FOCAL MECHANSIM OF SEPTEMBER 24th , 2013 AWARAN EARTHQUAKE

By

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CERTIFICATE OF APPROVAL

This dissertation submitted by Sarmad Rameez is accepted in its present form by the Department of Earth Sciences, Quaid-i-Azam University Islamabad as satisfying the requirement for the award of degree of BSGeophysics.

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Dedication

The intelligence alone is futile without sense of responsibility and subsequent hardwork. I dedicate my effort and success to that hard time which yielded these traits. I also dedicate my work to my parents, siblings, teachers, Engr Muhammad Hamza Rashid and Basit khan Jadoon.

Acknowledgement

First and foremost, praises and thanks to the God, the Almighty, for His showers of blessings throughout my Thesis work to complete it successfully. I would like to express my deep and sincere gratitude to Dr. ANEES BANGASH for giving me the opportunity to do research and completing my Thesis also providing invaluable guidance throughout this work. He has taught me the methodology to carry out the thesis and to present the thesis work as clearly as possible. It was a great privilege and honor to work and study under his guidance. I would also like to thank him for his friendship, empathy, and great sense of humor. DR. MONA LISA CHAIR PERSON EARTH SCIENSES DEPARTEMENT her dynamism, vision, sincerity and motivation have deeply inspired me to work on Earthquake seismology. I am extending my heartfelt thanks to DR FARHAN (NCP) for acceptance, patience and cooperation during the discussion I had with him on thesis work. I am extremely grateful to my parents for their love, prayers, caring and sacrifices for educating and preparing me for my future.

ABSTRACT

Earthquake seismology is a study of generation propagation and recording of elastic waves in earth (and other celestial bodies) and of the sources that produce them.

Our study aims at calculating the moment tensors of the AWARAN 24th slept 2013 Earthquake .we selected 6 stations (NIL KBL QAZ MSEY KMI DGAR) their wave forms were downloaded and processed by using the isolate GUI software initially the wave forms were displayed in units of counts then they were converted into units of displacements (m/s) green function were computed followed by inversion A plot of synthetic and observed waveforms was made and the correlation and 100 % dc was observed a magnitude was calculated to be 7.7 focal mechanism was found similar to USGS.

Table of Contents

TABLE OF FIGURES

TABLE

CHAPTER NO 1

INTRODUCTION

1.1 INTRODUCTION:

An Earthquake is a sudden rupture phenomena that takes place in earth's crust and mantle in response to tectonic stress (Elsevier, 1986).

Earthquakes are one of the most dramatic hazards that are likely to cause heavy human losses and can destroy entire cities on a scale of minutes. The more recent damaging events like in Awaran (Pakistan) in 2013 .

So far little is known about earthquake physics that could prevent people from their deadly effects. Taking place in earth's interior, a seismic event can be only detected and studied through its effects on earth's surface (Earth deformation and seismic waves).

Seismology is the study of the generation, propagation, and recording of elastic waves in the earth (and other celestial bodies) and of the sources that produce them. Both natural and human-made sources of deformational energy can produce seismic waves.The properties of seismic waves are governed by the physics of elastic solids, which is described by the theory of elastodynamics. This theory provides a quantitative framework for analysis of elastic waves in the earth (Segall, 2010). Seismological procedures provide the highest resolution of the internal earth structure of any geophysical method. This is because elastic waves have the shortest wavelengths of any geophysical wave, and the physics that governs them localizes their sensitivity spatially and temporally to the precise path traveled by the energy.

Decades of research involving numerous laboratories worldwide aim at investigating this large scale phenomena and trying to understand how it triggers, initiates, propagates and stops.

If earthquakes developed more slowly it would be possible to optimize our response to earthquake emergencies; earthquakes would be less devastating. There would be time for expert seismologists to examine the incoming data and advise the affected regions for the appropriate response. By examining the overall shape and relative frequency content of the available ground motions, and with their knowledge of factors such as where the faults are, what size events they are capable of generating, which seismic stations are operating, and recent levels of seismic activity, experienced seismologists can typically make judgments regarding whether the developing earthquake will be potentially damaging or not. They would be able to determine which areas will be significantly affected. There would be time for emergency response agencies, local governments, and the media to coordinate their efforts to inform, advise, and direct the response of the affected communities to the approaching earthquake (Newman, 2008). Unfortunately, earthquakes develop over short timescales; the time between the initiation of the rupture and the arrival of the damaging ground motions at a given site is on the order of seconds. It is not possible for a human to process incoming information and make the appropriate judgments (is it large or small, which regions will be affected, what levels of shaking are expected and when will the shaking commence.

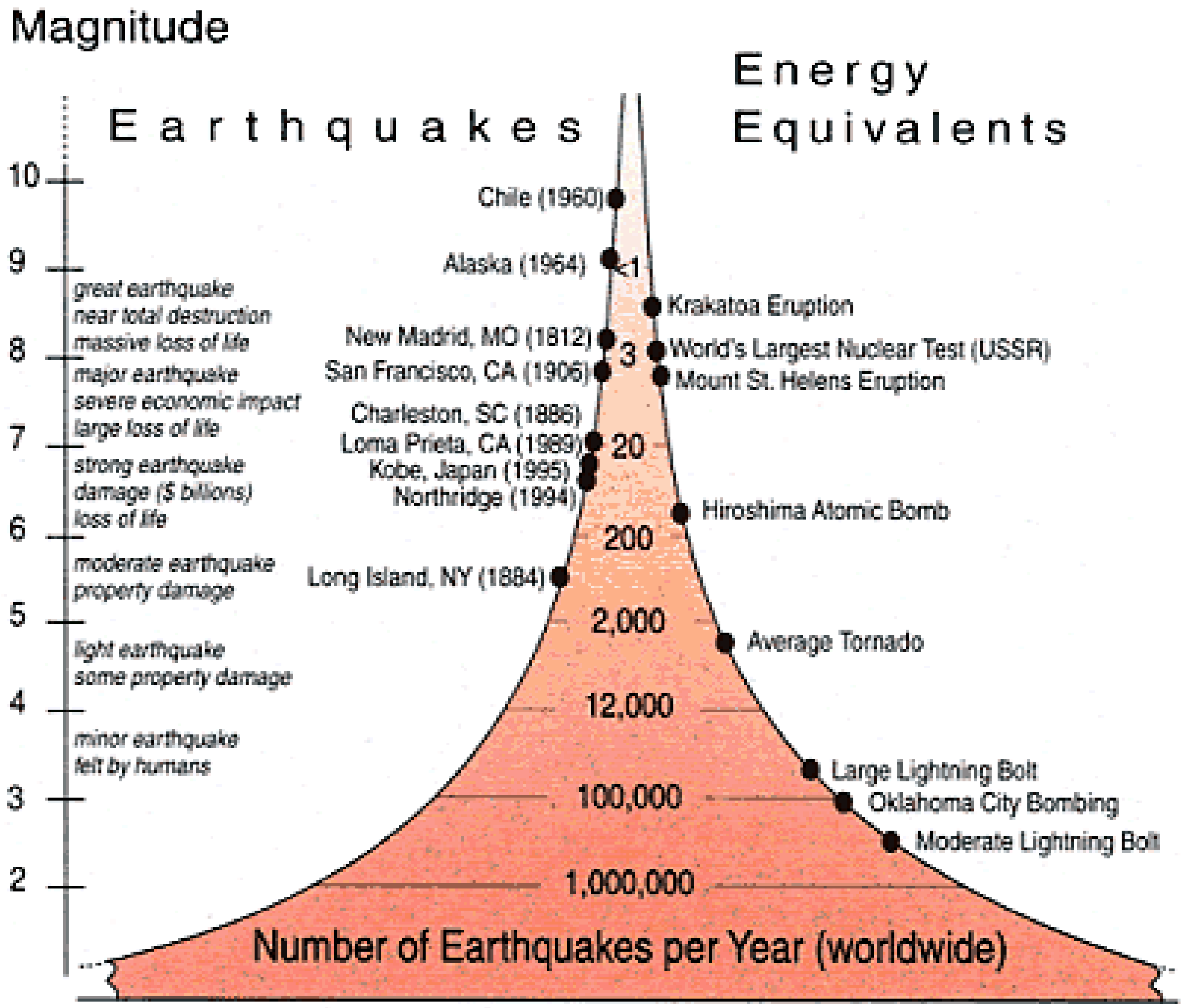

Figure 1.1 Number of earthquakes per year (USGS)

1.2 INTRODUCTION TO STUDY AREA

Pakistan is highly vulnerable to earthquake activity. Tectonically speaking, the country is affected by two major continental collision zones – that between the Indian subcontinent and Eurasia (responsible for the uplift of the Himalayas) and that between the Arabian and Eurasian plates.

Awaran District is a district located in south of Balochistan province. It was created as a separate district in November 1992; but previously it was a sub-division of khuzdar district. The old name of Awaran was Kolwa. Awaran district is bordered by Gawadar to its south and south west, Lasbela to its east and south, Kech and Panjgur to its west, Khuzdar to its north east and Kharan to its north.

A large and powerful earthquake struck on September 24, 2013 in a remote, mountainous region of Pakistan just near Awaran district. The earthquake measured 7.7 on the Richter scale; it was a very large earthquake. Reports suggest that at least 238 people were killed in the earthquake. A new island formed from a "mud volcano" on the sea floor following the earthquake (Lisa & Jan, Awaran, Pakistan, Earthquake of Mw Awaran,Pakistan,Earthquake of Mw7.7 in Makran Accretionary Zone, 24 September 2013: Preliminary Seismotectonic Investigations, 2015).The earthquake's epicenter lies in a region influenced by both of the above mentioned collision zones.The India-Eurasia collision is marked by a roughly north-south trending series of lateral (strike-slip) faults while the convergence of the Arabian plate with Eurasia is marked by a subduction zone, known as the Makran subduction zone(just near the coast). The relatively close proximity of these two has given rise to a complex sequence of folded and faulted mountain ranges parallel to the coast and curving northwards to the west of the India-Eurasia convergence zone.

The details of the 24th September 2013 earthquake are given by USGS and are as follows:

Event Time
2013-09-24 11:29:48 UTC
2013-09-24 16:29:48 UTC+05:00 at epicenter

Location
27.016°N 65.547°E

Depth=15.0km (9.3mi)

Nearby Cities
69km (43mi) NNE of Awaran, Pakistan
115km (71mi) NW of Bela, Pakistan
171km (106mi) NW of Uthal, Pakistan
174km (108mi) S of Kharan, Pakistan
795km (494mi) ENE of Muscat, Oman

Fig 1.2 Location map of September 24th,2013 earthquake.(www.google.com)

1.3 OBJECTIVES OF DISSERTATION:

The objectives of my thesis are as follows:

1. Define the crustal model.
2. Download the waveform data from IRIS website
3. Process the waveform data to compute the displacement.
4. Invert the displacement data to retrieve the moment tensor of the source.

1.4 DATA SOURCES:

The study is based on the seismic waveforms data that were recorded at different stations of the world in response to the Earthquake that struck just near the district Awaran on 24th September 2013.This is an area where the Indian plate is sliding past the Eurasian plate, which makes up much of western Pakistan. The rocks on either side of this boundary are stuck by friction most of the time, but eventually the stress builds up to the point where the rocks slip, causing an earthquake.

1.5 DATA INFORMATION:

1. We used waveforms data obtained from 6 stations for the calculation of our results.

Station name	**Latitude**	**Longitude**
NIL	33.65	73.269
KBL	34.541	69.043
DGAR	-7.412	72.452
MSEY	-4.674	55.479
QIZ	19.029	109.844
KMI	25.123	102.740

Table 1.1 station information

2. PREM'S crustal model for earth was used.

1.6 SOFTWARES TOOLS USED:

We have used the following software's to carry out our thesis work:

1. Pyweed
2. MATLAB
3. ISOLA-GUI
4. M-MAP 14

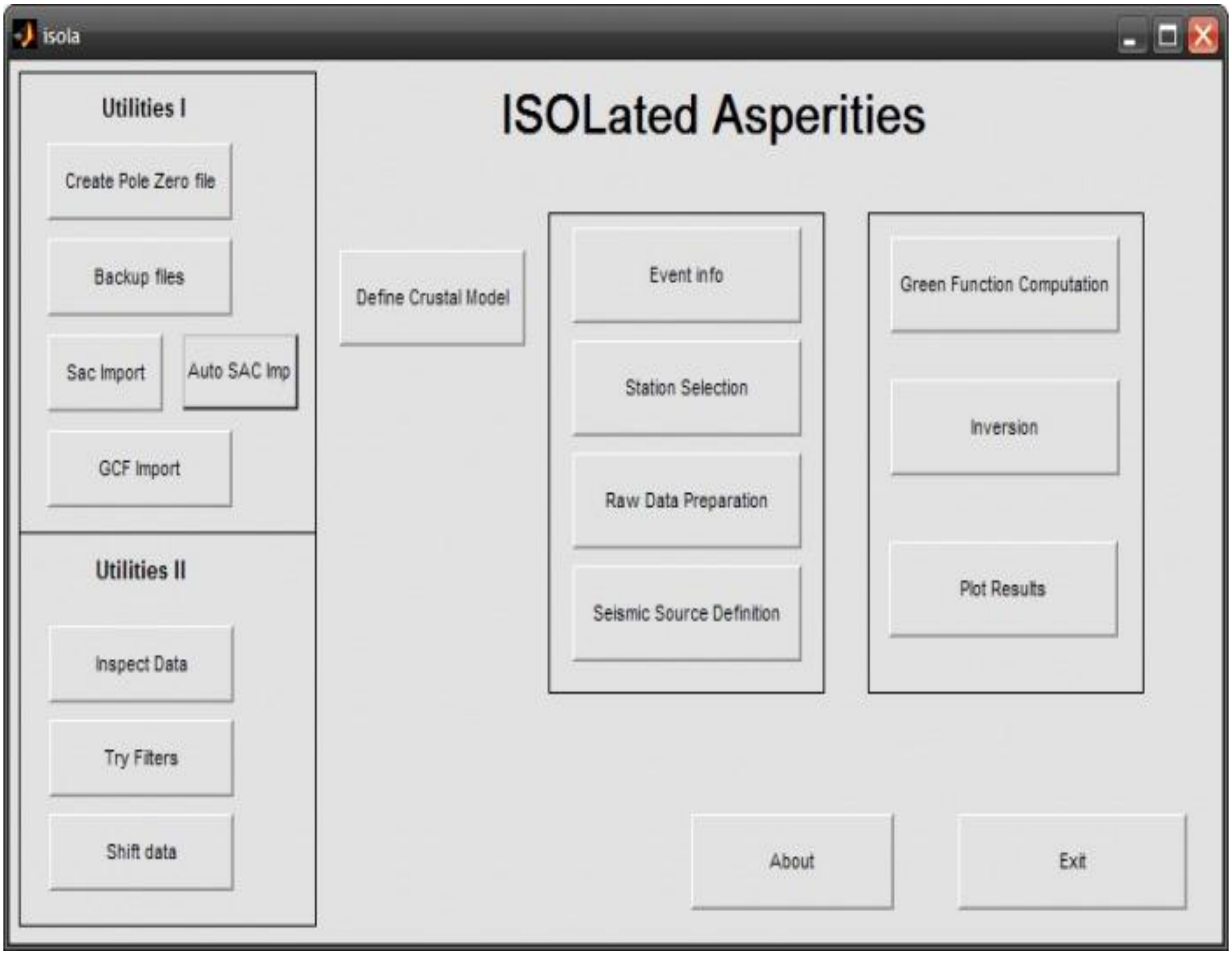

Fig 1.3 Main Form of ISOLA-GUI

1.7 METHODOLOGY:

- Raw waveforms data of selected stations is obtained by using the pyweed software. The start and end time are adjusted such that complete waveforms are obtained.
- Raw data obtained is then imported to convert it into SAC format and to remove and irregularities by origin aligning the data.
- A crustal model(1-D) is defined as it's the first step towards inversion procedure. There is an option for a maximum 15 layers in crustal model. For each layer we have given the depth of the layer top, the Vp, Vs velocities in km/sec, density in g/cm^3,Qp and Qs.
- The next step is the Event information. In this step the user provides the information that will be used in all further steps of inversion. The information provided includes Lat, Lon, Depth, Magnitude, Date, origin time of event.
- After the proper event information has been given the next step is the station selection for this purpose we require the complete lat,long description of all selected stations and m-map14 based on these two we select the stations of interest from the map.
- Raw data preparation is then done, it's the most important step in Isola-GUI as it processes the seismograms(instrument correction, origin time alignment, resampling) the end result of this step gives us the data files ready for inversion.
- Seismic sources were then defined by considering the sources below epicenter and the starting depth.
- The definition of proper seismic source was followed by Green function computation it's considered as the start of inversion process.
- Finally inversion is carried out and it gives us the strike,dip,rake and magnitude of earth quake.
- The synthetic and observed waveforms are checked in plots.
- Focal mechanisms are then obtained.
- Conclusions

Workflow for the dissertation is given below:

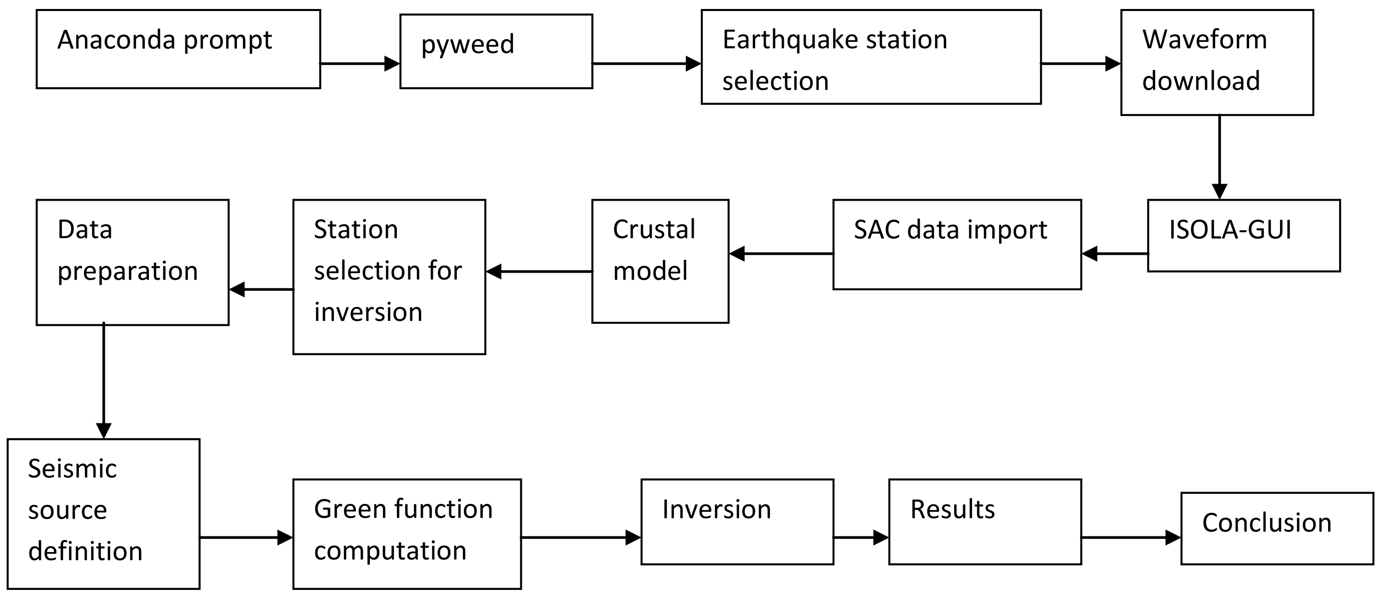

Fig 1.4 Dissertation Work flow

CHAPTER NO 2

GEOLOGY,STRATIGRAPHY AND TECTONICS

2.1 REGIONAL GEOLOGICAL SETTTING:

The planet EARTH came into being about 4.6 billion years ago, upto the JURRASIC Cage there was only one land mass on the earth which was called Pangaea, this landmass started breaking about 200 million years ago and was divided into two parts, the northern part was called laurasia southern part was called Gondwana land. This breakage was initiated by two rifts, one in the northern part, between North America and Africa; it gave to the birth North Atlantic Ocean. Second rift was in the southern part, south America and Africa which gave the birth to the south atlantic occean. Now due the rift that was produced between south America and Africa, a Y shaped crack was produced in the southern part of gondwana land due to which India was separated from the gondwana land, it was done about 130 million years ago (Tarbuck et al, 1997).

2.2 TECTONICS ZONE OF PAKISTAN:

On the basis of plate tectonic features, geological structure, organic history(age and nature of deformation, magmatic and metamorphism) and lithofacies, Pakistan may be divided into the following broad tectonic zones and these are also shown in Figure.

Indus platform and fore deep.

East Baluchistan folds and thrust belt.

Northwest Himalayan fold and thrust belt.

Kohistan-laddakh magmatic arc.

Karakoram block.

Chagai magmatic arc.

Pakistan offshore

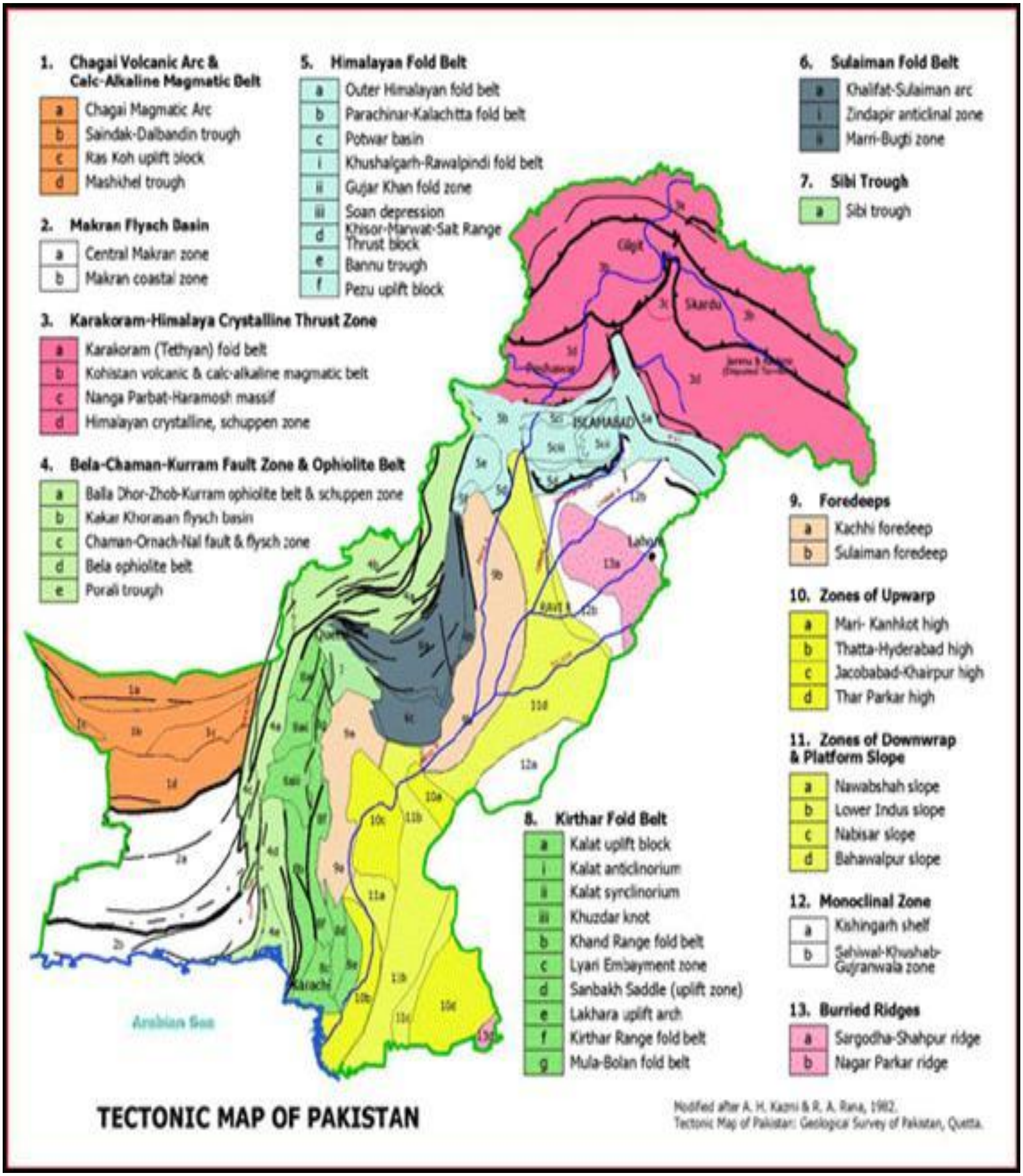

Fig 2.1Tectonic Map of Pakistan (www.google .com)

2.3 TECTONICS OF THE AREA:

In the southern region of Pakistan a subduction zone exists along Makran coast . Makran plate boundary is a zone of wide deformation in southwestern Pakistan and southeastern Iran.It extends for 400 Km NS and 1000 Km EW and accommodates a 3cm/yr northward subduction of Arabian and Ormara plates under Eurasian plate.

The boundaries of Makran Subduction Zone are mostly formed by transpressional strike-slip systems. Ornach-Nal fault system marks the eastern boundary whereas Minab-Zendan fault system marks the western boundary. Due to compression from Arabian plate, east-west directional structural trend is present in Makran zone and Chagai arc. It is subducting at a rate of 19.5 mm/yr with a subduction angle ranging from 2o to 8o. Makran mega thrust was ruptured by an Mw 8.0 earthquake in 1945.

Chaman fault system is a 1200 Km long, left-lateral fault system accommodating 3cm/yr northward motion of India with respect to Eurasia. It extends south towards the subduction zone through Ghazaband and Ornach Nal fault systems. Chaman fault system is left-lateral transform plate boundary separating Indian and Eurasian plates. Chaman fault abruptly terminates the western edge of the Chaman fault system . Chaman fault system comprises of Ornach Nal, Ghazaband and Chaman sinistral strike slip faults . Southwards, Chaman fault connects with Siahan, Panjgur and Hoshab faults which are faults of Makran ranges and these faults accommodate; the shear between India and Eurasia and shortening due to convergence of Arabia and Eurasia . Chaman and Ornach-Nal faults that are left lateral strike slip faults govern the colliding Indian and Eurasian Plate tectonics. Chaman fault comprises of four segments; Active fault, Chaman fault zone, Chaman fault system, Chaman Transform Boundary . Tectonics and structural style of Ziarat area is governed by 1300 Km long Sulaiman lobe, Chaman fault and Sibi trough. Chaman fault, Kalat-Chinjin Structure, Harnai-Tarta Structure, Ghazaband Zhob Structure and Mach structure are local fault systems present around Quetta . Seismic activity along coastal belt is concentrated on Ornach-Nal and Pub faults. A little south of Ormara and Pasni lies the 225 Km long Makrancoast thrust fault . According to Szeliga et al. 2012 , several faults in the region have shallow apparent locking depths (< 5 Km).So, At a broad scale, the tectonics of this region are complex. The earthquake occurred as the result of oblique strike-slip type motion at shallow crustal depths, above the Makran subduction zone. Here, there is a transition zone between northward subduction of the Arabia plate beneath the Eurasia plate and northward sliding of the India plate relative to the Eurasia plate.

Major earthquakes in Southern Pakistan

LOCATION	YEAR	MAGNITUDE	CASUALTIES
Ali Jaan	1935	7.8	30,000-60,000
Arabian Sea	1945	8.1	4000
Quetta	2008	6.4	170-200
Dalbandin	2011	7.2	3
Awaran	2013	7.7	825

Table 2.1Major earthquakes in Southern Pakistan

2.4 AWARAN EARTHQUAKE:

The 2013 Awaran earthquake was a strike slip event that occurred on Hoshab fault . Average slip was 4.2 m along the main trace of fault with an 11.4 m local maximum offset . Maximum displacements of 16m were noted . The earthquake occurred in south-eastern Balochistan and ruptured ~ 230 Km of the Hoshab fault, which is arcuate northwest-dipping fault . Hoshab fault is located in Makran accretionary complex. 3 cm/yr of convergence between Arabia and Eurasia is being accommodated by Makran convergence zone . The area is characterized by Panjgur, Naib Rub and Hoshab fault system (PHNFS) which are east west oriented reverse faults . Fault geometries are well defined in earthquake region . The Awaran earthquake was unusual in a sense that a curved reverse fault ruptured in mechanically weak Makran Accretionary Prism.

