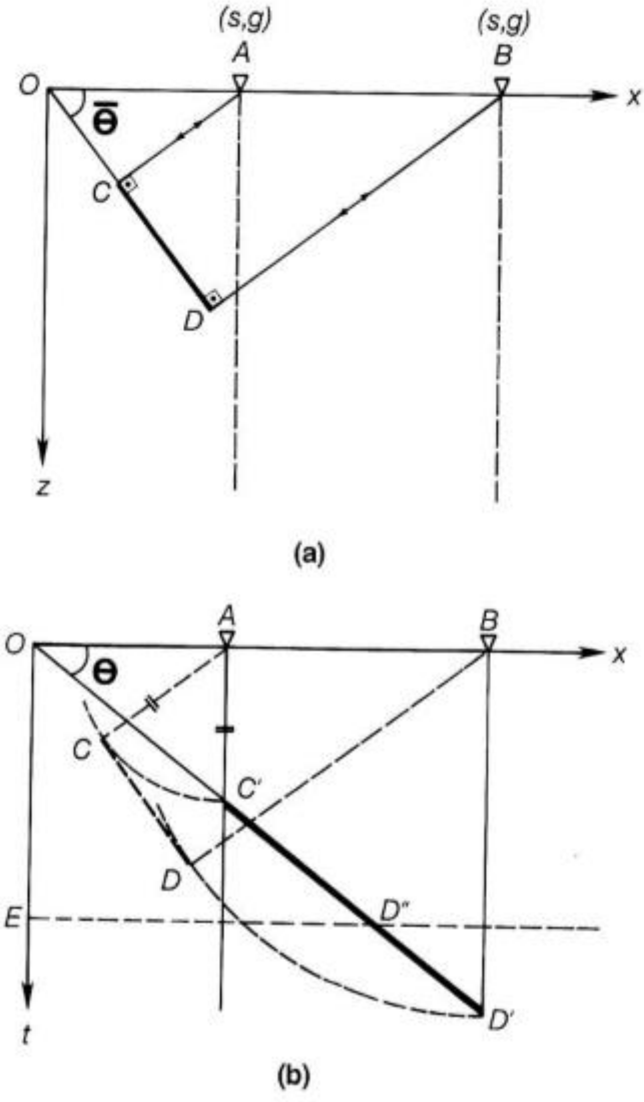

Figure 8.2: Migration principles: The reflection segment C'D' in the time section (b), when migrated, is moved updip, steepened, shortened, and mapped onto its true subsurface location CD (a) (Yilmaz, O., 1997)

8.3 Basic Migration Types

The migration process is a very significant and expensive method which is used in the seismic reflection data, and always prior the interpretation. Due to the fact that represents the last step prior the interpretation, the amplitude errors, due to lack of detailed information concerning the subsurface layers as well as errors on the previous processing steps, must be faced by the appropriate migration type. Hence, the good knowledge of the migration types is the key for the better confrontation of the previously mentioned problems.

Two main classification types of migration is the Pre-stack and Post-stack migration. Pre-stack migration (fig. 8.3) is used prior stacking as well as when the velocity profile of the subsurface layers is fairly complicated, or when the sequence of layers is too complex.. On the other hand, there is the Post-stack migration (fig. 8.4) that is applied after the stacking of the data.

Velocity variations are able to create a second classification for migration, between depth and time migration. When there is an area which has extremely large velocity variations then the depth migration is applied and the output corresponds to a depth section. For example, sub-salt areas constitute places for depth migration. On the other hand, when the lateral velocity ranges between 10 and 30 percent, then time migration is the appropriate migration type. Otherwise, for each other percentage, depth migration is applied again. Essentially, the main difference between those two migrations is the fact that time migration is simpler for interpretation than depth migration. It should be noted that Pre-stack as Post-stack migrated sections can be the input either for depth or for time migration.

