**ADDIS ABABA UNIVERSITY**

**SCHOOL OF GRADUATE STUDIES**
**FACULTY OF SCIENCE**
**DEPARTMENT OF EARTH SCIENCES**

# VELOCITY STRUCTURE OF THE UPPERMOST CRUST ALONG THE MAIN ETHIOPIAN RIFT

**A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULLFILMENT OF THE REQUIRMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN GEOPHYSICS**

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# ABSTRACT

Ethiopia is located at a plate tectonic triple-rift junction (Mohr 1980) where the East African Rift System meets the Gulf of Aden and Red Sea with spreading axes at Afar.

A seismic study over the area has obvious implications on our knowledge concerning the structure and evolution of the Earth. This study focuses on the determination of the velocity structure of the uppermost crust along the Main Ethiopian Rift, which runs from Awassa to Nazreth to a depth of 10km on a 104km seismic profile.

Seismic waves generated by explosive charges detonated in boreholes are used to study the area. The seismograph Texans deployed on the surface are used to record the seismic energy refracted back to the surface from geological interfaces.

The time of first arrivals of these refracted waves were picked, processed and inverted using the General Reciprocal Method (GRM).

Basically three refractors at an average depth of, 2000m, 4500m, and 7000m were identified with their corresponding average P wave velocities of 3950m/s, 5726m/s and 6320m/s. The geologic sections of the area are shown in Fig (6.11).

Attempts have been made to correlate the seismic layers with the various stratigraphic units.

# 1. INTRODUCTION

Seismic investigation utilizes the fact that elastic waves also called seismic waves travel with different velocities in different rocks. By generating seismic waves at a point and observing the times of arrival of these waves at a number of other points on the surface of the earth, it is possible to determine the velocity distribution and locate subsurface Interfaces where the Waves are reflected or refracted. The aim of this thesis is to map the P wave velocity distribution of the layers beneath the uppermost crust along the main Ethiopian rift.

## 1.1 Previous works

There was no detailed seismic study over the area. Recently the Ethiopian Afar Geo Scientific Lithospheric Experiment(EAGLE) group made a large scale seismic study in three phases. With a consequence, a number of geological studies has been conducted and reported.

## 1.2 Physiographic outlines

The area of study runs from Awassa to Nazreth along the main Ethiopian rift in a 104km profile line. This research is based on the data from the Ethiopian Afar Geoscientfic Lithospheric Experiment (EAGLE), which was undertaken in the years 2001-2003 in Ethiopia.

### 1.3 **Aim of the present study**.

The major objectives of this work are,

1. To understand the velocity structure of the uppermost crust along the main Ethiopian rift.
2. To correlate the seismic layers with the various stratigraphic units and to understand the geologic history of the region.
3. To map the major structural features like faults, fractures etc
4. To prepare a geodynamic and geologic model of the uppermost crust along the main Ethiopian rift.

### 1.4 **Methodology**

Seismic refraction method has been employed to produce the seismic model along the main Ethiopian Rift. In processing the data the GRM method was mainly used.
The geoseismic and the geologic model were then interpreted using the seismic P wave velocities to correlate the results obtained with previous regional geological works.

## 2. GENERAL GEOLOGY

The geology of the area is mainly controlled by activities, which control the geology of the country. These geologic activities are, the formation of the Precambrian basement and associated deformation, the deposition of Mesozoic sedimentary succession, the uplifting volcanism and rifting of the Cenozoic and much more recently the quaternary climate variation and associated lake level changes. All these geologic activities leave their imprint in the geology of the study area. The Cenozoic uplift and associated rifting have been associated with volcanic activity. This activity leads to the eruption of volcanic rocks such as basalts (the older trap series basalt and the much more recent basaltic scoria cones), ignimbrite, trachite, rhyolites and pumiceous and pyroclastic. The faulting also formed structural depressions and calderas, which are latter filled by lakes. The lakes occupied a wide area in the quaternary before they shrunk to the present day size due to climate change. The shrinking lakes left behind lacustrine sediments that cover the low-lying plain. Nevertheless, the dominant rocks in the study area are volcanic products of the Cenozoic and the quaternary to recent fluvio-lacustrine sediments. The Ethiopian volcanics were divided in to two main series: trap series or (plateau series) and Aden volcanic series or (Rift series)(Banford, 1869;Mohr, 1971).

**TRAP SERIES**

An early Cenozoic extrusion of flood lavas occurred from fissures and centers covered the great part of the Mesozoic sedimentary rocks.

**ADEN VOLCANIC SERIES**

Aden volcanic series rocks post date the formation of the rift system in Ethiopia,i.e post Miocene or Pilo-Quaternary.

### 2.1 Stratigraphic outline of the volcanic products.

In the central sector of the Main Ethiopian Rift, the rift shoulders are made of volcanic and pyroclastic rocks where as large areas of the rift floor are covered by volcano-lacustrine and flvio-lacustrine deposits. Di Paola(1972) reconstructed the stratigraphic succession of major products in to eight major categories.

### 2.1.1 Basalt and ignimbrite of the plateau trap series

The trap series is mostly made up of basaltic lava flows with subordinately associated ignimbrite units intercalated between the basic lavas. Also silicic lava flows and lava domes are sometimes associated with the basalt of the trap series. The age varies from 40 to 25ma for the basalt and from 37 to 27 Ma for the rhyloite. This rock unit is exposed around east of lake Langano. The unit consists sub horizontal flows of a few meter thick lava with rather well preserved scoraceous level between the flows.

### 2.1.2 Trachytic flows and domes

The eastern plateau is covered by Pliocene to early Pleistocene (4.6-1.6Ma) shield volcanoes (chilalo, 4005m,kecha4245m badda, 4179m). The unit consists of trachite with subordinate basalts and mugearites (Di Paola,1972;Giday Woldegabrieletal.,1990;Benvenuti et al.,2002)

### 2.1.3 Rift pyroclastic formation.

The formation covers most of the rift floor and includes three principal rock types: typical ignimbrite, sillar and layered pumice. They are the most ancient formation outcropping on the floor of the rift valley. They are early to middle Pliocene (4.3-3Ma) formations.(Gidaye Woldegabriel et al., 1990).

### 2.1.4 Old rhyloitic lava flows and domes.

These are alkaline and per alkaline rhyloitic lava flows and domes which was erupted later as viscous lava after the magma has lost its gases during previous explosive activity. Thin and subordinated layers of unwelded pumice and ash are often found interbeded in these silicic lava flows and domes. This lava was erupted from late Pliocene to middle Pleistocene and in some places crop out as remnants of large calderas and often shows vertical sheeting or flow folding.

### 2.1.5 Basalt Hyaloclastites

Limited occurrences of sub aqueous basaltic volcanism are found in the rift valley. Hyaloclastiete occur both as small monogenic rug and as horizontal layer of local extension. They are exposed around lake chitu on the southwestern shore of lake shalla and around lake ziway. These rocks consist of fine glassy material, generally yellowish to brown in colour. They contain small boulder of basaltic lava.

### 2..1.6 Recent Basalt

Recent basaltic cones are elongated parallel to the main tectonic trend of the rift and were produced by fissural eruption. The alignment of the spatter cones parallel the rift marks the feeding fissures. These flows consist of lots of scoria cones. Two main field of recent basalt having an area of 800 $km^2$ are located close to western and eastern escarpment. The lava fields close to the Butajira-Slite in the west and the spatter cones east of lake Ziway in the east.

### 2.1.7 Recent rhyolitic pyroclastic and obsidian lava flows.

These rocks are the latest volcanic products in the region. Many young volcanoes and calderas such as the bora-bericco complex, the Alutu volcano and Chabbi volcanoes that grew inside the Corbetti caldera, are made up of rhyolitic lava flows, pumice falls and ashes.

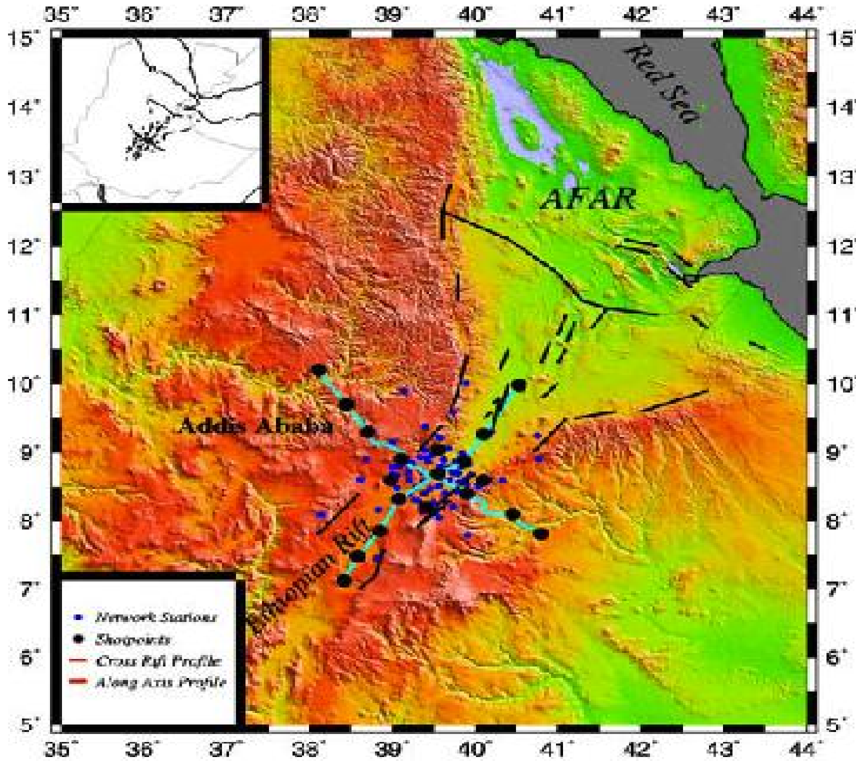
### 2.1.8 Lacustrine sediments

Lacustrine sediments are common in the rift valley.they are the result of drying up of a big lake that occupie the floor of the rift valley during pluvial periods.The lacustrine sediments include silts,clays and volcano clastic sediments.

# 3. PROJECT EAGLE

## 3.1 Introduction

The Ethiopian Afar Geoscientific Lithospheric Experiment(EAGLE) is a major initiative to investigate how the African continent is splitting along the Ethiopian Rift in the Horn of Africa. The project involves the Universities of Leicester, Leeds and Royal Holloway from the United Kingdom, Stanford University, California and the University of Texas, at El Paso both from the United States. There is significant involvement from other European and US institutions. These groups are working with principal counterparts from the Geophysical Observatory and the Department of Geology and Geophysics at the University of Addis Ababa together with many scientists from the Ethiopian Geological Survey and the Petroleum Operations Department of the Ethiopian Ministry of Mines. The Commission of Science and Technology of the Federal Democratic Republic of Ethiopia coordinate the whole project. The work involves seismic recording from controlled explosions and natural Earthquakes, to provide an image of the top 100km or so of the Earth over a region encompassing the north-eastern part of the main Ethiopian Rift where it enters Afar (Fig 3.1). As continental rift zones evolve to seafloor spreading they do so through progressive episodes of lithospheric stretching, heating and magmatism, yet the actual process of continental break-up is poorly understood. The East African rift system in northeastern Ethiopia is central to our understanding of this process as it lies at the transition between continental and oceanic rifting (Ebinger and casey,2001).




**Fig(3.1) study area showing profiles 1,2 and 3**

This research is based on the data from the Ethiopian Afar Geoscientfic Lithospheric Experiment (EAGLE), which was undertaken in the years 2001-2003 in Ethiopia. The study focuses on the determination of the velocity structure of the uppermost crust along the main Ethiopian Rift which runs from Awassa to Nazreth. Seismic waves generated by explosive charges detonated in boreholes of 50 meters deep and 50 inch diameter are used to study the area. Those waves refracted from geological interfaces back to the surface are recorded by the Seismograph Texans, which are deployed on the surface of the Earth separated with an average distance of 1km.

The time of first arrivals of refracted waves are then processed using the appropriate geophysical soft wares and is interpreted in terms of the geological boundaries and structures of the region.

# 4. Basics of the methods used in this work

## 4.1 Seismic waves

The particles in the surface of the Earth are in constant vibrations due to continuous disturbances from natural as well as artificial sources. Those disturbances also called Seismic waves have long been observed for a variety of reasons, and the number of applications continues to grow. Generally seismic waves can be considered as messengers that convey information about the Earth's interior. Therefore systematically studying these waves has obvious implications for man's safety, as well as for his curiosity concerning the structure and evolution of the Earth and is the primary concern of exploration seismology. In the application of seismic techniques to the determination of geological structures, the source of seismic radiation is usually man-made, such as an explosive charge.

## 4.2 Types of seismic waves

When a stress is applied to an elastic body (as when it is hit with a hammer) or when the stress is suddenly released (as when a previous state of stress is altered by fracturing), the corresponding strain (deformation pattern) is propagated outwards as an elastic wave. There are two principal types of elastic waves: body and surface waves.

### 4.2.1 Seismic body waves

We can categorize seismic body waves as P and S waves depending on the way the wave propagates. As the name indicates body waves can travel directly through a mass of some substance in any direction.

P waves also called compressional or longitudinal waves have vital importance in exploration seismology. It propagets in an elastic medium causing particles to vibrate back and fourth in line with the direction of the advancing wave.

On the other hand S waves also called shear waves or transverse waves propagates in a medium causing particles to vibrate perpendicular to the advancing wave.

### 4.2.2 Surface waves

Surface waves can be explained interms of combinations of body waves that interfere with one another in distinctive ways when traveling near the surface of a mass. Surface waves are of two types.

a. Rayleigh waves
b. Love waves

An important characteristic of surface waves is their dispersion. By dispersion, we mean the dependence of velocity on wavelength. For example, in a layer with elastic properties gradually varying with depth, the velocity of love waves for short wavelengths is equal to Vs in the upper part of the layer and for long wavelengths it approximates to the velocity of shear wave(Vs) in the lower part.

