Chapter 3:

1D CRUSTAL VELOCITY MODEL

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1D Crustal Velocity Model:P and S-wave travel Time Inversion Study

3.1. Introduction

This chapter focuses on the estimation of the 1D crustal velocity models for the NW Himalaya, India region. The minimum 1 D crustal velocity model for the Himachal Pradesh, NW Himalaya, India has been determined by the simultaneous inversion of arrival times and the velocity structure respectively. Seismic velocity is regarded as an important parameter in the assessment of regional tectonics and earthquake hazards, and it can also provide evidence of the evolutionary model of the Himalaya. The velocity structure determined enhances the knowledge of deep sub surface structures that can be regarded as the sources of strain accumulation at greater depths. In NW Himalaya the seismic activity is prone to the ongoing tectonic convergence of the Indian plate and the Eurasia plate. This collision of Indian and Eurasia plate has resulted in the origin of clustered seismicity between the Main Boundary Thrust (MBT) and Main Central Thrust (MCT) which illustrates the significant complexities in the tectonics of the region (Ni and Barazangi, 1984). As one tries to derive the seismic velocity structure beneath a certain area or region of interest one should first have the accurate location of the earthquake hypocenters in the area. The concept of deriving minimum 1 D P and S-wave velocity structure has been given by Kissling, 1994. This derived 1 D velocity model can be used as an initial velocity model in deriving the 3 D tomographic model (Kissling, 1994).

Here in the present study the initial hypocenter is determined utilizing the Hypo71 program (Lee and Lahr, 1975) encoded in the Seisan software package (Havskov and Ottemoller, 1999). The initial hypocenter locations are determined using the 1 D velocity model given by Kumar et al., 2009 for the Kangra-Chamba sector of the NW Himalaya. The minimum 1 D crustal velocity model obtained is inverted along with the previously established 1 D velocity model of Kamble et al., 1974 and Kumar et al., 2009 utilizing the well documented software VELEST (Kissling, 1994) . This is followed by joint inversion ofP- and S- wave velocity model and the earthquake hypocenter utilizing the Joint hypocenter determination (JHD) technique encoded in the same VELEST program.

3.2.Initial Hypocentral Locations

In the NW Himalaya a total of 476 local earthquakes having an epicentral distance of less than 1000 km were recorded utilizing a 20 station network operated by Wadia Institute of Himalayan Geology, Dehradun from a period of 2004 to 2013. A minimum of 3 P and 3 S-wave readings are observed and selected for travel time inversion utilizing the Hypo71 program (Lee and Lahr, 1975). The array operated in the Kangra-Chamba sector consists of seismic stations equipped with three-component CMG- 3T (120 sec natural time period) and again some seismic stations in the Sutlej valley, Kinnaur are equipped with Trillium- 240 broadband sensor having a velocity response between 0.004 to 35 Hz along with 24-bit Taurus digitizer (100 samples/s). The initial earthquake location is achieved utilizing the 1 D velocity model given by Kumar et al., 2009 given in *Table 3.1*.

Depth (Km)	P wave Velocity (Km/s)	S wave Velocity (Km/s)
0	5.27	3.01
10	5.55	3.21
15	5.45	3.05
18	6.24	3.59
46	8.25	4.73

Table 3.1: Preliminary velocity model of Kumar et al., 2009.

The error statistics obtained using this initial velocity model for hypocenter parameters like latitude, longitude and depth ranges from meters to 10 km all the cases.*Figure 3.1* shows the error in latitude plotted against the no. of earthquake events obtained with preliminary velocity model. *Figure 3.2* signifies the error in longitude plotted against the no. of earthquake events obtained with preliminary velocity model. *Figure 3.3* signifies the error in Depth plotted against the no. of earthquake events obtained with preliminary velocity model.

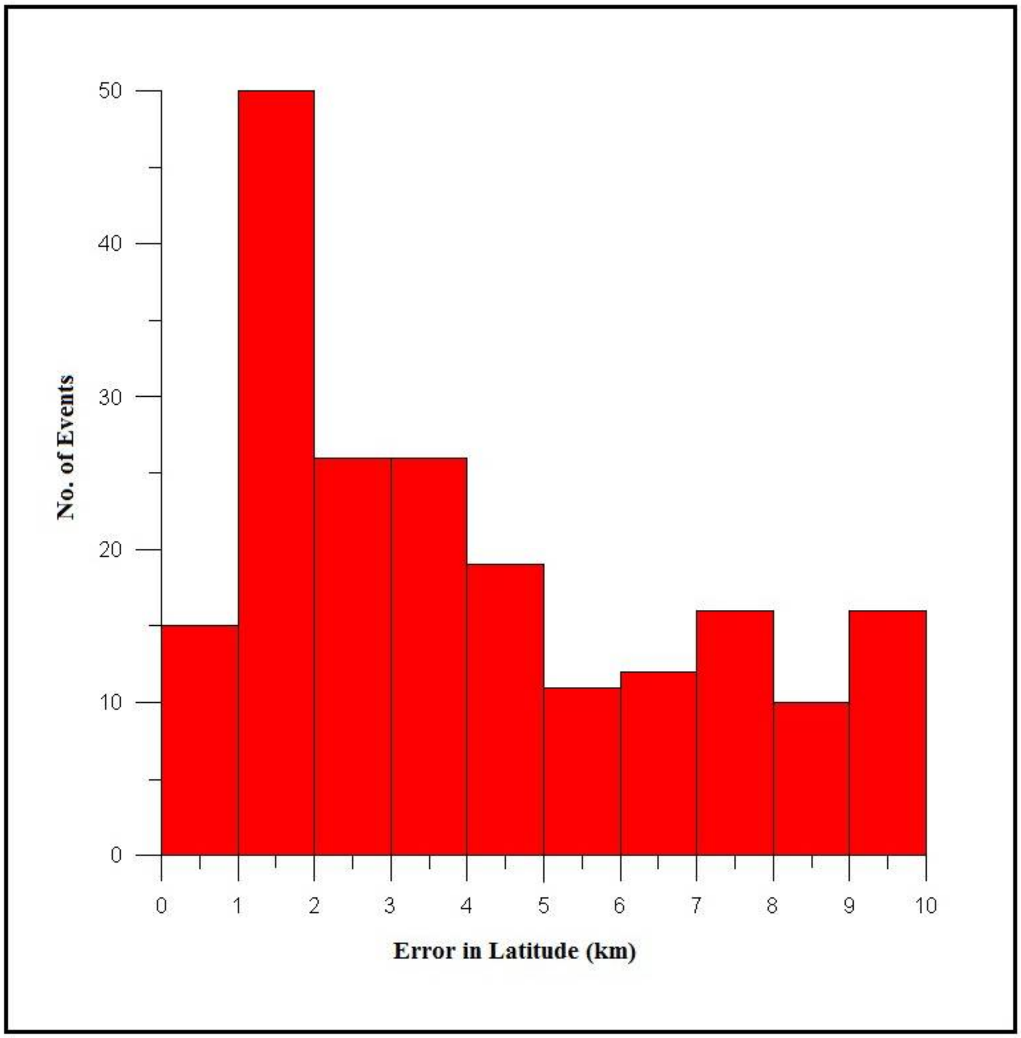


Figure 3.1: This Figure signifies the error in latitude plotted against the no. of earthquake events obtained with preliminary velocity model.