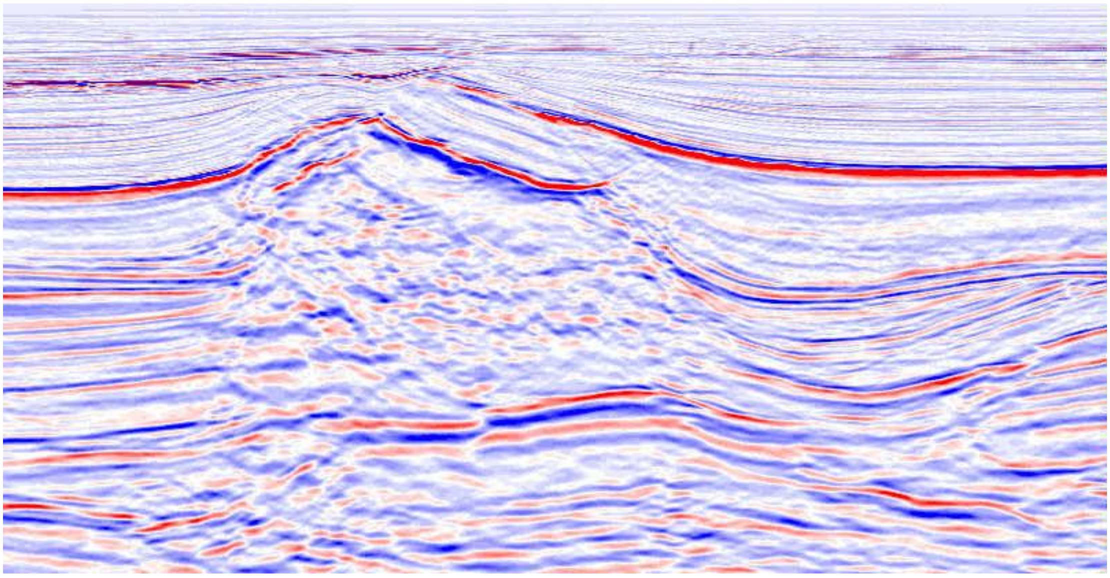

Figure 8.3: Pre-stack depth migration. (An introduction to migration by Mike Lorentz and Robert Bradley)[22].

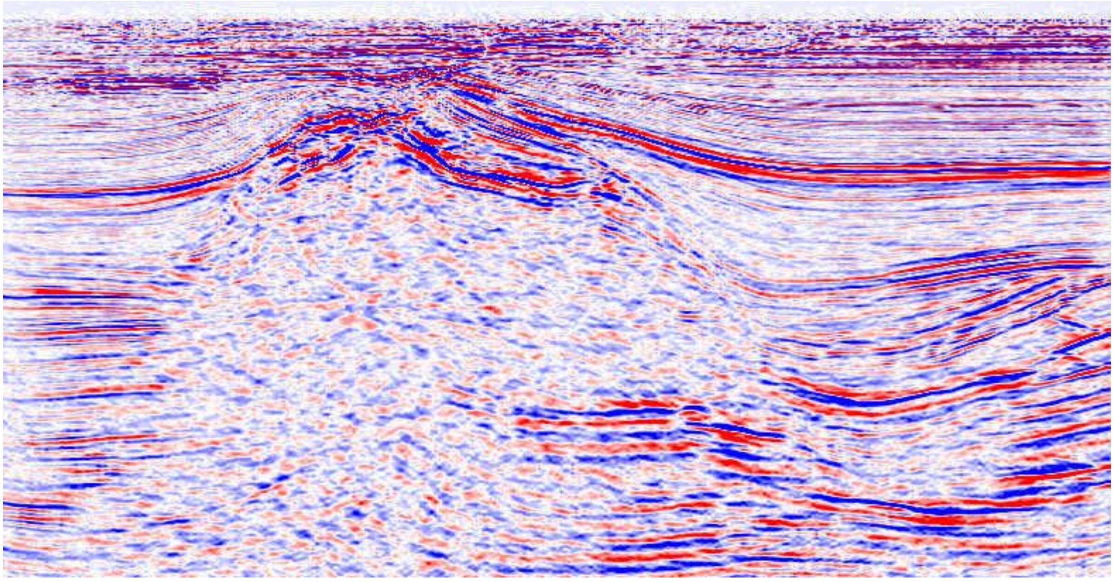

Figure 8.4: Post-stack depth migration. (An introduction to migration by Mike Lorentz and Robert Bradley)

