EXECUTIVE SUMMARY

The continent-continent collision between India and Asia has resulted in the spectacular Himalayan mountain range, development of large fold and thrust sequences and greater than 1500 km shortening of the crust (Molnar & Tapponnier, 1975; Yin, 2006). The Indian plate is being underthrusted beneath the Eurasian plate along a north-dipping detachment surface named as Main Himalayan Thrust (MHT), separating down-going Indian plate from overriding Himalayan wedge (Seeber et al., 1981). The over-thrusted wedge was formed due to uplift along south-verging thrust planes located from north to south. The Himalayan wedge adjoins with the lithotectonic units: Tethyan Himalaya, Higher Himalaya, Lesser Himalaya and Sub-Himalaya. These litho-tectonic units are separated by faults viz. South Tibetan Detachment System (STDS), Main Central Thrust (MCT) and Main Boundary Thrust (MBT), respectively. The Himalayan wedge is confined between the Himalayan Frontal Thrust (HFT) at the south separating the Sub-Himalaya from the Indo-Gangetic Plain (IGP) and Indus-Tsangpo Suture zone (ITSZ) towards the north, which is considered as the surface collision boundary of India-Asia collision. The major thrust faults are assumed to sole into the detachment-MHT (Seeber & Armbruster, 1981; Ni & Barazangi, 1984; Zhao et al., 1993; Yin, 2006; Avouac, 2007). The MHT accumulates the strain energy originated due to collision and releases accumulated energy in the form of large/great earthquakes e.g. the 1905 Kangra earthquake of magnitude Mw 8.0 and the 1934 Bihar-Nepal earthquake of magnitude Mw 8.0 (Middlemiss, 1910; Ni & Barazangi, 1984; Kayal et al., 2001). Seismological studies reported a ramp structure on the MHT that causes earthquakes (Pandey et al., 1995; Caldwell et al., 2013; Duputel et al., 2016). Significant variation of seismicity along the strike of the northwest (NW) Himalaya has been reported by recent studies (Gahalaut & Kalpna, 2001; Arora et al., 2012). Seismicity in the NW Himalaya mostly concentrates in the Himalayan Seismic Belt (HSB), a narrow belt of 30–50 km width spanning the northern Lesser Himalaya and the southern Higher Himalaya (Arora et al., 2012). The HSB seismicity beneath the Garhwal Himalaya is clustered at the ramp on the MHT (Caldwell et al.,

2013). On the other hand, the HSB seismicity is much less in the southern part of the Satluj river valley, which is possibly due to the absence of ramp structure beneath this segment (Arora et al., 2012; Gahalaut & Kundu, 2012). However, subsurface imaging experiments have not yet been conducted in the Satluj valley to explore the intra-crustal structures. The southern part of the MHT is reported as a locked zone (Bilham et al., 1995; Pandey et al., 1995; Larson et al., 1999) and no great earthquake has been observed in the Himalaya since more than 100 years after 1905 Kangra earthquake. Thus, investigating the geometry of the subsurface structure (e.g. Moho and MHT) is important to understand the seismogenesis of this part of the Himalaya. Moreover, the study of deformation pattern of the crust is an important issue for envisaging geodynamic evolution of the study region.