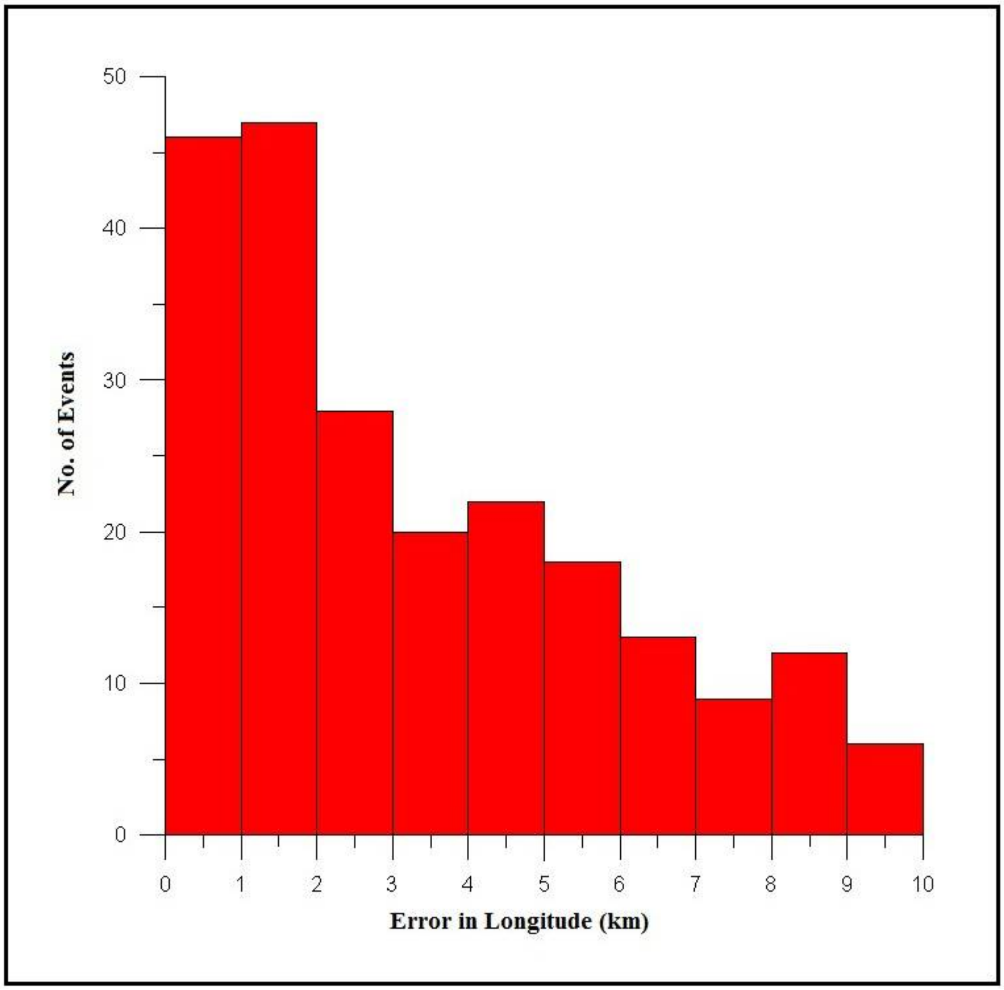


Figure 3.2: This Figure signifies the error in longitude plotted against the no. of earthquake events obtained with preliminary velocity model.

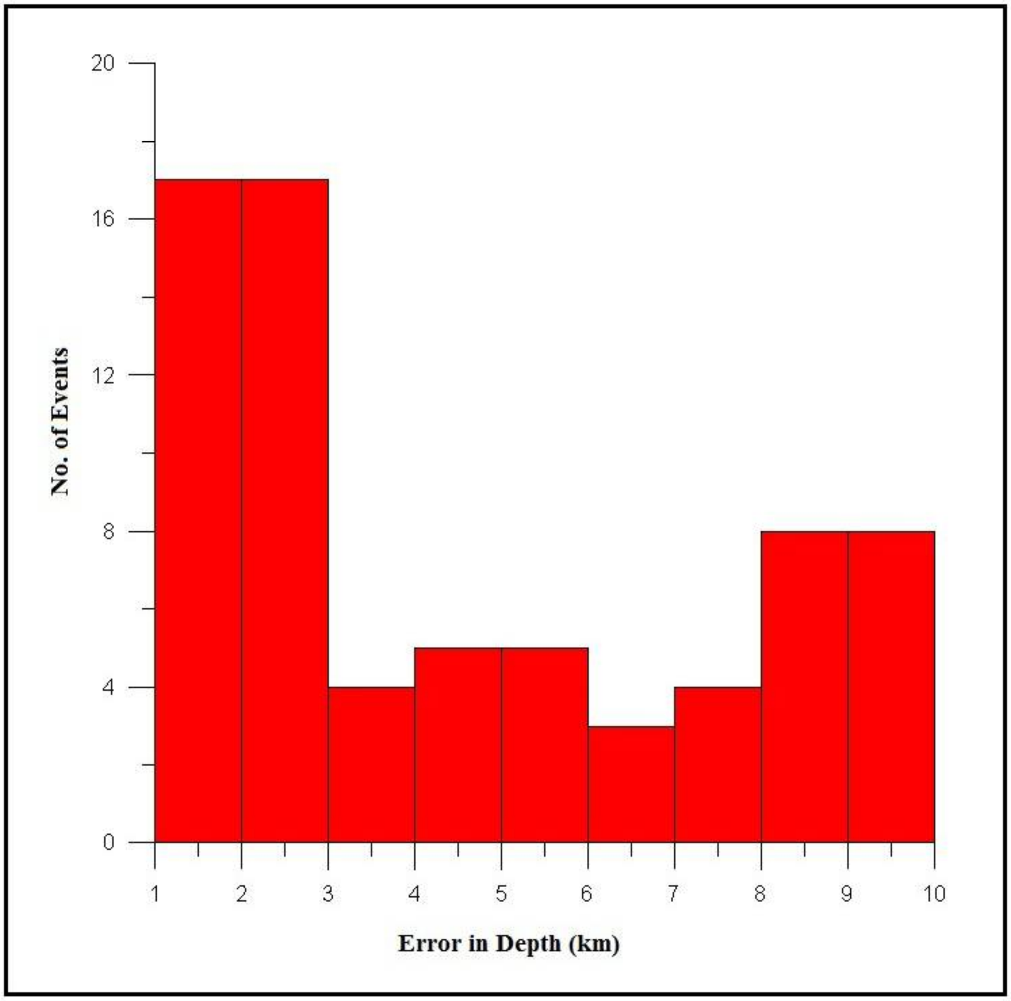


Figure 3.3: This Figure signifies the error in Depth plotted against the no. of earthquake events obtained with preliminary velocity model.

