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One-Dimensional Velocity Model of Sikkim Himalayan Region

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Abstract

A preliminary one-dimensional (1D) velocity model for Sikkim region has been developed using P- and S- wave travel-time data. The work has been performed in Seisan by taking 276 local earthquake events. Out of 276 events 76 best events has been selected for inversion. Most of the earthquake events are concentrated in depth range 10 to 40 km. The 1D velocity model obtained for the study region has six uniform layers with interfaces at depths of 0, 10, 20, 30, 40, and 50 km with P wave velocity of 5.23, 5.35, 5.85, 6.59, 7.49, and 8.03 km/sec and S-wave velocity of 3.03, 3.08, 3.38, 3.37, 4.19, 4.61 km/sec, respectively. Mainly the events are more clustered in the area lying between latitude 27.2°N to 27.8°N and 88°E to 88.6°E, which shows high seismotectonic activity in the area due to the strain accumulation caused by dipping of Indian plate under the Eurasian plate. From velocity model it can be observed that largest velocity occurs at a depth of 40 km which shows the major lithological variation at this depth. The approximate thickness of the upper crust (granitic layer) is around 30km which can be noticed from the velocity data. The analysis depicts that the layers with thickness range 10-20 km and P wave velocity 5.35 km/s and thickness range 30-40 km with P wave velocity 6.59 km/*s* contains 19 hypocenter within them. This study will play a vital role in the assessment of regional tectonics, earthquake hazards and will provide evidence of the evolutionary model of the Sikkim Himalayan region.

Keywords: Velocity model, Sikkim Himalayan region, Regional tectonic, Earthquake hazards, Evolutionary model

1. Introduction

Seismic velocity is an important parameter in the assessment of regional tectonics and earthquake hazards and provides evidence of the evolutionary model of the Himalaya. Earlier studies show that the Himalayan arc system is prone to intense seismicity due to collision of the Indian and Eurasian plates at the northern boundary of India. There is also evidence 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; Acharyya, 1992). Collision between India and Eurasia has increased sufficient amount of strain accumulation in the northern part of the Indian plate, and the pre-accumulated strain is released along the entire Himalayan arc system. The collection of small-scale earthquake data through temporary networks confirms such concentration of seismicity and wide variation in earthquake focal mechanisms in different parts of the Himalayan region (Pandey et al., 1995; Kayal et al., 2003; Bollinger et al., 2004). Himalayan arc comprises of regions of well-defined high/low seismicity, seismic gaps and tectonically stable zones (Khattri and Tyagi, 1983; Gaur et al., 1985; Srivastava et al., 1986; Khattri et al., 1989; Kayal, 2001; Kayal et al., 2003). It consists of five major faults, which are named as Indus-Tsangpo Suture Zone (ITSZ), South Tibetan Detachment (STD), MCT, MBT and Himalayan Frontal Thrust (HFT) of NW-SE trend. These major thrust faults and their associated fault systems are the center of high magnitude of the past earthquakes like the Kangra earthquake of 1905 with magnitude Ml≥7.8 and Kinnaur earthquake of 1975 with Ml≥6.8 in Himachal Pradesh, India.

Due to the absence of an efficient local velocity model along with poor azimuthal coverage of earlier seismic stations, it is quite difficult to understand the crustal structure and clustered seismicity patterns which further inhibit understanding the associated tectonics of the area. Hence, knowledge of optimum velocity structure of a region can fulfill many requirements especially for the crustal studies for the region. Therefore, with the objective of understating the regional tectonics of Sikkim Himalayan region, in this research, it is devised to perform the crustal seismic studies for the Sikkim Himalayan Region.

2. Tectonics and Geology of Study Area

Sikkim is a very small hilly state in the Eastern Himalayas, extending approximately 114km from north to south and 64km from east to west, surrounded by vast stretches of Tibetan Plateau in the North, Chumbi Valley of Tibet and the kingdom of Bhutan in the east, Darjeeling district of West Bengal in the south and the Nepal in the west (Mallet, 1875). The state being a part of inner ranges of the mountains of Himalayas has no open valley and no plains but carried elevations ranging from 300 to 8583 meters above means sea level consisting of lower hill, middle and higher hills, alpine zones and snow bound land, the highest elevation 8583 meters (Fig. 2)

This region comprises the lesser active part of the 2,500 km stretch of the active Himalayan belt. The major tectonic features traversing the Sikkim Himalaya are the well-defined main boundary thrust (MBT) and the circular overturned main central thrust (MCT) in the north (Raju et al., 2007). Seismic activity in the Sikkim Himalaya is confined between the MBT and MCT. The seismicity of the Sikkim region is shown in Fig. 1. The most significant earthquake that occurred in its neighborhood is the 1934 Bihar–Nepal border earthquake of magnitude 8.3 Mw that caused high damage in Sikkim Himalaya (Dunn et al., 1939). Earlier, an earthquake of magnitude 8.0 Mw was reported in 1833 (US Geological Survey Catalogue). More recently, an earthquake of magnitude 6.6 Mw was reported in Gangtok in 1988 (Raju et al., 2007).