A portion of the accretionary prism where the slab is only 20 Km deep was also ruptured thereby suggesting that almost no crystalline crust ruptured in the earthquake. The earthquake ruptured a structurally segmented fault and involved a ~ 6:1 strikeslip to dip-slip ratio. The rupture was associated to shallow depths from 0-7 Km. Most of energy (almost 80%) was released on south side of hypocenter whereas there is reduced slip in the north. Slower rupture propagation towards the north side is also confirmed.The rupture released a cumulative moment of 5.4 x 1020 Nm hence corresponding to a Mw 7.75. It begins on a 70o westward dipping fault and then propagated to the 40o northwestward dipping fault segments to the southwest (Jolivet, 2014).The 2013 rupture was majorly left-lateral strike slip and involves a minor oblique reverse motion. The majority of slip occurred at shallow depths of $< \sim 10$ Km. Large Mw > 7 upper plate earthquakes have not been observed in the region before. The earthquake was triggered on a 45o dipping fault plane and depicts strike-slip movement. These faults, which are regional and moderate angle, initially originated as thrust faults but now depicts near horizontal slip .

According to (Avouac, 2014), there is a switch between thrust and strike slip faulting in the kinematics of Hoshab fault slip during successive earthquake cycles and that the fault ruptured in left lateral motion for 200+ Km and it dips between 47o & 73o to the northwest.The failure is not solely constrained to Hoshab fault but occurs in a distributed fashion thus providing an explanation to lack of seismicity previously and also to long repeat times. Younger and thicker sediments have more off-fault deformation (Zhou, Elliot, Parsons, & Walker, 2015).

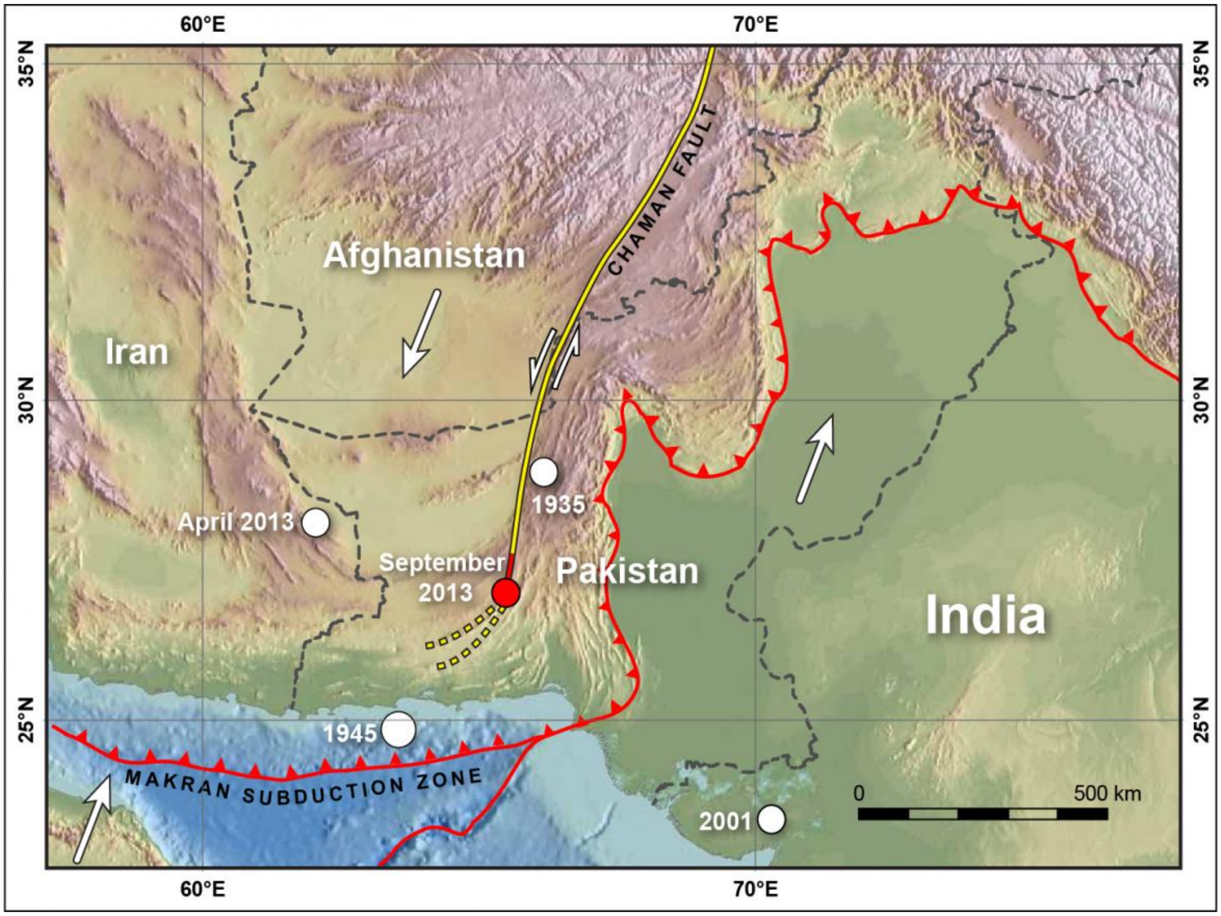

Fig 2.2 September 24th,2013 Earthquake.

2.5AWARAN EARTHQUAKE IN TERMS OF MODIFIED MERCALLI INTENSITY SCALE:

The effect of an earthquake on the Earth's surface is called the intensity. The intensity scale consists of a series of certain key responses such as people awakening, movement of furniture, damage to chimneys, and finally - total destruction. Although numerous intensity scales have been developed over the last several hundred years to evaluate the effects of earthquakes, the one currently used in the United States is the Modified Mercalli (MM) Intensity Scale. It was developed in 1931 by the American seismologists Harry Wood and Frank Neumann. This scale, composed of increasing levels of intensity that range from imperceptible shaking to catastrophic destruction, is designated by Roman numerals. It does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects.The Modified Mercalli Intensity value assigned to a specific site after an earthquake has a more meaningful measure of severity to the nonscientist than the magnitude because intensity refers to the effects actually experienced at that place.

The **lower** numbers of the intensity scale generally deal with the manner in which the earthquake is felt by people. The **higher** numbers of the scale are based on observed structural damage. Structural engineers usually contribute information for assigning intensity values of VIII or above.

For the case of September 24th earthquake whose epicenter was just near Awaran, A Very strong shaking (VII) was observed in the nearby town of Awaran; a strong shaking (VI) in the large town of Kharan; rather strong shaking in Hyderabad, and moderate shaking in Karachi. The Awaran Earthquake and its aftershocks, especially its largest aftershock (Mw 7.2)of 24th September, 2013 triggered some landslides also which resulted in additional damage. On the basis of information obtained from the print and electronic media, an intensity of MM IIX has been assigned at the epicenter of the main shock. The intensity map of the Awaran Earthquake was prepared using the damage and destruction information from the print media and local sources shows the intensity within 100 km area of the main shock. One possibility of this heavy damage is the very shallow focal depth of the main shock 10 km (Lisa & Jan, Awaran, Pakistan, Earthquake of Mw 7.7 in Makran Accretionary Zone,24 september 2013:Preliminary seismotectonic investigations, 2015)

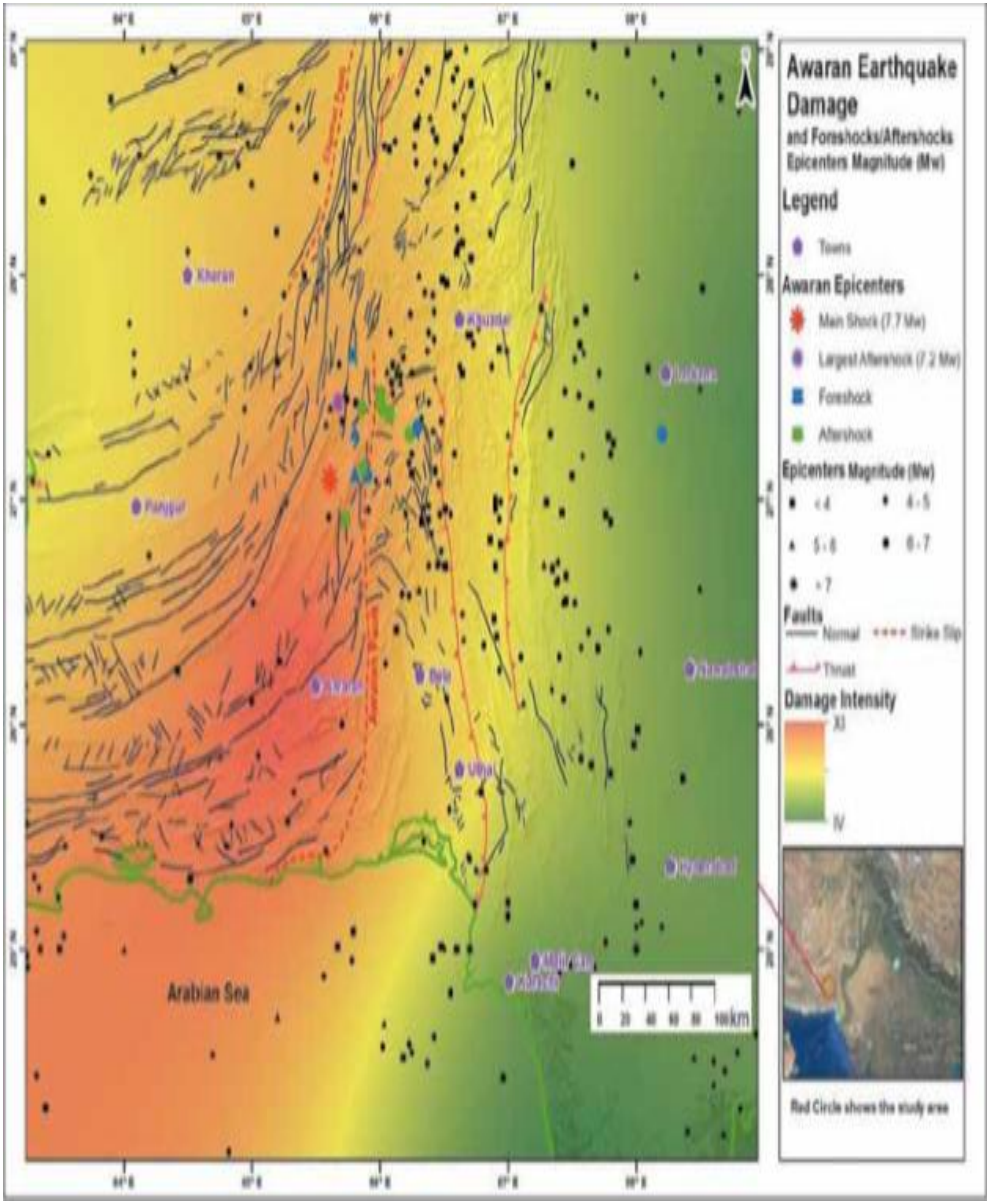

Fig 2.3September 24th 2013 Earthquake intensity Map(Mona Lisa and Qasim Jan)

Modified Mercalli Scale vs. Richter Scale

Category	Effects	Richter Scale (approximate)
I. Instrumental	Not felt	1-2
II. Just perceptible	Felt by only a few people, especially on upper floors of tall buildings	3
III. Slight	Felt by people lying down, seated on a hard surface, or in the upper stories of tall buildings	3.5
IV. Perceptible	Felt indoors by many, by few outside; dishes and windows rattle	4
V. Rather strong	Generally felt by everyone; sleeping people may be awakened	4.5
VI. Strong	Trees sway, chandeliers swing, bells ring, some damage from falling objects	5
VII. Very strong	General alarm; walls and plaster crack	5.5
VIII. Destructive	Felt in moving vehicles; chimneys collapse; poorly constructed buildings seriously damaged	6
IX. Ruinous	Some houses collapse; pipes break	6.5
X. Disastrous	Obvious ground cracks; railroad tracks bent; some landslides on steep hillsides	7
XI. Very disastrous	Few buildings survive; bridges damaged or destroyed; all services interrupted (electrical, water, sewage, railroad); severe landslides	7.5
XII. Catastrophic	Total destruction; objects thrown into the air; river courses and topography altered	8

Fig 2.4 Mercalli intensity scale(

2.6 AWARAN EARTHQUAKE IN TERMS OF RICHTER SCALE:

The Richter magnitude scale was developed in 1935 by Charles F. Richter of the California Institute of Technology as a mathematical device to compare the size of earthquakes. The magnitude of an earthquake is determined from the logarithm of the amplitude of waves recorded by seismographs (Thompson & Turk, 1998). Adjustments are included for the variation in the distance between the various seismographs and the epicenter of the earthquakes. On the Richter Scale, magnitude is expressed in whole numbers and decimal fractions. For example, a magnitude 5.3 might be computed for a moderate earthquake, and a strong earthquake might be rated as magnitude 6.3. Because of the logarithmic basis of the scale, each whole number increase in magnitude represents a tenfold increase in measured amplitude; as an estimate of energy, each whole number step in the magnitude scale corresponds to the release of about 31 times more energy than the amount associated with the preceding whole number value.. The earthquake was originally rated with a magnitude of Mw 7.4 on the Richter scale, later on upgraded to 7.8, but then revised to 7.7.

The details of September 24th earthquake are given below by USGS(www.USGS.com):

Moment	4.418e+20 N-m
Magnitude	7.7 Mww
Depth	23.0 km
Percent DC	96 %
Half Duration	–
Catalog	US
Data Source	US[3]
Contributor	US[3]

Nodal Planes

Plane	Strike	Dip	Rake
NP1	228°	46°	6°
NP2	134°	86°	136°

Principal Axes

Axis	Value	Plunge	Azimuth
T	4.458e+20 N-m	33°	81°
N	-0.080e+20 N-m	45°	309°
P	-4.377e+20 N-m	26°	189°

Richter Scale of Earthquake Energy:

Each level is 10 time stronger than the previous level

	Description	Occurrence	In Population	Movement
1	Small	Daily	Every minute	Small
2	Small	Daily	Every hour	Small
3	Small	Daily	Every day	Small
4	Small	Daily	Every week	Moderate sudden
5	Moderate	Monthly	Every 10 years	Strong Sudden
6	Moderate	Monthly	Every 30 years	Strong Sudden
7	Major	Monthly	Every 50 years	Severe Sudden
8	Great	Yearly	Every 100 years	Very Severe
9	Great	Yearly	Every 300 years	Very Severe
10	Super	Rarely	Every 1.000 years	Extreme

Fig 2.5 Richter scale of magnitude

CHAPTER NO 3

WAVEFORMS DATA LOADING AND PROCESSING

3.1 INTRODUCTION:

Pyweed software is used for the purpose of downloading waveforms from different stations of the world. For the proper coverage of the September 24th,2013 event stations were selected using pyweed such that the coverage to the event was being provided from all sides for better display of results. Data loading is proceeded by data processing stage and for that purpose we relied on ISOLA-GUI software to process the waveforms data for the ultimate purpose of calculating moment tensors.