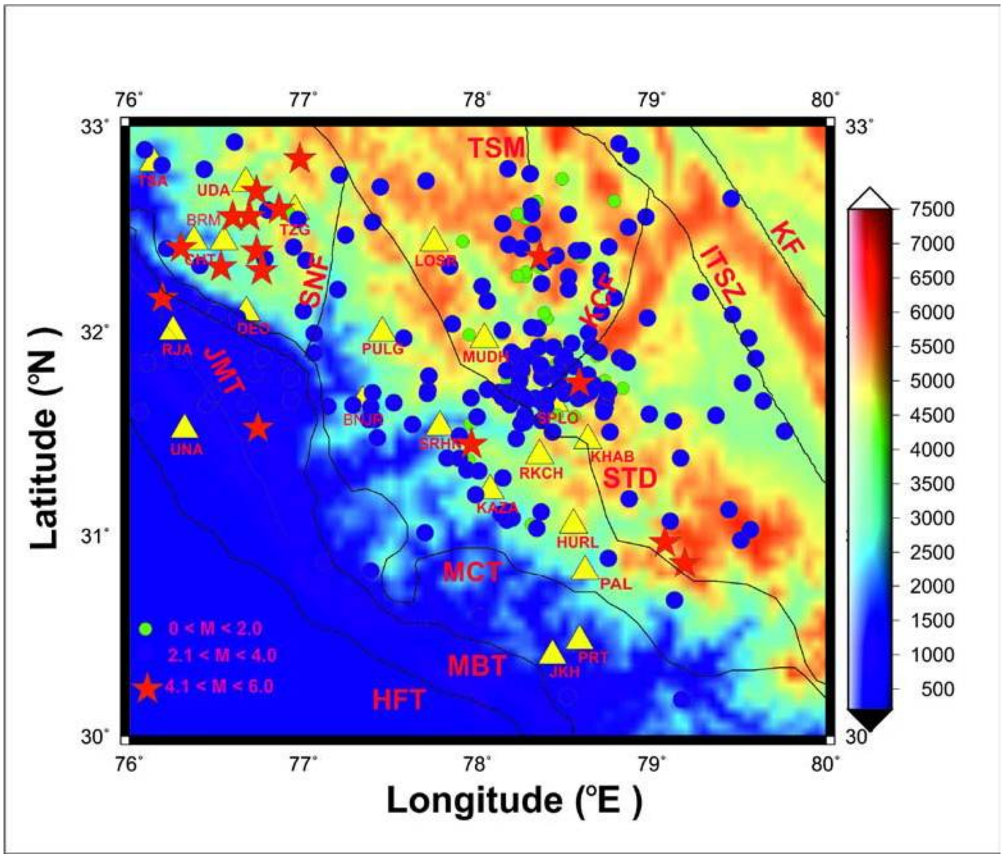


Figure 3.4: Seismicity plot of the NW Himalaya along with the major tectonic breaks such as HFT: Himalayan Thrust Fault; JMT: Jwalamukhi Thrust; MBT: Main Boundary Thrust; MCT: Main central Thrust; SNF: Sundarnager fault; STD: South Tibetan Detachment; KCF: Kaurik Chango fault; TSM: Tso-Morari fault; ITSZ: Indo-Tsangpo suture zone; KF: Karakoram fault. The yellow triangle specifies the seismic stations utilized in the study. The earthquake hypocenters are specified in the form of green solid circles, blue solid circles and ted solid stars based on its magnitude. The magnitude limit for each of the hypocenter is specified in the figure itself. The elevation colour scale given on the right side is expressed in meters.

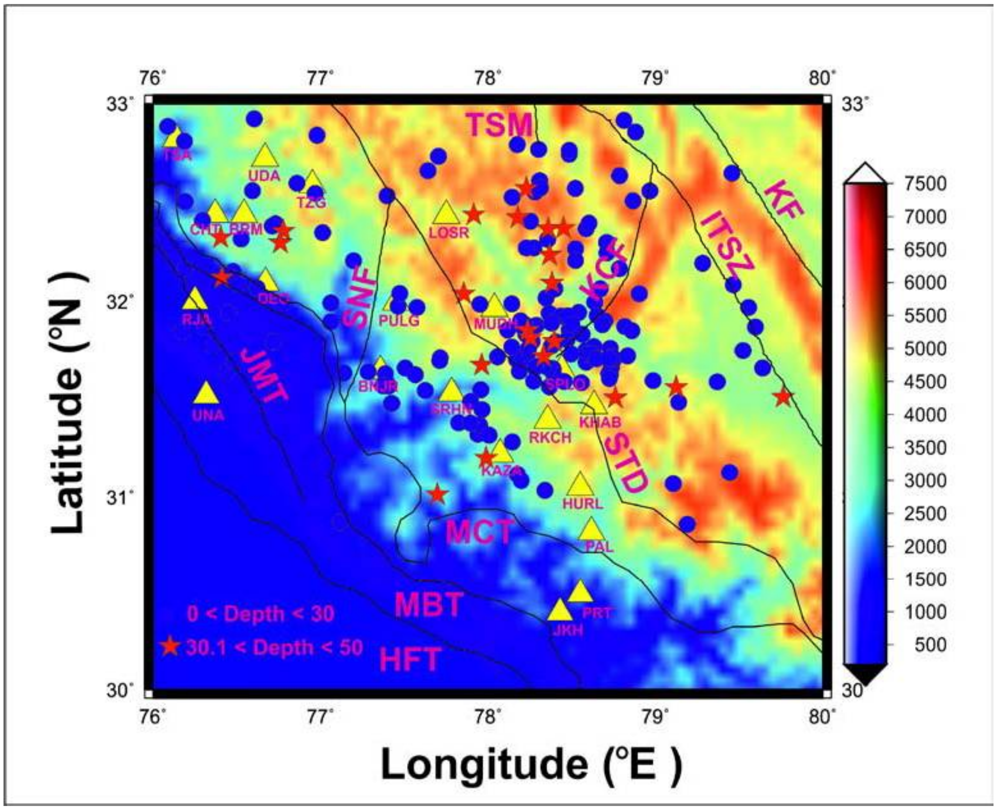


Figure 3.5: Seismicity plot of the NW Himalaya along with the major tectonic breaks such as HFT: Himalayan Thrust Fault; JMT: Jwalamukhi Thrust; MBT: Main Boundary Thrust; MCT: Main central Thrust; SNF: Sundarnager fault; STD: South Tibetan Detachment; KCF: Kaurik Chango fault; TSM: Tso-Morari fault; ITSZ: Indo-Tsangpo suture zone; KF: Karakoram fault. The yellow triangles specifies the seismic stations utilized in the study. The earthquake hypocenters are specified in the form of blue solid circles and ted solid stars based on its depth distribution. The depth limit for each of the hypocenter is specified in the figure itself. The elevation colour scale given on the right side is expressed in meters.

The initial locations of the hypocenters in the NW Himalaya show a distribution over an area of almost 500 km. The magnitude of these seismic events ranges from an M_L 1.0 to 5.0. The earthquakes are mainly more confined in the Higher and Tethys Himalaya segments of the western Himalayan sector. The depth distributions of most of the hypocenters are mostly within 30 km and a few hypocenters have a depth distribution of more than 30 km and less than 50 km. *Figure 3.4* and *Figure 3.5* shows seismicity plot of the NW Himalaya along with the major tectonic breaks plotted as the function of magnitude and depth

3.3. Calculation of minimum 1 D velocity model

The minimum 1 D velocity model for the NW Himalaya region is calculated utilizing the travel time inversion of recorded P and S phase at various seismic stations operated in the study area. The data that was recorded in the seismometer are nothing but contains the response or the information of the earth's internal structures. So before estimating an accurate 1 D velocity model these seismograms recorded in a raw SEED format are carefully studied. As mentioned above a total of 476 earthquake hypocenters with a minimum of 3 P and 3 S readings were recorded. Then after removing the high frequency noise from the data, these hypocenters are located and preliminary locations are shown above. But RMS residual error associated with the manual picking of the P and S arrival times is up to 0.87s and this high error associated with the earthquake hypocenters leads to a sparse distribution of epicentres. So to achieve a minimum 1 D velocity model in this study, out of a total 476 events, 125 best events with 452 P-phases and 937 S-phases and least square residual error below 0.40s are selected for inversion. The minimum 1 D velocity model with least square error misfit is derived by applying the inbuilt VELEST package within the Seisan software, (Kissling. E., 1995; Havskov and Ottemoller, 1999). Basically, VELEST is a FORTRAN77 based routine program that has been designed to derive 1-D velocity models for earthquake location procedures and as initial reference models for seismic tomography (Kissling, 1988; Kissling et al., 1994).