## 4.3 Seismic wave velocities

The capacity of a material to be temporarily deformed by passing seismic waves can be described by its physical properties. Therefore the physical properties of a material like elasticity and density determines the velocity of seismic waves through it.
The velocities of P and S waves in different materials are given by the following equations.

$$Vp = \sqrt{\frac{k + \frac{4\mu}{3}}{\rho}} \quad \text{and} \quad Vs = \sqrt{\frac{\mu}{\rho}}$$

Where:- Vp is the velocity of P wave

Vs =the velocity of S wave

$K$ is the bulk modulus

$\mu$ is the shear modulus

$\rho$ is the bulk density of the rock(material)

## 4.4 Principles of refraction seismic

The three principles (law's) which are back bones of refraction seismic are

a. Fermat's principle
b. Snell's law
**c.** Huygen's principle

- **Fermat's principle**.

According to Fermat's principle, seismic waves generated either naturally or by an artificial source always follows the path requiring the least time.

Of all waves that are generated during an explosion, P waves are the first ones to arrive on the seismograph obeying the three basic laws while traversing inside the earth.

Refraction of seismic wave occurs when they intercept a media of different acoustic property as shown in Fig(4.1).

The way a seismic wave refracted could be explained using snell's law, which states that "the direction of the reflected and refracted waves traveling away from a boundary
depends on the direction of the incident waves and their speeds"

Mathematically, $\frac{V1}{V2} = \frac{\sin\ i}{\sin\ r}$ ( Snell's law)

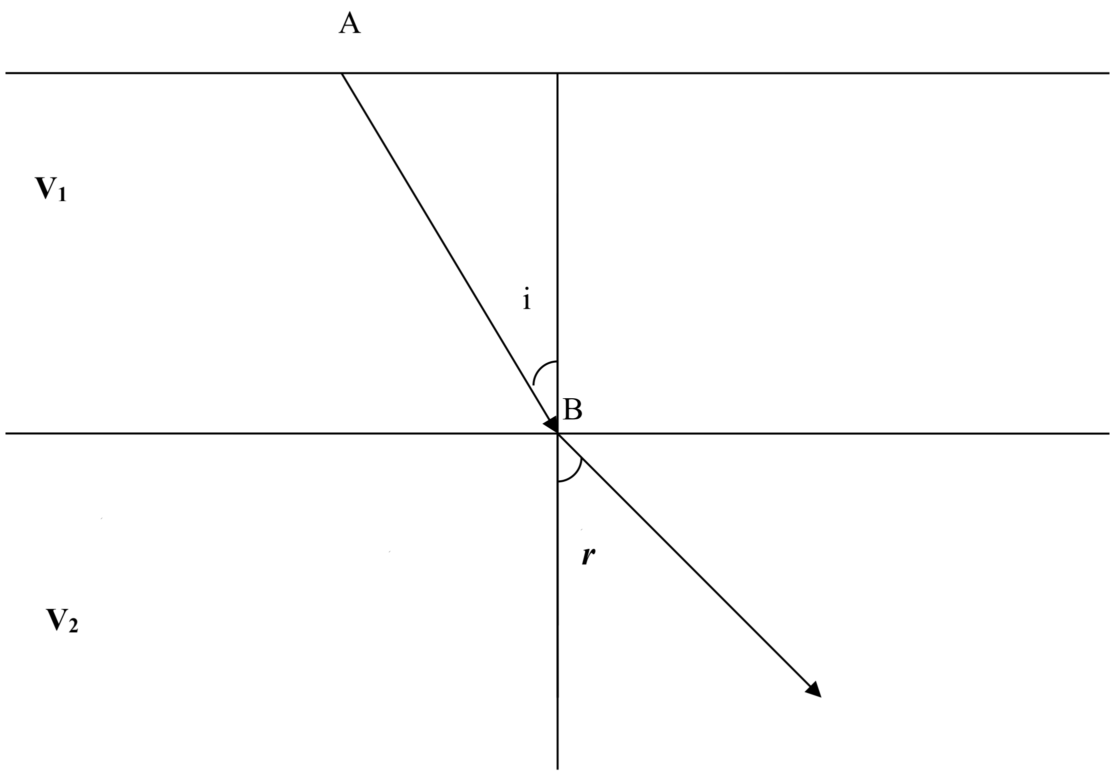


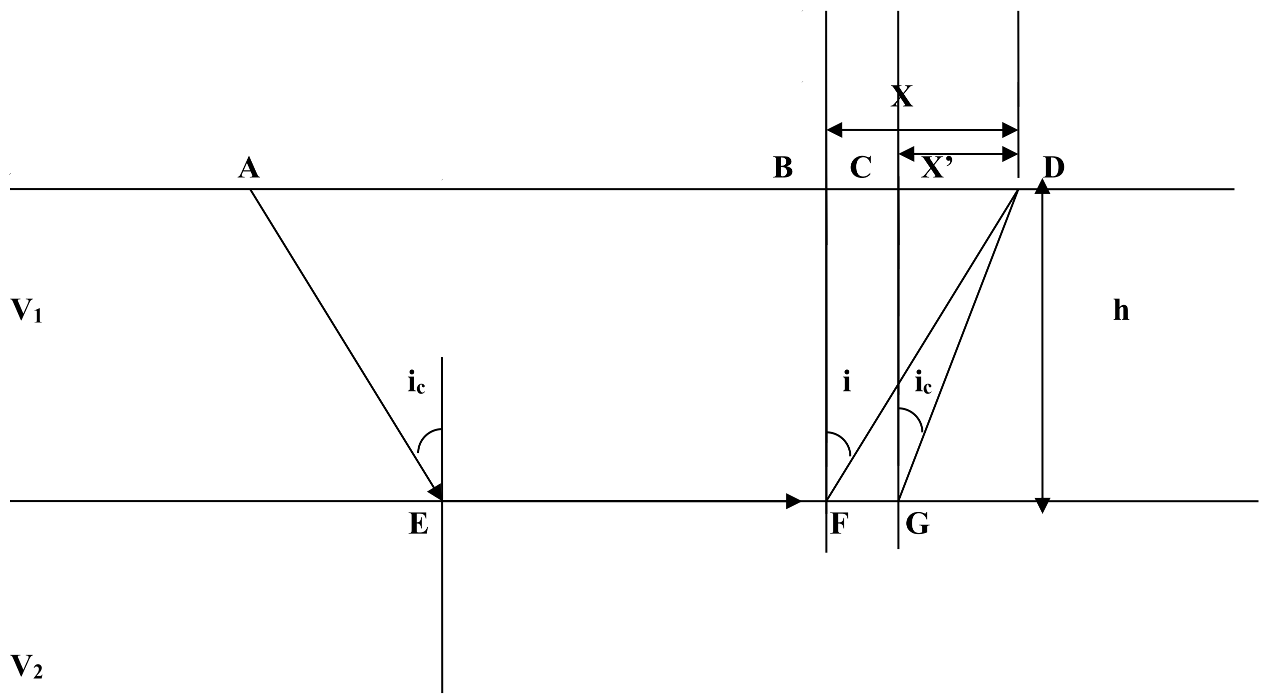

**Figure (4.1) diagram showing refraction of seismic wave**

Where, $V_1$ is the velocity of the seismic wave in medium one and,

$V_2$ is its velocity in medium two.

- **The following are the three consequences of Snell's law**

1. If $v_1 = v_2 \Rightarrow i = r$, there will be no refraction.
2. If $v_1 > v_2 \Rightarrow i > r$, then the refracted wave bends towards the normal and there will be no way to bring it up to the surface.
3. If $v_1 < v_2 \Rightarrow i < r$, then we will have a refracted wave coming up to the surface.




**Fig(4.2)Diagram showing critically refracted seismic wave**

When $r = 90^0$ , $\Rightarrow$ $\sin i_c = v_1/v_2$ (critical angle of incidence) and the refracted wave travels along the interface separating the two media Fig 4.2.

We ignore all other waves except the Head wave which is the one striking the interface at an angle of $i_c$ .

The critically refracted wave is made of infinite amount of point explosions, which simulate infinite amount of explosions inside the earth in all direction. Hence energy from with in the earth is again released and reaches the surface to be recorded. This principle is called huygen's principle and is stated formally as follows. "Every point on a wave front is a source of a new waves that travels away from it in all directions".

After the seismic energy has been critically refracted and started to rise up according to huygen's principle, the seismic wave that arrives first on the surface is the refracted wave, which has the same angle as the critical angle of incidence. Mathematically this can be shown as follows.

Considering the seismic radiation propagating along the two paths (path AEFD and path AEGD) as shown in fig (Fig 4.2) we have,

$T_1$ = Time to travel through path one (AEFD) and

$T_2$ =Time for path two (AEGD)

From the diagram we can easily see that,

$T_1 = AE/V_1 + EF/V_2 + FD/V_1$ and

$T2 = AE/V_1 + EG/V_2 + GD/V_1.$

Therefore, the difference between $T_2$ and $T_1$ will give us,

$$T_2 - T_1 = (AE/V_1 + EG/V_2 + GD/V_1) - (AE/V_1 + EF/V_2 + FD/V_1)$$

$$\Rightarrow T_2 - T_1 = (AE/V_1 + EF/V_2 + FG/V_2 + GD/V_1) - (AE/V_1 + EF/V_2 + FD/V_1)$$

$$\Rightarrow T_2 - T_1 = FG/V_2 + GD/V_1 - FD/V_1$$

$$\Rightarrow T_2 - T_1 = FG/V_2 + (GD - FD)/V_1 \qquad \text{Eqn 4.1}$$

But from simple trigonometry, we have the following.

$$\tan ic = x'/h \Rightarrow x' = h \tan ic$$

$$\tan i = x/h \Rightarrow X = h \tan i$$

$$X - X' = h(\tan i - \tan i_c)$$

$$FD = h/\cos i \quad \text{and}$$

$$GD = h/\cos i_c$$

Finally substituting the above expressions in equation 4.1,we will have.

$$T_2 - T1 = \frac{h}{V1 \cos i}[\cos(ic - i) - 1] \qquad \text{Eqn 4.2}$$

Since the term in the bracket is always negative, the result $T_2$-$T_1$ will be negative, showing that $T_2$ is less than $T_1$.

Therefore the refracted seismic radiation, which arrives first at the geophone on the surface, follows the path AEGD.

**Generalized Reciprocal method(GRM)**

This method was first developed and later introduced by the Australian scientist Derecke Palmer in 1980.It is the powerful method of all seismic refraction methods. The GRM,as described in palmer(1980,1981),centers on the key aspect that a geophone spacing, termed the XY spacing, can be found whereby up going rays from forward and reverse shots depart from the same point on a refractor. Once this spacing is found, it is theoretically possible to map refracting surfaces accurately and to determine an average velocity for the layers overlying the refractor. The average velocity allows depth to the refractor to be calculated; irrespective of whether undefined velocity inversions or hidden layers are present. The travel times at two geophones, separated by a variable distance XY ( Fig 4.3 ) are used in refractor velocity analysis and time depth calculations. At the optimum XY spacing, the upward traveling segment of the rays to each geophone emerge from near to the same point on the refractor. This results in the refractor velocity analysis being the simplest and the time-depths showing the most detail.

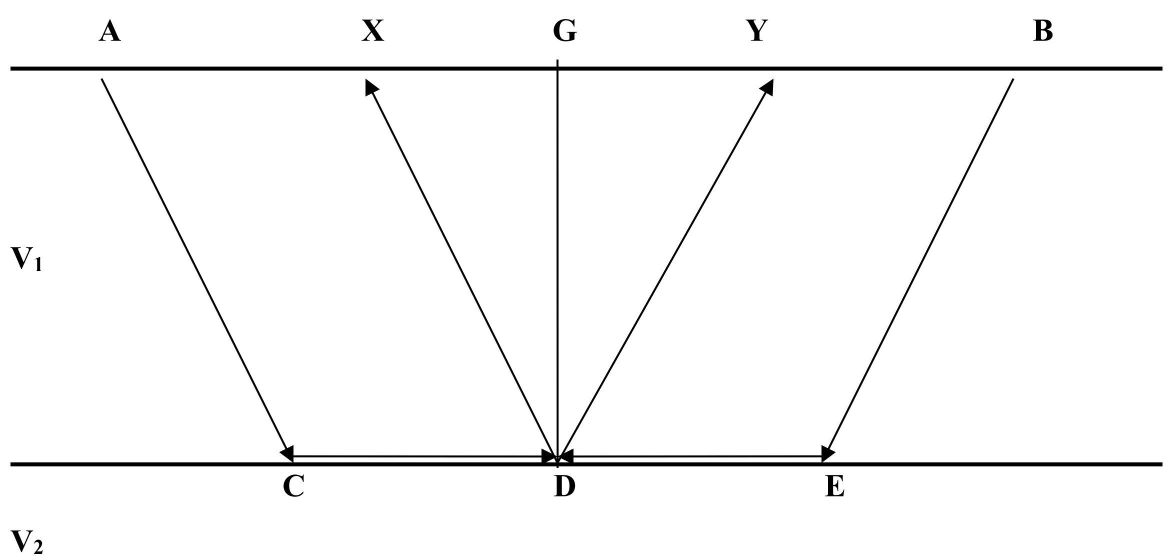



**Figure ( 4.3 ) Diagram showing the forward and reverse shots with the variable distance XY**

- **Undetected layers**

The hidden layer problem occurs where energy from a refractor of higher seismic velocity arrives at the surface before energy from an overlying refractor.

Another type of undetected layer is the velocity inversion problem, which occurs when a layer has a lower seismic velocity than the layer above it.

The GRM provides a means of recognizing and accommodating undetected layers through the two basic approaches of computing and observing the optimum XY values.

There are two distinct approaches for the determination of the optimum XY value, which is probably the most difficult, and the most important aspect of the GRM.

1. Direct calculation of XY values.
2. Observation of XY values.
3. 

- **Direct calculation of xy values**

We can directly calculate the optimum XY from the seismic velocities and thickness of the layers using the formula,

$$XY_{optimum} = 2\sum_{j=1}^{n-1} Z_{jG} \tan i_{jn} \text{-----------------------------------------------} \text{Eqn 4.3}$$

Where, $i_{jn} = \sin^{-1}(V_j/V_n)$

Hence an optimum XY value can be calculated for any seismic velocity versus depth section.