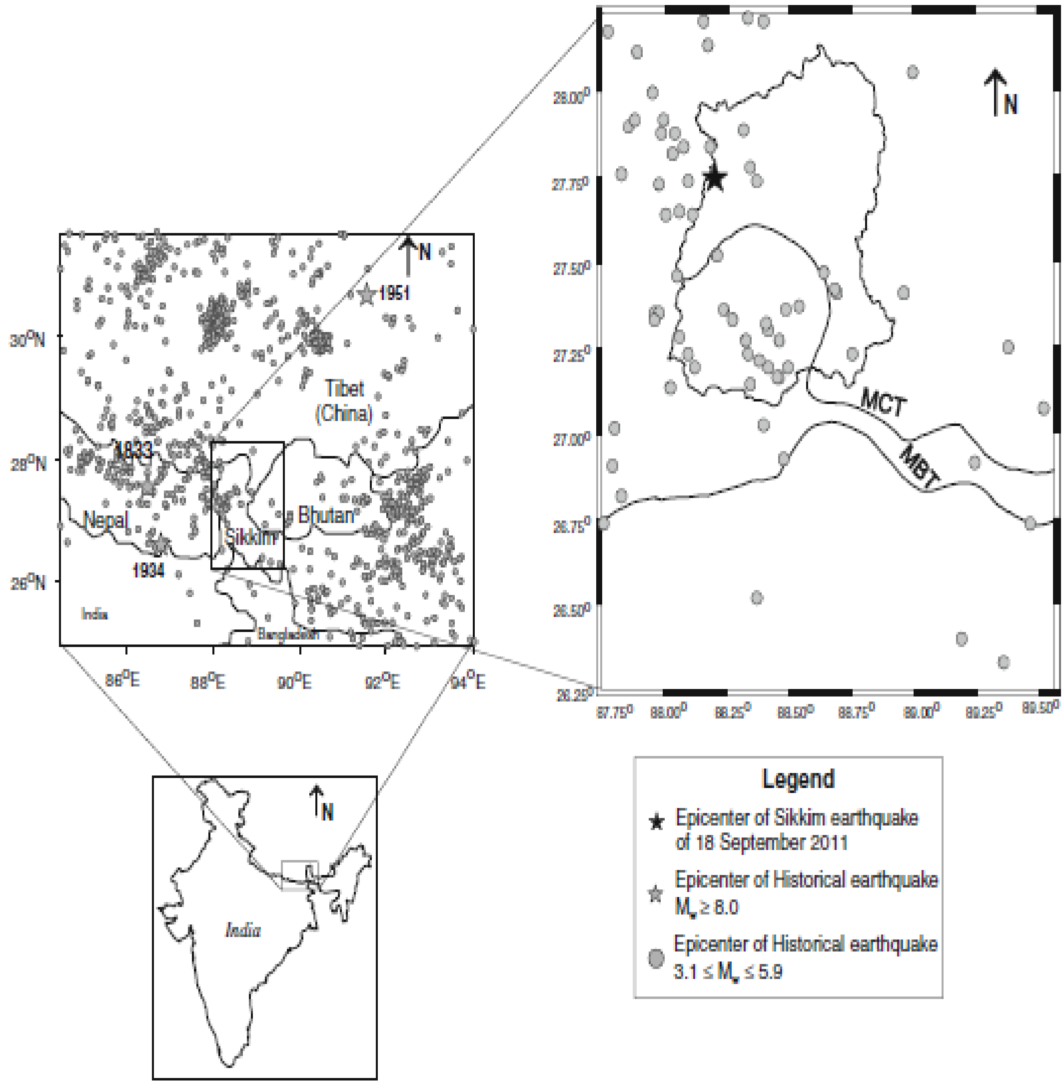

Figure 1. Seismicity map of the eastern Himalayan region indicating seismicity around the Sikkim and the tectonic of the region. Rectangle box shows study area (*modified after* Joshi et al., 2014).

