CHAPTER 1

CHAPTER 1

INTRODUCTION

1.1 RESEARCH PROBLEM

The continent-continent collision between India and Asia followed by northward underthrusting of the Indian plate beneath the Tibetan Plateau created most spectacular and highly seismically active Himalayan mountain belt (Gansser, 1964; Dewey & Bird, 1970; McKenzie & Sclater, 1971) (Fig. 1.1). The Indian plate is underthrusting beneath the Tibetan Plateau along a northerly dipping detachment surface, known as the Main Himalayan Thrust (MHT), which separates the down going Indian plate from the overriding Himalayan wedge (Seeber & Armbruster, 1981). Thus, the crust of the Indian continent is confined within the MHT above and the crust-mantle boundary i.e. the Mohorovičić discontinuity or Moho at the bottom. Imaging these boundaries all along the Himalayan arc is a long-standing research problem that is significant in understanding the geodynamics and origin of seismicity in the Himalaya. The collision and underthrusting processes have resulted in large scale crustal shortening, topographic variations, the formation of fold and thrust belts and significant lateral variations of crustal thickness and its composition. To understand the change in crustal configuration, geophysical investigations are required. In contrast to extensive geophysical experiments carried out in the Tibetan Plateaulike INDEPTH (International Deep profiling of Tibet and the Himalaya) and Hi-CLIMB (Himalayan Nepal Tibet Earthquake Seismic Experiment) for imaging the subsurface structure (Nelson et al., 1996; Hauck et al., 1998; Jain et al., 2003; Schulte-Pelkum et al., 2005;Nabelek et al., 2009), a limited number of studies have been carried out in selected profiles of northwest (NW) Himalaya under a programme, HIMPROBE (Integrated studies on Geology, Petrology, Geochronology, and Geophysics on the Trans-Himalaya and the Karakorum) (e.g. Jain et al., 2003; Rai et al., 2006; Arora et al., 2007). A large part of the NW Himalaya remains unexplored by any high-resolution geophysical experiments so far, particularly in the Satluj valley region.

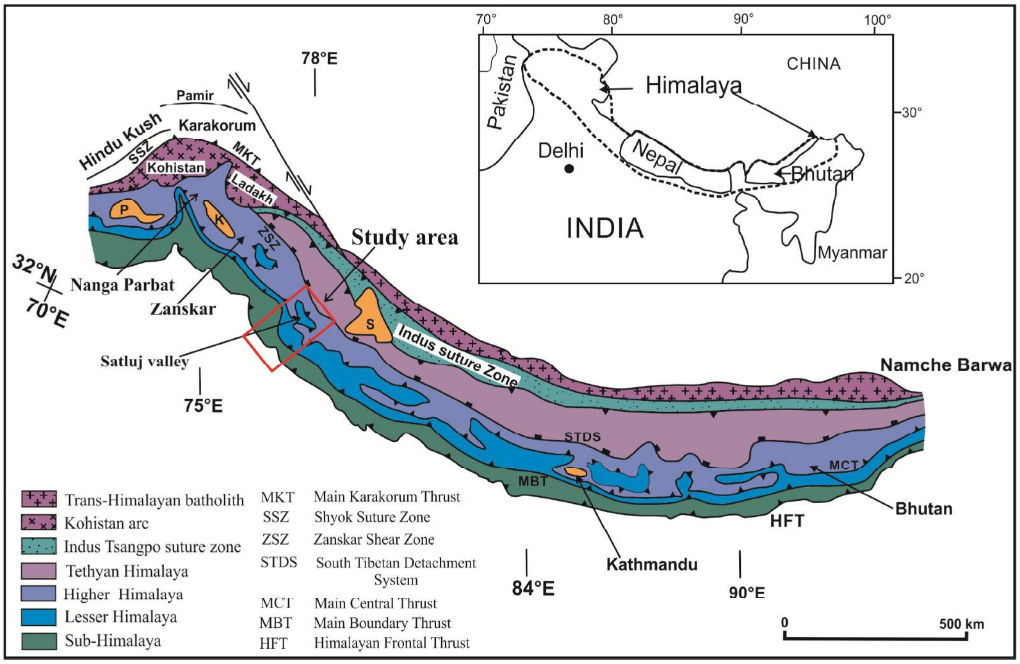

Figure 1.1 Generalized geological map of the Himalaya with major litho-tectonic divisions (modified after Searle et al., 2003 and Law, 2004). Red colour rectangular box indicates the study area.

The Seismological investigation is one of the best ways to image subsurface structure. This thesis is a contribution towards the study of crustal structure along a broadband seismological profile covering the area between the Himalayan Frontal Thrust in the south to the Tethyan Himalaya in the north passing along the Satluj valley and adjoining region in the NW Himalaya. The present study constrains the depths and geometry of Moho and other intra-crustal features (e.g. the MHT) existing beneath the study profile with the help of receiver function (RF) method. The seismic anisotropy in the crust has also been investigated with the help of shear wave splitting analysis for understanding the dynamics and deformation pattern in the crust. Finally, the seismicity pattern and its linkage with crustal configurations beneath the study region are evaluated.