In this way, VELEST program works for estimating the minimum 1 D model and improve the epicentre locations. After deriving the minimum 1 D velocity model, the earthquake hypocentres are relocated with the optimized velocity model with an average RMS value of 0.03s. The obtained average error for preliminary location of these selected events for depth, latitude and longitude is ±3 km. Then the P and S wave travel time inversion for these selected 125 seismic events is used to derive an optimal 1 D velocity model and these events were also relocated by joint hypocentre determination (JHD) for more refined seismicity within the region.*Figure 3.6* shows the Seismic network deployed and operated by Wadia institute of Himalayan Geology, Dehradun (WIHG) along with the seismicity plot utilized for 1 D crustal velocity model estimation in Himachal Pradesh, NW Himalaya, India. *Figure 3.7* shows a comparison between the RMS values with respect to number of earthquakes obtained for the Hypocentres before applying the VELEST (red line) algorithm and after (blue line) applying it.

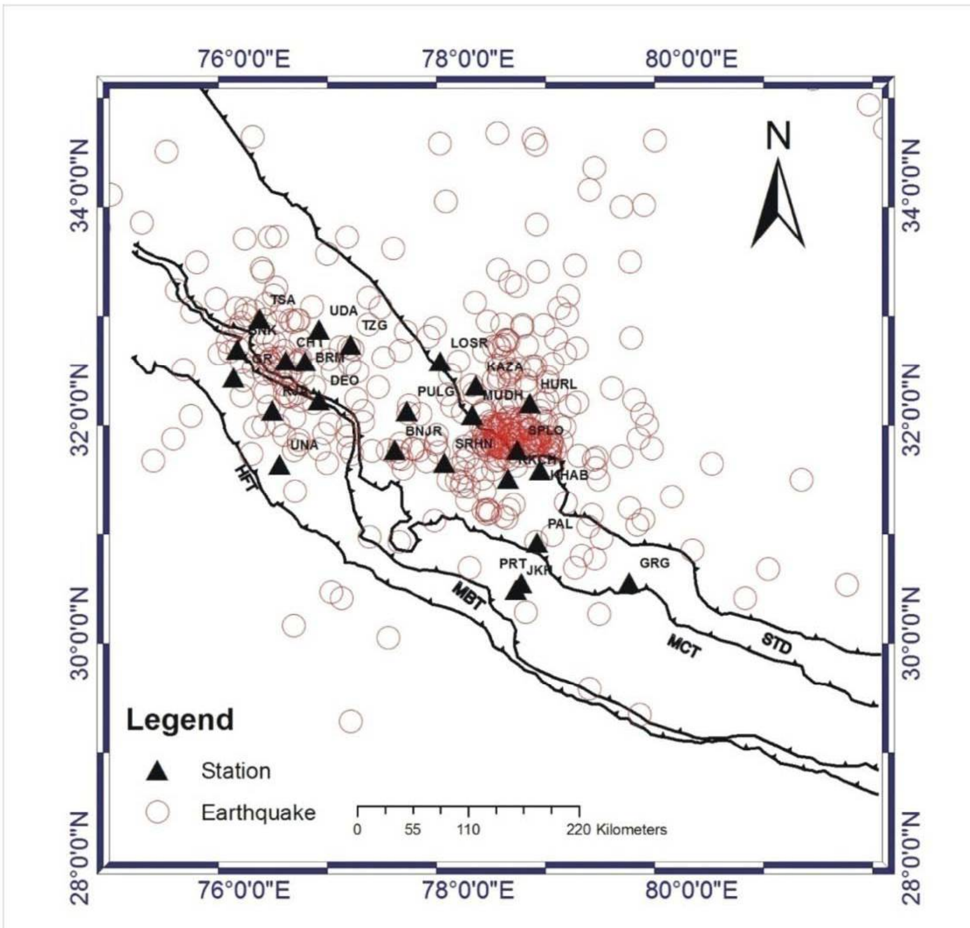


Figure 3.6: Shows the Seismic network deployed and operated by Wadia institute of Himalayan Geology, Dehradun (WIHG) along with the seismicity plot utilized for 1 D crustal velocity model estimation in Himachal Pradesh, NW Himalaya, India. The triangles indicate the seismic stations and the hollow red circles indicate the earthquake epicentres.

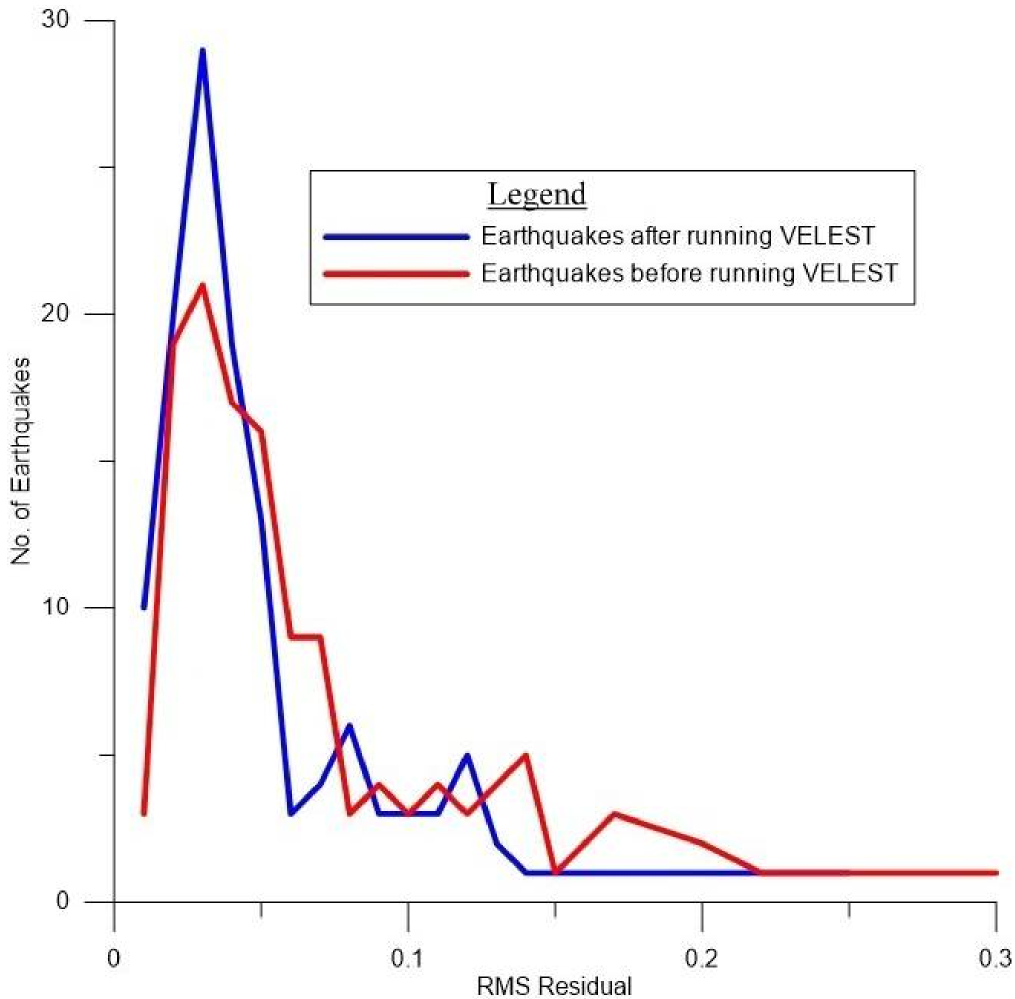


Figure 3.7: Shows a comparison between the RMS values with respect to number of earthquakes obtained for the Hypocentres before applying the VELEST (red line) algorithm and after (blue line) applying it. This shows a gradual decrease in minimum and maximum RMS residual values after VELEST is applied.