Finally, there is one more migration classification, the 2D and 3D migration. In the first case (2D), the data are migrated along the profile as well as, 2D migration is affected by reflections which origin comes from out of the profile (sideswipe effect). 3D migration migrates the data first in the inline direction and then in the crossline direction. Below are referred all the migrations (fig. 8.5) combinations as they were mentioned before. (Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail).

- 2D Pre-stack time migration
- 2D Post-stack time migration
- 2D Pre-stack depth migration
- 2D Post-stack depth migration
- 3D Pre-stack time migration
- 3D Post-stack time migration
- 3D Pre-stack depth migration
- 3D Post-stack depth migration

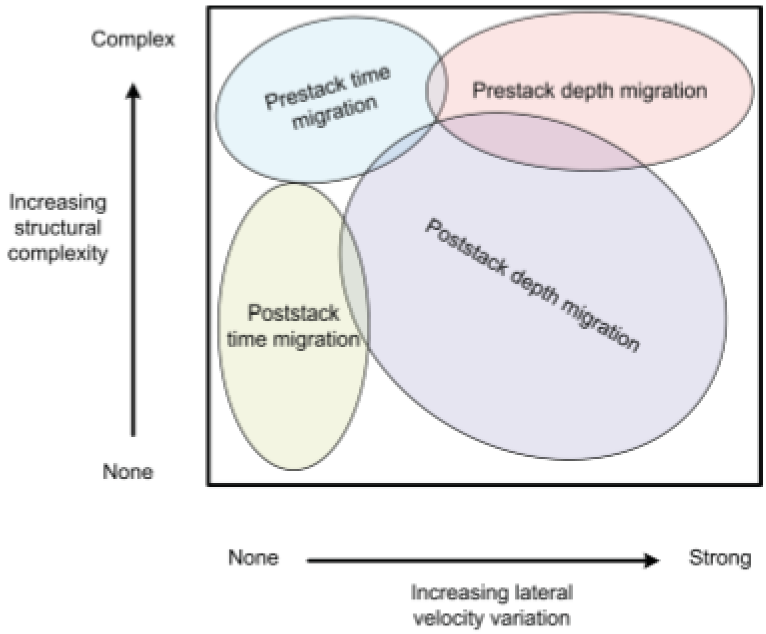

Figure 8.5: Migration types as a function of computational complexity and lateral velocity variations (modified by Mousa and Al-Shuhail, 2011).

8.4 Migration Algorithms

Kirchhoff migration, frequency wave-number migration and finite-difference migration represent the main post-stack migration algorithms. These three types include many others migration algorithms but below is going to be mentioned only these three kinds.

8.4.1 Kirchhoff Migration

Kirchhoff migration (figs. 8.6, 8.7) is a method which is used very often in the petroleum industry either for depth imaging or velocity analysis. In order to migrate a single event to the single trace, Kirchhoff migration stains the event energy for each possible underground point of model. Staining all points and stacking the sum of contributions, the creation of Kirchhoff migration image is implemented. In addition, Kirchhoff migration is able to compensate the skewness as well as the geometric spreading factor.