Keeping in mind the importance of the subsurface structure in the Himalayan region, the work in the present thesis entitled "*Shear wave velocity and crustal structure along Satluj valley, Northwest Himalaya*" has been planned to study the (i) Crustal structure: the nature and geometry of Moho discontinuity and the MHT beneath the Satluj valley, (ii) seismicity and its linkage with crustal configuration and (iii) Seismic anisotropy in the crust for investigating crustal deformation. To fulfill the objectives, earthquake data recorded by 18 broadband seismological (BBS) stations in the study area have been analyzed. The seismological stations are spread over all the major lithotectonic units present in the study area. The southernmost stations Bhagpur (BHAG) and Ramgarh (RMGR) were located over Indo-Gangetic Plain (IGP); Chicken (CKKN) and Garkal (GARH) stations over the Siwalik Group of rocks; Kandaghat (KGHT), Sadhora (SADH), Banjar (BNJR), and Digadhar (DIGA) stations over the Lesser Himalayan Sequence; and Rampur (RMPR) and Sarahan (SARA) stations over the Lesser HimalayanCrystalline Sequence (LHCS). Two stations, Pulga (PULG) and Tapri (TAPR), were located over the Higher Himalayan Crystalline Sequence (HHCS), close to the MCT/Vaikrita Thrust (VT) and the Rackchham (RACK) station is located close to the South Tibetan Detachment (STD). Five stations, namely, Spillo (SPLO), Mudh (MUDH), Kaza (KAZA), Losser (LOSR), and Hurling (HURL) were located over the Tethyan Himalaya (TH). Data from these stations have been analyzed using Receiver function (RF) method and shear wave splitting analysis. The results of this study are briefly summarized below.

(i) Crustal structure along Satluj valley

In order to investigate the crustal structure beneath the Satluj valley region, teleseismic earthquake data recorded by 18 BBS stations have been analyzed using *P*-wave RF method (Vinnik, 1977; Langston, 1979). The RF analysis is an effective technique that utilizes body waveforms of teleseismic earthquakes to image the crustal structures underneath isolated seismic stations. When *P*-waves of teleseismic earthquakes strike an interface between two media with significant velocity contrast, a part of *P*-wave gets converted to *S*-wave producing a *P*-to-*S* or *Ps* converted phases which are well recorded on the horizontal components of the seismogram. The *Ps* phase is isolated from the source and propagation effects by deconvolving the vertical component from the radial and transverse components of the seismogram which produces radial and transverse RFs, respectively. The iterative deconvolution technique of Ligorria and Ammon, (1999) has been adopted to compute RFs. More than 3000 RFs have been computed from 300 teleseismic earthquakes recorded by 18 BBS stations. The teleseismic earthquakes with body wave magnitude (M_b) $\geq$ 5.5 and epicentral distance (Δ) 30° - 90° is selected on the basis of high signal-to-noise ratio. The RFs computed at each station are plotted with respect to back azimuth (BAZ) for investigation of azimuthal variations.

Prior to the detailed modeling of RFs, an estimate of the average thickness of the crust and Poisson's ratio were obtained by applying H-*k* stacking method of Zhu andKanamori, (2000). The H-*k* stacking method uses the travel times of converted phases along with their multiples that arrive in the coda of *P*-wave and estimate the average crustal thickness of converting layer (H) and a ratioof seismic P-wave velocity (*Vp*) and *S* wave velocity (*Vs*). The value of *Vp*/*Vs* (or *k*) is associated with Poisson's ratio (σ) by the following equation:

$$\sigma=0.5[1-((Vp/Vs)^{2}-1)^{-1}]$$

In this study, H-*k* stacking method is applied to selected teleseismic earthquake data recorded at 9 BBS stations (GARH, KGHT, SADH, DIGA, RMPR, TAPR, RACK, SPLO and HURL). The selection of data is based on the clear record of *Ps* phase and its crustal multiples. This analysis could not be performed at rest of the stations due to unclear crustal multiples of *Ps* phase. The H-*k* stacking analysis shows comparatively low Poisson's ratio (σ: 0.225 - 0.249) in the Sub and Lesser Himalaya, intermediate ($\sigma \sim 0.261$) in the Higher Himalaya and high (σ: 0.265 - 0.293) in the Tethyan Himalaya. The low and intermediate Poisson's ratio at stations located in the Sub and Lesser Himalaya are observed to be mainly due to local geology and compositions. The study suggests felsic composition of the crust beneath the Sub and Lesser Himalaya. The most probable reason for the high Poisson's ratio in the TH is the presence of a fluid phase or partial melt in the crust rather than a bulk compositional change in the crust. The low and intermediate values of Poisson's ratio in the Sub-Himalaya, Lesser Himalaya, and Higher Himalaya suggest the absence of such significant partial melting to the south of the TethyanHimalaya. The H-*k* stacking study reveals gradual thickening of crust from ~45 km below the Sub-Himalayan region to ~50 km beneath the Higher Himalaya and ~62 km in the Tethyan Himalaya.