- **Observation of XY values**

- The velocity analysis function($T_v$)

The velocity analysis function Tv is defined by the equation,

$Tv = 1/2(t_{AY} - t_{BX} + t_{AB})$ Eqn (4.4) Where,

$t_{AY}$ =forward travel time from shot A to the geophone at Y

$t_{BX}$ =reverse travel time from shot B to the geophone at X

$t_{AB}$=the reciprocal time between the two shot points A and B

The value of this function is referred to G, which is mid way between X, and Y.
The values of Tv calculated using the above equation are plotted against distance for Different XY values until we get the optimum xy value.
The inverse of an apparent refractor velocity Vn' is defined as the slope of a line fitted to the Tv values for the optimum XY.i.e d/dx(Tr) =1/Vn'and it can be shown(palmer 1980)that $V_n \approx V_n' \cos\theta_{n-1}$,where Vn is the true refractor velocity and $\theta_{n-1}$ is the dip of the refractor.

- **The generalized time depth**

Using the symbols in(Fig 4.2)the generalized time depth at G is defined by the equation,

$$t_g = \frac{1}{2}\left[t_{AY} + t_{BX} - \left(t_{AB} + \frac{XY}{v_n}\right)\right] \text{------------------------------------Eqn 4.5}$$

The time depth function measures the depth to the refractor in units of time.

- **The depth conversion factor**

For plane layering between the forward and reverse arrival times,eqn ( 4.5 )can be shown to reduce to,

$$t_g = \sum_{j=1}^{n-1} ZjG / Vjn$$

Where, $V_{jn} \approx V'_n V'_j / (v'^2_n - V'^2_j)^{1/2}$

The insensitivity of the depth conversion factor to dip angles makes the GRM an extremely convenient method for dealing with irregular refractors, including those overlain by a layer with in which the velocity varies continually with depth.

Note that tg is measure of depth in units of time and ZG is measure of depth in units of space.

Therefore, ZG =Tg.DCF , where DCF =depth conversion factor.

The optimum XY value obtained using the above two equations is known as the observed XY value.

If the depth section is to be consistent with the travel time data, the computed and observed XY values must agree. If these values do not agree, then undetected layers are indicated.

i.e If $XY_{calc} = XY_{obs}$ (no hidden layer)

If $XY_{calc} > XY_{obs}$ (velocity inversion)

If $XY_{calc} < XY_{obs}$ (thin layer)

For a hidden layer problem the average velocity above the refractor is used to calculate the depth to the refractor with out defining all layers.

The average velocity is defined in equation ( 4.6 ) below.

$$\bar{V} = [V'_n XY/(XY + 2t_g V'_n)]^{1/2} \quad \text{---------------------Eqn 4.6}$$

And the depth to the refractor is defined as,

$$Z_{ref} = T_G \frac{\bar{V}}{\cos i} \text{ where, } i = \sin \frac{\bar{V}}{V'} \quad \text{---Eqn 4.7}$$

# 5. Data acquisition

### 5.1 The controlled source seismic study

Controlled Source Seismology involves the detonation of seismic explosive charges in deep boreholes distributed along profiles of seismic recording instruments deployed at regular intervals along the Earth's surface. The seismic waves generated by the charges travel down into the crust of the Earth and are reflected and refracted back to the surface from geological interfaces at depth. The seismic instruments record the resulting seismic waves as they reach the surface along the profiles. The time of arrival of the reflections and refractions at the recording instruments will be interpreted by the research seismologist in terms of the distribution of geological boundaries deep within the Earth. This image is used to constrain our understanding of the geological processes that form these deep geological structures. In the case of the EAGLE project, the processes are those that have generated the Ethiopian Rift at its junction with the region of Afar.

### 5.2 Report on shot details

Preparations for the controlled source effort began in April 2001 and 91 broadband instruments were first deployed at a nominal 5km interval along the 450km cross rift profile in November – December 2002. The controlled experiment took place in January of 2003 and involved 18 sources in boreholes (typically 1 mt dynamite at 50 m depth) and 2 sources in lakes (Shalla and Arenguade) and the deployment of ~1000 short-period recorders. An environmental impact assessment required by the Ethiopian government incorporating a full report on the lake flora, fauna, and chemistry both before and after the shots were detonated, should provide data of immense value for future seismic studies elsewhere in the world. The controlled source seismic study was undertaken in January 2003.The details of this part of the project, which involved more than 70 scientists deploying nearly 1000 recorders over an 8 day period, which instruments recorded the seismic waves generated from the detonation of 19 charges in both boreholes and lakes involved a major logistical exercise. The results will provide a very high-resolution image of the top 30 km of the Earth both across and along the axis of the Main Ethiopian Rift and also a detailed 3-D image of the subsurface beneath the central Nazret volcanic segment. They will determine the amount of extension that has already occurred across the Rift; provide understanding about the geological controls on the process of continental break-up, illuminate the magmatic processes that are occurring deep with in the crust of the Earth in this volcanic region, information about the distribution of near surface sedimentary and basement rocks and so aid in understanding of the distribution of mineral resource in the study area. They will also provide further information about the possible distribution of geothermal resource beneath the controlled source project area.

## 5.3 Recording instrument deployment phase

**Phase III** consisted of the deployment of a further 1100 seismic instruments during a controlled source seismic project involving 20 seismic charges being fired into one 450km cross-rift profile (Profile 1), one 450km axial profile (Profile 2), and a dense 2-D array of instruments in a 150km diameter circle around the profiles' intersection (Profile 3), all centered on the magmatically active Nazret region Fig ( 5.1 ). The crust and upper mantle velocity models to be derived will be used to provide estimates of total crustal thinning across the rift, to assess the role of basement in the location of major faults and magmatic segments, and to determine whether significant under plating takes place during the syn-rift stage.  The high-density array around the intersection of the two profiles was designed to image any magma bodies beneath the Boset magmatic segment.

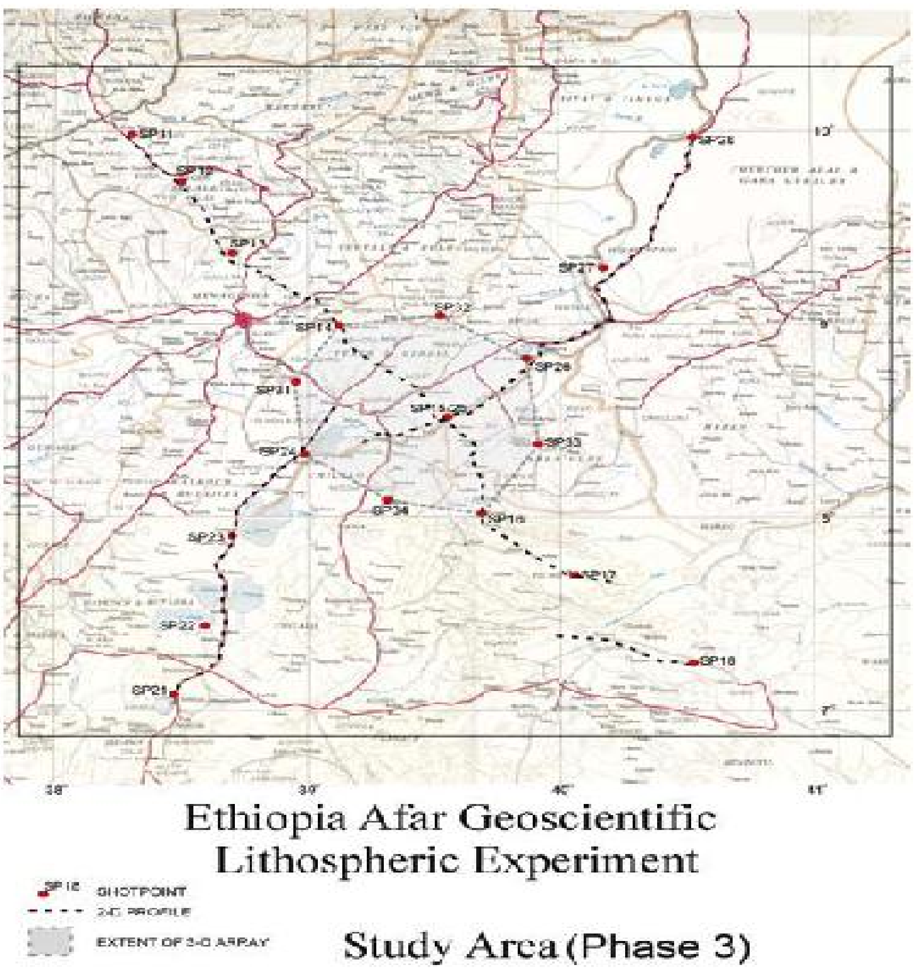


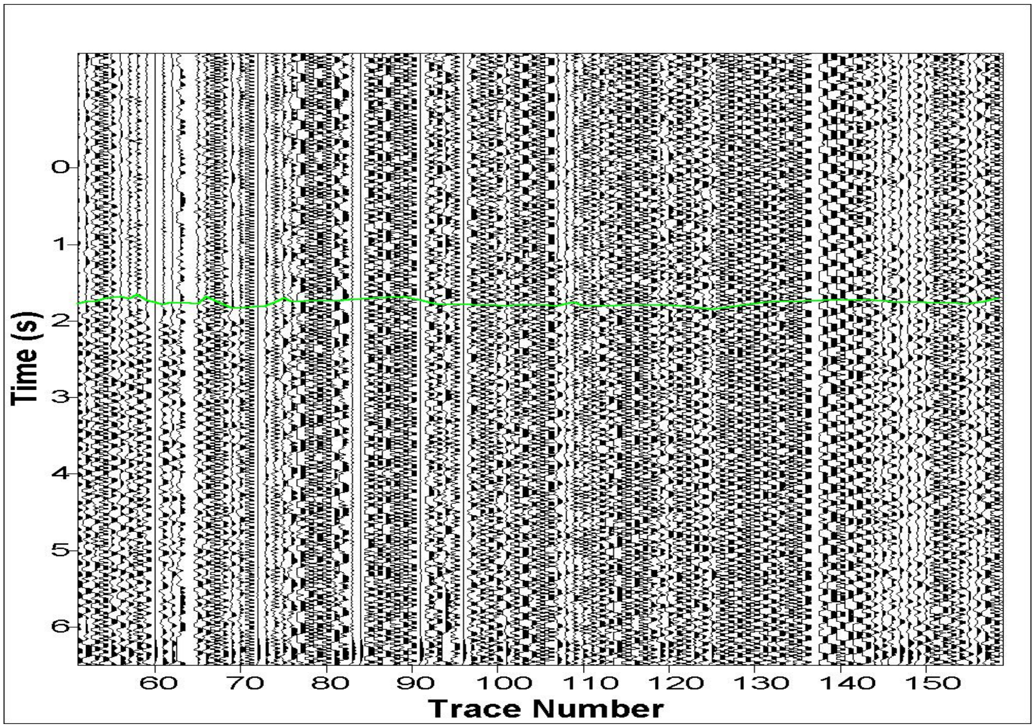

Fig (5.1)

| Shot point | Name | Easting | Northing | Elevation (m) |
|---|---|---|---|---|
| 21 | **Awassa** | 441578 | 785718 | 1706 |
| 22 | Lake shalla | 538072 | 967557 | 1797 |
| 23 | Ziway | 469359 | 870684 | 1653 |
| 24 | Koka | 500547 | 920584 | 1602 |
| 25 | Doni B | 568063 | 943141 | 1236 |

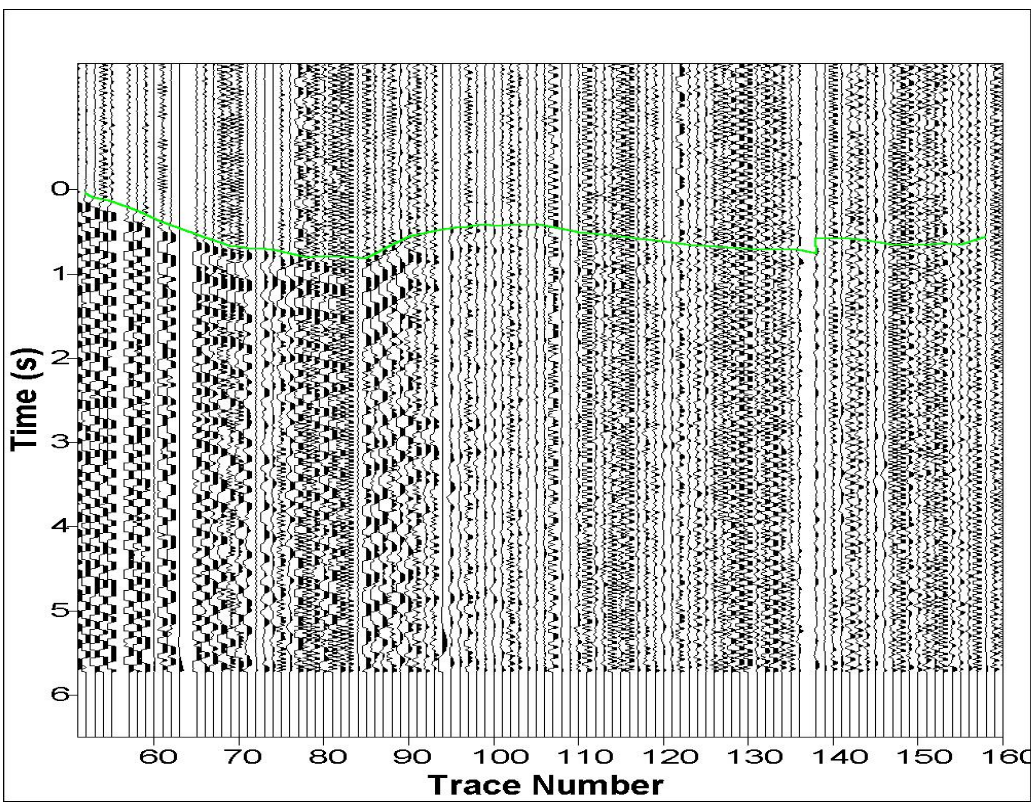
**Table (5.1) shot points with their position and elevation.**

## 5.1 DATA PROCESSING

The objective of a seismic refraction survey is to use the information contained in travel time data to determine the depth and configuration of refracting layers. Simply, the interpreter studies the travel time curves, assigns each arrival to a particular refractor, and determines the velocity of the refractor from the slope of the travel time curve. While there are similarities among the various methods of seismic refraction analysis, there are substantial differences in the field procedures, computations, and assumptions that each involves. For several reasons the GRM method is used to process the whole data in this study. Fig 6.1-Fig 6.6 show reduced arrival times for each geophone from each shot.