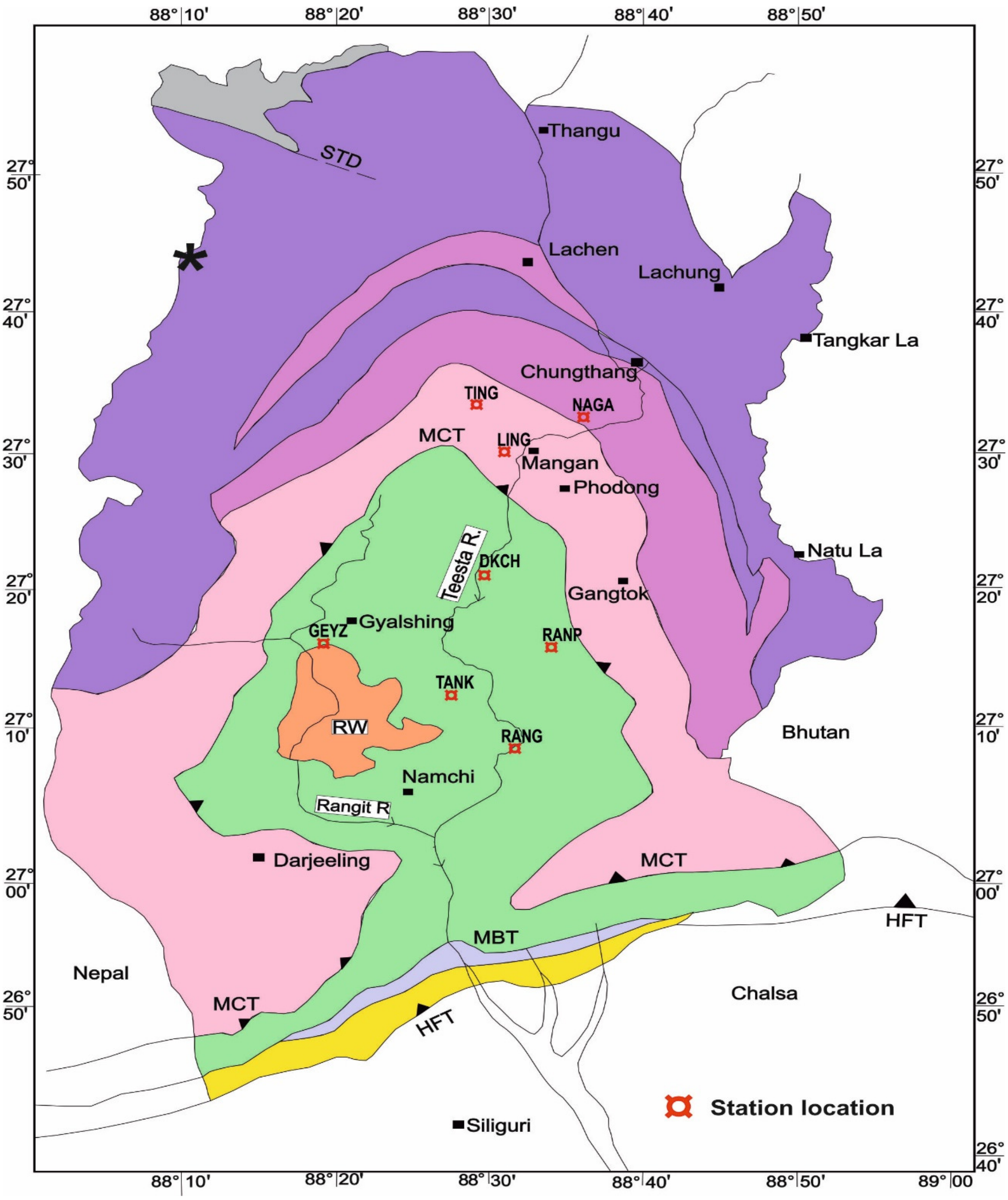

Figure 2. The Seismic network deployed and operated by Wadia institute of Himalayan Geology.

The present tectonic framework of the Himalaya and adjacent orogenic belts is the result of tectonic collage of autochthonous to allochthonous linear crustal blocks, geologically unrelated to each other and sutured together during different periods of its evolutionary history. Such unrelated crustal blocks of regional extent having their distinctive tectono-stratigraphic characters, which are generally fault bounded, are being termed "terrain" following Howell et al. (1985).

The Himalaya and adjacent parts of the Trans- Himalayan regions are generally subdivided into the following morpho-tectonic units from north to south.

Karakoram/Changtang Belt
—Shyok (SS)/Bangong-Nujian (BNS) Suture Zone —
Kohistan/Ladakh/Lhasa Terrane
—Indus Tsangpo Suture Zone (ITS)—
Tethyan Zone
South Tibetian Detachment System (STDS)
Higher Himalayan Zone

—Main Central Thrust (MCT)—
Lesser Himalayan Zone
—Main Boundary Thrust (MBT)—
Sub-Himalayan (Foothill) Zone
—Main Frontal Thrust (MFT)—
Indus-Ganga-Brahmaputra foreland basins

These morpho-tectonic units also represent distinctive tectono-stratigraphic terrains, bounded by major thrusts or sutures and constitute the main tectonic framework of the Himalaya and adjacent regions. The Himalayan region comprising of Higher, Lesser and Sub Himalaya (Foothill) is bounded by the Indus-Tsangpo Suture (ITS) in the north and the Main Frontal Thrust (MFT) in the south. A substantial part of the Himalayan region constitutes recently elevated Indian platform (Wadia, 1966) and the main Himalayan region up to the Indus-Tsangpo Suture is represented by the reactivated northern part of the Indian shield (Gansser, 1964 and1981).

3. Data Used and Methodology

3.1 Description of Network:

In the Sikkim region, a local seismic network consisting of 8 broadband seismic stations were deployed by WIHG, Dehradun from 2011 onward around the source region of Sikkim earthquake of 2011 of Mw≥6.9 in a campaign mode. These stations were generally deployed to understand the Seismotectonics or the tectonics of the Sikkim Himalaya. The station information's used in the network along with the station corrections are completely summarized in Table 1.

Table 1. Station details with elevation

S. No.	Station	Code	Latitude(^{0}N)	Longitude(^{0}E)	Elevation(m)
(1)	Dikchu	DKCH	27.368	88.49	1078
(2)	Lingdong	LING	27.503	88.521	982
(3)	Nagarmote	NAGA	27.529	88.604	1380
(4)	Rangpo	RANG	27.184	88.529	542
(5)	Ranipool	RANP	27.293	88.584	926
(6)	Tingvong	TING	27.527	88.47	1480
(7)	Tanak	TANK	27.242	88.442	953
(8)	Geyzing	GEYZ	27.197	88.189	1900

Figure 2 illustrates the WIHG Stations deployed in the Sikkim Himalaya by Wadia Institute of Himalayan Geology, Dehradun. Study area shows major fault system with station locations. Most of the seismic stations are concentrated within the circular turn of MCT. Map also shows the major river flowing in the area.