The H-*k* stacking method provides an average estimation of Poisson's ratio and thickness of crust beneath a seismological station; however, for obtaining shear wave velocities at different depths, modeling of RFs is essential. In the present study, Neighborhood algorithm (NA) formulated by Sambridge, (1999*a*, *b*) has been used for RF modeling at all the 18 BBS stations.

The shear wave velocity models at each station are plotted to investigate the characteristic features in the velocity models. In addition to NA modeling, Common Conversion Point (CCP) Migration method (Yuan et al., 1997) is applied to the RFs to obtain an RF image that helps to trace the along-profile variations in crustal structure. The depth migration approach is useful as it projects the Moho depth as well as intra-crustal phases at each location based on ray piercing points. Both the results from NA and CCP are used to infer the crustal structure. The results from NA inversion shows extremely low shear wave velocity (~0.8-1.8 km s^{-1}) in the upper most 3-4 km of the crust beneath the stations near the HFT, which is interpreted as the effect of the sedimentary column of the IGP. An intra-crustal low-velocity layer (IC-LVL) is detected beneath the study profile at most of the stations with variable depth and percentage of velocity reduction. Origin of the IC-LVL at a shallow depth at stations south of the STD is most likely due to the presence of aqueous fluid expelled from underthrusting sedimentary rocks. On the other hand, the presence of partial melt and/or aqueous fluid might be the possible cause of the IC-LVL at a deeper depth in the TH (e.g. at HURL station). The depth of the MHT as identified from both CCP image and the NA models varies within ~16-27 km in the Sub, Lesser and Higher Himalaya and increases to ~38 km beneath the TH, thus forming a ramp. The depth of the MHT thus obtained in the present investigation is comparable with other observations reported in the vicinity of the study profile (Thakur et al., 2000; Chamoli et al., 2011; Caldwell et al., 2013). However, this study reveals gentle northward dipping structure of the MHT between the Sub and Higher Himalaya unlike the reported ramp structure in the Garhwal Himalaya (Caldwell et al., 2013) and central part of the Nepal Himalaya (Pandey et al., 1995; Lavé & Avouac, 2001). The ramp structure is, however, identified further north (~180 km from the HFT), beyond the STD in the Satluj valley. This is significantly a different structure of the MHT beneath the Satluj valley. The thickness of the crust obtained from all the three methods show similar results. The results show ~44 km crustal thickness beneath the HFT, and it gradually increases to ~62 km beneath the TH.

(ii) Seismicity and its tectonic linkage

The spatial distribution of local earthquakes ($M \geq 3.0$) has been studied in Satluj valley for the period 1964 –April, 2017 using the catalog of International Seismological Centre (www.isc.ac.uk). Usually, small and moderate magnitude earthquakes in the NW Himalaya are confined in the HSB (Arora et al., 2012). The spatial distribution pattern of epicenters in the study area shows three well-defined zones based on seismic activity namely (a) Kangra–Chamba region, the seat of the 1905 Kangra earthquake, (b)

Satlujvalley region and (c) the Garhwal Himalaya region. It has been observed that large and moderate magnitude earthquakes are less in the segment of the HSB belonging to the southern part of Satluj valley intervening Shimla region in contrast to Kangra-Chamba region and the Garhwal Himalaya. This suggests disruption of seismicity in this part of the HSB and migration of seismicity towards north near Kaurik Chango Fault (KCF) zone.