1.2 RESEARCH MOTIVATION

The Himalayan wedge is a result of uplift along south verging thrust faults e.g. the Himalayan Frontal Thrust (HFT), Main Boundary Thrust(MBT) and Main Central Thrust (MCT) from south to north respectively. These thrust faults sole down at depth and merge with the MHT (Fig. 1.2). The MHT accumulates a large part of strain energy originated due to the India-Asia collision. The geophysical studies suggest the presence of locked zone in the southern part of the MHT and the accumulated strain is released from time to time in the form of large and great earthquakes in the Himalaya e.g. the 1905 Kangra earthquake (Mw 8.0), the 1934 Bihar-Nepal earthquake (Mw 8.0) and the 2015 Gorkha earthquake of Mw 7.8 (Middlemiss, 1910; Bilham et al., 1995; Pandey et al., 1995; Larson et al., 1999; Ni & Barazangi, 1984; Kayal, 2001; Hayes et al., 2015; Duputel et al., 2016).

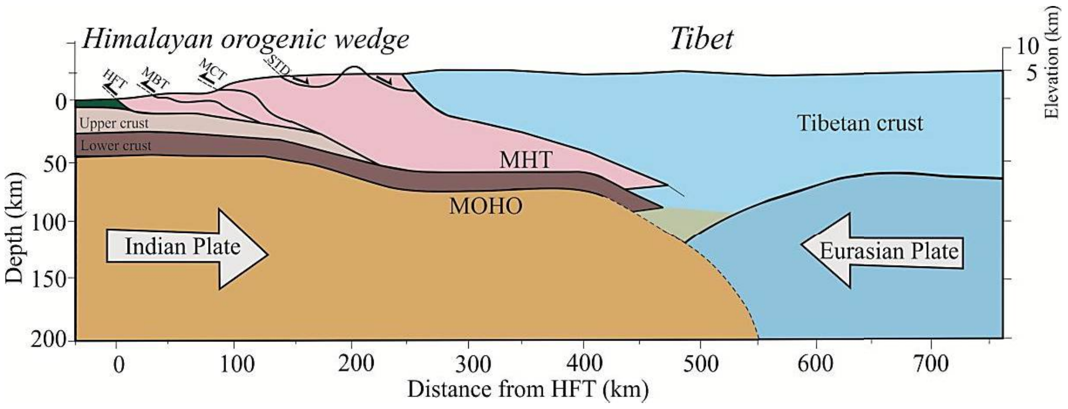

Figure 1.2 General cross section of major thrusts and upper crustal features in the NW Himalaya (modified after Godin & Harris, 2014). HFT: Himalayan Frontal Thrust, MBT: Main Boundary Thrust, MCT: Main Central Thrust, STD: South Tibetan Detachment, MHT: Main Himalayan Thrust.

In the recent years, however, no great earthquake (M > 8) had occurred in the Himalayan region. Several studies have reported the presence of ramp structure in the MHT, particularly in the Garhwal and the Nepal Himalaya that causes intense seismicity (Pandey et al., 1995; Caldwell et al., 2013; Rawat et al., 2014). The recent 2015 Gorkha earthquake of Mw 7.8 has also been reported to be caused due to the ramp on the MHT (Duputel et al., 2016). It is, therefore, crucial to understand the subsurface geometry of the MHT and its relationship with the seismicity pattern.

The seismicity in the Himalaya is largely concentrated in a narrow belt of 30-50 km width, known as the Himalayan Seismic Belt (HSB), spanning the northern Lesser Himalaya and southern Higher Himalaya (Arora et al., 2012). The significant variation of seismicity along the HSB has been reported along the strike of the Himalayan arc by recent studies (Gahalaut & Kalpna, 2001; Arora et al., 2012). In the Garhwal Himalaya, seismicity cluster is observed in the HSB at the ramp on the MHT (Caldwell et al., 2013). On the other hand, much less seismicity has been observed in the southern part of the Satluj valley which was speculated to be due to the absence of ramp structure on the MHT beneath this segment of the HSB (Arora et al., 2012; Gahalaut & Kundu, 2012). However, in this region, no subsurface imaging experiment was conducted to investigate the geometry of the MHT. Some studies focused on the estimation of crustal thickness in the NW Himalaya but did not emphasize on intra-crustal features (Rai et al., 2006; Oreshin et al., 2008, 2011). Significant lateral segmentation of subsurface structure particularly along-strike variation in geometry of the MHT has been reported in some parts of the Himalaya indicating the fact that subsurface structure in the Himalaya is not laterally uniform all along the Himalayan arc (Hetenyi et al., 2016;Singer et al., 2017). The variation of seismicity pattern along the strike of the Himalayan Arc and the possible role of the intra-crustal features on seismicity pattern in Satluj valley are the primary motivating factors to carry out a passive seismic study in the area.