3.2 About the Program Used: SEISAN (v 10.1)

The SEISAN seismic analysis system is a complete set of programs and a simple database for analyzing earthquakes from analog and digital data. With SEISAN it is possible using local and global earthquakes to enter phase readings manually or pick them with a cursor, locate events, edit events, determine spectral parameters, seismic moment, azimuth of arrival from 3-component stations and plot epicenters. The system consists of a set of programs tied to the same database. Using the search programs it is possible to use different criteria to search the database for particular events and work with this subset without extracting the events. Most of the programs can operate both in a conventional way (using a single file with many events), or in a database manner. Additionally, SEISAN contains some integrated research type programs like coda Q, synthetic modeling and a complete system for seismic hazard calculation.

The data is organized in a database like structure using the file system. The smallest basic unit is a file (the S-file) containing original phase readings (arrival times, amplitude, period, azimuth, and apparent velocity) for one event. The name of that file is also the event ID, which is the key to all information about the event in the database. Although the database in reality only consists of a large number of sub-directories and files (all of which the user has access to), the intention is that by using the surrounding software, the user should rarely need to access the files directly, but rather do all work from the user's own directory.

The programs are mostly written in Fortran, a few in C and almost all source codes is given, so the user should be able to fix bugs and make modifications. The programs have been compiled and linked with system compilers and linkers on SUN, GNU compiler on Linux Windows and MaxOSX. SEISAN runs under Sun Solaris, Linux, MacOSX, and Windows. The SEISAN system is built of programs made by many different individuals time to time. SEISAN is freely available for all non-commercial use.

The system has two basic modes of operation. The first is to work interactively with the database. That means jumping around from event to event, plotting, interactive phase picking, locating, deleting, typing, editing or appending events (S-files). This mode is invoked with the command EEV, which uses several programs, controlled by a driver program and is intended for testing and editing of single events. Once the input data seems OK, the second mode of operation can be used.

3.3 Data Processing

All local events having clear P and S phases are extracted from the raw seed data set of 2 years with the help of the Seisan software (Havskov and Ottemoller, 1999) and filtered with Butterworth filter of frequency range 1–5 Hz. After removing the low- and high-frequency noise from the data, 275 local events having a magnitude range from 1.0 to 6.0 (Ml) were located. To achieve a best minimal error in the location of the hypocenters out of a total of 275 events, 76 best events with least square residual error below 1.20 s were selected for inversion. This criterion was set to obtain a minimum RMS misfit because there was a huge error associated with the hypocenter location beyond this value that can lead to systematic biases in the earthquake locations (Parija et al., 2015). Residual error below 1.20s is used for selecting the best seismic events which is further used for travel time inversion. The minimum 1D velocity model with least square error misfit is derived by applying the inbuilt VELEST package (Kissling, 1995).

Inside the Seisan software (Havskov and Ottemoller, 1999) Basically, VELEST is a FORTRAN77-based routine program that has been designed to derive 1D velocity models for earthquake location procedures and as initial reference models for seismic tomography (Kissling, 1988; Kissling et al., 1994, Kissling 1995). This program was originally written by W.L. Ellsworth and S. Roecker for seismic tomography studies in 1976 under the program name HYPO2D (Ellsworth 1977; Roecker, 1981). VELEST has been again modified by R. Nowack and implemented in the layered-model ray tracer by Thurber (1981).

Table 2. Station details with correction

S. No.	Station	Code	Latitude	Longitude	Elevation(m)	P delay	S delay
(2)	Lingdong	LING	27.3018N	88.3126E	982	0.0589	-0.2066
(3)	Rangpo	RANG	27.1104N	88.3174E	542	-0.063	-0.8569
(4)	Nagarmote	NAGA	27.3246N	88.3744E	1380	0.1037	-0.2013
(5)	Tingvong	TING	27.3324N	88.2868E	1480	-0.2255	-0.0429
(6)	Dikchu	DKCH	27.2252N	88.2940E	1078	-0.3509	-0.422
(7)	Geyzing	UPPT	27.1452N	8826.52E	1900	0	-0.4177

3.4 Calculation of Minimum 1D Model from Travel Time Inversion

To obtain an optimal 1D velocity model for the study region, eminent algorithm VELEST (Kissling et al., 1984; Kissling, 1988) has been used. This algorithm is highly efficient and widely accepted for calculating the crustal velocity structure in the tectonically complex and seismically active areas around the globe (Haslinger et al., 1999; Ojeda and Havskov, 2001; Langer et al., 2007). With this approach, we have deduced hypocenter locations, 1D crustal structure and station corrections by the simultaneous inversions of travel time data along with least square residual error. We have used a total of 76 seismic events containing 304 P-phases and 608-S phases, lying within the array having a higher accuracy in hypocenter parameters for travel time inversion and calculation of minimum 1D crustal model. The seismic events with at least 6 P-phases and 6 S-phases are selected for the inversion. We have taken the 6 layer model of Bhattacharya et al. (2005) as a preliminary reference model for the computation of a least 1D velocity model which is given in Table 3. After five iterations, we have obtained an optimal 1D velocity model with a least square residual error of 0.07 s as minimum and maximum up to 0.99 s which was initially up to 1.20 s before the iterations. This shows that the optimal model obtained from this algorithms of higher accuracy compared to the initial reference model. In this process, maximum seismic events lie within 30 km depth, which are able to provide the high accuracy crustal structure for this depth.