Fig( 6.1 ) Traces from shot 21



Fig( 6.2 ) Traces from shot

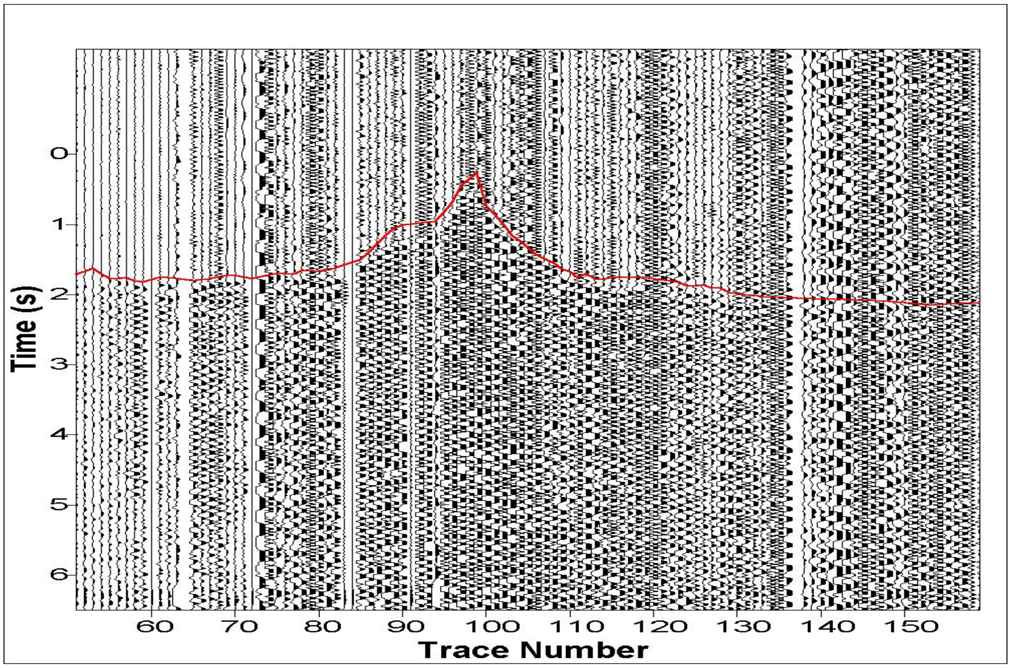



Fig ( 6.3 )traces from shot 23

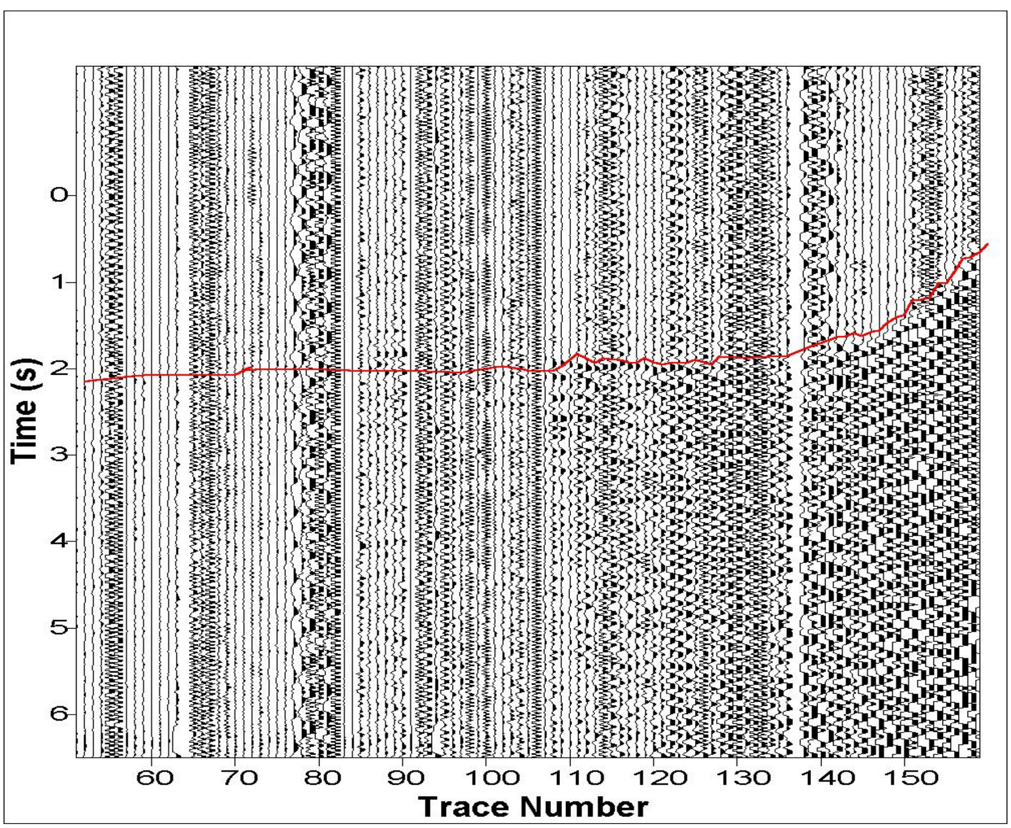


Fig ( 6.4 )Traces from shot 24

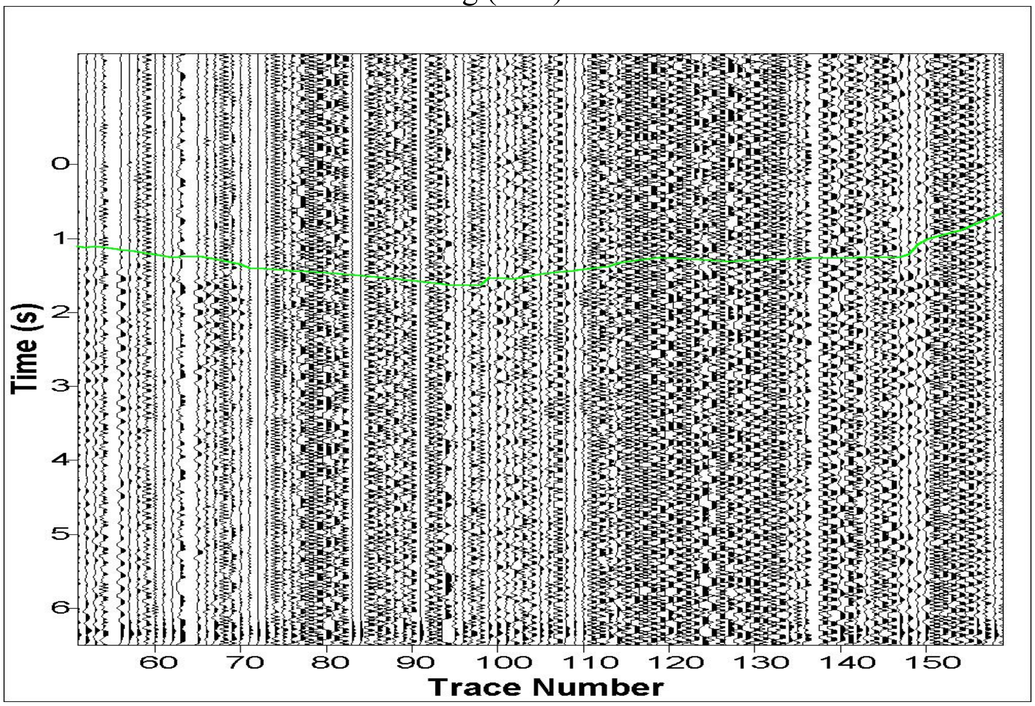



Fig ( 6.5 )Traces from shot 25

## 6.1 Steps to be employed while processing the data are,

i. Picking of first arrivals.
ii. Setting the actual first arrival times.
iii. Entering the data( actual arrival time of each geophone together with its elevation and geophone position) in to the inverting software.
iv. Assigning layers to arrival times, on the travel time curves.
v. Interpreting the assignments to produce the Geoseismic model.

### 6.1.1 Entering the data

The software type used for analyzing and interpreting the seismic data is GREMIX, which requires,

- ❖ Actual first arrival time
- ❖ Elevation
- ❖ And exact position of each geophone.

The raw data, which was reduced by assuming average crustal velocity of 6000m/s, should be converted and the actual first arrival time must be used while processing the data. The following equation is used,to convert the reduced arrival times in to their actual values.

$T_t = T_{red} + \frac{X}{V}$ Where,

$T_t$= the actual arrival time of the head waves.
$T_{red}$ =the reduced arrival time as it is picked from the trace.
X =the offset of each geophone from the active shot.
V= crustal velocity = 6000m/s

The input data to the inverting software GREMIX adheres to the shot geophone nomenclature shown in the diagram below.(Fig 6.6 ).GREMIX uses the first-arrival times nominated from forward and reverse shots to calculate the time depth and velocity-analysis values needed for the geophysical interpretation. These are plotted with the travel time curves. The calculations can be made for a range of XY values.

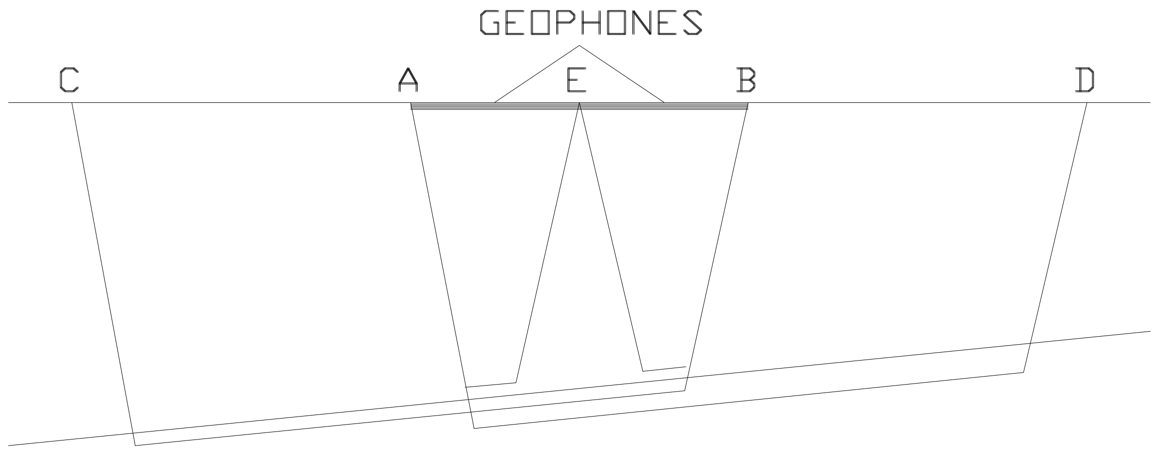



**Fig ( 6.6 ) Sketch showing the nomenclature of GREMIX**

GREMIX recognizes each shot; based on the offset data input it. In this study shot 21 is taken as a reference (with offset zero) to take measurements of offset distances for the remaining shots and sensors on the profile line. There fore, for this study all values that have been recognized as offsets are positive, as indicated in the diagram below. Based on the data input to GREMIX, the following association between the shot points and the letters in the GRIMIX nomenclature was found.

SP 21=C

SP22 =A

SP23 =E

SP 24=B

SP 25=D

REFERENCE

\- +

SP 21 SP 22 SP 23 SP 24 SP 25

| Shot type | Shot number | Shot position | Elevation(m) |
|---|---|---|---|
| **C** | **21** | **0** | 1706 |
| **A** | **22** | **26.93** | 1797 |
| **E** | **23** | **54.096** | 1653 |
| **B** | **24** | **88.399** | 1602 |
| **D** | **25** | **120.703** | 1236 |

Table 6.1 Input shot data

### 6.1.2 Data inversion

Following the input data, Gremix automatically give us the travel time curve Fig( 6.9 ) after making a static correction based on the elevation parameters of each geophone.

➢ Figure showing recorded signals with varying degree of signal to noise ratio.

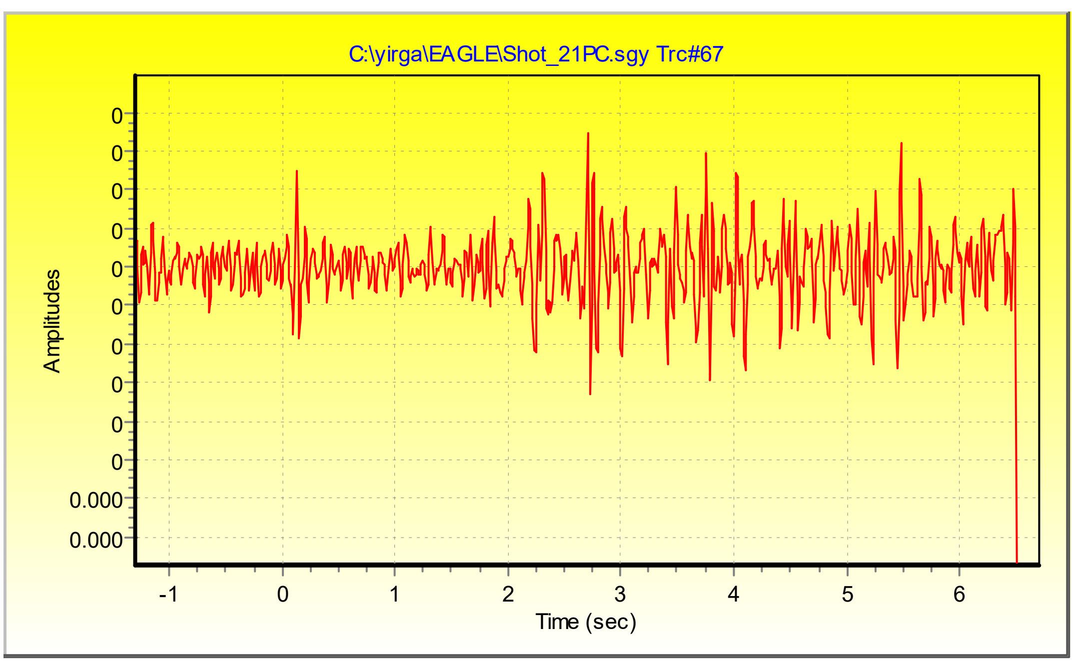



Fig (6.8 ) Low signal to noise ratio recorded from SP 21.