The study area is characterized by several normal and thrust faults obtained through field data and focal mechanism solution of earthquakes (Molnar & Lyon-Cean., 1989; Burchfiel et al., 1992; Thiede et al., 2006; Yadav et al., 2017) suggesting complicated stress pattern and deformation in the crust. These studies, however, did not provide deformation pattern in the lower crust. The seismic anisotropy study with the help of shear wave splitting of Moho converted P-to-S (*Ps*) phase is a useful tool for characterizing the deformation pattern of the entire crust which has been carried out in the present study.

1.3 STUDY AREA

The study area lies in the NW Himalaya traverses along the Satluj River (Figs. 1.1 and 1.3) and it extends from village Ramgarh (Haryana) located in the south of the Indo-Gangetic Plain (IGP) to Kaza (Himachal Pradesh) in the north of the Tethyan Himalaya, covering a traverse of about 200 km nearly

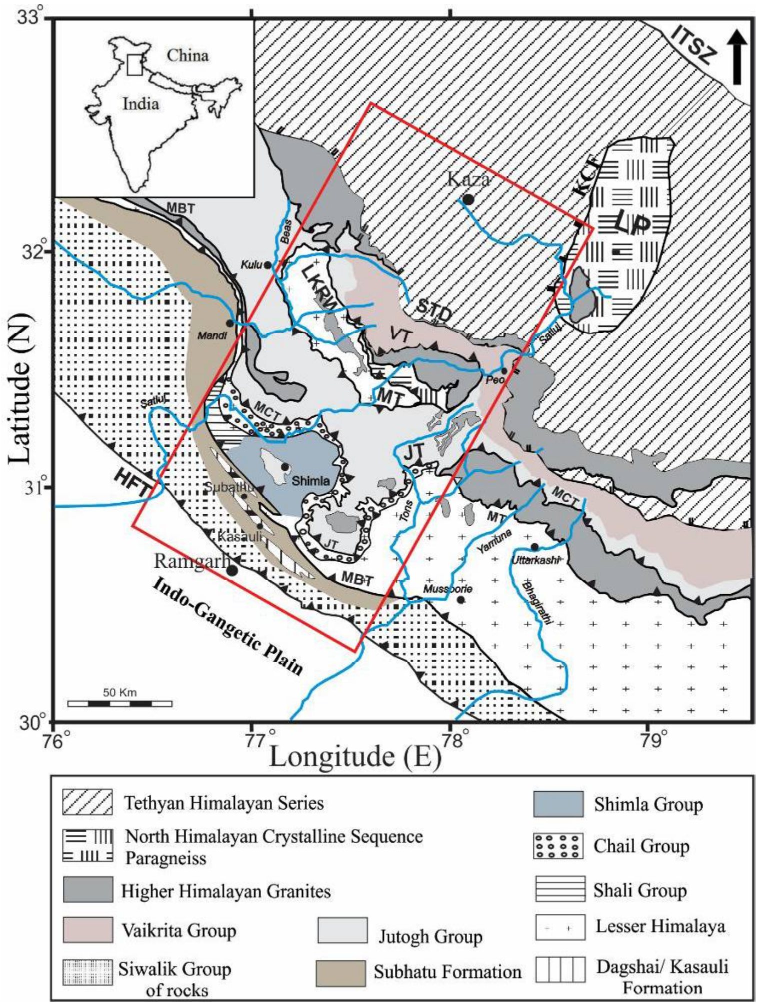

Figure 1.3 Geological map of the study area along with its regional geology and major tectonics features (modified after Vannay&Grasemann, 2001; Vannay et al., 2004 and Thakur &Rawat, 1992). MT: Munsiari Thrust, VT: Vaikrita Thrust, LKRW: Larji-Kulu-Rampur Window, LP: Leo Pargil, ITSZ: Indus Tsangpo Suture Zone and KCF: KaurikChango Fault. Red colour rectangular box indicates the study area.

perpendicular to the Himalayan Arc (Fig. 1.3). This part of the NW Himalaya is characterized by highly rugged and unstable topography due to its high relief varying from ~260 to ~4000 m. The thesis work is mainly carried out along the Satluj valley and adjacent regions that across the major litho tectonic units of the NW Himalaya lying between the HFT in the south to the Indus Tsangpo Suture Zone (ITSZ) in the north.

1.3.1 GEOLOGICAL SETUP OF THE STUDY AREA

The study area consists of five major litho-units viz. Indo-GangeticPlain (IGP), Sub (Siwalik) Himalaya (SH), Lesser Himalaya (LH), Lesser Himalayan Crystalline Sequence (LHCS), Higher Himalayan Crystalline Sequence (HHCS) and Tethyan Himalaya (TH) from south to north. These litho-units are separated by a number of faults from the south, Himalayan Frontal Thrust (HFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), and South-Tibetan Detachment (STD) system to the north.