Table 3. Preliminary velocity model from Bhattacharya et al. (2005)

Depth(km)	P wave velocity(km/sec)	S wave velocity(km/sec)
0	5.56	3.22
10	6.1	3.59
20	6.45	3.74
30	6.9	4.00
40	7.6	4.40
50	8.4	4.87

4. Results and Discussions

4.1 Optimal 1D Velocity Model for Sikkim Himalaya and Its Interpretation for Crustal Structure

The optimal 1D velocity model is achieved by inverting the earthquake epicenters along with earlier published velocity model of P and S wave for the study region. Here we have studied to obtain a result based on the least square residual error and also make sure that all the results derived clearly matches with the previous information obtained from initial locations. We started our first inversion on the basis of the initial model of Bhattacharya et al. (2005) for the Northeast Himalaya. We changed the preliminary model in successive trials till we obtained the smaller misfits. After five successful iterations, we observed that the RMS values are constant at lower than 0.07, meaning that it is 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 1.20 to .99 s. i.e. the velocity model is highly accurate and can significantly explain the crustal structure variations of the study region. Thus the minimum 1D velocity model is obtained from travel time inversion of P and S waves.

Table 4. Final 1 D velocity model obtained through VELEST

Depth(km)	P wave velocity(km/sec)	S wave velocity(km/sec)
0	5.23	3.03
10	5.35	3.08
20	5.85	3.38
30	6.59	3.37
40	7.49	4.19
50	8.03	4.61

A comparison of both input and output models (Figure 3) show that they differ more at shallower depth but becomes almost equal at greater depth. From the Fig. 3, it is obvious that the velocity values for different depth for output model are slightly lower than that of the input.

This final velocity model shows a variation in the velocities of P and S waves at subsequent layers is the optimal velocity model. The used events are maximally concentrated up to 40 km depth in this study (Figures 3, 4 & 5). 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 6 drawn for RMS residuals shows a significant decrease in RMS residual values after locating the selected subset of 76 events with VELEST in comparison to the epicenters located previously with routine epicenter location software.

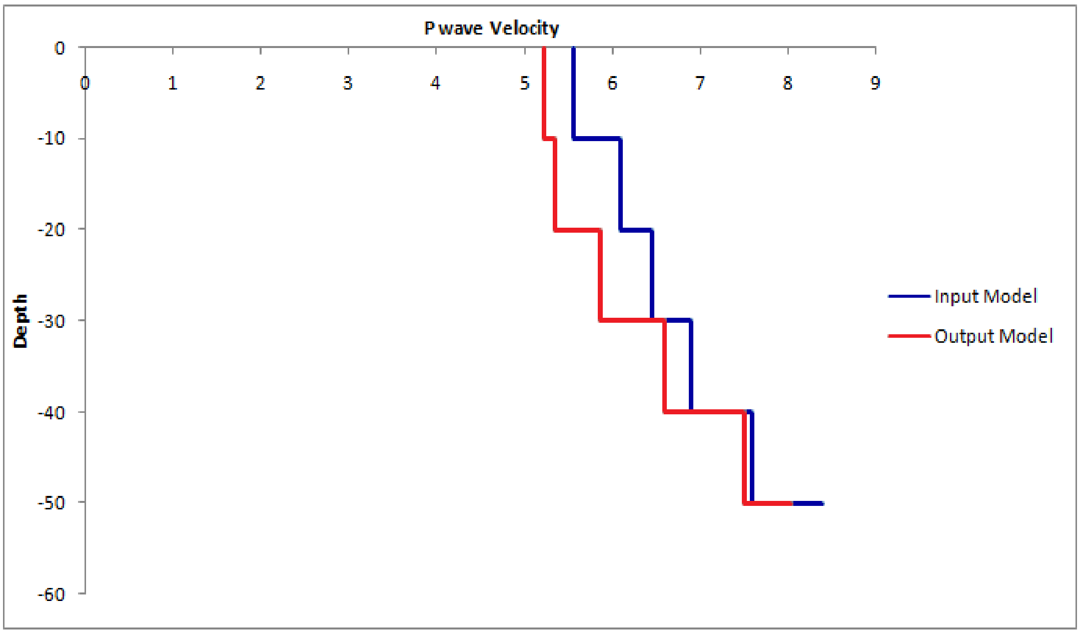

Figure 3. Comparison of input model for P wave from Bhattacharya et al. (2005) with the output model obtained through VELEST.