3.2 DOWNLOADING WAVEFORMS DATA:

The first step of our thesis is to download the waveform data of selected stations. Stations should be selected in such a way that coverage is provided from all directions. This selection of proper stations is done by using pyweed. To activate this software we use a command prompt known as Anaconda prompt.

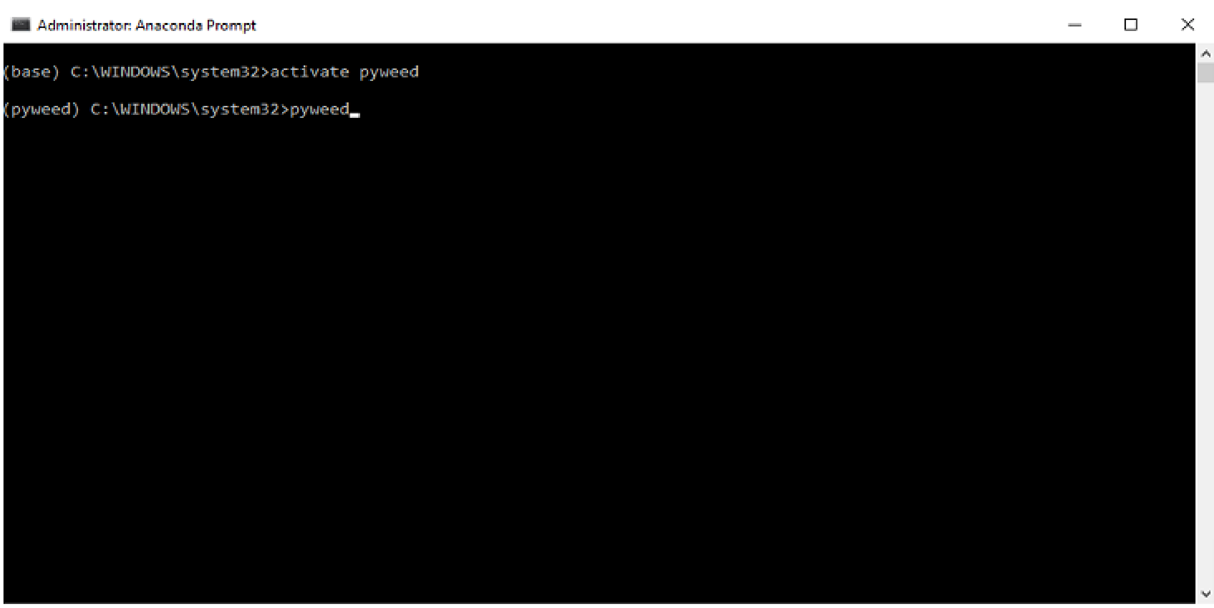

Fig 3.1 Anaconda prompt window

As the pyweed software opens the first step is to apply proper constraints to data in form of the time(start,end) the proper magnitude is selected. Then we select the Get events,opening the get events will give us all the earthquakes that occurred within our given time ,magnitude constraints.As we want to download the proper waveform data, so select the get stations option.Proper care should be taken when selecting the stations.The stations for September 24th,2013 Awaran Earthquake were selected such that a proper coverage to the earthquake epicenter was being given from all sides.Stations for different networks are available but for our thesis work we selected the IRIS stations.To get worldwide IRIS stations that have recorded the Awaran earthquake event we set the distance from 0 to 180 degrees. So a total of 6 stations were selected that were providing coverage to the event. For each station there is given a particular longitude and latitude value. Keeping in mind the ultimate aim to calculate the moment tensor we select the station for which waveform data for all N,E,Z and time component is available.For each station there can be two location 00 or 10 so for downloading proper waveforms either we proceed with 00 or with 10.Considering both 00 and 10 waveforms can lead to error during the data preparation for invert files in further steps. In the figure below the orange circle shows the location of September 24th,2013 Awaran earthquake epicenter,While the red triangle shows the location of the recording NIL station(located in Nilore Islamabad)

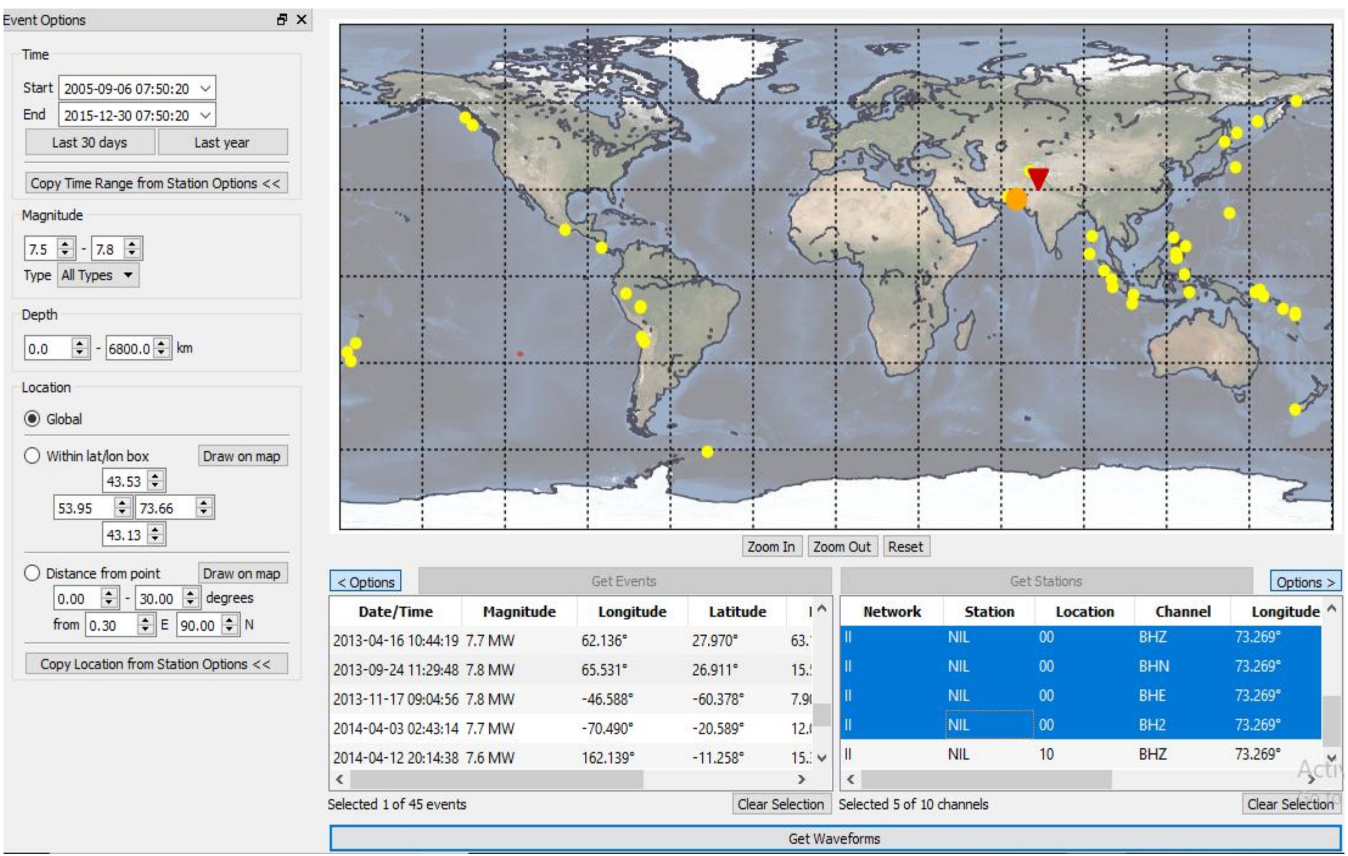

Fig 3.2 Earthquake station selection

After selection 0f all the given 5 channels of NIL station we click Get waveforms to obtain the waveforms of the event that were recorded by this station.A incomplete waveform if saved can lead to significant deviation from our expected results of proper focal mechanism estimation.S0,to get complete waveforms it's better to change start and end time from already given 0-600 to 0-4000. Only those waveforms are saved whose data is available, so for each station three waveforms are saved(BHZ,BHE,BHN).BHN,BHE may sometimes also be written as BH1,BH2.The 3 waveforms are then stored in SAC format ,the same process is repeated for all the selected stations. As for Awaran earthquake we selected 6 stations so a total of 18 waveforms(BHZ,BHE,BHN) were saved in raw data folder. With this step,our data loading procedure is completed.

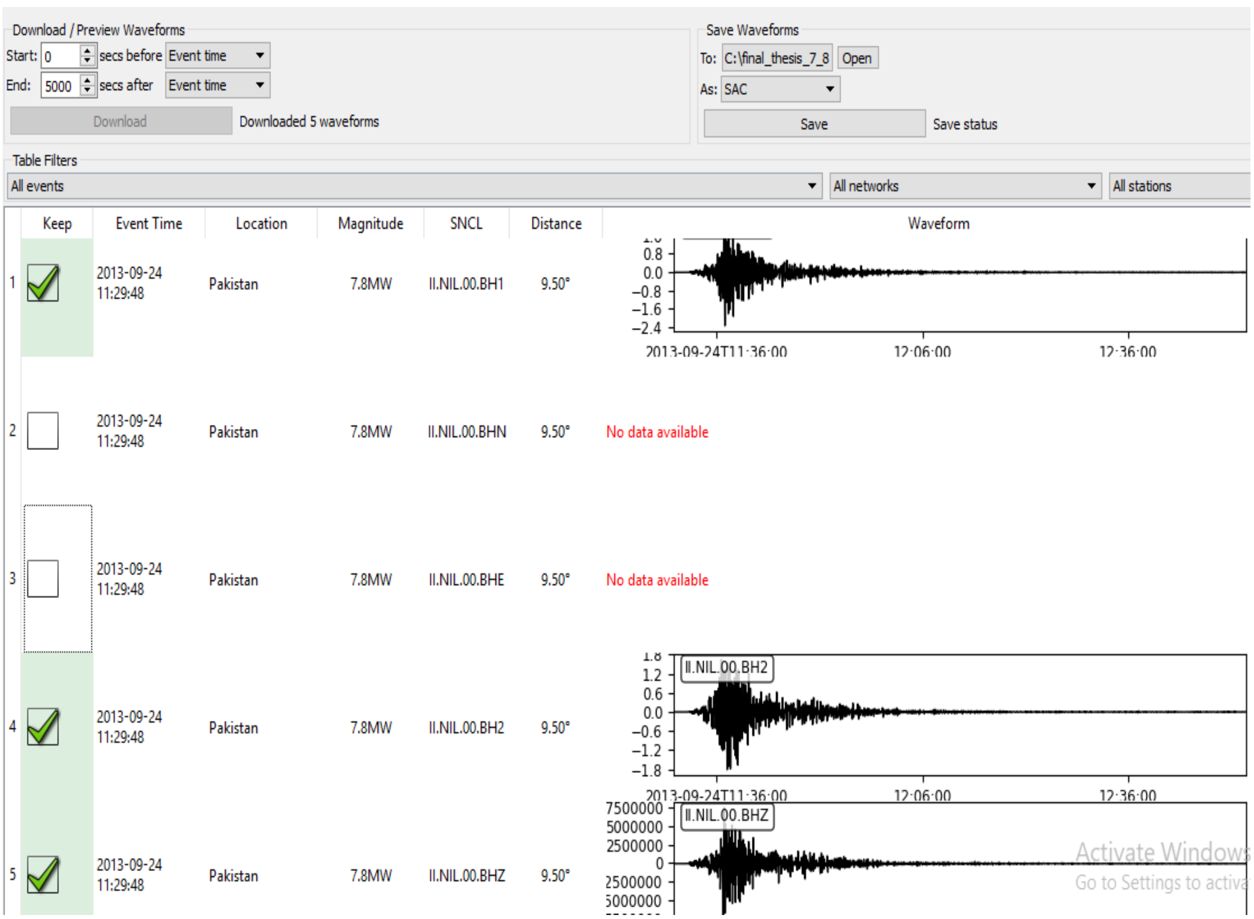

Fig3.3 Downloading NIL station waveform data

3.3 PROCESSING THE WAVEFORMS DATA:

The downloaded raw waveforms data is then sequentially processed in different steps by the ISOLA-GUI software.To begin the data processing steps with ISOLA-GUI software we used matlab 2013 version.In order to run the code,within the matlab command window,change the directory to the required final thesis folder and type isola.This will run theMain GUI file and we will get the following form:

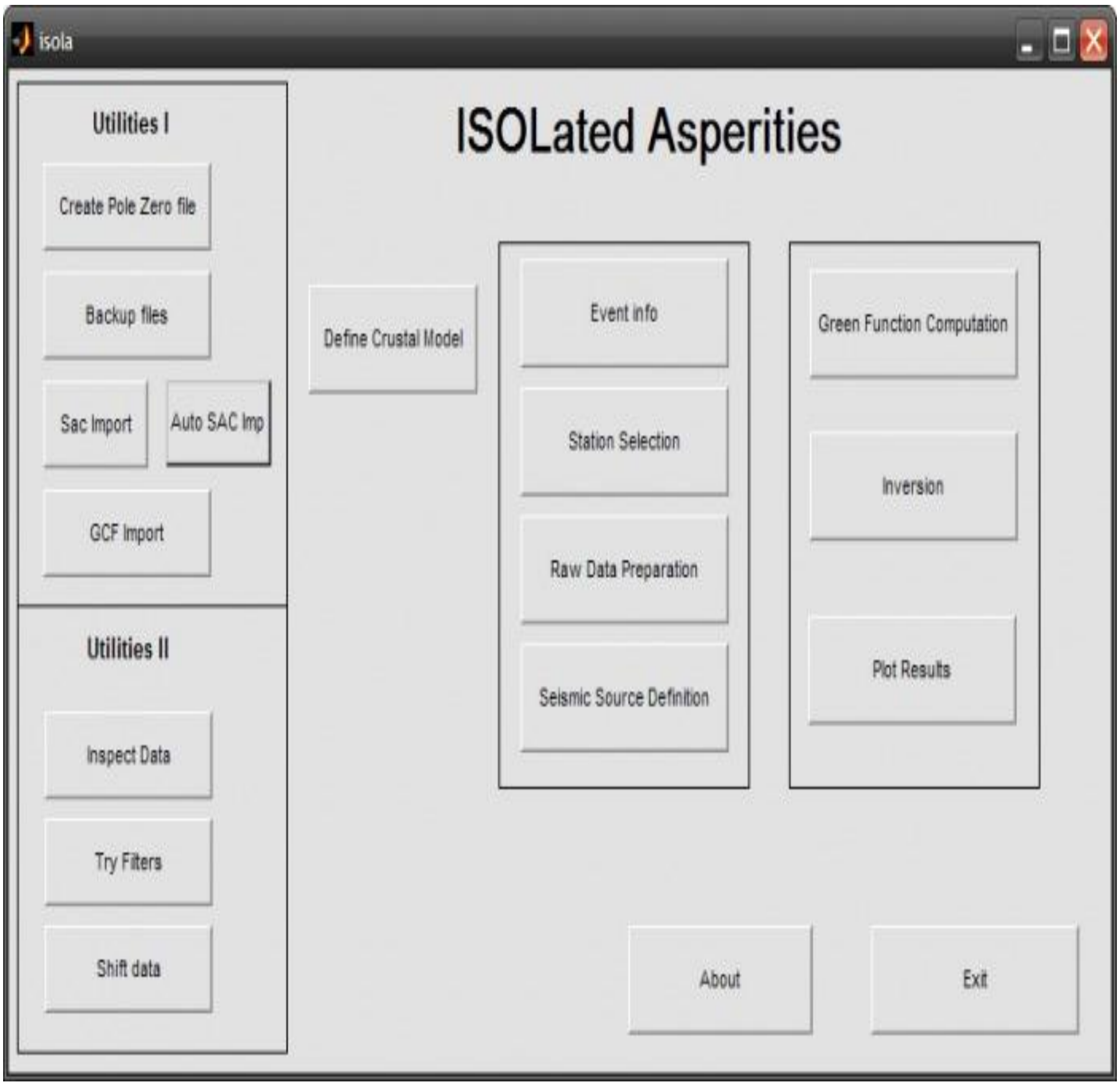

Fig 3.4 Main form of ISOLA MATLAB GUI

3.3.1IMPORTING THE DOWNLOADED DATA:

The 6 stations waveform data which was downloaded by us using the pyweed software is then AUTO SAC imported by us one by one for each station. Considering the fact that for each station three waveforms were saved in rawdata folder, this step of data import data the three components NS,EW,vertical to be given one by one.Most of the stations waveforms are saved easily but some stations waveforms require a common start time to be saved properly.All the imported waveforms are then saved by selecting Save ISOLA ascii option.

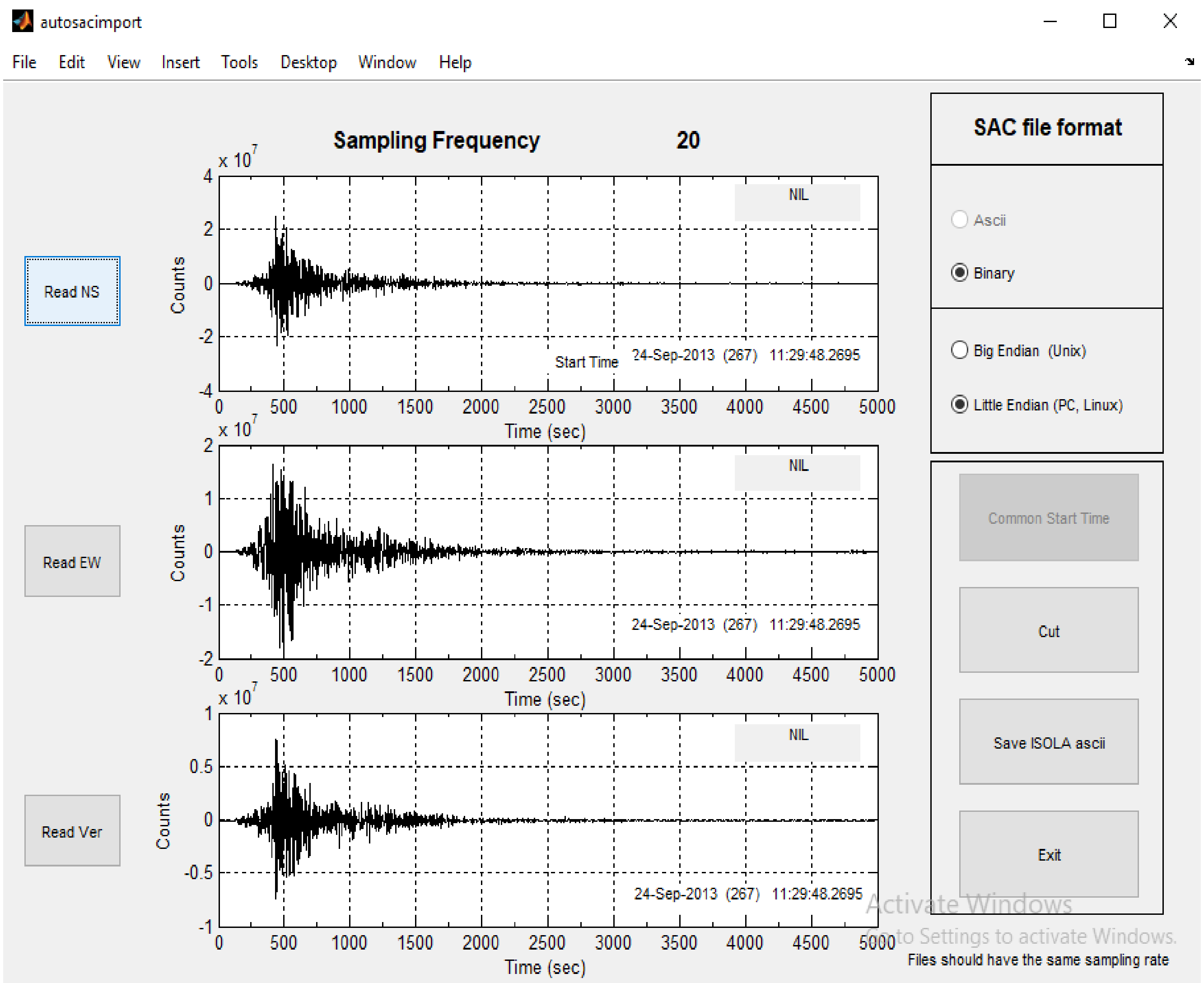

Fig3.5 Auto sac imported waveforms (NE,EW,vertical) for NIL station

3.4 DEFINING PROPER CRUSTAL MODEL FOR EARTH:

For determining the moment tensor of 24th September ,2013 Awaran earthquake we used PRELAMINARY REFERENCE(PREM)CRUSTAL MODEL.

3.4.1 PREM MODEL:

The Preliminary Reference Earth Model is an average Earth model that incorporates anelastic dispersion and anisotropy and therefore it is frequency-dependent and transversely isotropic for the upper mantle (Anderson., 1981).

PREM MODEL is the most widely used 1-D model for seismic velocities. It was also used for surface wave dispersion observations, travel time data for a number of body wave phases and for basic astronomical data(Earth's radius, mass).PREM model is transversely isotropic between 80-220 km depth in upper mantle in order to fit love and Rayleigh waves observations simultaneously.The word transverse anisotropy refers to a symmetrical form of anisotropy in which SH and SV waves travel at different speeds.All other models of earth are reasonably close to PREM Model.The major difference however exists in upper mantle where PREM shows a discontinuity at 220 km(which has not been observed in other models).

3.4.2 USING THE PREM CRUSTAL MODEL:

It's the first step in inversion procedure is the definition of PREM Crustal model.This is done by pressing Define Crustal model button on main form which will open the model's definition form.There is an option of maximum 15 layers that can be added in crustal model.For each layer we need to give value for depth of layer top,the Vp,Vs velocities in km/sec,density in g/cm^3,Qp,Qs.A title can also be given optionally.A point to remember here is that density and the attenuation(Qp,Qu) are less precisely known than seismic velocity but these parameters are required for computing synthetic seismograms.For the crustal model used in our thesis 12 layers were used starting from earth's surface(0 depth) to inner core(6371 km).

3.4.3 PLOTTING THE PREM MODEL:

To check whether our selected crustal model is correct our not we click the plot option given in the definition form of model. The following plot is obtained:

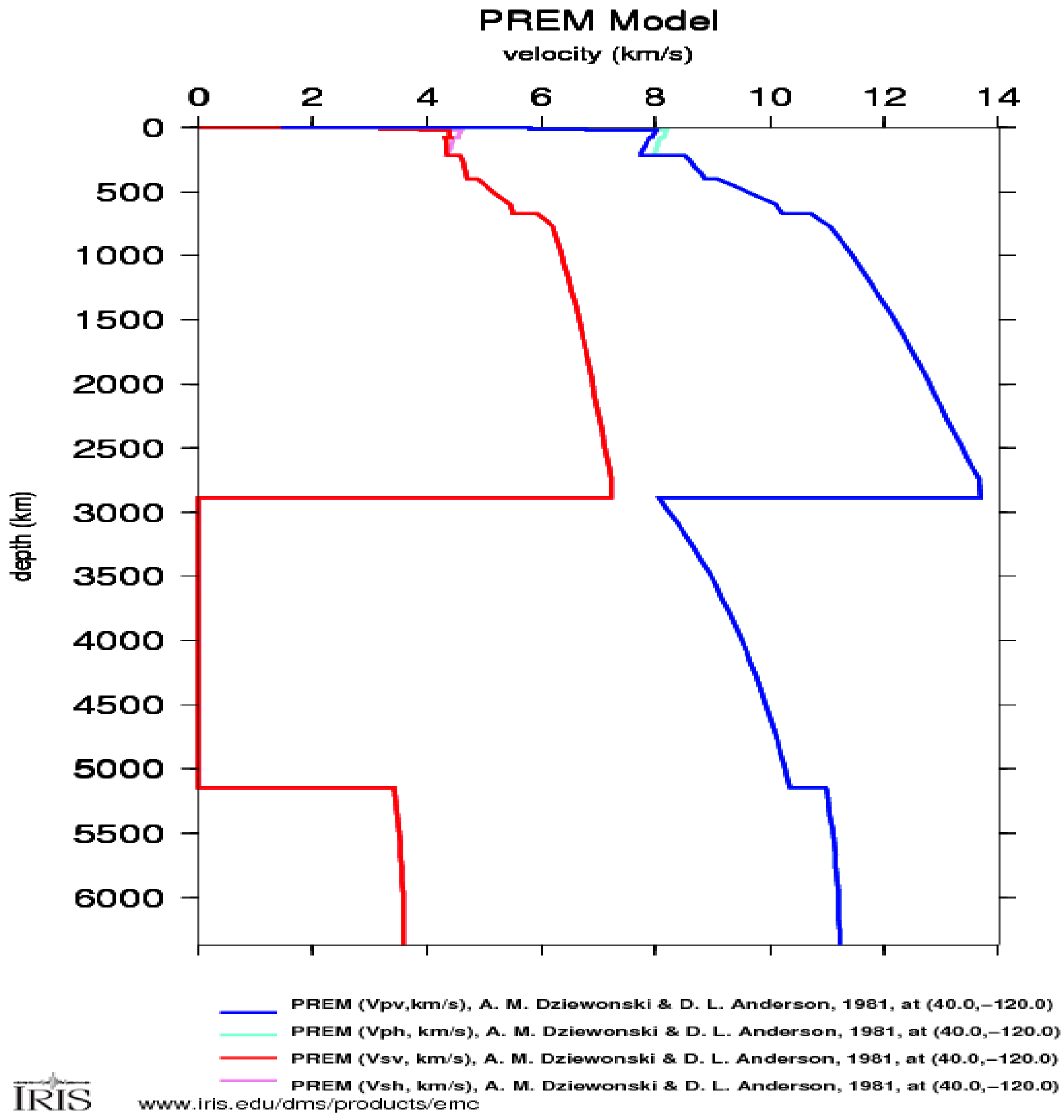

Fig3.6 PREM model

In the figure above the red line shows Vs(Shear wave velocity) and blue line shows the Vp(Primary wave velocity). We notice that from 3000-5200 the Shear wave velocity(Vs) value obtained is zero. The reason for this is that it's the region of outer core and in outer core the shear waves velocity is zero. It's an important validation that indicates our model is correct. The Next step involves Saving the data(Save) in a text format file suitable for ISOLA Fortran, as well as reading it back in the form read.The latter one is useful for editing a previously saved model.The model is saved in a file named as crustal.dat

3.5 EVENT INFORMATION:

The next important step towards green function computation and inversion is to give the proper information related to the event he wants to analyze.This can be done by pressing the Event info option in ISOLA-GUI main form. Event information step requires the values of event latitude, longitude, depth, magnitude, date, origin time of event, sampling frequency and time length of data to be computed. We added the following information to the Awaran earthquake event information.

Fig3.7 Event information for AWARAN earthquake

There is a save or update button given towards right-hand side,After pressing the update button the GUI writes or updates the appropriate files(event.isl, rawinfo.isl, duration’s).These are files are actually ISOLA text files and these are stored in ISOLA folder.