SUB-HIMALAYA

The Sub-Himalaya is a foreland basin of the Himalayan orogeny of Pleistocene age with total thickness 1700-2300 meter. It is separated from the LHby the MBT in the north and HFT in the south (Srikantia & Sharma, 1976; Powers et al., 1998; Raivermann, 2002; Kumar et al., 2006). It is the southernmost part of Tertiary and Quaternary alluvium sediments and also known as the Sub-Himalaya foot hills, rises above the IGP along the HFT (Medlicot, 1864; Pilgrim, 1910). On the basis of lithology, the Siwalik is divided into three subgroups: Lower, Middle and Upper Siwalik (Karunakaran & Ranga Rao, 1979; Prakash et al., 1980).

The Lower Siwalik comprised of fine grained sandstone, clay and gray sandstone with mudstone. It is overlain by the Middle Siwalik comprising of a thick sequence of coarse micaceous sandstone with gravel and clay beds. It is very well exposed near the northern end of the Kasauli town. The Upper Siwalik constitutes ~2300 meter thick sequence of sandstone, conglomerate with some clays (Prakash et al., 1980). Three formations are also considered as a part of Sub-Himalaya: Subathu, Dagshai and Kasauli formations (Medlicott, 1864; Raivermann & Raman, 1971). The Subhatu Formation is very well exposed in the study area near Subathu town (Himachal Pradesh) and composed of limestone, sandstone and contains marine shallow facies in the form of alternate green and red shale. Further, it is overlain by Dagshai Formation characterized with the presence of conglomerate and gray sandstone. The rocks of the Kasauli Formation are very well exposed near Kasauli town and predominantly comprised of sandstone, green shale with clay slate.

LESSER HIMALAYA (LH)

The LH is bounded by the MBT in the south and by the MCT or regionally known as Jutogh Thrust (JT) in Himachal Pradesh. The LH comprises predominantly of dolomites, pyritous–carbonaceous slates, marls and interbeddedcalcitic marbles and low-grade detrital sediments along several thrusts and klippen structures (Frank et al., 1977; Dubey, 2014) reverse stratigraphic features and inverted metamorphic sequence (Virdi, 1977). The uppermost part of the LH in Satluj valley is characterized by metasediments and exposed as a window known as Larji-Kulu-Rampur Window (LKRW) that consists of quartzites and low-grade phyllites (Sharma, 1977; Frank et al., 1995) and bounded at the base by MCT. The LKRW is maily exposed in the crystalline core of lesser Himalaya known as Lesser Himalayan Crystalline Sequence (LHCS). The LHCS is separated from the Paleo-Proterozoic gneissic basement of the lesser Himalaya sequence (LHS) by theJutogh Thrust (JT), called the Wangtu Gneissic Complex (WGC).

In the present study area, the LHS sequence is subdivided into three Groups viz.Shali Group, Simla Group and Chail Group.

(i) SHALI GROUP

The Shali Group is formed as a basement of LHS and is composed of shale, limestone, slates, quartzites, and siltstone (Srikantia & Shrama, 1976). It represents a typical shallow stable form of sedimentation with the presence of sedimentary structures like mud cracks, cross-bedding, and stromatolites. This group is well exposed with thin beds of limestone, white quartz arenites, and shale.

(ii) SIMLA GROUP

The Simla Group is named after the beautiful Shimla town, the rocks of Simla Group are unconformably overlies the Shali Group and composed of the lenticular interbeds, limestone, dolomites, sandstone, greywacke, siltstone and carbonaceous shales (Pilgrim & West, 1928; Srikantia& Bhargava, 1998). It is characterized with several asymmetrical folds, faults and structures like klippe. The Simla klippe is formed a syncline is composed of Chail and Jutogh Groups of rocks which are surrounded by the younger meta-sedimentary rocks of Simla Group.

(iii) CHAIL GROUP

The Chail Group is characterized by the metamorphic sequence of phyllites, schists, orthoquartzites, limestones, and amphibolites. These rocks of the Chail Group are occurred in two tectonic units - Lower Chailallochthon as a thrust sheet over the Shali Formation and Upper Chailallochthon as Jutogh Thrust sheet. In the Satluj valley, it is separated from the high grade metamorphic rocks of the Jutogh Group by the JT/ MCT.