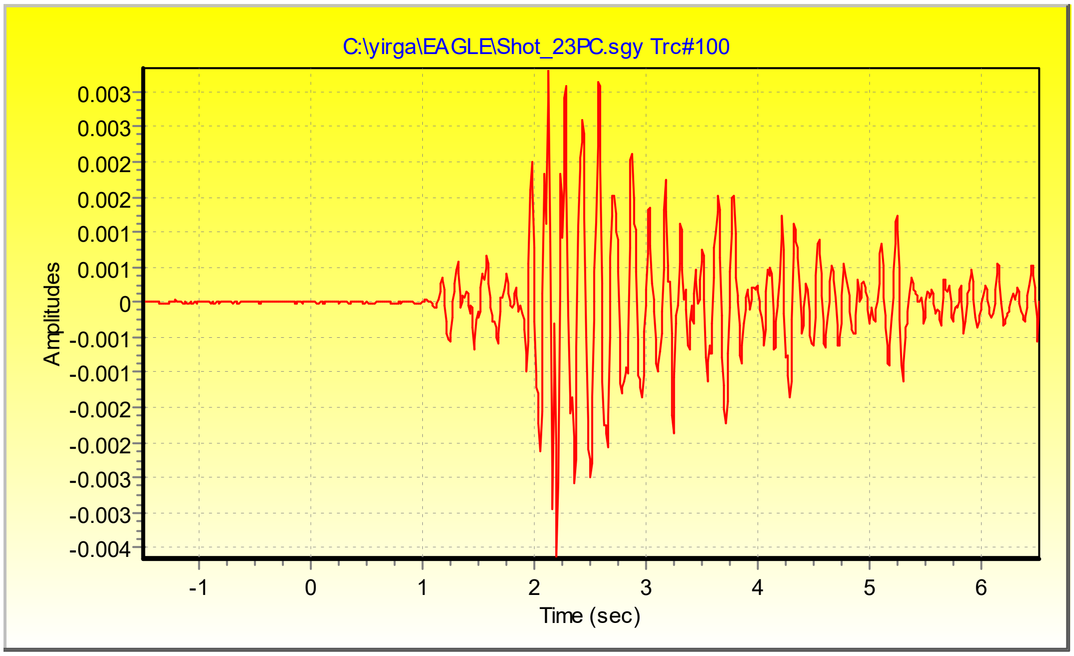



Fig ( 6.9 ) High signal to noise ratio recorded from shot point 23.

### 6.1.3 **Assigning layers to arrivals on the travel time curve**

Although processing is done by computer, the interpreter has to inspect the data and decide whether arrivals at different geophones are from head waves, which have traveled on the same refractor or different refractors. To calculate a valid velocity analysis or time-depth, we must be able to establish that the waves involved in the first arrivals at the two geophones and that the wave involved in the reciprocal time all traveled on the same refractor.

Basically we use the difference curves to assign layers to arrival times on the travel time curve. For curves with opposite slopes, difference curves show constant slope for areas in which arrivals come from the same refractor. Whereas for curves with slopes of the same sign, difference curves are flat (constant difference) for the same situation.

- The layer assignments for the arrival times on the travel time curves Fig( 6.9) were,
    - One refractor each for the arrival times from the two far end shots(SP 21 and SP25 )
    - Two refractors were identified for the middle shot on either side of the travel time curve (Sp 23)
    - Three refractors each for the arrival times for the end shots (SP 22 and SP 24).

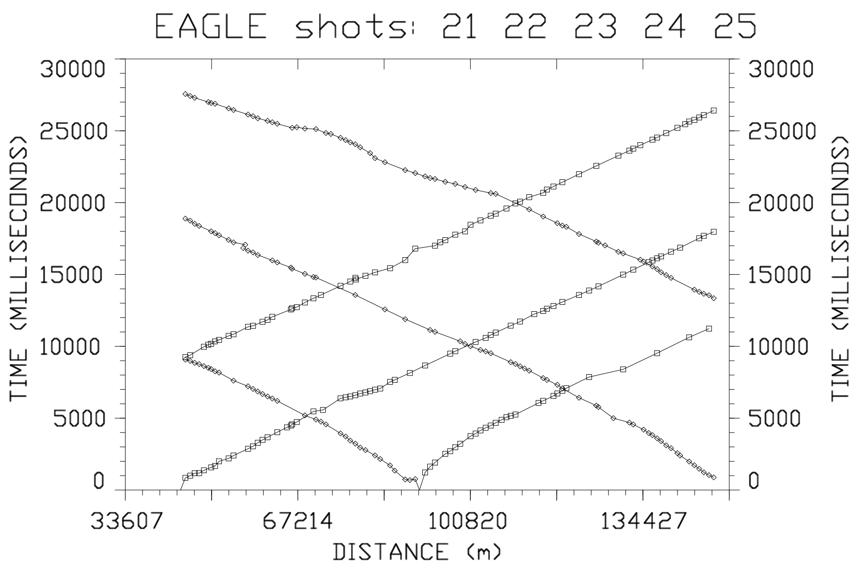



Fig ( 6.9 ) assigned arrival curves

- At the out set four layers are identified to a maximum depth of 10km.

# 7. Interpretation

At the outset, four layers of different acoustic property are identified**.**

The average seismic velocities of the layers from top to bottom are 2800m/s, 3950m/s, 5726m/s and 6320m/s respectively.

The uppermost layer with velocity 2800m/s has more or less constant thickness. The layers are characterized by undulating refractors may be due to continuous tectonic disturbance.

The low velocity section in the first layer indicates that the uppermost crust has been covered by weathered and fractured low-density material which include quaternary sediments, late Miocene, Early Pliocene, ignimbrites, rhyolites, Oligocene basalts, Mesozoic sediments, etc.

The average thickness of the second layer is 2800m.The layer has rugged topography. It is most likely that a series of Meta sediments and metavolcanics of low-grade metamorphic basement comprises the layer.

The average thickness of the third layer is 3500m.The velocity of this layer is high (5726m/s), Which corresponds to a high grade crystalline basement rock.

The seismic velocity in the fourth layer has a typical crustal velocity greater than 6300m/s. This probably is mafic and ultramafic rock.

Generally the rift shows higher velocities Fig (6.10) in the second, third and fourth layers. This could probably be the result of mafic intrusions beneath the rift magmatic centers.

# 8. Conclusions And Recommendiations

### 8.1 Conclusions

The result of the research work reveals that there are four major seismic layers down to a depth of 10km along the main Ethiopian rift with average velocities of 2800m/s, 3950m/s, 5726.6 m/s and 6320 m/s respectively. The velocity model constrains velocity anomalies especially in the third layer, which probably is an indication of mafic lower crust.

### 8.2 Recommendations

Based on the result obtained from the study, the following points are recommended.

1. Other geophysical methods like the gravity method should be employed so as to have an integrated and refined result.
2. Amplitude studies of first arrivals should also be made to understand the attenuating behavior of the rocks..
3. Reflection seismic methods must be employed to delineate the structures beneath The area with high resolution.

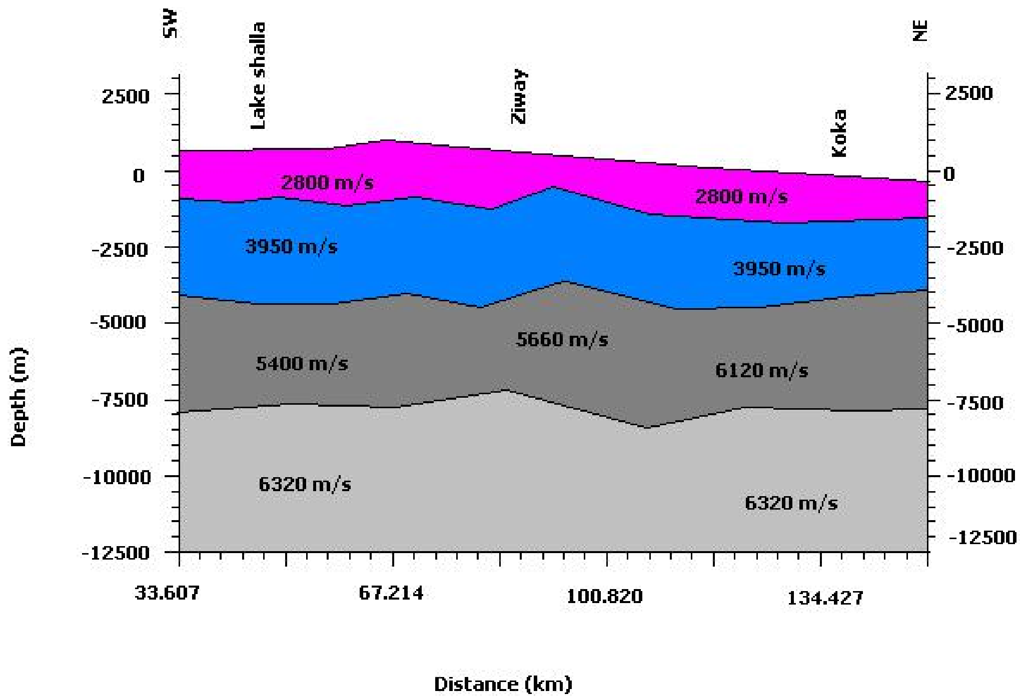
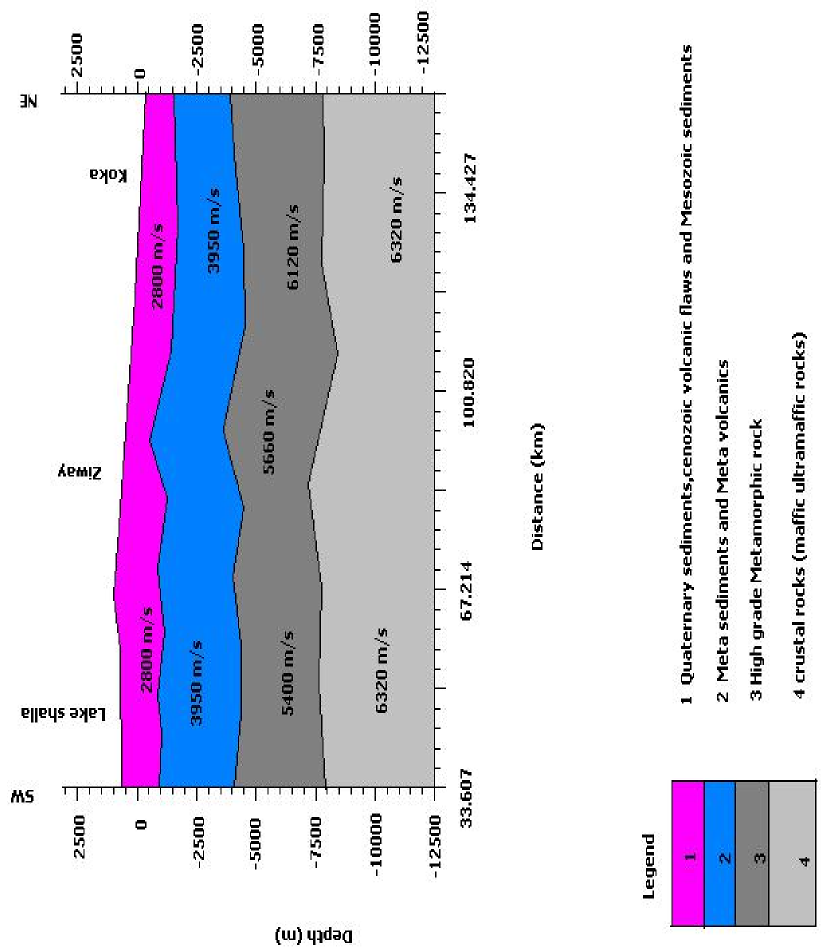



Fig 6.10 Seismic model along the main Ethiopian Rift



SW
NE
Lake shalla
Ziway
Koka
2800 m/s
3950 m/s
5400 m/s
6320 m/s
5660 m/s
6120 m/s
Depth (m)
2500
0
-2500
-5000
-7500
-10000
-12500
33.607
67.214
100.820
134.427
Distance (km)
Legend
1
2
3
4
1 Quaternary sediments,cenozoic volcanic flaws and Mesozoic sediments
2 Meta sediments and Meta volcanics
3 High grade Metamorphic rock
4 crustal rocks (maffic ultramaffic rocks)

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Press, Cambridge,Great Britain.