3.6 STATION SELECTION FOR INVERSION:

After the proper event information has been created and saved the next most important step is the selection of stations for inversion. For this purpose we created a station file that was in ascii format had three columns station name ,Latitude, Longitude separated by spaces.The station names should have 3 characters. If a longer named is used than a warning is given to reduce the station name to 3 characters.For the case of Awaran earthquake we had selected 16 stations so our stations file consisted of the names of 16 stations, their long, lat. There is another requirement for the step of station selection that a proper M_MAP should be installed.By pressing the make map option a map of station distribution(depending on the station file given as input) is created.If the stations are very close to eachother so that difficulty is being encountered for their selection there is a option given just below make map to adjust the values if stations are very close to each other.The value already given by the software is 0.1 but for picking the September 24^{th},2013 Awaran earthquake stations we changed it to 0.5 and then we selected all the 6 stations for inversion. The station selection was done by using the left mouse button. The last station was however picked by using the right mouse button so that a window opens which shows total number of selected stations. After this step we pressed the exit button on station selection form which led the GUI software to create station.isl, station.dat files in green folder and allstat.dat file in invert folder. The station selection step figure is given below:

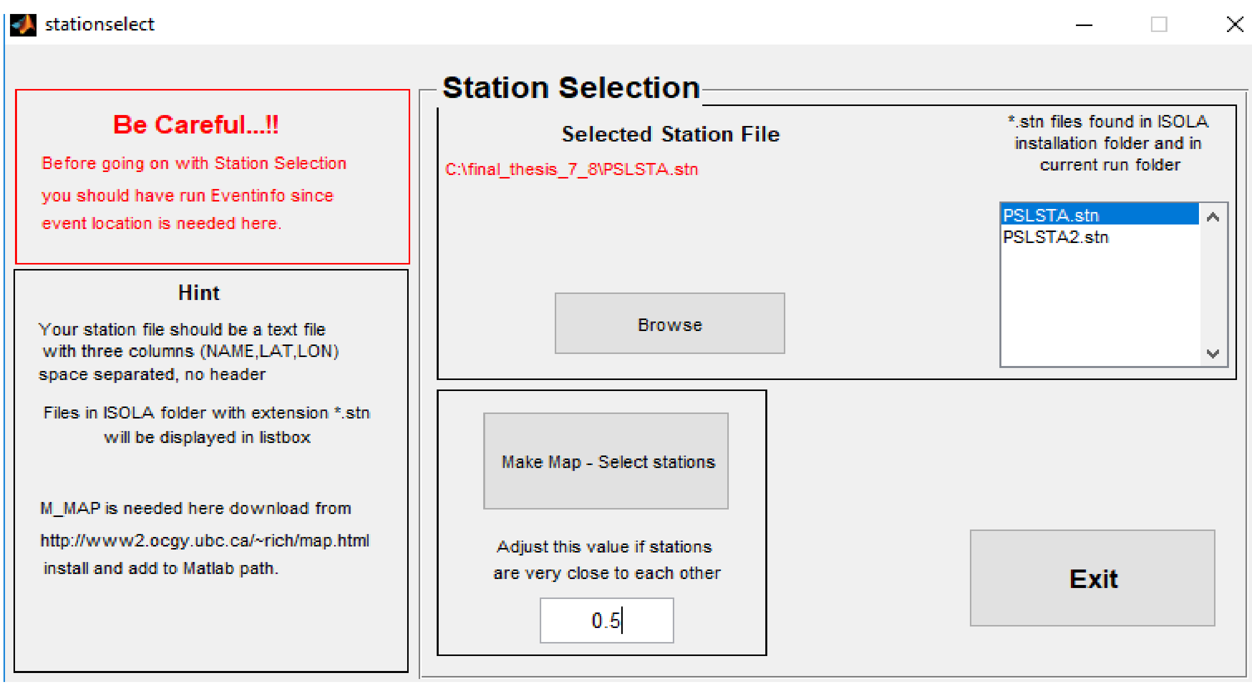

Fig 3.8 Station selection

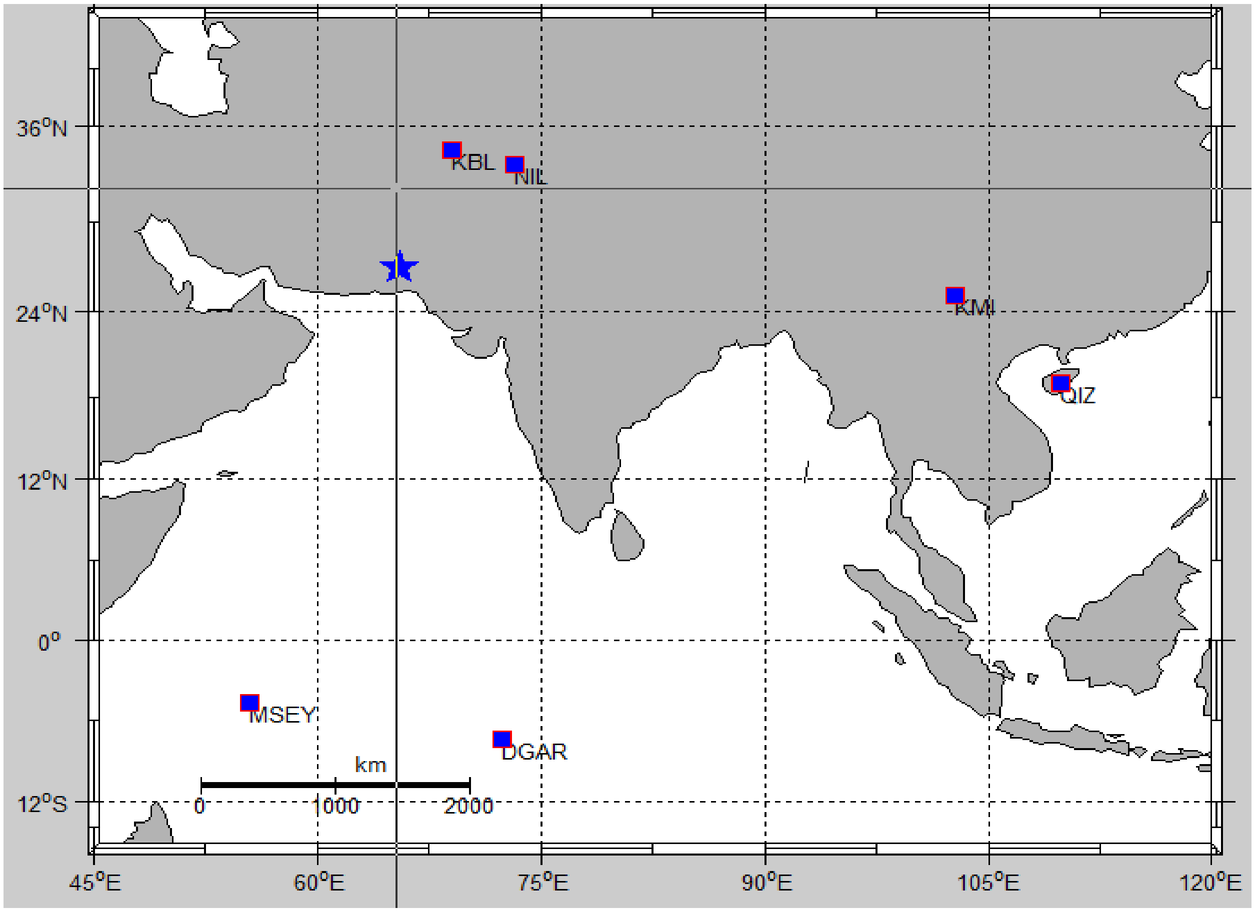

Fig 3.8.1 station selection for inversion

In the figure above the blue star on the world's map shows the position of the earthquake's epicenter. Blue boxes show the selected stations, red boxes show the stations yet to be selected for inversion. By using this procedure a total of 6 stations were selected by us for inversion.

3.7 RAW DATA PREPARATION:

It's a very important step for the calculation of focal mechanisms. Raw data preparation is important for us for the purpose of units conversion. Originally the data recorded at the earthquake station is in form of counts(usually in powers of ten). For better calculation of magnitude its necessary to convert this data into units of m/sec as counts are usually a large number for calculating magnitude. We integrate them to convert into units of displacement and finally invert them.

3.7.1 INTRODUCTION:

After the 6 stations were successfully selected and saved we proceeded towards the most important option of GUI known as the Raw data Preparation. It's considered as the most important option as this step processes the seismograms by applying:

- Instrument correction
- Origin time alignment
- Resampling

This step produces the files that are ready for inversion. The data for this step is available in a 4-column text files having Time in seconds, NS,NE,Z components in counts all of these column data is separated by spaces. One file is created for one station. The filename is just like station name for a station named YSS the filename starts with YSS the remaining part of filename, its location is arbitrary. The next step is the creation of PZ files .Filename for these files should be a combination of station name and the BH.pz string. for example the filename for NIL station East component will be NILBHE.pz, the location of these files is not arbitrary we saved them properly in PZ folder.

3.7.2 RAW DATA GENERATION:

We begin this step on ISOLA-GUI software by selecting the data preparation option located just below station selection. A new window of the following form opens:

We select the high cut frequency for each station as 0.1 hertz. The start time option given is set by us to be same as the origin time 11 hour,29 minute,48 seconds for each of the 6 stations. Pressing the load Ascii file, a standard open file dialog appears and we select a data file.When the file is read, the sampling frequency is displayed(in red color) at the top and just adjacent to it resampling frequency is displayed(in blue color).After the waveform of a particular station has been loaded the instrument correction option is enabled, which allows the ISOLA software to search for PZ files and then performs instrument correction on them. After instrument correction has been applied by us, we notice that the origin time option can now be selected by us. This origin time alignment option is then pressed by us for the purpose of time alignment of seismogram. Finally after origin time alignment step we select the Save data option in order to save the files in Invert folder. ISOLA-GUI saves these files as text files consisting of 4 columns, time in sec, NS, EW, Z in m/sec) one file per station is saved. The ISOLA-GUI also creates suitable filenames for resampled data forexample for the station NIL, the file name will be saved as NILraw.dat . The inversion and Green function computation step will not proceed if the names of these files are changed by us.

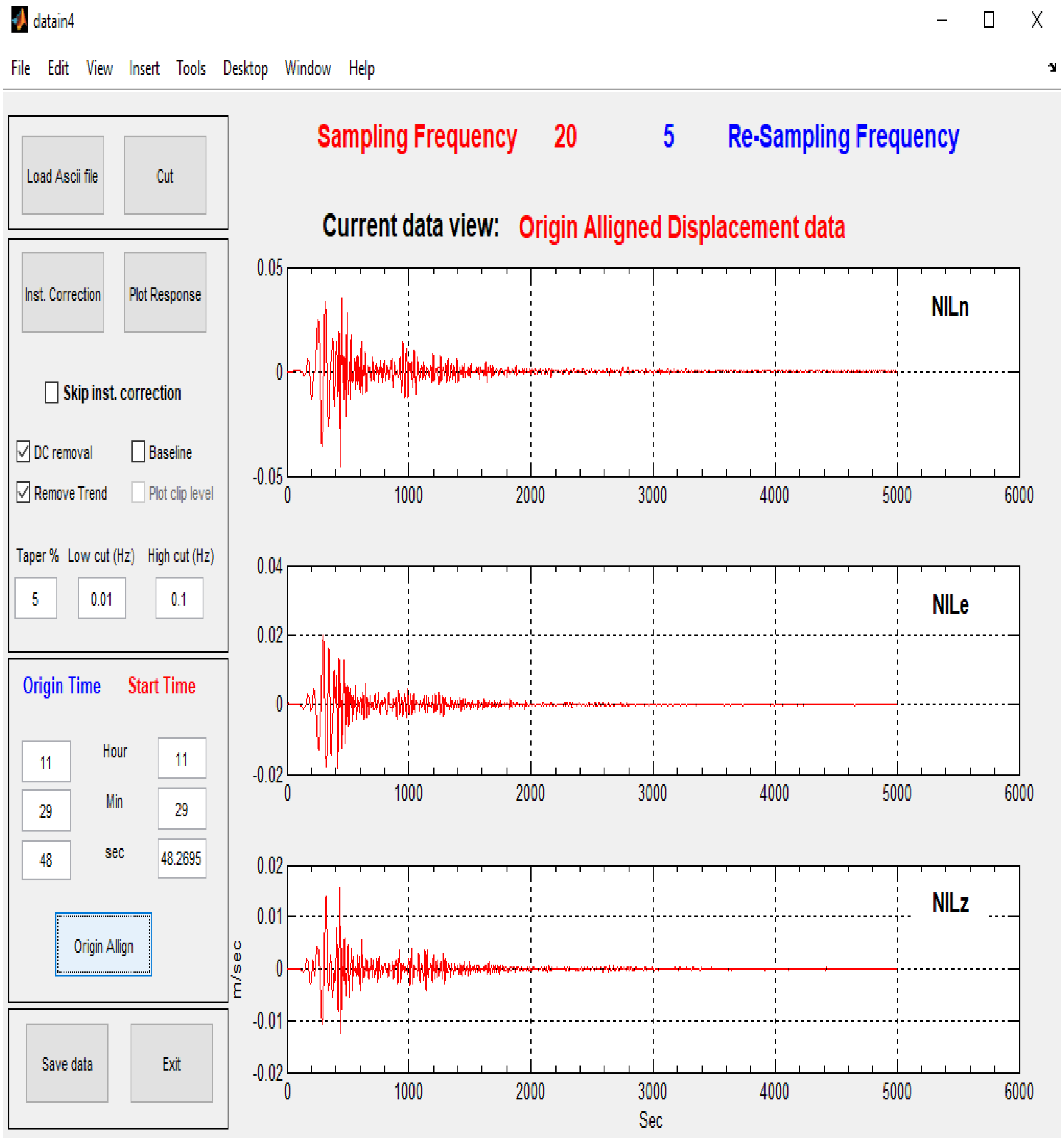

Fig 3.9 Raw data preparation for NIL(Nilore) station

3.8 TRIAL SOURCE DEFINITION:

The final data that we prepare just before the computation of green functions is the trial source location. For this purpose we press the seismic source definition option given in ISOLA-GUI software main form. There is a option either to select sources below epicenter(in order to prepare trial sources below epicenter) or sources on a line or plane(to prepare trial sources on a line or plane). For our thesis work we proceeded with the sources below epicenter option.