3.4. Optimal 1 D crustal velocity model

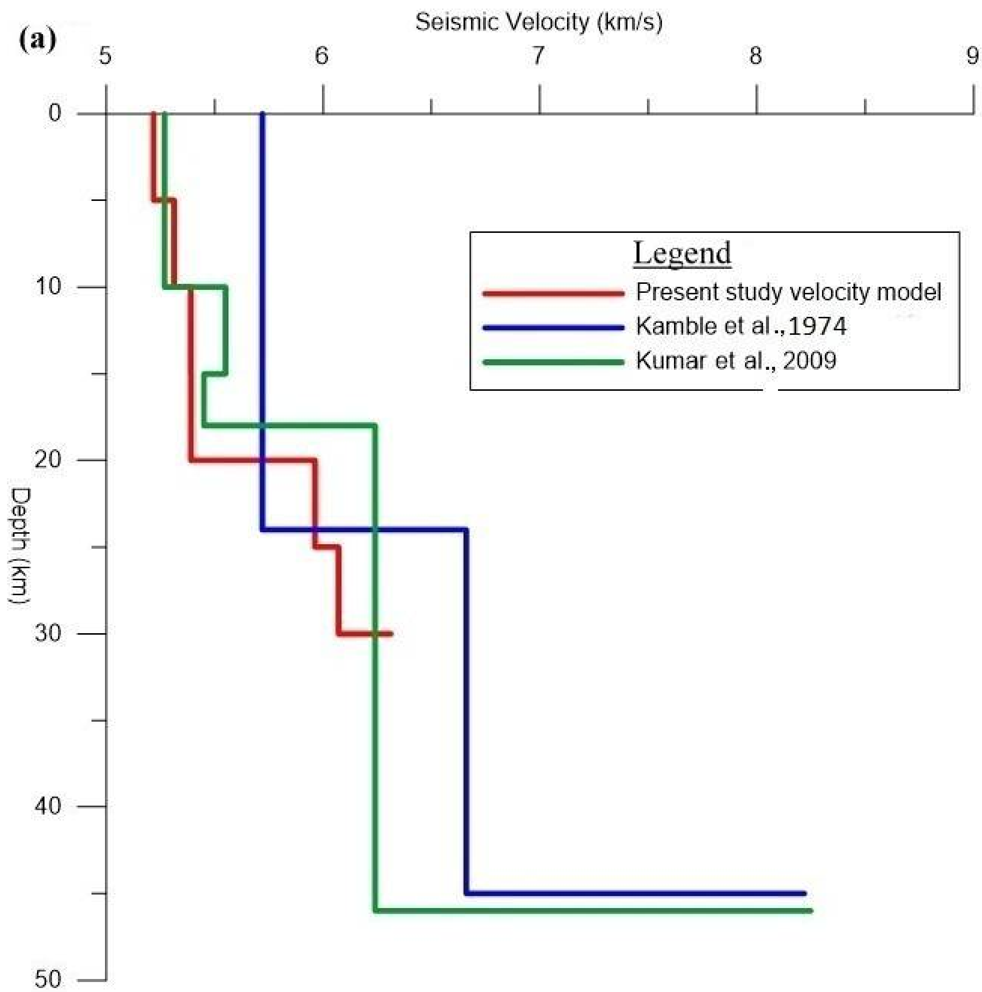
The optimal 1 D velocity model obtained utilizing the VELEST package (Kissling. E., 1995). This model has resulted through the simultaneous travel time inversion of the earthquake locations and the initial or preliminary velocity models provided by previous researchers in the study region. The model proposed was obtained with the application of travel time inversion technique and the best-fit model was obtained after getting a wide range of models tested with earthquake locations. The first inversion is carried out on the basis of the initial model of Kumar et al. (2009) for the NW Himalaya. The preliminary model has been changed in successive trials till it has obtained a smaller misfit. After five successful iterations, the RMS values became constant at lower than 0.03, resulting in the final result. The obtained RMS residual for arrival time of the events with the new velocity model showed a dramatic decrease of earlier maximum of 0.40 sec to 0.24 sec. i.e. the velocity model is highly accurate and cansignificantly explain the crustal structure variations of the study region. The estimated 1 D velocity model for the study region can be said to be composed of seven uniform layers with interfaces at depths of 0, 5, 10, 15, 20, 25 and 30 km and the estimated P-wave velocity of 5.219 km/s, 5.314 km/s, 5.391 km/s, 5.392 km/s, 5.964 km/s, 6.071 km/s, 6.073 km/s and S-wave velocity of 2.998 km/s, 3.015 km/s, 3.134 km/s, 3.135 km/s, 3.441 km/s, 3.482 km/s and 3.647 km/s, respectively. The observed P and S-waves station correction ranges from -0.88 to 1.50 and -0.58 to 3.59 sec, respectively.

This low variation in station residuals indicates small lateral velocity changes that confirm the accuracy and stability of the proposed 1 D velocity model. Using the new derived 1 D velocity model the earthquake epicentres are relocated and it shows a shallow seismic activity in the region at a depth of around < 30 km that clearly describes the ongoing convergence of the India-Eurasia plates in the study region. The final 1 D velocity model is shown below in *Table 3.2. Figure 3.8* (a) and (b) shows the minimum 1 D velocity model of seven layers (red line) obtained with VELEST from travel time inversion of P and S-wave arrival times and its comparison plot with the preliminary velocity of Kumar et.al; 2009 (green line) and Kamble et al., 1974 (blue line).

Depth (Km)	P wave Velocity (Km/s)	S wave Velocity (Km/s)
0	5.219	2.998
5	5.314	3.015
10	5.391	3.134
15	5.392	3.135
20	5.964	3.441
25	6.071	3.482
30	6.313	3.647

Table 3.2: Final velocity model obtained through VELEST.

(a)