The observed seismicity pattern is interpreted as due to the absence of major crustal scale ramp structure beneath the HSB of Satluj valley. The absence of ramp structure is attributed to the effect of underthrusting Delhi-Hardwar Ridge (DHR), a transverse structure to the Himalayan arc (Sastri et al., 1971; Valdiya, 1976; Karunakaran & Ranga Rao, 1979; Raiverman, 2002; Arora et al., 2012; Gahalaut & Kundu, 2012). The subsurface structures in the Himalayan region are controlled by topographic ridges on the underthrusting Indian Plate as well as by rift and nappe structures in the overriding wedge of the Himalaya (Arora et al., 2012; Gahalaut & Kundu, 2012). Underthrusting bathymetric features like the DHR can change the crustal configuration and geometry of the MHT as observed in this study. This segment of the HSB is located west of the DHR and east of rupture zone of 1905 Kangra earthquake. The contrasting seismicity pattern in the HSB beneath the Satluj valley region and adjacent Garhwal Himalaya (Caldwell et al., 2013) along with the corresponding geometry of the MHT in both the regions clearly, reflect the role of ramp structure of the MHT in generating clustered seismicity in the HSB.

(iii) Seismic anisotropy in the crust

Seismic anisotropy is a useful technique to investigate crustal deformation and existing stress pattern in a tectonically active region. It is a common feature in rocks due to the presence of fabric which leads to a directional dependence in seismic velocities causing shear wave splitting. The direction of the fast polarized wave (Φ) and delay time between the split waves (δt) are two measurable quantities that characterize direction and strength of anisotropy. The anisotropy in the crust is mainly originated by aligned micro-cracks developed due to tectonic stresses referred as shape preferred orientation (SPO) and also due to the alignment of intrinsic anisotropic minerals of rocks, defined as lattice preferred orientation: (LPO) (Meissner et al., 2006). The anisotropy induced by micro-cracks is the main cause of upper-crust anisotropy (Crampin & Peacock, 2008), while the LPO is the major source of occurrence of seismic anisotropy in the middle-to-lower crust (Barruol & Mainprice, 1993). The anisotropic minerals in the lower crust are aligned due to tectonics stresses and deformation. The cross-correlation method has been used to study shear wave splitting using *Ps* phases of RFs to investigate crustal anisotropy. It estimates the degree of similarity between two different waveforms as a function of delay time relative to one another. The method involves finding a set of splitting parameters (Φ, δt) that maximize the correlation between the two orthogonal horizontal components.

A total of 137 numbers of *Ps* phases has been selected from 124 teleseismic earthquakes recorded by 13 BBS stations (viz. SADH, DIGA, RMPR, TAPR, BNJR, SARA, RACK, PULG, MUDH, SPLO, LOSR, KAZA, and HURL). The rest of the stations are not used due to the complicated nature of *Ps* phases in tangential components of RFs. The obtained results of FPDs beneath the study area predominantly show NW-SE trend and the delay time ranges from 0.15 to 0.80 s. The splitting parameters show variations at single stations and between different stations. The wide variation of FPDs are observed at few stations (e.g. DIGA, HURL and KAZA) which may be due to the combined effect of anisotropy due to micro-cracks developed owing to tectonic force and also induced by the structure. Another source of scattering of FPDs is the interaction of shear wave with the irregular surface or subsurface topography along the propagating path (Crampin & Lovell, 1991). The result of the present study is comparable to the reported splitting parameters observed in adjacent Ladakh-Karakoram zone (Paul et al., 2017). Despite the scattering of FPDs at the individual station and between different stations, in most cases the average polarization direction of the faster split waves are parallel or sub parallel surface geological features rather than following NE oriented compressive stress pattern suggesting structural anisotropy. This indicates that contribution of anisotropy induced by upper crustal micro-cracks is insignificant. The average FPDs and considerable strength of anisotropy (δt: 0.15 to 0.80 s) suggest a primary contribution of anisotropy from middle and lower crust. The coincidence of anisotropy with orogen-parallel extension direction prevailing in the NW Himalaya suggests that the anisotropy mainly results from the LPO of anisotropic crustal minerals of the middle and lower crust caused by extensional deformation. The predominant NW-SE orientation of FPDs observed in the present study follows the regional tectonic features rather than the NE oriented Ground PositioningSystem velocity vectors (Jade et al., 2011). The observations of splitting parameters indicate that the middle and lower crust within the study region has undergone widespread and relatively uniform strain in response to crustal shortening and extension along the Himalayan arc.