HIGHER HIMALAYA CRYSTALLINE SEQUENCE

The Higher Himalayan Crystalline Sequence (HHCS) is the core metamorphic part of the Himalaya received many names such as Greater Himalayan Crystalline, Higher Himalayan Crystalline and Central Himalayan Crystalline sequences and occupies the highest elevation of the Himalayan range. It is lying in the north of Lesser Himalaya and separated by north-dipping south-verging MCT in the south and bounded by the MCT at the base and by the

STD at top from the TH in the north (Burg et al., 1984; Burchfiel et al., 1992). Along the Satluj River, the Higher Himalayan Crystalline rocks shows an inverted metamorphic field characterized by garnet-staurolite rocks at the base, kyanite and silimanite in the middle and migmatiteBarrovian mineral units at the bottom (Vannay & Grasemann, 1998). In the present study area along the Satluj valley, HHCS is further subdivided into following groups

(i) JUTOGH GROUP

The Jutogh Group is a succession of metamorphosed sediments with distinct lithostratigraphic sequences. It is mainly composed of carbonaceous schist, limestone and quartzite bands and found to be well developed near Shimla. The base of the group is marked by Jutogh Thrust. The rocks of this group are highly foliated and have undergone folding and thrusting, simultaneously (Dubey & Bhat, 1991). The Jutogh Group of rocks have some unique and intrusive granitoids of Neoproterozoic and some Paleaozoic granites.

(ii) VAIKRITA GROUP

The Vaikrita Group comprises of ~5-7 km thick succession of crystalline rocks Proterozoic age mainly of banded gneisses, amphibolitesfacies, calc-silicate gneisses and migmatites (Thakur, 199; Valdiya, 1998). This group is divided into two subunits, the lowermost unit shows banded gneisses, kyanite, sillimanite, alternate bands of coarse biotite gneisses and leucogranites and the uppermost unit comprises of meta-sediments, gneisses, migmatites with schist and marble (Vannay & Grasemann, 1998). It has undergone several phases of deformation and metamorphism and represents a basement of Palaeozoic granite known as the KinnaurKailash Granite (KKG).

TETHYAN HIMALAYA

The Tethyan Himalaya is separated by the STD from the HHCS. The THis ~10 km thick sedimentary sequence dominantly consists of Cambro-Oridivician to Eocene age which are highly deformed and one characteristically lie in normal fault (known as STD) contact with underlying crystalline units of the Higher Himalayas (Burchfiel et al., 1992). The rocks of TH are named as Haimanta

Group of rocks and mainly consists of a thick pile of sediments ranging in age between Paleoproterozoic to Eocene (1840-40 Ma) which comprising the grey-green phyllite, grayquartzites, and carbonaceous phyllites and found to be inter-bedded with Paleozoic and Mesozoic volcanic rocks (Srikantia & Bhargava, 1982; Gaetani & Garzanti, 1991; Thakur, 1992; Brookfield, 1993;Garzanti, 1993, 1999; Steck et al., 1993). In the study area, the TH sequence comprises of Haimanta Group of rocks (Frank et al., 1995). In the extreme north of study area, the metamorphic Leo Pargil (LP) dome is exposed within the TH and the western edge of the dome is characterized by a normal fault that has a transverse strike to the Himalayan arc and is known as the Kaurik-Chango fault (KCF) (Hayden, 1904; Sharma, 1977; Thiede et al., 2006).

1.4 OBJECTIVES

In this thesis, an attempt has been made to address some of key questions related to the configuration of the crust, deformation process in the crust, intra-crustal features and its linkage with the present day seismicity in the study area. The teleseismic earthquake data recorded by seismological profile comprising of 18 broadband seismological (BBS) stations established between the HFT and TH along the SatlujRiver has been analysed. The present study includes following objectives:

1. To image the Main Himalayan Thrust and the Moho beneath the Satluj valley, NW Himalaya for investigating their nature and geometry in terms of shear wave velocities at different depths.
2. To investigate the composition of the crust based on average Poisson's ratio.
3. To understand the relationship of crustal configuration and composition with the recent seismicity pattern in and around the Satlujvalley.
4. To understand the crustal deformationusing shear wave splitting of teleseismic earthquakes as well as laboratory investigations of rock samples under normal ambient conditions.

1.5 PREVIOUS STUDIES

The knowledge of subsurface structure is very crucial in understanding the geodynamic evolution and seismogenesis of the Himalayan mountain belt. There are numerous studies in the Himalaya and Tibetan Plateau to investigate the crustal shear wave velocity structure (Zhao et al., 1993; Nelson et al., 1996; Brown et al., 1996; Hauk et al., 1998; Gokarn et al., 2002; Jain et al., 2003; Tilmannet al., 2003; Unsworth et al., 2005; Schulte-Pelkum et al., 2005; Klemperer, 2006; Rai et al., 2006; Arora et al., 2007; Oreshin et al., 2008; 2011; Nabelek et al., 2009). These are briefly discussed below:

The structure of crust and upper mantle beneath the Himalaya-Tibetorogeny have been documented by a number of passive seismological studies (Kind et al., 2002; Wittlinger et al., 2004; Schulte-Pelkum et al., 2005; Kumar et al., 2006; Rai et al., 2006; Nabelek et al., 2009; Zhao et al., 2010, 2011; Hazarika et al., 2013, 2014). In comparison to the Tibetan Plateau, information of crustal structure in the NW Himalaya is significantly less due to lack of sufficient geophysical data. RF studies in the NW Himalaya (Rai et al., 2006, Oreshin et al., 2008; 2011) were mainly focused on regional scale variation of crustal thickness and did not accentuate on intra-crustal features. Rai et al. (2006) show northward deepening of the Indian Moho from ~40 km beneath the Himalayan foredeep to ~75 km beneath the Trans Himalaya (Ladakh-Karakoram zone). Hazarika et al. (2013) estimated average crustal thickness varying from ~ 50 km to ~ 80 km in a profile passing through the Tethyan Himalaya to Eastern Ladakh-Karakoram zone (LKZ). This study also reported low Poisson’s ratio in the Lesser and Higher Himalaya, intermediate in the Tethyan Himalaya and extremely high beneath LKZ.Hazarika et al. (2014) emphasized on intra-crustal features and reported the presence of partial melt or aqueous fluids at the mid-crustal depths beneath a profile covering the TH to the eastern LKZ and also detected the eclogitized Indian lower crust beneath Ladakh at 47-50 km depth.

Despite the study of first order discontinuity e.g. Moho, very few studies have been carried out on intra-crustal features like the MHT which is a prominent intra-crustal feature observed throughout the Himalaya.The MHT is mainly inferred by the studies related to source model of large and great earthquakes (e.g. Seeber & Armbruster, 1981; Ni & Barazangi, 1984) and with the help of balanced geological cross sections (e.g. Schelling & Arita, 1991; Srivastava & Mitra, 1994; Powers et al., 1998). Limited number of geophysical studies including active (e.g. Prasad et al., 2011; Gao et al., 2016) as well as passive source (e.g. Schulte-Pelkum et al., 2005; Nabelek et al., 2009, Acton et al., 2011; Caldwell et al., 2013) seismic studies were carried out in the Himalaya for the investigation of geometry of the MHT. A significant ramp structure on the MHT was reported in the Nepal Himalaya beneath the Lesser and Higher Himalaya (Pandey et al., 1995; Lemonnier et al., 1999; Lavé & Avouac, 2001). Duputel et al. (2016) have also reported ramp structure on the MHT beneath the Nepal Himalaya based on high-resolution RF data coupled with source mechanism study of the 2015 Gorkha earthquake of Mw 7.8 sequence. Few studies have also reported the substantial ramp structure on the MHT beneath the NW Himalaya (e.g. Thakur et al., 2000; Gahalaut & Kalpna, 2001; Caldwell et al., 2013).The RF study carried out across the Garhwal Himalaya reported a flat-ramp-flat geometry in the MHT beneath the Munsiari Thrust (MT), which is responsible for intense seismicity observed in the Garhwal Himalaya (Caldwell et al., 2013). A few recent studies suggest significant lateral variation in the geometry of the MHT (Hetényi et al., 2016; Singer et al., 2017). Moreover, considerable variation in topography and relief (Duncan et al., 2003), exhumation rate (Robert et al., 2011) along the strike of the Himalaya have also been reported.

Magneto-Telluric (MT) investigations were also conducted by several researchers to investigate the geometry of the MHT and delineate the geoelectrical crustal structure in different parts of the Himalaya (Lemmonier et al., 1999; Gokran et al., 2002; Unsworth et al., 2005; Arora et al., 2007; Rawat et al., 2014).Lemmonier et al. (1999) used MT study investigatedthe major conductive features beneath the Nepal Himalaya, detected Intra-crustal high conducting layer (IC-HCL) and revealed mid-crustal ramp on the MHT. Gokran et al. (2002) constrained the geoelectric structure beneath the Siwalik Himalaya and modeled the fold and thrust zone of the Sub-Himalaya. Arora et al. (2007) carried out Long-period MT survey in the NW Indian Himalaya and identified a mid-crustal low resistivity zone beneath the ITSZ and Ladakh. This study also detected a north dipping zone of low resistivity above the MHT beneath the TH which is due to underthrusting of the sedimentary rocks. Unsworth et al. (2005) postulated the electrical structure using MT profile in INDEPTH cross-section from the Nepal to central Tibet. Israil et al. (2008) carried out MT study from the IGP to Higher Himalaya in the Garhwal Himalaya and inferred a low resistivity zone and partial melting or fluid phase at the mid-crustal depth. Similar MT study has also been carried out by Rawat et al. (2014) and they emphasized on fluid-seismicity linkage beneath the Garhwal Himalaya. The studies carried out by Israil et al. (2008) and Rawat et al. (2014) also imaged IC-HCL and detected a flat-ramp-flat geometry of the MHT beneath the Garhwal Himalaya. The origin of the IC-HCL observed was interpreted by these MT studies as the presence of mid-crustal fluid which may be released from metamorphic reactions in the down-going plate slab or expelled from the underthrusted sediment.