APPENDIX

| APPENDIX 1 -GEOPHONE STATION, LOCATION AND ALTITUDE | | | | | | |
|---|---|---|---|---|---|---|
| Order | Trace | Station | Easting | Northing | Elevation | Offset in (km) from shot 21 |
| 1 | 51 | 2051 | 464068 | 824000 | 1755.95 | 45.317 |
| 2 | 52 | 2052 | 464098 | 825018 | 1730.6 | 46.243 |
| 3 | 53 | 2053 | 464216 | 826014 | 1727.5 | 47.12 |
| 4 | 54 | 2054 | 464262 | 826989 | 1679.55 | 47.987 |
| 5 | 55 | 2055 | 464244 | 827986 | 1662.2 | 48.913 |
| 6 | 56 | 2056 | 464345 | 828980 | 1643 | 49.773 |
| 7 | 57 | 2057 | 464215 | 830011 | 1626.65 | 50.323 |
| 8 | 58 | 2058 | 463742 | 830862 | 1650.3 | 51.087 |
| 9 | 59 | 2059 | 463453 | 831854 | 1636.75 | 51.862 |
| 10 | 60 | 2060 | 463249 | 832802 | 1647.2 | 52.816 |
| 11 | 61 | 2061 | 463382 | 833788 | 1653.5 | 53.737 |
| 12 | 62 | 2062 | 463375 | 834801 | 1647.7 | 54.687 |
| 13 | 63 | 2063 | 463499 | 835786 | 1643.7 | 55.602 |
| 14 | 64 | 2064 | 463510 | 836776 | 1634.8 | 56.579 |
| 15 | 65 | 2065 | 463621 | 837791 | 1635.4 | 57.506 |
| 16 | 66 | 2066 | 463619 | 838794 | 1622.45 | 58.484 |
| 17 | 67 | 2067 | 463753 | 839798 | 1627.4 | 59.41 |
| 18 | 68 | 2068 | 463752 | 840795 | 1616.6 | 60.333 |
| 19 | 69 | 2069 | 463814 | 841766 | 1611.6 | 61.323 |
| 20 | 70 | 2070 | 463949 | 842774 | 1612.25 | 62.232 |
| 21 | 71 | 2071 | 463929 | 843755 | 1602.75 | 63.204 |
| 22 | 72 | 2072 | 464016 | 844766 | 1602.75 | 64.186 |
| 23 | 73 | 2073 | 464158 | 845760 | 1598.65 | 65.108 |
| 24 | 74 | 2074 | 464139 | 846752 | 1601.2 | 65.864 |
| 25 | 75 | 2075 | 463819 | 847672 | 1598.3 | 66.092 |
| 26 | 76 | 2076 | 463484 | 848030 | 1591.95 | 67.002 |
| 27 | 77 | 2077 | 462540 | 849313 | 1598.4 | 68.582 |
| 28 | 79 | 2079 | 462024 | 851138 | 1606.1 | 70.253 |
| 29 | 80 | 2080 | 461667 | 852101 | 1605.5 | 70.736 |
| 30 | 81 | 2081 | 461403 | 853070 | 1609.35 | 71.704 |
| 31 | 82 | 2082 | 460774 | 853751 | 1611.8 | 72.675 |
| 32 | 83 | 2083 | 460718 | 854771 | 1605.9 | 73.643 |
| 33 | 84 | 2084 | 460776 | 855764 | 1612.95 | 74.567 |
| 34 | 85 | 2085 | 460681 | 856792 | 1621 | 75.527 |
| 35 | 86 | 2086 | 460796 | 857716 | 1636.55 | 76.519 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 36 | 87 | 2087 | 461334 | 858566 | 1650.45 | 77.421 |
| 37 | 88 | 2088 | 461826 | 859459 | 1654.4 | 78.406 |
| 38 | 89 | 2089 | 462390 | 860239 | 1652.4 | 79.351 |
| 39 | 90 | 2090 | 462860 | 861129 | 1650 | 80.381 |
| 40 | 91 | 2091 | 463480 | 861935 | 1654.9 | 81.289 |
| 41 | 92 | 2092 | 463934 | 862876 | 1656 | 82.24 |
| 42 | 93 | 2093 | 464470 | 863667 | 1655 | 83.258 |
| 43 | 94 | 2094 | 465082 | 864475 | 1655.25 | 84.165 |
| 44 | 95 | 2095 | 465633 | 865372 | 1665.35 | 85.168 |
| 45 | 96 | 2096 | 466151 | 866161 | 1666.2 | 86.09 |
| 46 | 97 | 2097 | 466597 | 867074 | 1649.85 | 88.117 |
| 47 | 98 | 2098 | 467202 | 867851 | 1651.9 | 89.025 |
| 48 | 100 | 2100 | 467930 | 869746 | 1640.45 | 91.999 |
| 49 | 101 | 2101 | 467830 | 870727 | 1646.35 | 92.97 |
| 50 | 102 | 2102 | 468158 | 871725 | 1648.75 | 93.922 |
| 51 | 104 | 2104 | 468206 | 873719 | 1646.75 | 95.926 |
| 52 | 105 | 2105 | 468354 | 874690 | 1649.65 | 96.886 |
| 53 | 106 | 2106 | 468530 | 875630 | 1648.75 | 97.873 |
| 54 | 107 | 2107 | 468614 | 876667 | 1651.4 | 98.837 |
| 55 | 108 | 2108 | 468698 | 877669 | 1641.8 | 99.774 |
| 56 | 109 | 2109 | 468863 | 878621 | 1641.1 | 100.845 |
| 57 | 110 | 2110 | 468929 | 879629 | 1645.15 | 101.837 |
| 58 | 111 | 2111 | 469039 | 880601 | 1645.4 | 102.776 |
| 59 | 112 | 2112 | 469219 | 881524 | 1643.7 | 103.797 |
| 60 | 113 | 2113 | 469278 | 882621 | 1648.8 | 104.783 |
| 61 | 114 | 2114 | 469395 | 883618 | 1651.9 | 105.75201 |
| 62 | 115 | 2115 | 469500 | 884565 | 1656.6 | 106.90501 |
| 63 | 116 | 2116 | 469660 | 885578 | 1660.95 | 107.84001 |
| 64 | 117 | 2117 | 469685 | 886595 | 1666.4 | 108.67201 |
| 65 | 118 | 2118 | 469853 | 887553 | 1657.3 | 109.59301 |
| 66 | 119 | 2119 | 470036 | 888697 | 1668.25 | 110.49101 |
| 67 | 120 | 2120 | 470157 | 889633 | 1669.05 | 111.36501 |
| 68 | 121 | 2121 | 470769 | 890328 | 1670.4 | 112.27301 |
| 69 | 122 | 2122 | 471459 | 891089 | 1668.15 | 113.24601 |
| 70 | 123 | 2123 | 472091 | 891843 | 1669.9 | 114.08801 |
| 71 | 124 | 2124 | 472787 | 892551 | 1668.5 | 114.99401 |
| 72 | 125 | 2125 | 473460 | 893300 | 1671.1 | 115.73101 |
| 73 | 126 | 2126 | 474150 | 894107 | 1662.85 | 117.00001 |
| 74 | 127 | 2127 | 474818 | 894785 | 1655.95 | 117.75001 |
| 75 | 128 | 2128 | 475439 | 895542 | 1655.5 | 118.72801 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 76 | 129 | 2129 | 475951 | 896154 | 1665.1 | 119.51101 |
| 77 | 130 | 2130 | 476794 | 897218 | 1651.55 | 120.44901 |
| 78 | 131 | 2131 | 477625 | 897741 | 1652.3 | 121.97101 |
| 79 | 132 | 2132 | 478244 | 898570 | 1662.95 | 122.90201 |
| 80 | 133 | 2133 | 478811 | 899204 | 1665.75 | 123.94001 |
| 81 | 134 | 2134 | 479453 | 899982 | 1665.6 | 125.33901 |
| 82 | 136 | 2136 | 481045 | 901052 | 1667.15 | 127.04201 |
| 83 | 137 | 2137 | 481696 | 901813 | 1665.15 | 127.69201 |
| 84 | 138 | 2138 | 482258 | 902715 | 1661.25 | 128.67101 |
| 85 | 139 | 2139 | 483302 | 903830 | 1665.25 | 129.63801 |
| 86 | 140 | 2140 | 483353 | 904253 | 1664.75 | 130.57301 |
| 87 | 141 | 2141 | 484307 | 905280 | 1683.1 | 131.77801 |
| 88 | 142 | 2142 | 484710 | 905824 | 1689.85 | 132.53901 |
| 89 | 143 | 2143 | 485121 | 906718 | 1691.1 | 133.90701 |
| 90 | 144 | 2144 | 485964 | 907439 | 1691.4 | 134.56101 |
| 91 | 145 | 2145 | 486452 | 908257 | 1686.75 | 135.55501 |
| 92 | 146 | 2146 | 487016 | 909333 | 1689.25 | 136.27801 |
| 93 | 147 | 2147 | 487385 | 910005 | 1692.4 | 137.18101 |
| 94 | 148 | 2148 | 487847 | 911291 | 1694.55 | 137.95401 |
| 95 | 149 | 2149 | 488366 | 911796 | 1692.4 | 138.94701 |
| 96 | 150 | 2150 | 489235 | 912531 | 1695.4 | 139.89601 |
| 97 | 151 | 2151 | 489817 | 913089 | 1690.35 | 141.13701 |
| 98 | 152 | 2152 | 490652 | 913735 | 1681.95 | 141.66401 |
| 99 | 153 | 2153 | 491221 | 914343 | 1681.6 | 142.65101 |
| 100 | 154 | 2154 | 492216 | 915023 | 1674.5 | 143.42101 |
| 101 | 155 | 2155 | 492782 | 915816 | 1661.65 | 144.44101 |
| 102 | 156 | 2156 | 493828 | 916735 | 1656 | 145.38201 |
| 103 | 157 | 2157 | 494333 | 917104 | 1650.95 | 146.27601 |
| 104 | 158 | 2158 | 495156 | 917835 | 1639.25 | 147.29901 |
| 105 | 159 | 2159 | 495756 | 918419 | 1627.5 | 148.20701 |
| 106 | 160 | 2160 | 496415 | 919255 | 1607.4 | 149.19201 |

| APPENDIX 2-OFFSET OF EACH GEOPHONE FROM EACH SHOT | | | | | |
|---|---|---|---|---|---|
| Station | OFFSET FROM SP21 | Offset from SP 22 (km) | Offset from SP 23 (km) | Offset from sp 24 (km) | Offset from SP 25 (km) |
| 2051 | 45.317 | 6.594 | -45.993 | -102.35 | -157.45 |
| 2052 | 46.243 | 6.699 | -44.99 | -101.37 | -156.62 |
| 2053 | 47.12 | 6.869 | -44.014 | -100.44 | -155.86 |
| 2054 | 47.987 | 7.115 | -43.025 | -99.522 | -155.13 |
| 2055 | 48.913 | 7.593 | -42.026 | -98.56 | -154.33 |
| 2056 | 49.773 | 8 | -41.016 | -97.646 | -153.65 |
| 2057 | 50.323 | 8.129 | -40.235 | -97.035 | -153.34 |
| 2058 | 51.087 | 8.592 | -39.297 | -96.233 | -152.82 |
| 2059 | 51.862 | 9.177 | -38.392 | -95.437 | -152.27 |
| 2060 | 52.816 | 10.045 | -37.395 | -94.476 | -151.46 |
| 2061 | 53.737 | 10.88 | -36.396 | -93.548 | -150.74 |
| 2062 | 54.687 | 11.784 | -35.405 | -92.597 | -149.95 |
| 2063 | 55.602 | 12.655 | -34.426 | -91.684 | -149.23 |
| 2064 | 56.579 | 13.607 | -33.406 | -90.711 | -148.43 |
| 2065 | 57.506 | 14.512 | -32.417 | -89.795 | -147.72 |
| 2066 | 58.484 | 15.482 | -31.406 | -88.826 | -146.92 |
| 2067 | 59.41 | 16.401 | -30.424 | -87.918 | -146.21 |
| 2068 | 60.333 | 17.325 | -29.458 | -87.013 | -145.5 |
| 2069 | 61.323 | 18.318 | -28.442 | -86.039 | -144.69 |
| 2070 | 62.232 | 19.234 | -27.482 | -85.16 | -144.03 |
| 2071 | 63.204 | 20.214 | -26.476 | -84.215 | -143.27 |
| 2072 | 64.186 | 21.204 | -25.473 | -83.256 | -142.49 |
| 2073 | 65.108 | 22.142 | -24.507 | -82.375 | -141.83 |
| 2074 | 65.864 | 22.933 | -23.681 | -81.694 | -141.44 |
| 2075 | 66.092 | 23.192 | -23.413 | -81.523 | -141.44 |
| 2076 | 67.002 | 24.221 | -22.442 | -80.824 | -141.29 |
| 2077 | 68.582 | 25.915 | -20.887 | -79.468 | -140.47 |
| 2079 | 70.253 | 27.728 | -19.334 | -78.091 | -139.68 |
| 2080 | 70.736 | 28.325 | -18.99 | -77.82 | -139.72 |
| 2081 | 71.704 | 29.333 | -18.111 | -76.973 | -139.11 |
| 2082 | 72.675 | 30.326 | -17.218 | -76.097 | -138.44 |
| 2083 | 73.643 | 31.339 | -16.385 | -75.274 | -137.87 |
| 2084 | 74.567 | 32.271 | -15.542 | -74.427 | -137.2 |
| 2085 | 75.527 | 33.174 | -14.54 | -73.424 | -136.26 |

| | | | | | |
|---|---|---|---|---|---|
| 2086 | 76.519 | 34.12 | -13.521 | -72.404 | -135.31 |
| 2087 | 77.421 | 34.969 | -12.559 | -71.443 | -134.39 |
| 2088 | 78.406 | 35.917 | -11.556 | -70.437 | -133.46 |
| 2089 | 79.351 | 36.81 | -10.541 | -69.425 | -132.48 |
| 2090 | 80.381 | 37.813 | -9.508 | -68.388 | -131.55 |
| 2091 | 81.289 | 38.686 | -8.556 | -67.435 | -130.64 |
| 2092 | 82.24 | 39.594 | -7.539 | -66.421 | -129.66 |
| 2093 | 83.258 | 40.582 | -6.487 | -65.368 | -128.68 |
| 2094 | 84.165 | 41.462 | -5.542 | -64.422 | -127.79 |
| 2095 | 85.168 | 42.448 | -4.544 | -63.414 | -126.89 |
| 2096 | 86.09 | 43.339 | -3.558 | -62.433 | -125.93 |
| 2097 | 88.117 | 45.351 | -1.703 | -60.441 | -124.22 |
| 2098 | 89.025 | 46.285 | -1.521 | -59.672 | -123.72 |
| 2100 | 91.999 | 49.288 | 3.246 | -56.977 | -121.68 |
| 2101 | 92.97 | 50.268 | 4.132 | -56.098 | -121.01 |
| 2102 | 93.922 | 51.224 | 5.018 | -55.228 | -120.34 |
| 2104 | 95.926 | 52.255 | 6.033 | -54.34 | -119.69 |
| 2105 | 96.886 | 53.254 | 7.021 | -53.479 | -119.06 |
| 2106 | 97.873 | 54.22 | 7.958 | -52.617 | -118.4 |
| 2107 | 98.837 | 55.22 | 8.961 | -51.776 | -117.8 |
| 2108 | 99.774 | 56.195 | 9.928 | -50.94 | -117.18 |
| 2109 | 100.845 | 57.135 | 10.848 | -50.107 | -116.54 |
| 2110 | 101.837 | 58.222 | 11.945 | -49.22 | -115.92 |
| 2111 | 102.776 | 59.223 | 12.942 | -48.376 | -115.3 |
| 2112 | 103.797 | 60.171 | 13.89 | -47.59 | -114.72 |
| 2113 | 104.783 | 61.198 | 14.907 | -46.717 | -114.07 |
| 2114 | 105.752 | 62.2 | 15.924 | -45.943 | -113.54 |
| 2115 | 106.905 | 63.173 | 16.887 | -45.125 | -112.92 |
| 2116 | 107.84 | 64.332 | 18.037 | -44.164 | -112.19 |
| 2117 | 108.672 | 65.274 | 18.978 | -43.406 | -111.63 |
| 2118 | 109.593 | 66.076 | 19.707 | -42.485 | -110.77 |
| 2119 | 110.491 | 66.963 | 20.526 | -41.455 | -109.79 |
| 2120 | 111.365 | 67.833 | 21.348 | -40.476 | -108.88 |
| 2121 | 112.273 | 68.677 | 22.148 | -39.483 | -107.94 |
| 2122 | 113.246 | 69.558 | 22.999 | -38.478 | -106.99 |
| 2123 | 114.088 | 70.505 | 23.924 | -37.415 | -106 |
| 2124 | 114.994 | 71.323 | 24.727 | -36.467 | -105.1 |
| 2125 | 115.731 | 72.21 | 25.607 | -35.488 | -104.2 |
| 2126 | 117 | 72.931 | 26.326 | -34.695 | -103.46 |
| 2127 | 117.75 | 74.177 | 27.574 | -33.344 | -102.23 |