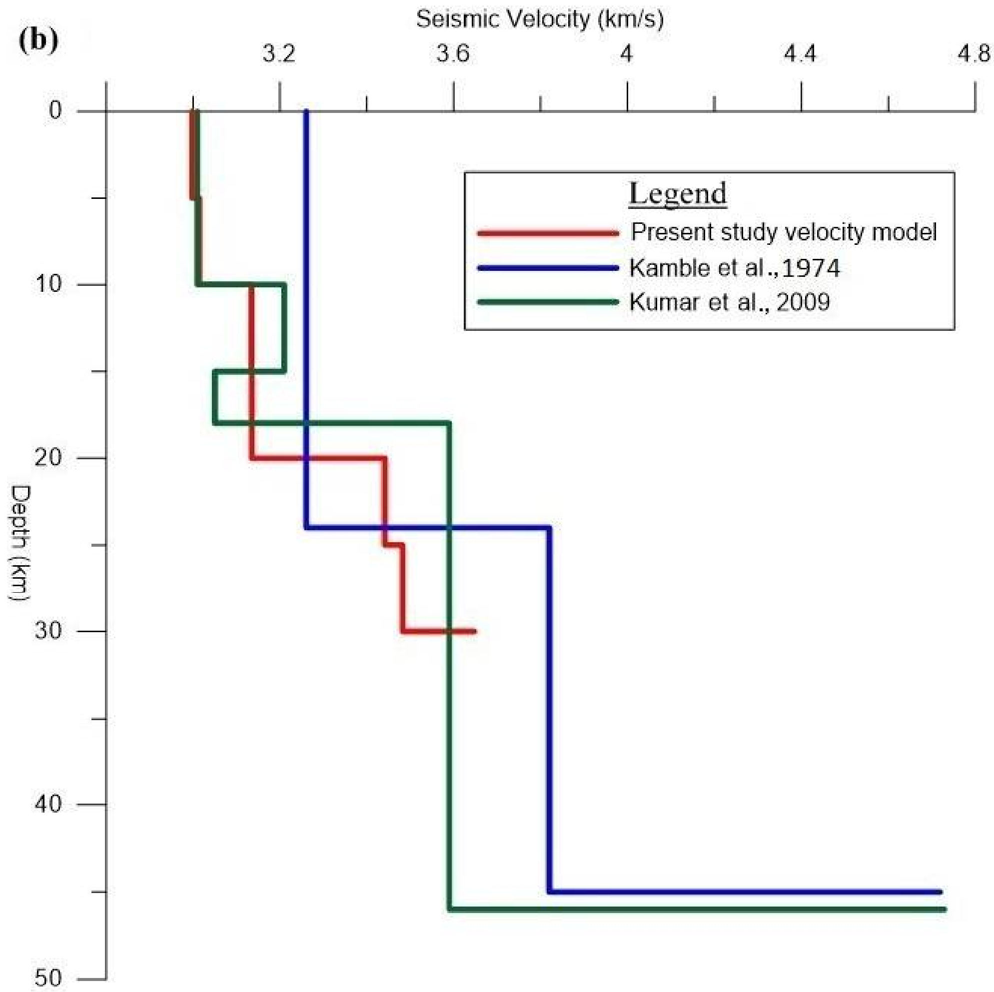
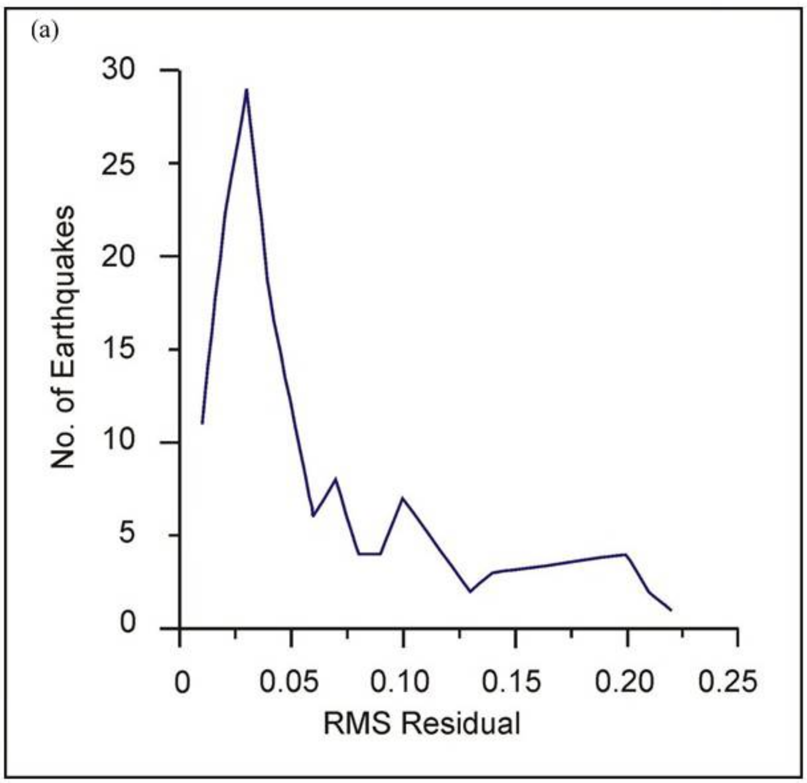


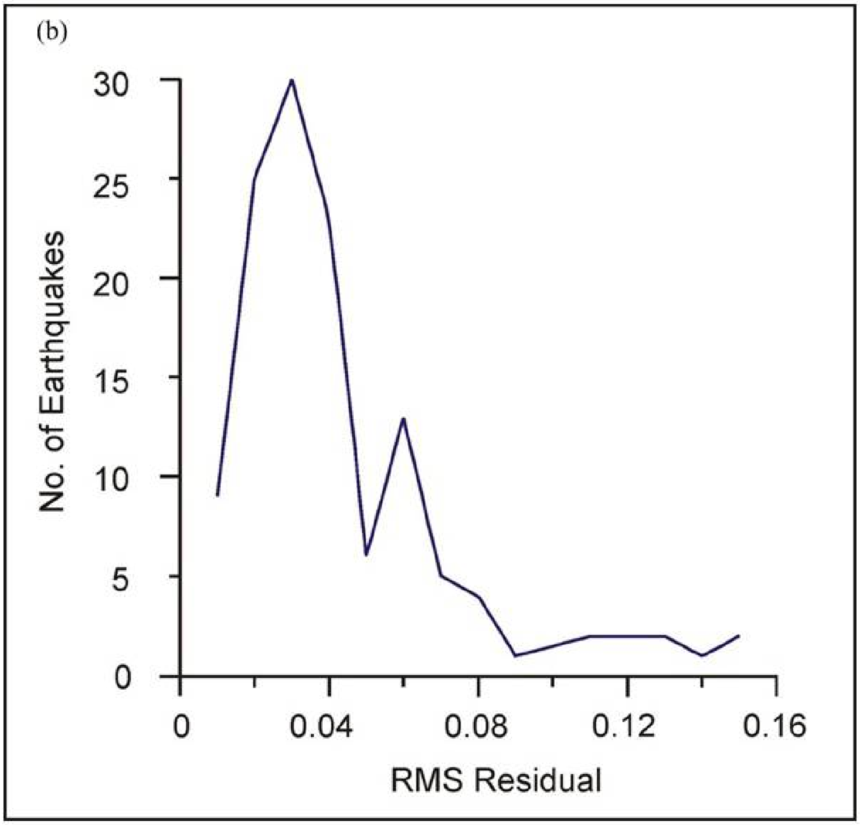
Figure 3.8: (a) and (b) shows the minimum 1 D velocity model of seven layers (red line) obtained with VELEST from travel time inversion of P and S-wave arrival times and its comparison plot with the preliminary velocity of Kumar et.al; 2009 (green line) and Kamble et al., 1974 (blue line).

3.5. Stability Test for the derived minimum 1 D crustal velocity model

To check the stability of the obtained model the initial model are broken at 3.5 and 4.0 km intervals with certain assumed velocity. While inverting, these two models converge and match with same least square residual of earlier obtained value. The starting velocities for both the iteration models were same with the velocity of Kumar et al. (2009). These velocities are varied in subsequent runs and reduce the RMS misfits. By conducting this test, there is a negligible variance in the velocity value at subsequent layers.

Finally, these two models are combined to obtain our final model. This final velocity model shows a variation in the velocity of P and S at subsequent layers is the optimal velocity model. The used events are highly concentrated up to 30 km depth in this study. Therefore, this velocity model has been proposed mainly for the upper crustal layer. Final velocity model occurs due to the presence of maximum number of events having lowest RMS which shows that the obtained model is highly stable and can be used extensively for earthquake hypocentre location. *Figure 3.9 (a), (b) and (c)* shows the number of earthquake hypocentre and its variation with the RMS residual (blue line) for the two iteration velocity models at an interval of 3.5 Km, 4.0 Km and for the final obtained model at an interval of 5.0 Km.