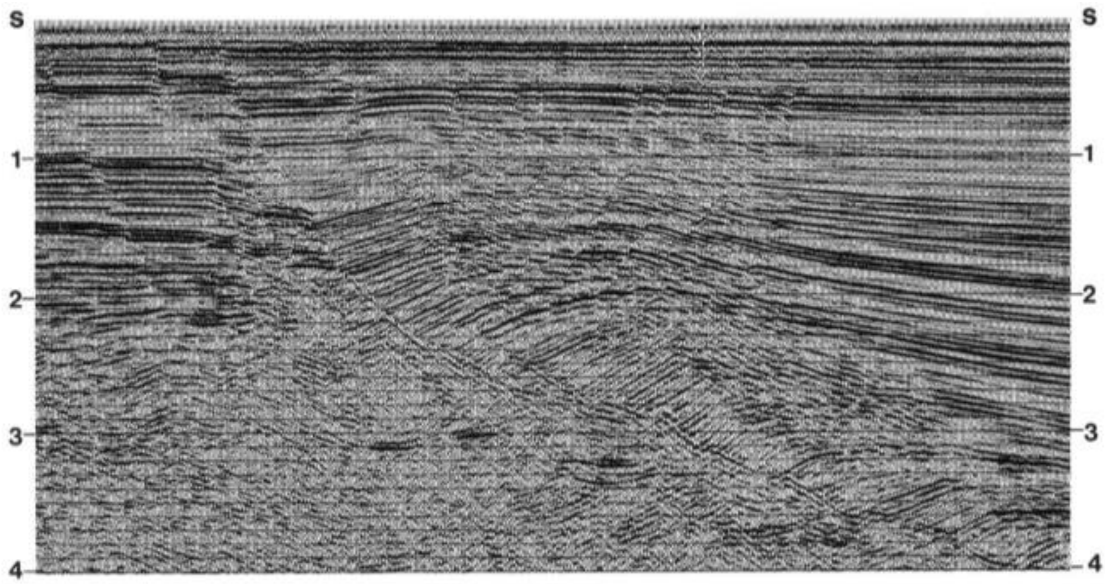

Figure 8.6: Prestack migration (Kirchhoff) (Yilmaz, O., 1994, Seismic Data Processing, Series: Investigations in Geophysics, Vol. 2, ISBN: 0-931830-41-9, SEG Tulsa, US.).

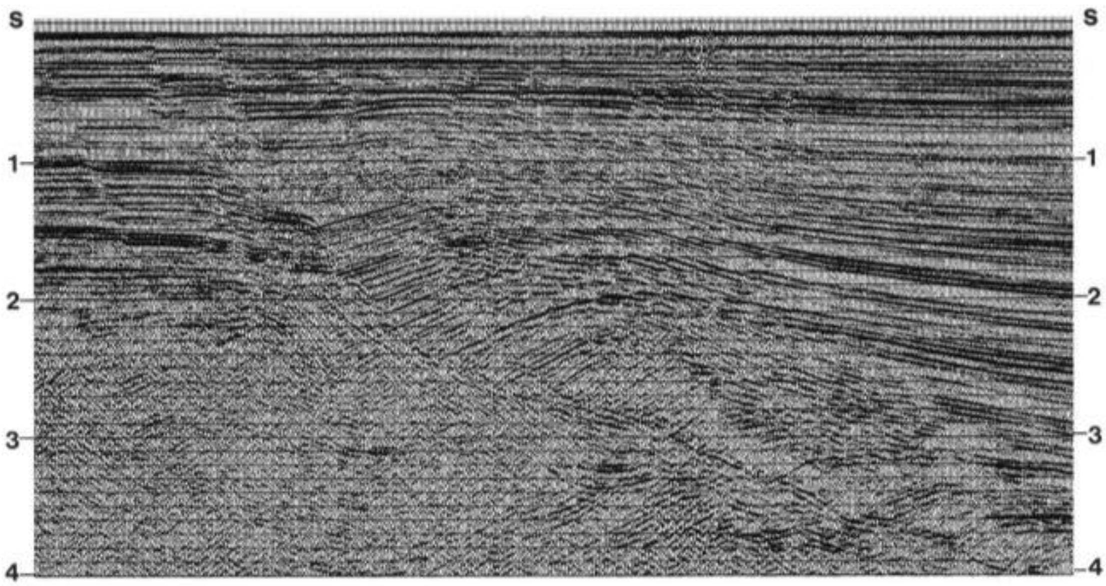

Figure 8.7: Poststack migration (Kirchhoff) (Yilmaz, O., 1997).