| | | | | | |
|---|---|---|---|---|---|
| 2128 | 118.728 | 74.9 | 28.31 | -32.387 | -101.25 |
| 2129 | 119.511 | 75.865 | 29.285 | -31.365 | -100.33 |
| 2130 | 120.449 | 76.635 | 30.067 | -30.51 | -99.533 |
| 2131 | 121.971 | 77.56 | 31.008 | -29.51 | -98.616 |
| 2132 | 122.902 | 79.046 | 32.559 | -27.627 | -96.72 |
| 2133 | 123.94 | 79.967 | 33.504 | -26.629 | -95.804 |
| 2134 | 125.339 | 80.999 | 34.552 | -25.594 | -94.908 |
| 2136 | 127.042 | 82.802 | 36.394 | -23.733 | -93.26 |
| 2137 | 127.692 | 84.077 | 37.71 | -22.338 | -91.971 |
| 2138 | 128.671 | 84.723 | 38.372 | -21.668 | -91.375 |
| 2139 | 129.638 | 85.701 | 39.355 | -20.763 | -90.64 |
| 2140 | 130.573 | 86.659 | 40.358 | -19.65 | -89.573 |
| 2141 | 131.778 | 87.591 | 41.304 | -18.744 | -88.804 |
| 2142 | 132.539 | 88.794 | 42.518 | -17.617 | -87.866 |
| 2143 | 133.907 | 89.553 | 43.286 | -16.901 | -87.263 |
| 2144 | 134.561 | 90.921 | 44.648 | -15.75 | -86.352 |
| 2145 | 135.555 | 91.571 | 45.324 | -15.033 | -85.684 |
| 2146 | 136.278 | 92.559 | 46.36 | -13.897 | -84.605 |
| 2147 | 137.181 | 93.279 | 47.11 | -13.108 | -83.87 |
| 2148 | 137.954 | 94.178 | 48.059 | -12.05 | -82.856 |
| 2149 | 138.947 | 94.949 | 48.859 | -11.234 | -82.105 |
| 2150 | 139.896 | 95.94 | 49.914 | -10.032 | -80.938 |
| 2151 | 141.137 | 96.888 | 50.883 | -9.121 | -80.127 |
| 2152 | 141.664 | 98.128 | 52.185 | -7.751 | -78.83 |
| 2153 | 142.651 | 98.655 | 52.744 | -7.137 | -78.239 |
| 2154 | 143.421 | 99.643 | 53.781 | -6.063 | -77.217 |
| 2155 | 144.441 | 100.414 | 54.585 | -5.264 | -76.454 |
| 2156 | 145.382 | 101.435 | 55.632 | -4.355 | -75.571 |
| 2157 | 146.276 | 102.378 | 56.597 | -3.595 | -74.763 |
| 2158 | 147.299 | 103.272 | 57.521 | -2.927 | -73.949 |
| 2159 | 148.207 | 104.298 | 58.578 | -2.418 | -73.032 |
| 2160 | 149.192 | 105.208 | 59.521 | 2.285 | -72.193 |
| | | | | | |

| APPENDIX 3-FIRST ARRIVAL RECORDS FOR EACH GEOPHONE FROM EACH SHOT | | | | | |
|---|---|---|---|---|---|
| Trace | First arrival from SP 21 | First arrival from SP 22 | First arrival from SP 23 | First arrival from SP 24 | First arrival from SP 25 |
| 51 | 1.697 | 0.009 | 1.409 | 18.8907 | 1.318 |
| 52 | 1.682 | 0.026 | 1.485 | 18.7435 | 1.318 |
| 53 | | 0.06 | 1.515 | 18.5287 | 1.318 |
| 54 | | 0.102 | 1.591 | 18.379 | |
| 55 | 1.818 | 0.119 | 1.621 | | |
| 56 | 1.818 | | 1.667 | | 1.394 |
| 57 | 1.788 | 0.264 | 1.712 | 18.0055 | 1.379 |
| 58 | 1.833 | 0.213 | 1.712 | 17.8798 | 1.409 |
| 59 | 1.803 | 0.29 | 1.773 | 17.7272 | |
| 60 | | | | | |
| 61 | 1.773 | 0.375 | | 17.4093 | 1.439 |
| 62 | 1.727 | 0.366 | 1.712 | 17.2328 | 1.455 |
| 63 | | | | 17.0737 | |
| 64 | | | | 16.8405 | |
| 65 | 1.773 | 0.554 | 1.818 | 16.6568 | 1.515 |
| 66 | 1.682 | 0.563 | 1.803 | 16.5363 | 1.53 |
| 67 | | 0.554 | 1.788 | 16.354 | 1.5 |
| 68 | 1.652 | 0.605 | 1.773 | | |
| 69 | 1.621 | 0.622 | 1.773 | | 1.576 |
| 70 | 1.682 | | 1.788 | 15.9813 | 1.591 |
| 71 | | 0.656 | 1.788 | 15.8388 | 1.606 |
| 72 | | | | | |
| 73 | | 0.673 | | | |
| 74 | 1.591 | 0.665 | | 15.4797 | |
| 75 | 1.636 | 0.707 | | 13.5872 | 1.636 |
| 76 | 1.561 | 0.699 | | | 1.701 |
| 77 | 1.621 | | 1.712 | 15.0457 | 1.744 |
| 78 | | | 1.727 | 14.9332 | |
| 79 | 1.636 | 0.852 | | 14.8262 | |
| 80 | | 0.852 | 1.742 | 14.791 | 1.833 |
| 81 | 1.621 | | 1.742 | | |
| 82 | | | 1.697 | | 1.773 |
| 83 | | | | | 1.801 |

| | | | | | |
|---|---|---|---|---|---|
| 84 | | | | | |
| 85 | 1.621 | 0.852 | 1.515 | | 1.803 |
| 86 | | 0.767 | 1.47 | | 1.803 |
| 87 | 1.606 | 0.682 | 1.348 | | 1.803 |
| 88 | 1.697 | 0.614 | 1.303 | 13.5725 | 1.818 |
| 89 | 1.727 | 0.58 | 1.197 | | 1.773 |
| 90 | 1.712 | 0.486 | 1.197 | | |
| 91 | | 0.435 | | | 1.672 |
| 92 | 1.742 | 0.384 | 1.152 | | 1.485 |
| 93 | | 0.298 | 1.076 | | |
| 94 | | | | 12.57 | 1.515 |
| 95 | 1.742 | 0.452 | 0.955 | | |
| 96 | | 0.443 | 0.758 | | |
| 97 | 1.773 | | 0.455 | 11.8915 | 1.561 |
| 98 | | 0.435 | 0.439 | | |
| 99 | 1.788 | | 0.5 | | 1.576 |
| 100 | | 0.452 | 0.682 | | 1.545 |
| 101 | | | 0.939 | 11.1377 | 1.545 |
| 102 | 1.742 | | 1.076 | 11.0077 | 1.591 |
| 103 | 1.818 | | 1.212 | | |
| 104 | 1.803 | | 1.348 | | 1.606 |
| 105 | | 0.452 | 1.379 | | |
| 106 | 1.758 | 0.46 | 1.485 | | 1.667 |
| 107 | | | 1.561 | 10.354 | |
| 108 | 1.621 | | | 10.1692 | 1.667 |
| 109 | 1.652 | | 1.758 | 10.0063 | |
| 110 | | 0.435 | 1.773 | | 1.667 |
| 111 | 1.636 | | 1.833 | 9.74967 | |
| 112 | | 0.384 | 1.848 | 9.65017 | |
| 113 | 1.621 | 0.426 | 1.833 | 9.52117 | 1.742 |
| 114 | 1.606 | 0.426 | 1.864 | | 1.788 |
| 115 | | | 1.879 | | |
| 116 | 1.621 | | 1.909 | | |
| 117 | | 0.426 | 1.879 | 8.89883 | |
| 118 | 1.682 | | 1.833 | 8.77317 | |
| 119 | 1.652 | 0.418 | | 8.61 | |
| 120 | | | | 8.4595 | |
| 121 | 1.667 | | | 8.307 | 1.697 |
| 122 | | 0.494 | | | |
| 123 | | | 1.939 | | |

| | | | | | |
|---|---|---|---|---|---|
| 124 | 1.515 | 0.426 | 1.939 | 7.79367 | 1.667 |
| 125 | 1.621 | 0.46 | | 7.6615 | |
| 126 | 1.621 | 0.443 | 1.955 | | |
| 127 | | | 2 | 7.32183 | 1.697 |
| 128 | 1.636 | 0.443 | 2.03 | 7.0755 | 1.682 |
| 129 | | | 2.076 | | 1.727 |
| 130 | | | | | |
| 131 | 1.652 | 0.401 | | 6.4225 | 1.697 |
| 132 | | | | | |
| 133 | | 0.384 | 2.106 | | |
| 134 | 1.667 | | | 5.87483 | 1.712 |
| 135 | | 0.375 | | 5.7735 | 1.667 |
| 136 | | | | 5.541 | 1.697 |
| 137 | | | | | |
| 138 | | | | 5.2485 | |
| 139 | 1.667 | | | | 1.652 |
| 140 | | 0.392 | 1.515 | | 1.667 |
| 141 | 1.654 | | | 4.69417 | |
| 142 | 1.667 | 0.409 | | 4.55883 | |
| 143 | 1.682 | | | | 1.636 |
| 144 | | | | 4.2025 | 1.621 |
| 145 | | 0.426 | | 3.96817 | |
| 146 | 1.667 | 0.429 | | 3.82067 | 1.576 |
| 147 | 1.667 | 0.431 | 1.515 | 3.59933 | 1.561 |
| 148 | | 0.433 | | 3.40233 | 1.47 |
| 149 | 1.682 | | | 3.111 | 1.47 |
| 150 | | 0.435 | | 2.91417 | 1.409 |
| 151 | 1.682 | | | 2.56483 | |
| 152 | | 0.426 | | 2.4015 | |
| 153 | 1.682 | | | | |
| 154 | 1.742 | | 1.53 | 1.98333 | |
| 155 | 1.682 | | | 1.72583 | 1.348 |
| 156 | 1.697 | 0.46 | | 1.47817 | 1.333 |
| 157 | 1.712 | 0.477 | | 1.22983 | 1.333 |
| 158 | | | 1.47 | 1.039 | 1.379 |
| 159 | 1.712 | 0.435 | 1.424 | 0.88083 | 1.318 |
| | | | | | |

APPENDIX – 4 FIRST ARRIVAL DATA AS OBTAINED IN THE RAW FORMAT (Example taken from SP 22 )

| Trace No | First arrival |
|---|---|
| 51.029 | 0.009 |
| 51.975 | 0.026 |
| 52.987 | 0.06 |
| 54.015 | 0.102 |
| 54.994 | 0.119 |
| 56.986 | 0.264 |
| 57.998 | 0.213 |
| 59.043 | 0.29 |
| 61.034 | 0.375 |
| 61.98 | 0.366 |
| 64.991 | 0.554 |
| 65.987 | 0.563 |
| 66.982 | 0.554 |
| 68.066 | 0.605 |
| 69.04 | 0.622 |
| 70.942 | 0.656 |
| 72.978 | 0.673 |
| 73.996 | 0.665 |
| 75.013 | 0.707 |
| 75.987 | 0.699 |
| 79.031 | 0.852 |
| 80.004 | 0.852 |
| 85.049 | 0.852 |
| 86.044 | 0.767 |
| 87.04 | 0.682 |
| 88.035 | 0.614 |
| 89.053 | 0.58 |
| 90.004 | 0.486 |
| 91 | 0.435 |
| 92.018 | 0.384 |
| 93.058 | 0.298 |
| 95.035 | 0.452 |
| 96.031 | 0.443 |

| | |
|---|---|
| 98 | 0.435 |
| 100.013 | 0.452 |
| 105.035 | 0.452 |
| 106.031 | 0.46 |
| 110.035 | 0.435 |
| 111.982 | 0.384 |
| 112.044 | 0.443 |
| 113.018 | 0.426 |
| 113.991 | 0.426 |
| 116.978 | 0.426 |
| 118.969 | 0.418 |
| 122 | 0.494 |
| 123.969 | 0.426 |
| 125.009 | 0.46 |
| 126.004 | 0.443 |
| 128.04 | 0.443 |
| 131.027 | 0.452 |
| 131.032 | 0.401 |
| 133.021 | 0.384 |
| 135.01 | 0.375 |
| 140.046 | 0.392 |
| 141.971 | 0.409 |
| 144.955 | 0.426 |
| 150.055 | 0.435 |
| 152.044 | 0.426 |
| 154.964 | 0.46 |
| 156.054 | 0.477 |
| 157.049 | 0.46 |
| 159.07 | 0.435 |