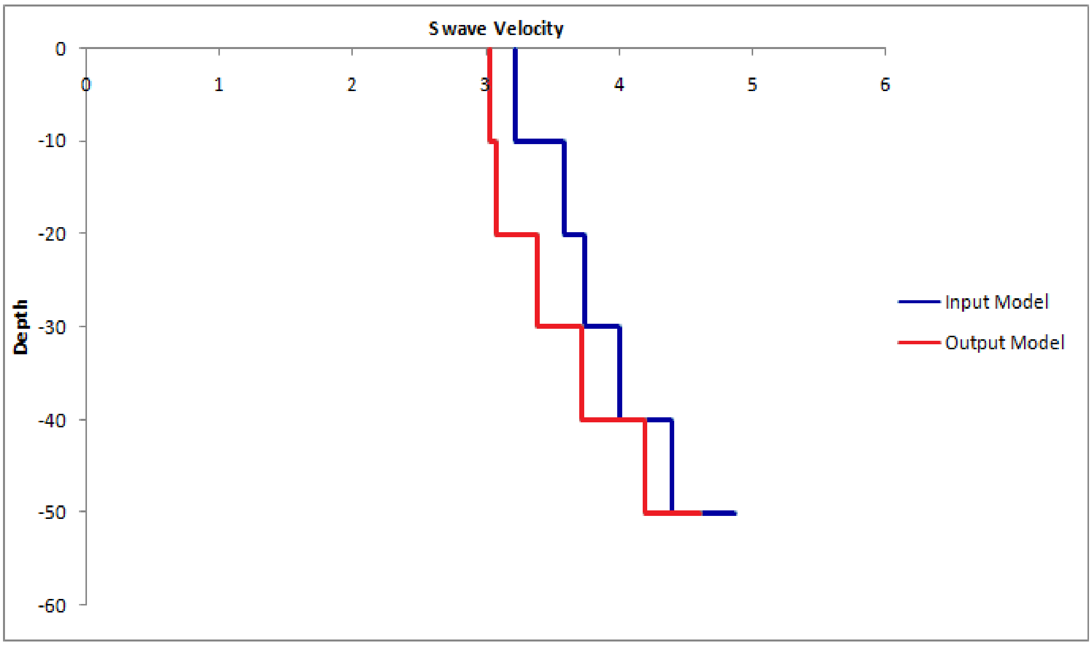

Figure 4. Comparison of input model for S wave from Bhattacharya et al. (2005) with the output model obtained through VELEST.

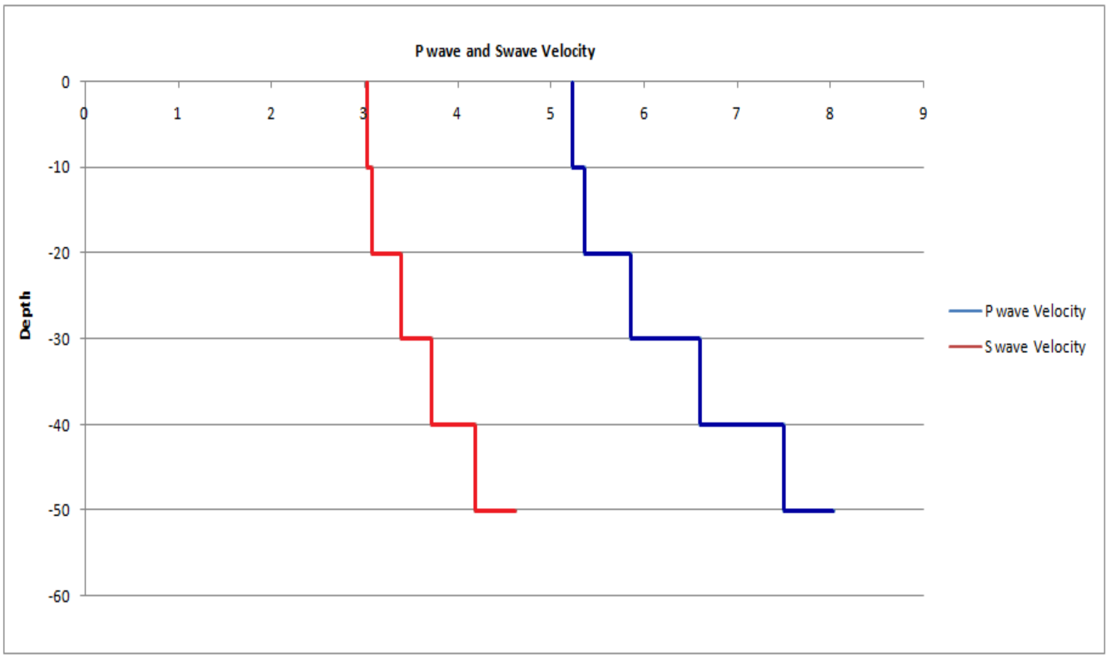

Figure 5. A comparison of P and S wave velocity.