In addition to the RF and MT studies, gravity data is also an important tool in constraining the structure of the lithosphere of a tectonic regime. Several gravity studies were carried out across the Himalaya to draw the crustal configuration. Chamoli et al. (2011) modelled the gravity response and crustal shortening in the NW Himalayan and obtained the geometrical constraints of intra-crustal to sub-crustal regional faults in the space scale domain. Hetényi et al. (2016) compiled a large amount of land gravity dataset in the Himalayan region enabling the highest resolution gravity data and revealed lateral segmentation of subsurface structure in the Himalaya. Lyon and Molnar, (1983, 1985) estimated the flexure rigidity of underthrusting Indian plate beneath the Eurasian plate. Jordan and Watts (2005) estimated the elastic effective thickness (EET) in Indian-Asia collision zone using gravity anomaly data and postulated the apparent thickness of crustal slabs. Hetényi et al. (2006) observed the high value of the effective elastic thickness (EET >60-70 km) of Indian plate under the Indian continent. Similar studies were carried out in the Nepal Himalaya (Cattin et al., 2001) with the support of petrological and mechanical behaviour of the Indian lithosphere.

Global Positioning System (GPS) studies provide an estimation of the rate of convergence and plate motion. Bilham et al. (1997, 1998) determined 20 ± 5 mm/yr convergence rate of the Indian plate with the maximum velocity of 58 ± 4 mm/yr in the Nepal Himalaya. Paul et al. (2001) estimated the elastic strain~ 2-6 x 10^{-9}mm/yr corresponding to the Himalayan mountain belt and determined arc normal velocity vectors between 77°E to 92°E. Banerjee and Burgmann, (2002) estimated the northward plate motion of Indian plate and suggested crustal shortening and thickening of crust. Jade et al. (2004, 2007) estimated convergence rate near Karakorum fault zone, Ladakh Himalaya and provides an estimation of surface deformation along the Himalayan Arc. Wang et al. (2001) and Jade et al. (2011) provide 10-12 mm/yr convergence rate in the northeast part of Himalaya. Kundu et al. (2014) reported the crustal deformation in the Kashmir Himalaya andestimated the N-S oblique motion of 17± 2 mm/yr between the Indian plate and southern Tibet.

Seismic anisotropy in the crust and upper mantle beneath the Himalaya-Tibet orogeny system has been the subject of several studies (McNamara et al., 1994; Hirn et al., 1995; Sandvol et al., 1997; Huang, 2000; Herquel & Tapponnier, 2005; Lev et al., 2006; Singh et al., 2007; Sol et al., 2007; Kumar & Singh, 2008; Oreshin et al., 2008; Heintz et al., 2009; Hazarika et al., 2013; Wu et al., 2015). The majority of these studies emphasized on mantle deformation/flow pattern in the Tibetan Plateau (e.g. Hirn et al., 1995; Sandvol et al., 1997; Huang 2000; Herquel&Tapponnier, 2005; Lev et al., 2006). The clockwise rotation of mantle strain beneath the Tibetan Plateau has been documented based on shear wave splitting of core refracted phases - SKS/SKKS phases and GPS velocity vectors (Sol et al., 2007). The seismic anisotropy studies (Flesch et al., 2005; Lev et al., 2006) reported apronounced crust–mantle decoupling in Yunnan, SE Tibetan Plateau. A limited number of such kind of studies were carried out in the Himalaya for understanding the mantle deformation (e.g. Singh et al., 2007; Kumar & Singh, 2008; Oreshin et al., 2008; Heintz et al., 2009; Hazarika et al., 2013). In the NW Himalaya and the Sikkim Himalaya, the fast polarization direction is nearly parallel to the strike of the mountain chain (Singh et al., 2007; Oreshin et al., 2008, Heintz et al., 2009). Heintz et al. (2009)

investigated seismic anisotropy in the peninsular India and in the Himalaya and reported NNE–SSW oriented polarization directions in the southern Indian shield that becomes nearly E-W in the Himalaya. Most of these studies used SKS/SKKS phases for investigating deformation in the lithosphere primarily in the upper mantle. However, the contribution of crust towards seismic anisotropy was not ascertained by these studies. Some of the studies in the Tibetan Plateau emphasized on crustal anisotropy and discussed the mechanisms of deformation in the whole crust beneath the Tibetan Plateau (Ozacar et al., 2004; Sherrington et al., 2004; Sun et al., 2012; Chen et al., 2013; Yang et al., 2015; Wu et al., 2015; Cai et al., 2016). Most of these studies support eastward extrusion of the Tibetan Plateau. Sun et al. (2012) and Yang et al. (2015) reported that major active faults and deep crustal features are the main sources of crustal deformation in eastern Tibet. Such kind of study related to crustal anisotropy is scarce in the Himalaya. A recent study by Paul et al. (2017) discussed the crustal anisotropy in the Trans Himalayan (Eastern Ladakh) region and reported the considerable strength of crustal anisotropy with FPD oriented along the strike of the regional tectonic features.