(b)
30
25
20
15
10
5
0
No. of Earthquakes
0
0.04
0.08
0.12
0.16
RMS Residual

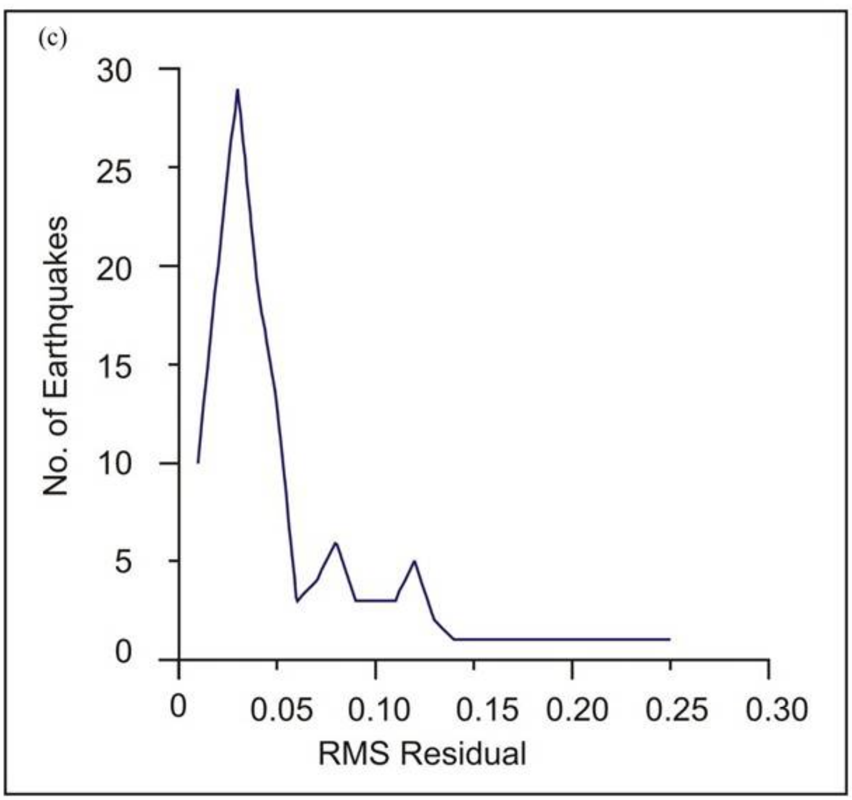

(c)
30
25
20
15
10
5
0
No. of Earthquakes
0
0.05
0.10
0.15
0.20
0.25
0.30
RMS Residual

Figure 3.9: (a), (b) and (c) shows the number of earthquake hypocentre and its variation with the RMS residual (blue line) for the two iteration velocity models at an interval of 3.5 Km, 4.0 Km and for the final obtained model at an interval of 5.0 Km.

3.6. Seismicity study and JHD

The obtained least square residual 1 D velocity model is used for computing the JHD (Joint Hypocenter determination) and station corrections by the method of VELEST algorithm. The station correction is defined as a parameter for velocity deviation from optimal 1 D velocity model. Thus, station corrections for 14 stations out of 22 stations in this network are calculated and given in tabular form in *Table 3.3*. The stations lying in the borderline are ignored for calculation of station corrections. Calculated station corrections are then plotted in the form of contours with different values. These station corrections are computed taking into consideration about the PULG station as the reference station since it lies almost at the centre of the network. Positive variation in station corrections for P waves from -0.8856 at DEO to 1.5044 at LGR and from -0.5807 at LOSR to 3.5929 at LGR for S waves are obtained. This variations resembles to the 3 D nature of the velocity in the study region. Positive variations are observed where the actual velocity is less than the predicted one and vice versa. The negative value of the station correction deciphers the possibility of a deeper velocity variation. This marks the presence of overriding wedge which occurs due to increase in thickness of the crust. *Figure 3.10 (a) and Figure 3.10 (b)* completely depict the contour map of P and S delay at various stations lying within the array by considering PULG as the reference station.

Station Name	Station code	Latitude (°N)	Longitude (°E)	Elevation (m)	P- wave delay	S- wave delay
SARHAN	SRHN	31.533	77.792	1983	-0.050	-0.282
RACKCHHAM	RKCH	31.393	78.356	3129	-0.070	-0.337
SPILO	SPLO	31.650	78.441	2353	0.012	-0.216
KHAB	KHAB	31.469	78.644	2715	-0.031	-0.301
HURLING	HURL	32.062	78.551	3190	-0.075	-0.397
MUDH	MUDH	31.963	78.038	3811	-0.104	-0.525
KAZA	KAZA	32.219	78.072	3701	-0.121	-0.519
LOSSER	LOSR	32.435	77.750	4141	-0.170	-0.581
PULGA	PULG	31.995	77.452	2274	-0.100	-0.495
BANZAR	BNJR	31.645	77.348	1369	0.000	-0.250
DEOL	DEO	32.093	76.672	700	-0.886	-0.283
CHHATRARI	CHT	32.440	76.372	1800	-0.205	0.844
LAGORE	LGR	32.292	75.907	800	1.504	3.592
UNA	UNA	31.520	76.318	550	0.766	2.551

Table 3.3: Seismic stations details with station corrections.