8.4.2 Frequency – Wavenumber Migration (Stolt Migration)

Stole method is a way to move the reflectors on their real position. Stolt method, similar to other migration methods, is able to be reversed into a modeling program and it is mainly affected by one forward and backward 2D FFT (Fast Fourier Transform) computations. Below it becomes clear how this algorithm works. Moreover, it should be mention that stacked data is denoted by a time and distance function u(t,χ).

The first step is the determination of $U(\omega,k_\chi)$ (angular frequency, spatial wavenumber) which is obtained by 2D Fourier Transform of time-distance function $u(t,\chi)$. From the $U(\omega,k_\chi)$ function arises the $U(k_z,k_\chi)$ function, where k_z represents the depth wavenumber and was arise by ω variable.

$$k_z = \sqrt{(\frac{2\omega}{u})^2 - k_\chi^2} \qquad \text{eq. 8.4}$$

The next step is the calculation of scale value by the next equation.

$$S = \frac{u}{2}\frac{kz}{\sqrt{kz^2+k\chi^2}} \qquad \text{eq. 8.5}$$

The result that arises by the 8.5 equation is multiplied by $U(k_z,k_\chi)$. The result, inversed by 2D Fourier Transform will be the migrated section(Processing of Seismic Reflection Data Using Matlab - Wail Mousa and Abdullatif Al Shuhail).

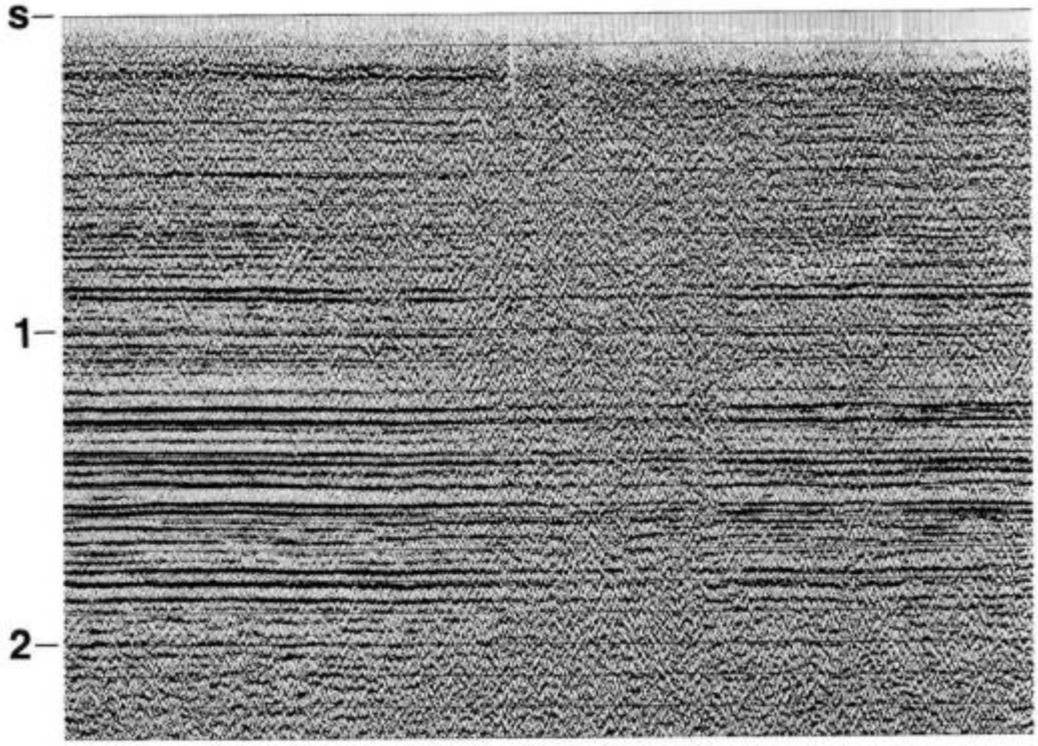

Figure 8.8: CMP stack before residual statics corrections. (Yilmaz, O., 1997)