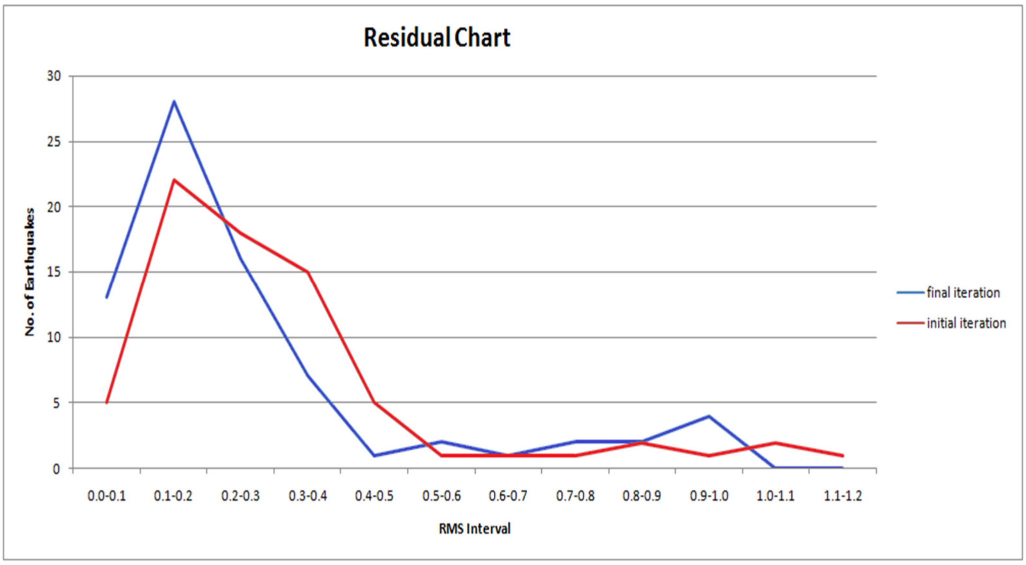

Figure 6: Comparison of RMS error between initial and final iteration.

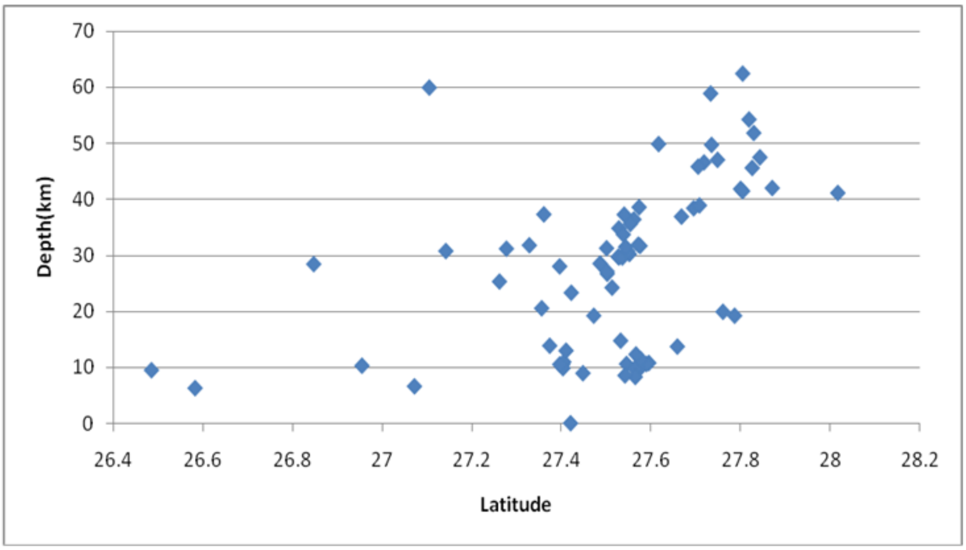

Figure 7. Hypo-center plot with latitude.

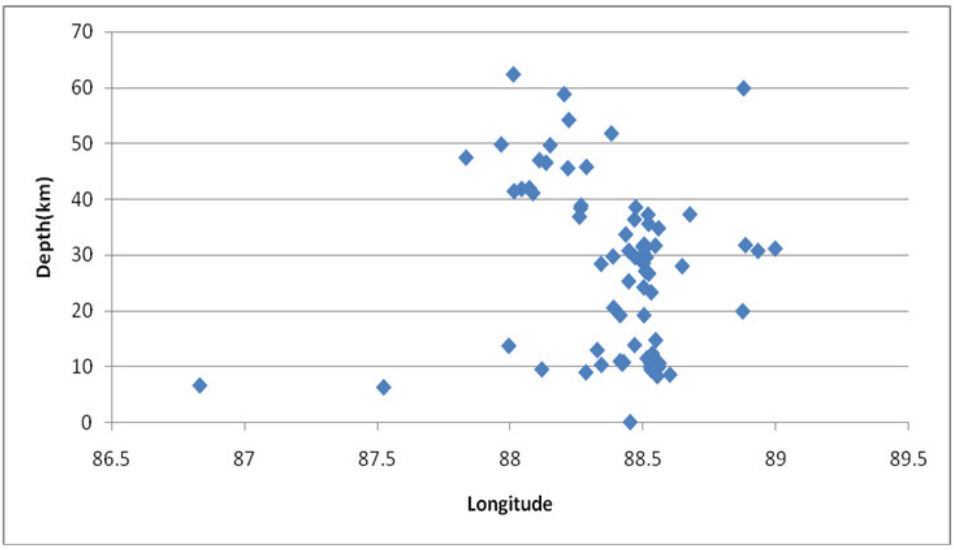

Figure 8. Hypo-center plot with longitude.

From the Figures 7 and 8, it can be deciphered that most of the events are concentrated below 40 km depth. Most of the Events are centered on the latitude 88.5^{0}E and distributed between 27.4 to 27.7^{0}N latitude. The seismicity map of the area (Figure 9) visually shows this variation in hypo-center of the events over the geology of the area. Map is prepared in GMT after finding the events location through VELEST taking a preliminary model.