| APPENDIX 5 -ACTUAL X-T DATA THAT WAS INVERTED TO GIVE THE GEOSEISMIC MODEL | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Trace No | Station | Elevation | Offset from Sp21 | Actual time from SP 21 | Actual time from SP 22 | Actual time from SP 23 | Actual time from SP 24 | Actual time from SP 25 |
| 51 | 2051 | 1755.95 | 45.317 | 9.24983 | 1.108 | 9.0745 | 18.8907 | 27.5595 |
| 52 | 2052 | 1730.6 | 46.243 | 9.38917 | 1.1425 | 8.9833333 | 18.7435 | 27.4217 |
| 53 | 2053 | 1727.5 | 47.12 | | 1.20483 | 8.8506667 | 18.5287 | 27.2948 |
| 54 | 2054 | 1679.55 | 47.987 | | 1.28783 | 8.7618333 | 18.379 | |
| 55 | 2055 | 1662.2 | 48.913 | 9.97017 | 1.3845 | 8.6253333 | | |
| 56 | 2056 | 1643 | 49.773 | 10.1135 | | 8.503 | | 27.002 |
| 57 | 2057 | 1626.65 | 50.323 | 10.1752 | 1.61883 | 8.4178333 | 18.0055 | 26.9363 |
| 58 | 2058 | 1650.3 | 51.087 | 10.3475 | 1.645 | 8.2615 | 17.8798 | 26.8793 |
| 59 | 2059 | 1636.75 | 51.862 | 10.4467 | 1.8195 | 8.1716667 | 17.7272 | |
| 60 | 2060 | 1647.2 | 52.816 | | | | | |
| 61 | 2061 | 1653.5 | 53.737 | 10.7292 | 2.18833 | | 17.4093 | 26.5622 |
| 62 | 2062 | 1647.7 | 54.687 | 10.8415 | 2.33 | 7.6128333 | 17.2328 | 26.4463 |
| 63 | 2063 | 1643.7 | 55.602 | | | | 17.0737 | |
| 64 | 2064 | 1634.8 | 56.579 | | | | 16.8405 | |
| 65 | 2065 | 1635.4 | 57.506 | 11.3573 | 2.97267 | 7.2208333 | 16.6568 | 26.1347 |
| 66 | 2066 | 1622.45 | 58.484 | 11.4293 | 3.14333 | 7.0373333 | 16.5363 | 26.016 |
| 67 | 2067 | 1627.4 | 59.41 | | 3.2875 | 6.8586667 | 16.354 | 25.869 |
| 68 | 2068 | 1616.6 | 60.333 | 11.7075 | 3.4925 | 6.6826667 | | |
| 69 | 2069 | 1611.6 | 61.323 | 11.8415 | 3.675 | 6.5133333 | | 25.6912 |
| 70 | 2070 | 1612.25 | 62.232 | 12.054 | | 6.3683333 | 15.9813 | 25.5952 |
| 71 | 2071 | 1602.75 | 63.204 | | 4.025 | 6.2006667 | 15.8388 | 25.4848 |
| 72 | 2072 | 1602.75 | 64.186 | | | | | |
| 73 | 2073 | 1598.65 | 65.108 | | 4.36333 | | | |
| 74 | 2074 | 1601.2 | 65.864 | 12.5683 | 4.48717 | | 15.4797 | |
| 75 | 2075 | 1598.3 | 66.092 | 12.6513 | 4.57233 | | 13.5872 | 25.209 |
| 76 | 2076 | 1591.95 | 67.002 | 12.728 | 4.73583 | | | 25.2485 |
| 77 | 2077 | 1598.4 | 68.582 | 13.0513 | | 5.1931667 | 15.0457 | 25.1555 |
| 78 | | | 69.401 | | | | 14.9332 | |
| 79 | 2079 | 1606.1 | 70.253 | 13.3448 | 5.47333 | | 14.8262 | |
| 80 | 2080 | 1605.5 | 70.736 | | 5.57283 | 4.907 | 14.791 | 25.1202 |
| 81 | 2081 | 1609.35 | 71.704 | 13.5717 | | 4.7605 | | |
| 82 | 2082 | 1611.8 | 72.675 | | | 4.5666667 | | 24.8467 |
| 83 | 2083 | 1605.9 | 73.643 | | | | | 24.7795 |
| 84 | 2084 | 1612.95 | 74.567 | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 85 | 2085 | 1621 | 75.527 | 14.2088 | 6.381 | 3.9383333 | | 24.5122 |
| 86 | 2086 | 1636.55 | 76.519 | | 6.45367 | 3.7235 | | 24.3548 |
| 87 | 2087 | 1650.45 | 77.421 | 14.5095 | 6.51017 | 3.4411667 | | 24.2005 |
| 88 | 2088 | 1654.4 | 78.406 | 14.7647 | 6.60017 | 3.229 | 13.5725 | 24.0618 |
| 89 | 2089 | 1652.4 | 79.351 | 14.9522 | 6.715 | 2.9538333 | | 23.853 |
| 90 | 2090 | 1650 | 80.381 | 15.1088 | 6.78817 | 2.7816667 | | |
| 91 | 2091 | 1654.9 | 81.289 | | 6.88267 | | | 23.4458 |
| 92 | 2092 | 1656 | 82.24 | 15.4487 | 6.983 | 2.4085 | | 23.0952 |
| 93 | 2093 | 1655 | 83.258 | | 7.06167 | 2.1571667 | | |
| 94 | 2094 | 1655.25 | 84.165 | | | | 12.57 | 22.8128 |
| 95 | 2095 | 1665.35 | 85.168 | 15.9367 | 7.52667 | 1.7123333 | | |
| 96 | 2096 | 1666.2 | 86.09 | | 7.66617 | 1.351 | | |
| 97 | 2097 | 1649.85 | 88.117 | 16.4592 | | 0.7388333 | 11.8915 | 22.264 |
| 98 | 2098 | 1651.9 | 89.025 | | 8.14917 | 0.6925 | | |
| 99 | | | 90.075 | 16.8005 | | 0.7651667 | | 22.0555 |
| 100 | 2100 | 1640.45 | 91.999 | | 8.66667 | 1.223 | | 21.8253 |
| 101 | 2101 | 1646.35 | 92.97 | | | 1.6276667 | 11.1377 | 21.7137 |
| 102 | 2102 | 1648.75 | 93.922 | 17.3957 | | 1.9123333 | 11.0077 | 21.6468 |
| 103 | | | 94.938 | 17.641 | | | | |
| 104 | 2104 | 1646.75 | 95.926 | 17.7907 | | 2.5181667 | | 21.4497 |
| 105 | 2105 | 1649.65 | 96.886 | | 9.48867 | 2.7053333 | | |
| 106 | 2106 | 1648.75 | 97.873 | 18.0702 | 9.66333 | 2.9785 | | 21.3002 |
| 107 | 2107 | 1651.4 | 98.837 | | | 3.2156667 | 10.354 | |
| 108 | 2108 | 1641.8 | 99.774 | 18.25 | | | 10.1692 | 21.0907 |
| 109 | 2109 | 1641.1 | 100.845 | 18.4595 | | 3.7488333 | 10.0063 | |
| 110 | 2110 | 1645.15 | 101.837 | | 10.3055 | 3.93 | | 20.8828 |
| 111 | 2111 | 1645.4 | 102.776 | 18.7653 | | 4.148 | 9.74967 | |
| 112 | 2112 | 1643.7 | 103.797 | | 10.5837 | 4.3325 | 9.65017 | |
| 113 | 2113 | 1648.8 | 104.783 | 19.0848 | 10.7927 | 4.487 | 9.52117 | 20.6645 |
| 114 | 2114 | 1651.9 | 105.752 | 19.2313 | 10.9548 | 4.6785 | | 20.6073 |
| 115 | 2115 | 1656.6 | 106.905 | | | 4.8851667 | | |
| 116 | 2116 | 1660.95 | 107.84 | 19.5943 | | 5.072 | | |
| 117 | 2117 | 1666.4 | 108.672 | | 11.4387 | 5.1635 | 8.89883 | |
| 118 | 2118 | 1657.3 | 109.593 | 19.9475 | | 5.254 | 8.77317 | |
| 119 | 2119 | 1668.25 | 110.491 | 20.0672 | 11.7235 | | 8.61 | |
| 120 | 2120 | 1669.05 | 111.365 | | | | 8.4595 | |
| 121 | 2121 | 1670.4 | 112.273 | 20.3792 | | | 8.307 | 19.529 |
| 122 | 2122 | 1668.15 | 113.246 | | 12.2448 | | | |
| 123 | 2123 | 1669.9 | 114.088 | | | 6.0601667 | | |
| 124 | 2124 | 1668.5 | 114.994 | 20.6807 | 12.461 | 6.2068333 | 7.79367 | 19.0328 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 125 | 2125 | 1671.1 | 115.731 | 20.9095 | 12.6152 | | 7.6615 | |
| 126 | 2126 | 1662.85 | 117 | 21.121 | 12.8058 | 6.5506667 | | |
| 127 | 2127 | 1655.95 | 117.75 | | | 6.7183333 | 7.32183 | 18.5722 |
| 128 | 2128 | 1655.5 | 118.728 | 21.424 | 13.0872 | 6.9108333 | 7.0755 | 18.4033 |
| 129 | 2129 | 1665.1 | 119.511 | | | 7.0871667 | | 18.3158 |
| 130 | 2130 | 1651.55 | 120.449 | | | | | |
| 131 | 2131 | 1652.3 | 121.971 | 21.9805 | 13.5753 | | 6.4225 | 17.817 |
| 132 | 2132 | 1662.95 | 122.902 | | | | | |
| 133 | 2133 | 1665.75 | 123.94 | | 13.8838 | 7.8646667 | | |
| 134 | 2134 | 1665.6 | 125.339 | 22.5568 | | | 5.87483 | 17.293 |
| 135 | | | 125.756 | | 14.1753 | | 5.7735 | 17.2103 |
| 136 | 2136 | 1667.15 | 127.042 | | | | 5.541 | 17.0255 |
| 137 | 2137 | 1665.15 | 127.692 | | | | | |
| 138 | 2138 | 1661.25 | 128.671 | | | | 5.2485 | |
| 139 | 2139 | 1665.25 | 129.638 | 23.2733 | | | | 16.5808 |
| 140 | 2140 | 1664.75 | 130.573 | | 14.9905 | 8.399 | | 16.4677 |
| 141 | 2141 | 1683.1 | 131.778 | 23.617 | | | 4.69417 | |
| 142 | 2142 | 1689.85 | 132.539 | 23.7568 | 15.3345 | | 4.55883 | |
| 143 | 2143 | 1691.1 | 133.907 | 23.9998 | | | | 16.028 |
| 144 | 2144 | 1691.4 | 134.561 | | | | 4.2025 | 15.9017 |
| 145 | 2145 | 1686.75 | 135.555 | | 15.8525 | | 3.96817 | |
| 146 | 2146 | 1689.25 | 136.278 | 24.38 | 15.9755 | | 3.82067 | 15.5543 |
| 147 | 2147 | 1692.4 | 137.181 | 24.5305 | 16.1273 | 9.5248333 | 3.59933 | 15.3703 |
| 148 | 2148 | 1694.55 | 137.954 | | 16.2578 | | 3.40233 | 15.1542 |
| 149 | 2149 | 1692.4 | 138.947 | 24.8398 | | | 3.111 | 14.9597 |
| 150 | 2150 | 1695.4 | 139.896 | | 16.583 | | 2.91417 | 14.7635 |
| 151 | 2151 | 1690.35 | 141.137 | 25.2048 | | | 2.56483 | |
| 152 | 2152 | 1681.95 | 141.664 | | 16.8685 | | 2.4015 | |
| 153 | 2153 | 1681.6 | 142.651 | 25.4572 | | | | |
| 154 | 2154 | 1674.5 | 143.421 | 25.6455 | | 10.6275 | 1.98333 | |
| 155 | 2155 | 1661.65 | 144.441 | 25.7555 | | | 1.72583 | 13.9432 |
| 156 | 2156 | 1656 | 145.382 | 25.9273 | 17.523 | | 1.47817 | 13.7935 |
| 157 | 2157 | 1650.95 | 146.276 | 26.0913 | 17.689 | | 1.22983 | 13.6578 |
| 158 | 2158 | 1639.25 | 147.299 | | | 11.233 | 1.039 | 13.551 |
| 159 | 2159 | 1627.5 | 148.207 | 26.4132 | 17.9697 | 11.344167 | 0.88083 | 13.3502 |

APPENDIX 5

P-wave velocities of different materials

| Earth materials | $V_p$ (m/s) |
|---|---|
| Water | 1450-1530 |
| Petroleum | 1300-1400 |
| Loess | 300-600 |
| Soil | 100-500 |
| Snow | 350-3000 |
| Solid glacier ice | 3000-4000 |
| Sand loose | 200-2000 |
| Sand (dry, loose) | 200-1000 |
| Sand (water saturated loose) | 1500-2000 |
| Glacial moraine | 1500-2700 |
| Sand and gravel (near surface) | 400-2300 |
| Sand and gravel at 2km depth | 3000-3500 |
| Clay | 1000-2500 |
| Estuarine mud's/clay | 300-1800 |
| Flood plain alluvium | 1800-2200 |
| Permafrost quaternary sediments | 1500-4900 |
| Limestone (soft) | 1400-4500 |
| Limestone (hard) | 2800-7000 |
| Dolomites | 2500-6500 |
| Anhydrite | 3500-5500 |
| Rock salt | 4000-5500 |
| Gypsum | 2000-3500 |

| | |
|---|---|
| Shale | 2000-4100 |
| Granites | 4600-5200 |
| Basalts | 5500-7000 |
| Peridotite | 7800-8400 |
| Serpentite | 5500-6500 |
| Gneiss | 3500-7600 |
| Marbles | 3780-7000 |
| Sulphide ores | 3950-6700 |
| Pulverised fuel ash | 600-1000 |
| | |
| Landfill refuse | 400-750 |
| Concrete | 3000-3500 |
| Disturbed soil | 180-380 |