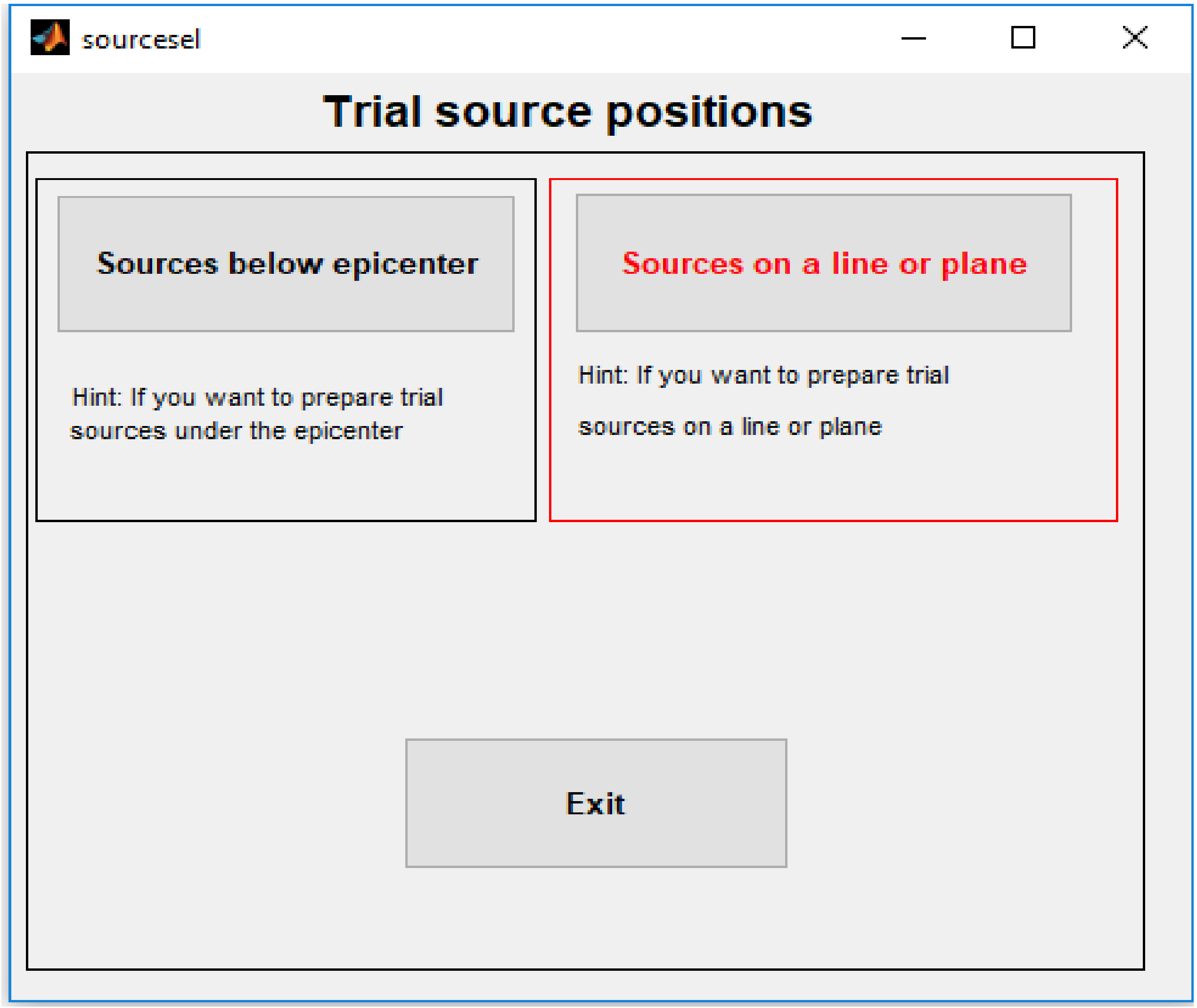

Fig 3.10 Trial source definition

For calculation of sources below epicenter there are three requirements to be fulfilled. Which are listed below:

- Appropriate Starting depth (km) according to the event of interest.
- Depth steps (km)
- Number of sources(should be less than 99)

For our thesis work the starting depth was given to be equal to 10 km, followed by depth steps of 2.5 km and the number of sources were given to be 5.

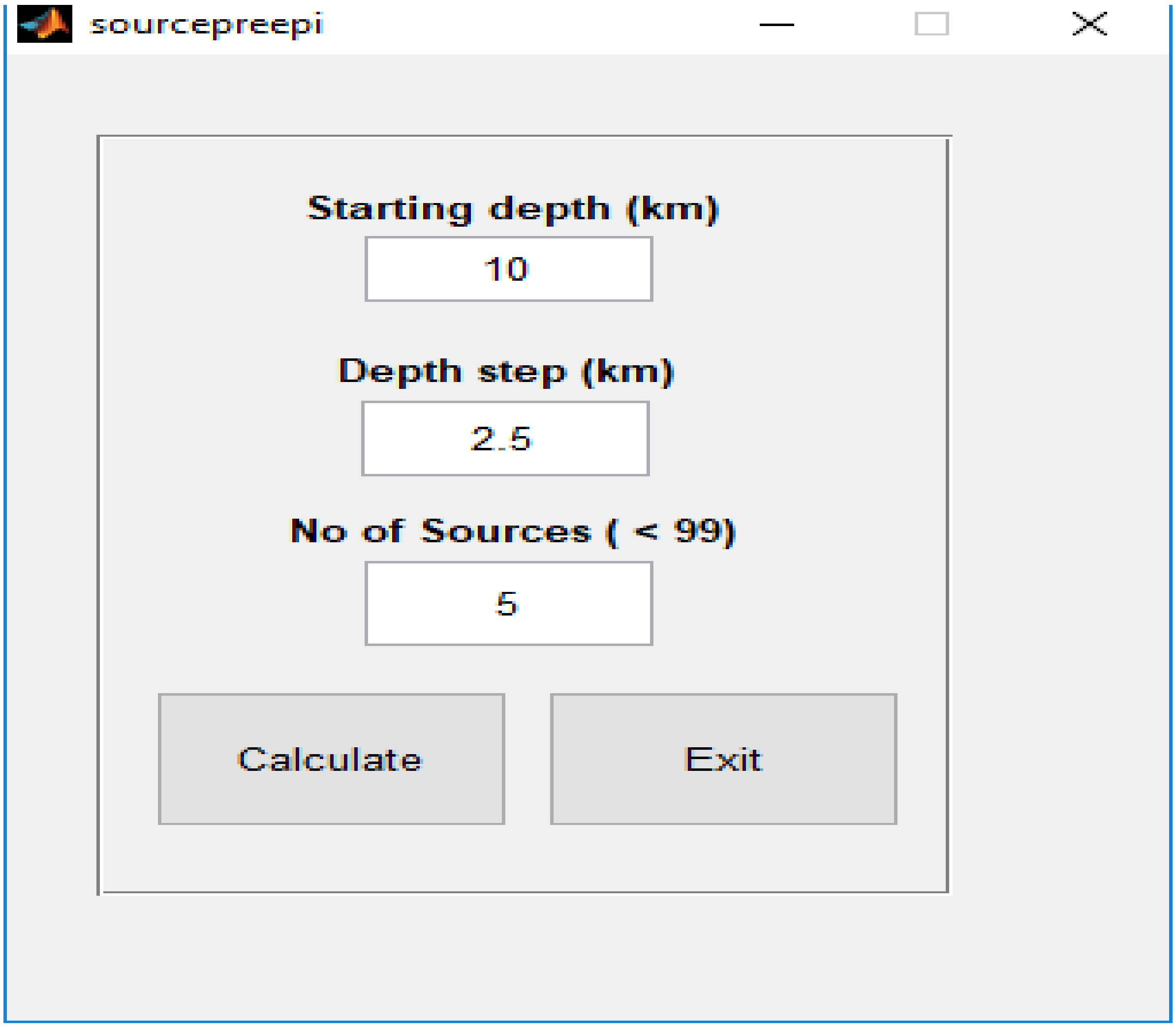

Fig 3.11 parameter of sources below epicenter

CHAPTER NO 4

GREEN FUNCTIONS, INVERSION AND RESULTS

4.1 INTRODUCTION:

A useful way to estimate source time function is based upon green function. Green function actually describes a signal that would arrive at the seismometer if the source time function was a delta function. These green functions are very important for our thesis work as by deconvolving these we can get earth quake's source time function. We already know that deconvolution can be done either in time domain or in frequency domain, however it's easier to divide spectra in frequency domain but small amplitudes should be avoided that occur at some frequencies. So, by using green functions derived from a simple source in a fault region we can model even large complex earthquakes.

4.2 GREEN FUNCTIONS COMPUTATION:

After completing the step of trial source definition, the inversion process finally starts. However to run inversion there is a requirement of computing the green functions. For this purpose we select the green function computation option in the ISOLA-GUI main window. As we select this option a new window opens for the Green function in which there is only one option to be filled by the user which is the maximum frequency of the green functions to be computed known as fmax. A point to remember here is that the frequency value should be given with proper consideration as once given at green function computation stage then no higher frequency than fmax can be given in later steps of inversion. Maximum frequency for green function computation for our thesis work was given to be 0.1 .Using such a low frequency for our thesis work was vital for our results as for such low frequencies the effects of attenuation are not very prominent and our results are thus not effected largely by attenuation problem. Some of parameters are also visible in the green function window which include the time length window that was already given by us in Event info step , the number of sources that we selected during trial source definition stage and the most important is the number of station that form the basis of our work.

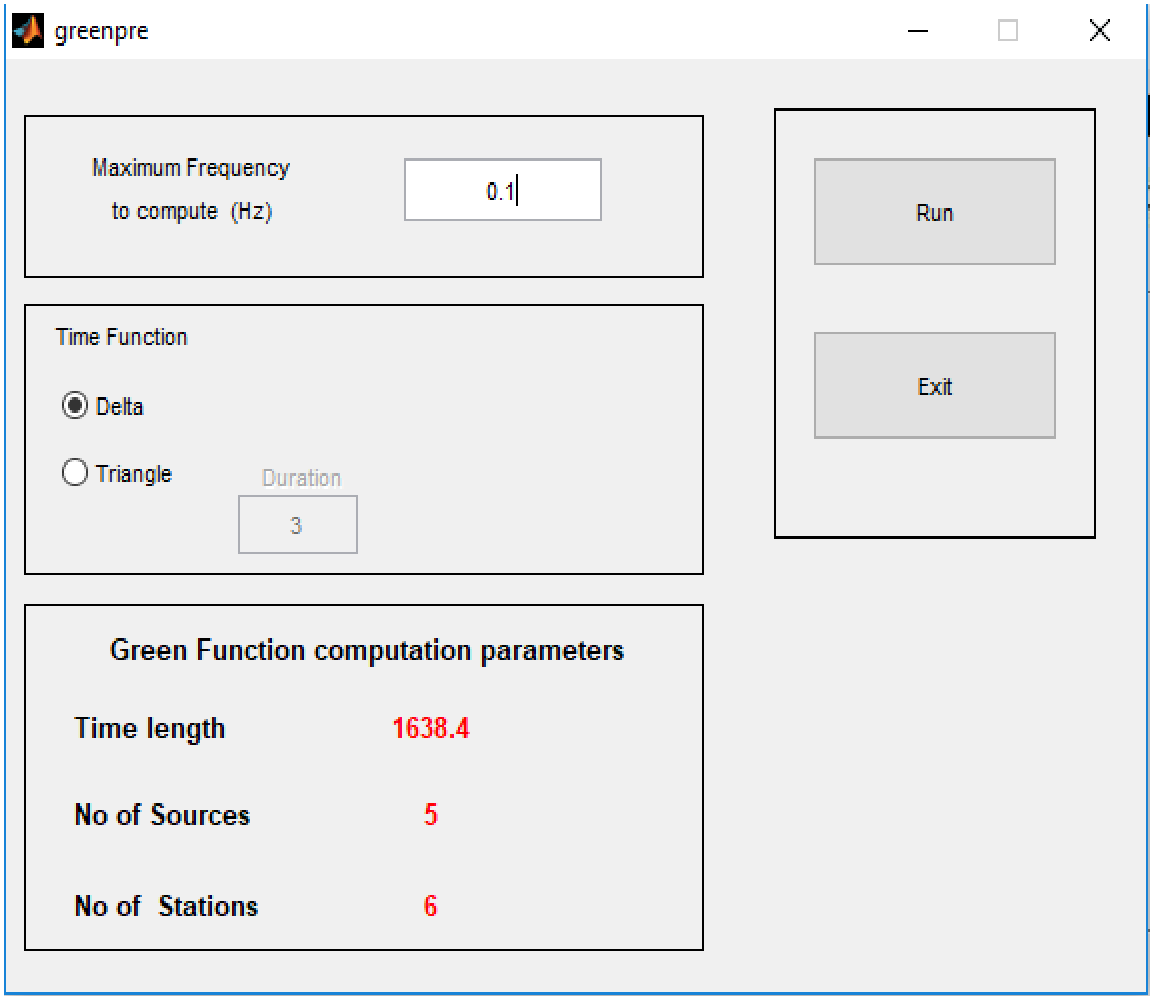

Fig 4.1Green function computation

After computing the maximum frequency we press the run option, due to which some necessary files are created in Green folder and the executable fortran codes are called from matlab for the green functions calculations and for elementary seismograms. The most important codes are the gr_xyz.exe and elemse.exe respectively. This execution process is continuously monitored by us in the command window. The fortran codes are being executed one by one and should be carefully observed to check for any errors. After the execution of fortran codes has been completed a dialog of copy files in invert folder emerges for which we press ok. The copying process starts and a message is issued by ISOLA as the files are copied in invert folder.

4.3 INVERSION:

To understand about inversion we should have to get familiar with the idea of focal mechanisms and earthquake moment tensors. Focal mechanisms can be explained as when an earthquake occurs, seismologists create graphics of focal mechanisms, informally referred to as beach balls, to show the faulting motions that produce the earthquake. They use the patterns of compressions and dilatations received by seismometers. The focal mechanisms are based on the direction of the first arriving P wave. However nowadays focal mechanisms can also be computed using a method that attempts to find the best fit to the direction of P-first motions observed at each station. So, focal mechanisms computed using only first-motion directions, these incorrect first-motion observations may greatly affect the computed focal mechanism parameters. Depending on the distribution and quality of first-motion data, more than one focal mechanism solution may fit the data equally well. Modern software's rely on the use of waveform modeling to calculate focal mechanisms. The second most important terminology to consider for inversion are the moment tensors these are defined as a representation of the movement on a fault during an earthquake, comprising of nine generalized couples, or nine sets of two vectors (Wysession, 2003). The tensor depends of the source strength and fault orientation. It is often represented with "beach balls" just like the focal mechanism (or fault plane solution. Hence the moment tensor actually represents both the earthquake's fault geometry by means of values of its different components and its size by means of the scalar moment. It gives us idea about seismic waves produced by a complex rupture which involves displacements that vary in space and time on an irregular fault. Additionally a plus point for us is that when solving moment tensor problems we can write these in any orthogonal coordinate systems as vector and tensor equations are valid regardless of the coordinate system. A moment tensor has a key advantage that it makes it easier for us to invert seismograms to find source parameters. Moment tensors can be found by us by inverting the seismograms.Moment-tensors provide a valuable resource for tectonic analysis.

Now, after computation of green function the most important step of our thesis starts. For carrying out inversion we select the inversion option in ISOLA-GUI main window. There are few options to be filled in the inversion window before the inversion can start, we have to give proper filter, select type of inversion, Number of sub events to be retrieved and some parameters for time search which describes the temporal grid search of the sub events. After selecting the suitable options we press the compute weights option which calculates the weights that are to be used for the inversion procedure. Then we press the run option and the main isola.exe FORTRAN code starts in command window. There is also an option of deselect stations which opens the allstat.dat file on word pad so that we can remove a station from inversion. An important point to note here is that the larger the numbers in allstat.dat file the lower is the weight.