Seismic anisotropy using laboratory analysis of rocks

Seismic anisotropy of rocks has been studied in the laboratory using time of flight' Ultrasonic pulse transmission (ULT) technique (Birch, 1960) at normal pressure andtemperature conditions. This technique uses high energy pulse receiver unit which supplies the electric pulse to the transmitter transducer and the transducer converts the electric signal into a sound wave, by passing through the cylindrical core sample, which is later picked up by the receiving transducer. It determines the compressional and shear wave velocities (V_P and V_S) by measuring the arrival time of the observed signal passing through the specimen (Birch, 1960; Ramana & Rao, 1974; Rao & Lakshmi, 2003). The time required for the wave to propagate through the specimen can be determined by analyzing arrival times of the recorded signal. A total number of 23 samples were collected, including 5 slates (Tethyan meta-sedimentary), 8 gneisses, 5 granites and 5 quartzites. Each sample was drilled to obtain four cylindrically shaped samples by cutting it into two orthogonal directions that are perpendicular and parallel to the foliation plane. Thus, a total of 92 cylindrical cores were drilled from 23 block samples. All cylindrical cores were of 2.50 cm in diameter and 4.0-5.0 cm in length. In this study, the variation in seismic wave velocities (V_P and V_S) and their associated anisotropy coefficient (Ap and As) for all the studied rocks along and across foliation are measured.

The variation in *P*-and *S*-wave velocities for slates is found to be very low. The slates cores exhibit the lowest average *Vp* (2266 m/sec) and *Vs* (1927 m/sec) along the foliation and *Vp* (1261 m/sec) and *Vs* (1114 m/sec) across the foliation planes. The seismic anisotropy coefficient of seismic velocities is measured for all slates cores and it is observed to be lowest for these cores; for *P*-wave, it is varying from 16-21% and for *S*-wave, it is 12-19%. The variation in *P*- and *S*-wave velocities for gneisses core samples is observed to be high. The average seismic velocities for gneisses core samples are *Vp*: 5181 m/sec and *Vs*: 2359 m/sec that measured along the foliation and seismic velocities measured are also highest *Vp*: 5181 m/sec and *Vs*: 2359 m/sec when measured across the foliation. The gneisses core samples exhibit the highest seismic anisotropy coefficient for both *P*- and *S*-wave. For *P*-wave, anisotropy coefficient is varying from 48-79% and for *S*-wave; it is 30-71%. The average *Vp* and *Vs*observed for granites coresamplesare 4811 m/sec, 2570 m/sec, that cut along the foliation plane, while across the foliation it is observed 2485 m/sec and 1850 m/sec. The anisotropy coefficient is also found to be higher in granites cores. For *P*-wave, it is varying from 40 to 61% and similarly, for *S*-wave; it is varying from 21 to 33%. The quartzite core samples found to have highest seismic velocities than the above-measured cores. The average value of seismic velocities is highest for quartzites that are*Vp*: 5436 m/s and *Vs*: 4272 m/sec measured along the foliation and for across the foliation, quartzite core has highest *Vp*: 2855 m/sec and *Vs*: 2493 m/sec seismic velocities. The quartzites core samples are found to have lowest anisotropy coefficient. The Ap is observed to vary from 12 to 24% and As is from 10 to 17%. The velocities observed along the foliations are larger than those measured across the foliations in all the rock samples.

The anisotropy coefficient is also measured for all core samples. It has been observed that the quartzites and slates cores are having low Ap and As. The quartzites core samples are having Ap: 12-24% and As: 10-18% and the slates core samples are having Ap varying from16 to 21% and As from12 to 19%.

The quartzites, being mono-mineralic, show the lowest seismic anisotropy coefficient indicating its isotropic nature. The gneisses which are highly folded and foliated show high coefficient of anisotropy signifies its anisotropic nature. The slates cores are observed to have less developed fracture/foliation and hence have a lowpercentage of anisotropy coefficient. Granites and gneisses are having well-developed fabric/foliation, and are polymineralic rocks. Thus, these core samples have a high value of anisotropy coefficients.