All the events are distributed in depth range of 10 to 60 km that implies the presence of maximum shallow seismicity in the region. Mainly the events are more clustered in the area lying between latitude 27.2°N to 27.8°N and 88.°E to 88.6°E, which shows high seismo-tectonic activity in the area due to the strain accumulation caused by dipping of Indian plate under the Eurasian plate.

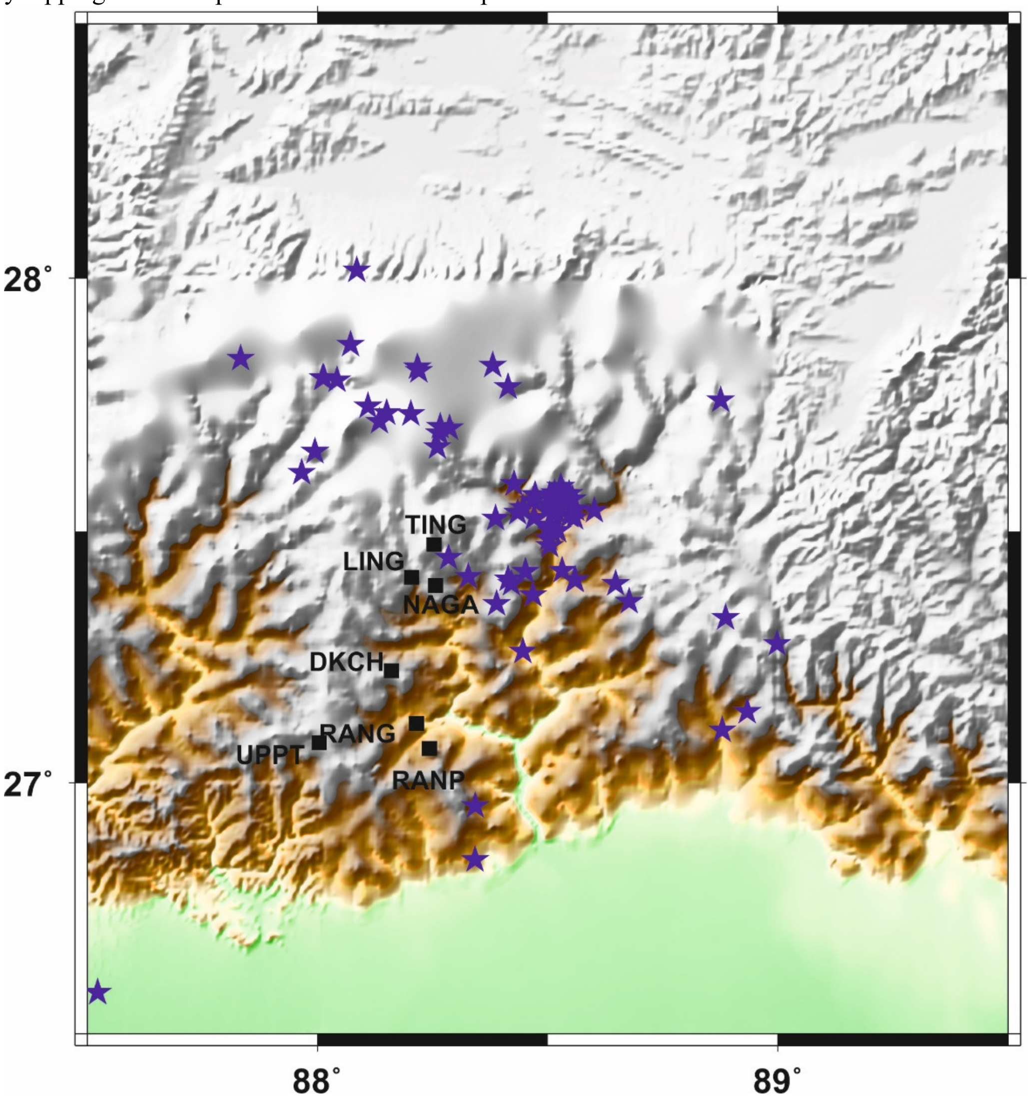

Figure 9. The seismicity plot in Sikkim, NE Himalaya, India along with the Seismic network deployed and operated by Wadia institute of Himalayan Geology, Dehradun.

5. Conclusion and Future Research Work

The seismic events recorded through the local network are used to derive the velocity structure of the region by travel time inversion of P- and S- waves, respectively. Most of the earthquake events are concentrated in depth range of 10 to 40 km, so that one can state that the calculated velocity structure for this region is most precise than other available velocity structure of the area. Velocity for this region varies from a value of 5.35 to 7.79 km/s for P wave and 3.08 to 4.19 km/s for S wave. From the velocity model it can be noticed that the largest velocity occurs at the depth of 40 km, which imply that the major lithological variation is present at this depth. The approximate thickness of the upper crust (granitic layer) is around 30 km which can be seen from velocity data. The analysis also reveals that the layers with thickness range 10-20 km with P wave velocity 5.35 km/s and 30-40 km with P wave velocity 6.59 km/s contains 19 hypocenter within them. The depth to Moho in the study area can be approximated around 60 km. Moreover, this study would be very much useful for the further seismological study in the area and the detailed seismicity map of the area would also be helpful for the future work in the area.

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