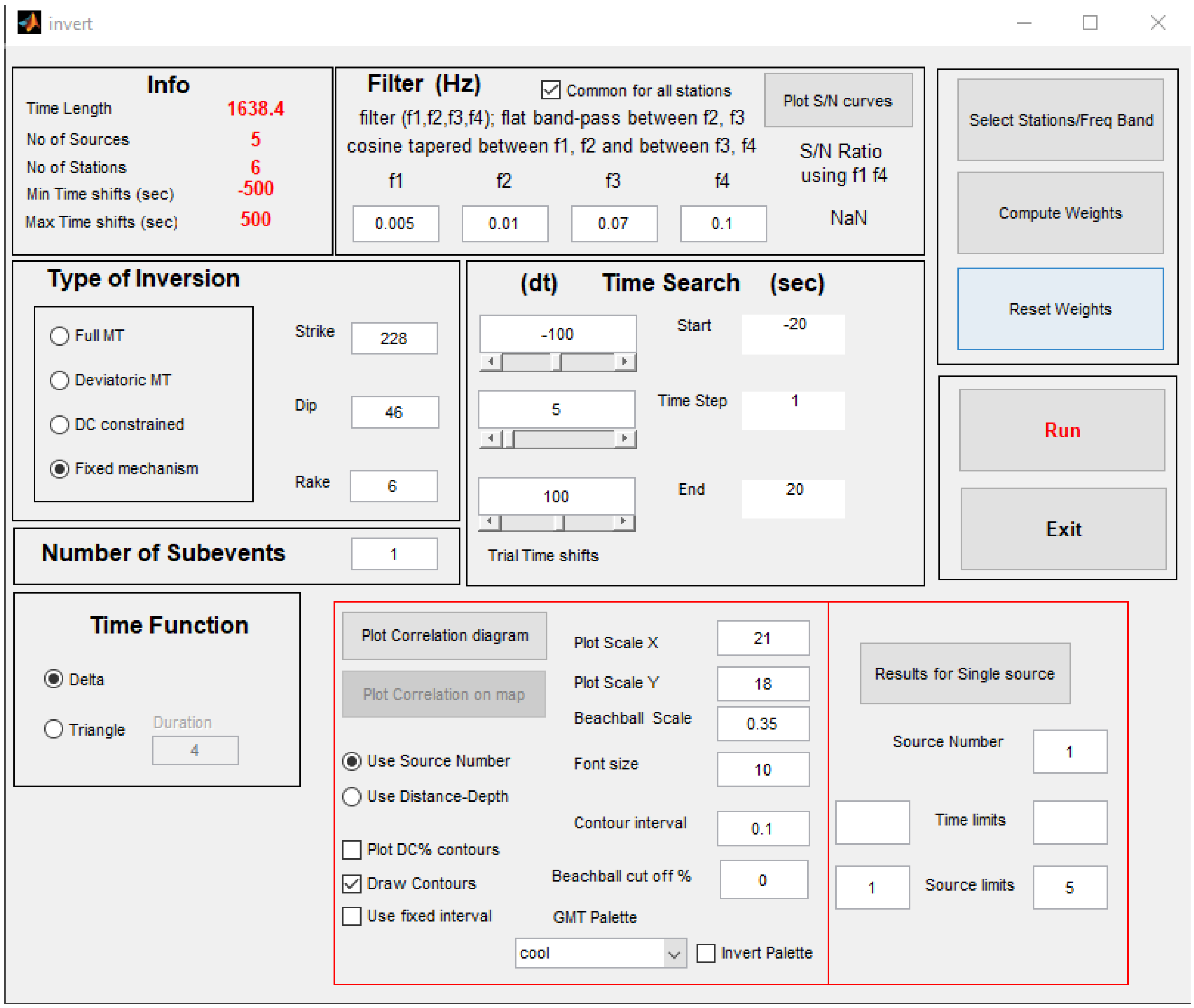

Fig 4.2 Inversion calculation

4.4 RESULTS:

The isola.exe code that we used in inversion leads to creation of a number of output files that can be plotted after the inversion process has been completed. For the purpose of plotting we select the plot results button that is present in main ISOLA-GUI window. The names of stations that we have selected during the pyweed step are available either we can plot a single station to check the synthetic of its NS, EW, Z components or we can select multiple or all stations for plotting like synthetic vs. real data, the MT results, also for comparing the solution with first motion polarities.

The moment tensor calculation of this research includes two steps. In the first step, we fix the horizontal source position (at the SED position, i.e., the USGS epicenter) and repeat the waveform inversion for a set of trial depths. The correlation between observed and synthetic seismograms, as a function of depth, is shown in Fig. 2, illustrating stability of the focal mechanism and the best fitting depth of 17.5 km. We found the maximum correlation of 0.43 at 17.5 km depth with 100 percent double couple (DC) solution.

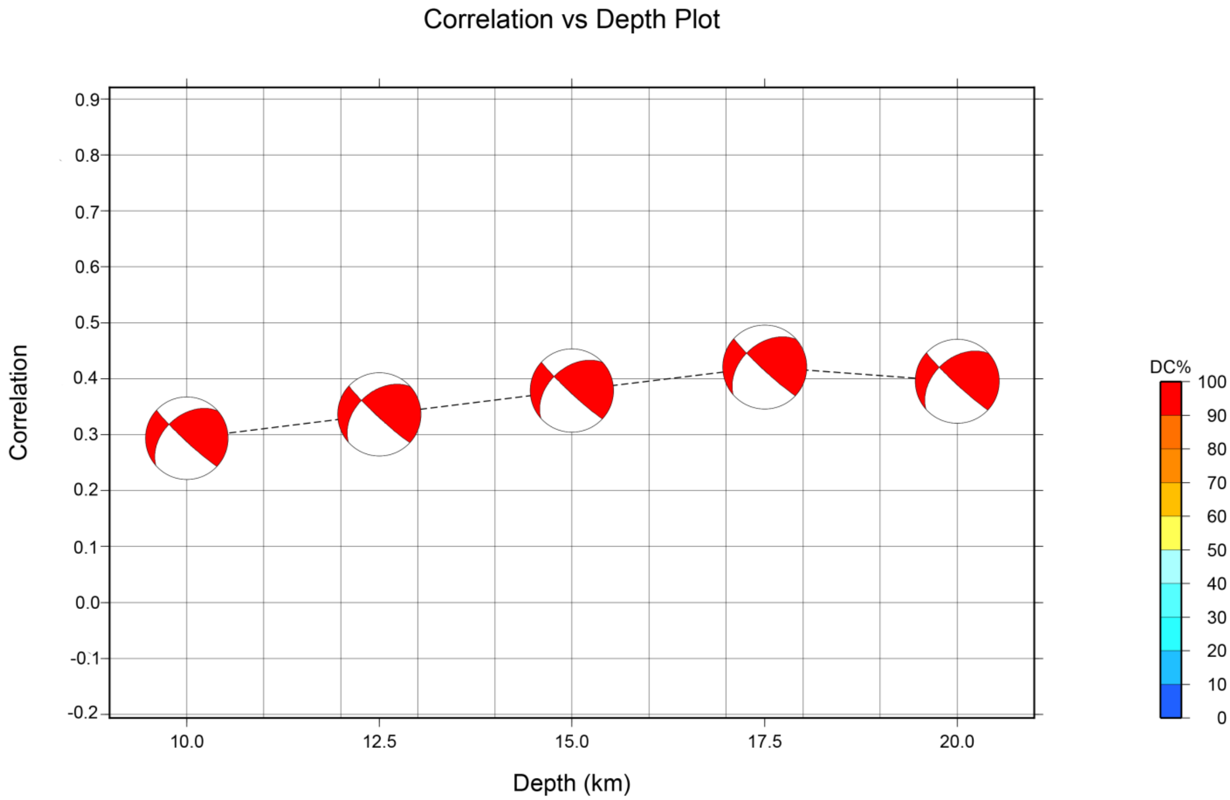

Figure: 4.3 The correlation between observed and synthetic waveforms and focal mechanism as a function of the trial source depth below the epicenter of SED. Colors represents the DC%

In the second step, we also fix the focal mechanism of the earthquake, equal to strike, dip and rake provided by the USGS agency. We then inverted the seismograms to compute the moment release, magnitude of the earthquake and six component of the moment tensor. The results of the inversion are shown in the figures 2 and 3. We found the seismic moment is approximately 4.037e+20 Nm, which is equal to Mw 7.7. We obtained the similar magnitude as reported by the USGS. The best solution is computed at 17.5 km depth as compare to 15.5 km depth. As seen in the figure 3, the synthetic seismograms are quite well fitted the observations.

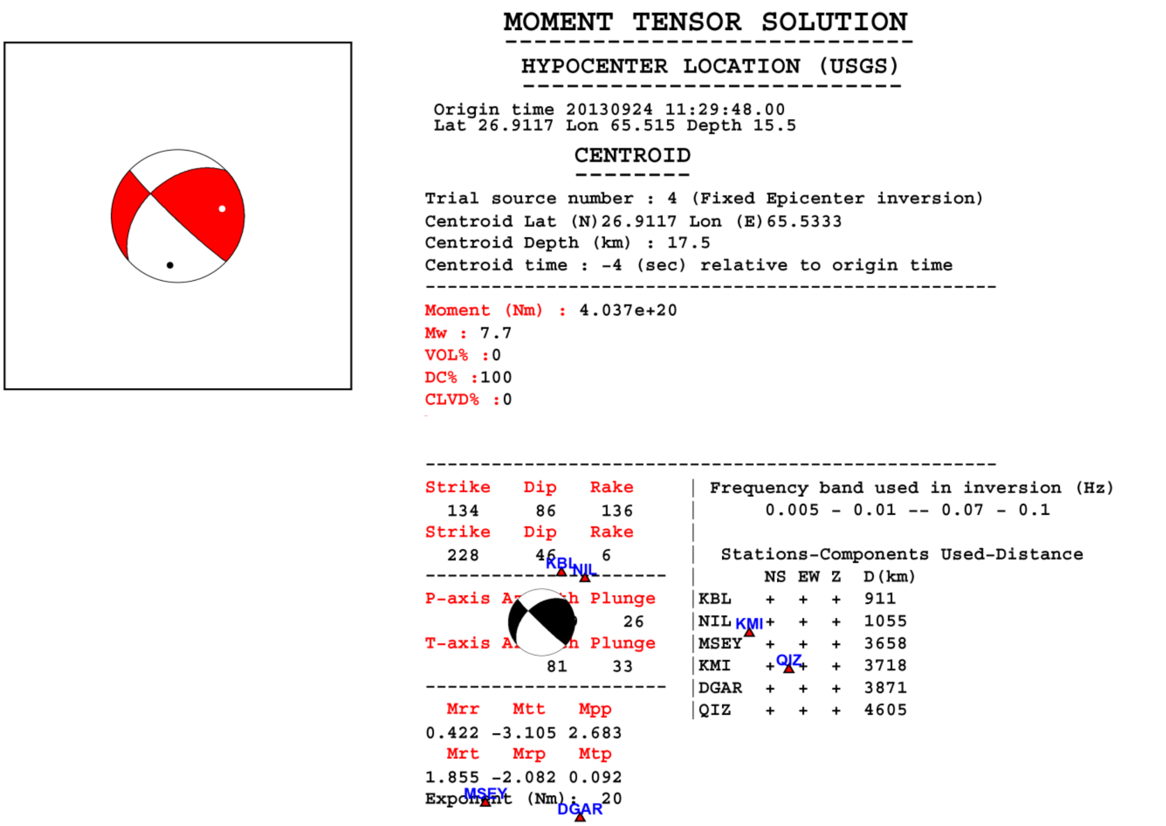

Figure:4.4 Moment tensor solution of the Awaran earthquake. Triangles show the stations used in the inversion.

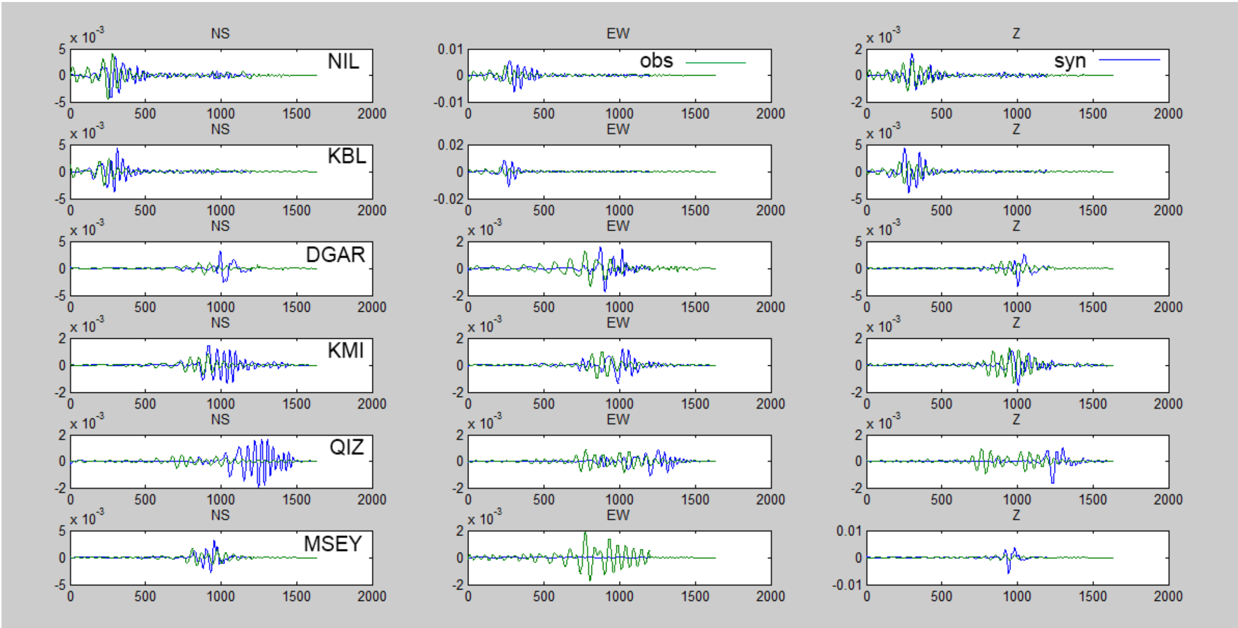

Figure:4.5 Observed (green line) and synthetic (blue line) velocity (m/s): Frequency ranges 0.005–0.1 Hz, Event 1. Peak amplitudes (in m/s) are on the right-hand side of the figure. Since the occurrence of event, the times (in second) are given on the bottom of the plot.

CONCLUSIONS:

- 6 stations(NIL, KBL, MSEY, KMI, QIZ, DGAR) were used for inversion of focal mechanisms.
- By using the low frequencies(0.05-0.1) the problems arising due to attenuation were significantly reduced.
- Maximum correlation was observed by us to be at 17.5 focal depth.
- The plot of observed vs. synthetic waveforms are correlated very well.
- The magnitude was calculated to be 7.7
- 100 percent DC (Double couple) was observed .
- focal mechanisms were found similar to USGS.

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