A number of laboratory experiments have been carried out to study the anisotropic properties of rocks under the controlled pressure and temperature conditions (Birch, 1960, Balakrishna et al., 1976; Siegesmund et al., 1989, Fountain et al., 1992; Christensen & Mooney, 1995; Kern et al., 2001; Punturo et al., 2005; Přikryl et al., 2007; Ji et al., 2007; 2013). The velocities of seismic waves in various igneous and metamorphic rocks have been studied as early as by Birch, (1960), at room temperature and pressure of up to 10 kilo bars which showed that these rocks are anisotropic to seismic velocities. Later, in Balakrishna et al. (1976) estimated the elastic properties of ultramafic rocks of the Peninsular India. Their conclusion led to the understanding that dunite possesses a large range of elastic anisotropy due to great variation in their fabric/foliation. In another study of Johnston and Christensen (1995) the anisotropic behaviour of shale on the seismic velocities was measured through the laboratory experiments and they observed a positive correlation between preferred orientation of minerals and anisotropy. Punturo et al. (2005) studied the effect of anisotropy on the seismic velocities of silicate and calcite rocksandobserved significant anisotropy due to the presence of lattice preferred orientation of the minerals. Přikryl et al. (2007) measured the spatial distribution of seismic velocities in rocks samples and concluded that anisotropy occurs mainly due to microstructures and texture of rocks. Similarly, Ji et al. (2007, 2013) studied the seismic anisotropy characteristics of ultrahigh pressure metamorphic rocks and amphibolitesat high-pressure conditions and provided the constraints on the occurrence of seismic anisotropy. However, very limited numbers of studies on the seismic velocities and its anisotropic characteristics of rocks have been carried out in the Himalaya (Gogte & Ramana, 1982; Gupta, 2009; Sharma et al., 2011; Sharma, 2011; Gupta & Sharma, 2012; Tandon & Gupta, 2015). Gogte and Ramana, (1982) studied the elastic properties of granitoid of the Himalayan and observed that the Trans Himalayan granitoid shows higher density and different velocities than the Lesser and Higher Himalayan granitoid. Gupta, (2009) studied the seismic velocities characteristics of Higher Himalayan rocks of Satluj valley and yield the anisotropic behavior of such rocks. Sharma et al. (2011) studied seismic and petrophysical characteristics of Himalayan granitoid and inferred that the variations of the seismic velocities are controlled by preferred orientation of minerals. Gupta and Sharma, (2012) estimated the seismic velocities parameters of quartzites of Lesser and Higher Himalaya and described their anisotropic behaviour. Tandon and Gupta, (2015) studied the seismic properties of quartzites of the Garhwal Himalaya and estimated the relationship between seismic velocities and preferred orientation of minerals.

1.6 ORGANIZATION OF THE THESIS

The work in the present thesis is outlined into seven chapters and each chapter having separated sections and subsections. The brief description of each chapter is given below:

Chapter 1 titled '*Introduction*' includesthe research problem, motivation, and objectives of the study. It also includes the geological setting with a brief description of all the litho-tectonic units of the study area.A literature review related to the structure of the crust and crustal deformation pattern is also incorporated. Numerous research gaps are identified on the basis of literature are presented in this chapter.

Chapter2 titled '*Receiver Function Method*' mainly focuses on the theoretical framework of RF method, deconvolution technique and pre-processing steps involved in the RF computation. The stacking and inversion techniques used to obtain the shear wave velocity models arealso described.

Chapter 3 titled '*Instrumentation and Seismological Network*' describes the seismological networks: locations of seismological stations, the period of operations and details about different components of seismological stations. The site selection criteria for installation of seismological stations and installation procedure are also briefly discussed.

Chapter 4 titled '*Geometry of the Moho and Main Himalaya Thrust*' describes the crustal structure of the study region as obtained by three different methods e.g. *H-k* stacking of Zhu and Kanamori, (2000), Neighbourhood Algorithm (NA) inversion method of Sambridge, (1999*a*, *b*) and Common Convergent Point (CCP) stacking (Yuan et al., 1997). The variation of crustal thickness and composition of the crust have also been presented in this chapter along with the geometry and characteristic features of the MHT and its linkage with seismicity.

Chapter 5 tilted '*Seismic Anisotropy ofthe crust*' describes the seismic anisotropy of the crust in the study area with the help of shear wave splitting of Moho converted *P*-to-*S* (*Ps*) phases ofteleseismic earthquakes using cross-correlation method of Bowman and Ando, (1987) and laboratory analysis of rock samples using ultrasonic pulse transmission technique of Birch, (1960). The results of the seismic anisotropy presented in this chapter are interpreted in terms of crustal deformation and existing prevailing stressinthe study region.

Chapter 6 titled '*Summary of Results and Conclusions*' summarizesand conclude the research findings of the whole research elaborated in the above-mentioned chapters. Besides, this chapter also incorporates the limitation of the present study and the scope for further research in future.

Chapter 7 titled '*References*' presents the Bibliography cited in the thesis.