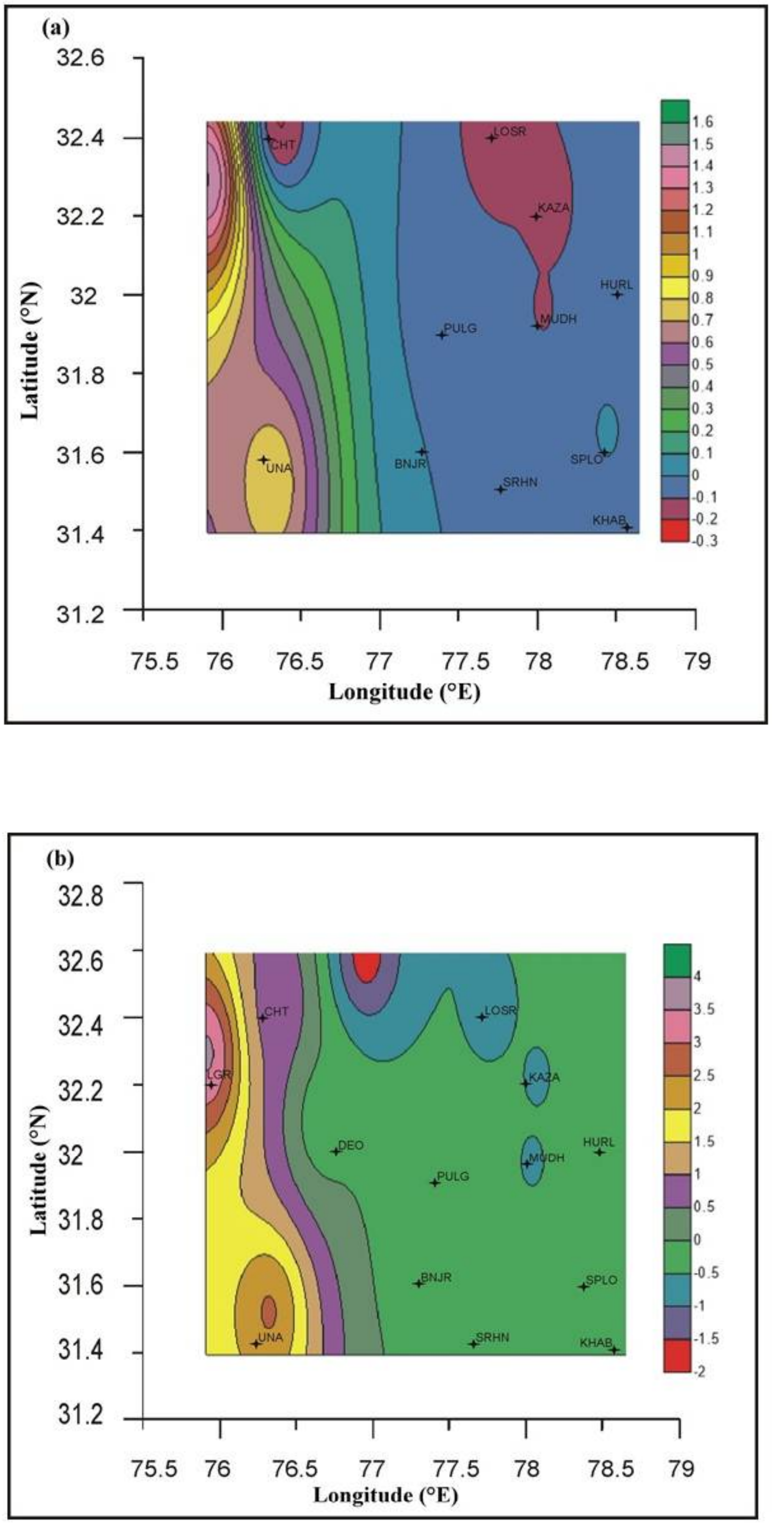
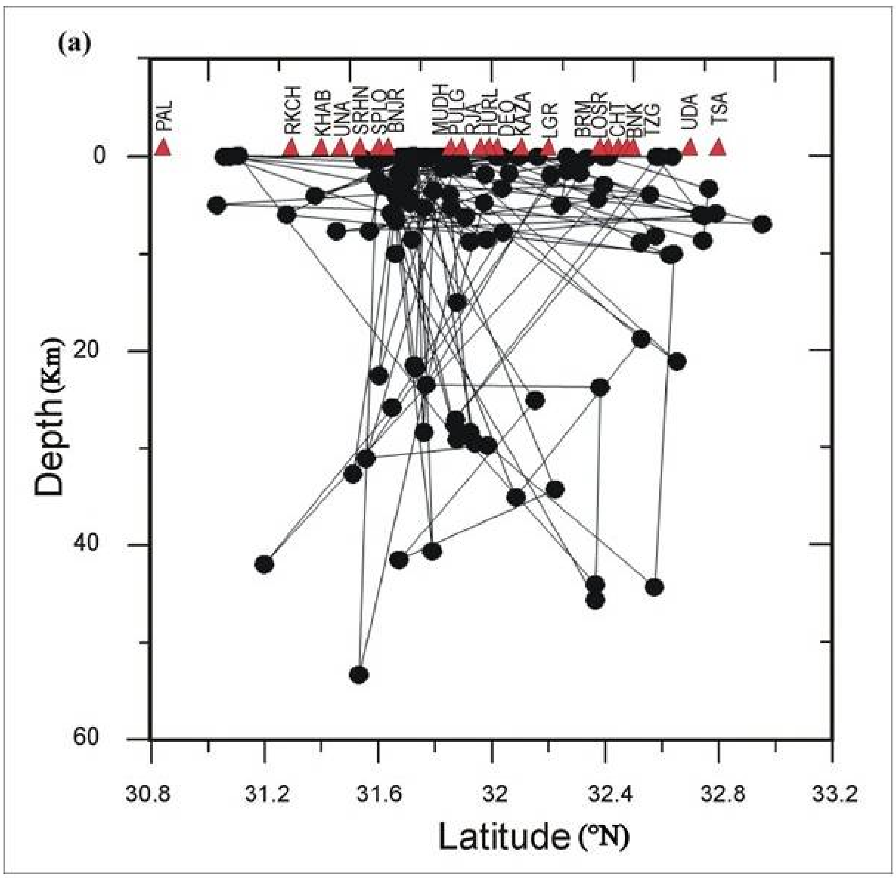


Figure 3.10: (a) and (b) describes the variation of station corrections with respect to P delay and S delay by taking PULG station as the reference station. Solid black star indicates seismic stations.

3.7. JHD and earthquake hypocenter depth in NW Himalaya

The JHD computed by including the station corrections resulted in the relocation of hypocentres with higher precision and accuracy. A total of 125 seismic events are considered for travel time inversion, the overall least square residual error reduced from a minimum of 0.03s to 0.01s and the errors significantly related with Hypocentre determination reduced to ± 1 km. *Figures 3.11 (a) and (b)* shows the spatial distribution of seismic events within an array after taking station corrections into account. The depth distribution of a large number of earthquake hypocentres lies between the range of 0 to 10 km range, and a maximum up to 50 km which implies the presence of maximum shallow seismicity in the region.



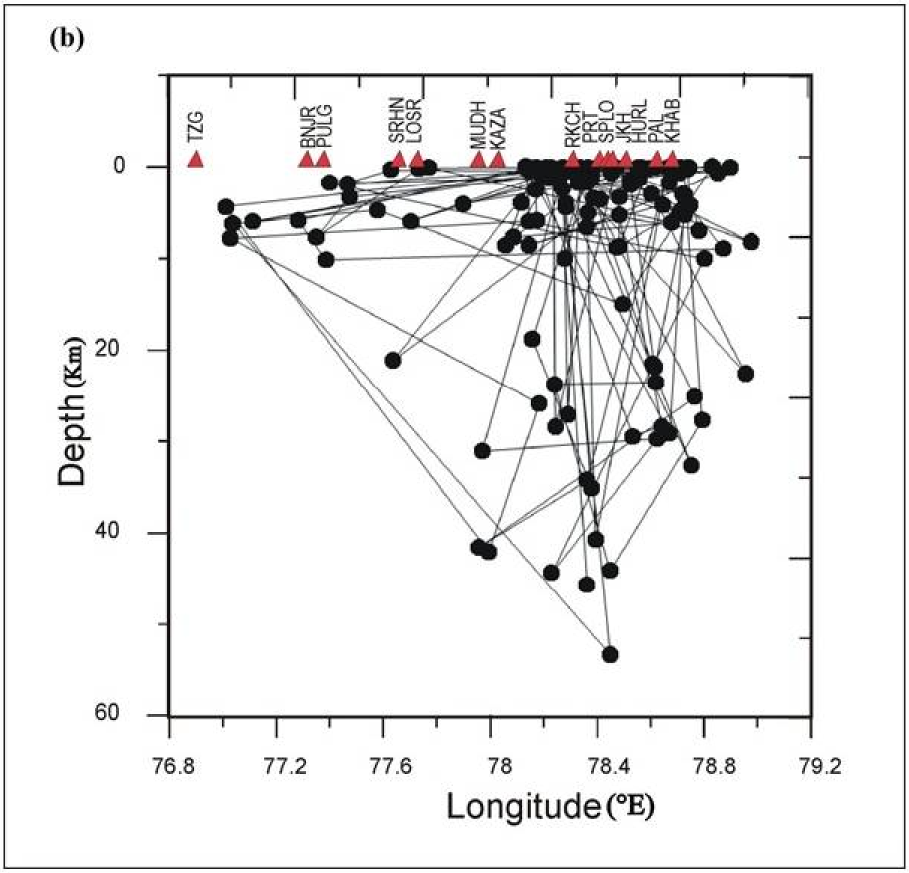


Figure 3.11: (a) and (b) shows the Ray path coverage of the seismic events to reach different stations with respect to latitude and longitude. Solid black circles indicate earthquake hypocenters and solid red triangles shows recording stations.

In general the events are more clustered in the area lying between latitude 31.0 °N to 32.8 °N and 76.8 °E to 78.8 °E, which shows high seismotectonic activity in the area due to the strain accumulation caused by dipping of Indian plate under the Eurasian plate. It is also inferred from earlier studies that high concentration of seismic events in this region are due to compressive environment that signifies thrust mechanism of fault orientation which completely agrees with the tectonics of the region.

The shifting of the earthquake epicentres located with the help of new 1 D velocity model was observed and the data was relocated with the help of the JHD technique.