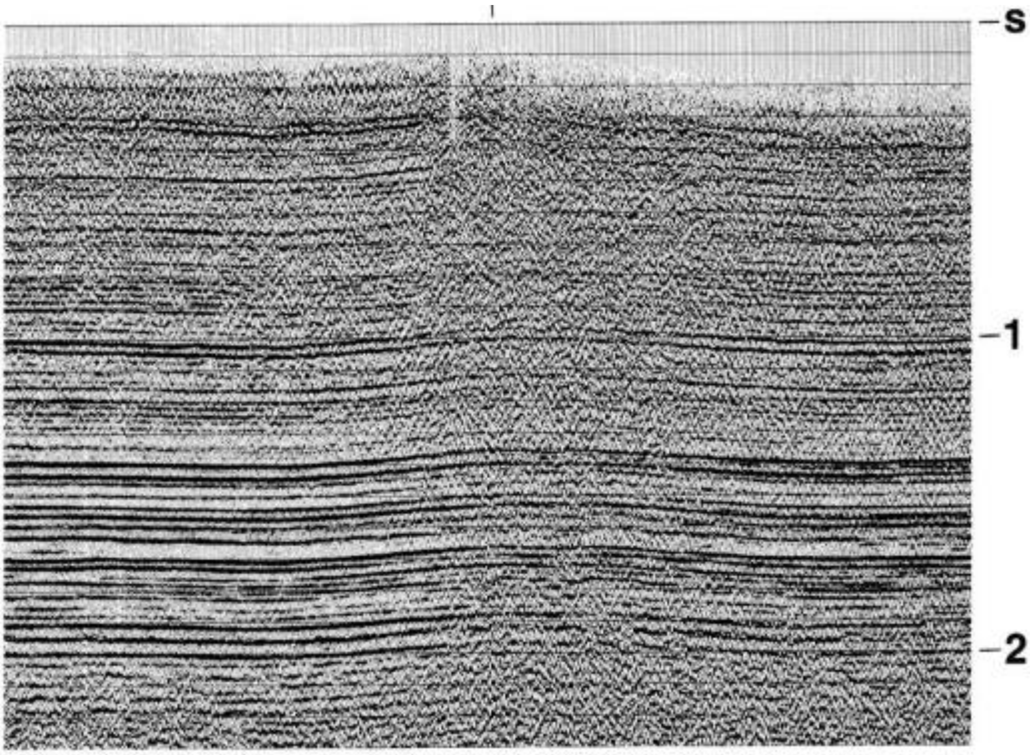

Figure 8.9: CMP stack after residual statics corrections. (Yilmaz, O., 1997).

8.4.3 Finite – Difference Migration

Finite Difference migration is usually applied in order to handle the downward continuation as well as variable lateral velocities. This type of migration can be used to give solution at steep dip and dip-limited time migrations, as well as, dip-limited migration, depending mainly on the velocity, the depth and the trace space. Moreover, there is a relationship between Finite Difference migration solutions and dispersion and this fact is able to reduce more the dip accuracy.

9. Conclusions

In this thesis the main concepts of a typical seismic dataset processing flow were introduced. All data came from the area of Texas (USA) in 2D form and the processing included:

- Geometry information
- Preprocessing involving only the gain application using various methods
- Ground roll removal via bandpass filtering
- Spiking deconvolution
- CMP sorting
- Velocity analysis on several CMPs using the velocity spectrum method
- Residual static correction using the surface-consistent method
- NMO correction and muting
- Stacking
- Migration

Matlab codes were used for each one of the above processes. These codes were written by the authors of the book ''Processing of Seismic Reflection Data Using Matlab - Mousa and Al-Shuhail (2011)'', and they were used in this thesis to give clear meaning to the above concepts. As was mentioned in preface, this thesis aims to provide the necessary industrial background of seismic data processing using MATLAB and by extension to give a different approach on seismic data processing, using this software.

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