CHAPTER 6

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SUMMARY OF RESULTS AND CONCLUSIONS

6.1 SUMMARY OF RESEARCH WORK

The study is mainly focused on the investigation of crust and intra-crustal features along the Satluj river valley and adjoining area covering the region from the HFT in the south to the Tethyan Himalaya in the north. An attempt has been made in this thesis to address some of the key questions related to the configuration of the crust, deformation processes in the crust, intra-crustal features and its linkage with the present day seismicity in the study area. Seismological data used in this study was obtained from 18 BBS stations along the Satluj valley region. The locations of these seismological stations are chosen as it cuts through all the major litho tectonic units of the NW Himalaya. The RF study carried out in this region provides new information regarding the geometry of the MHT along with the average crustal Poisson's ratio. The study also correlates the relationship between the geometry of MHT with existing seismicity pattern in the study region. Although the complicated stress pattern in the study area is evident from the focal mechanism solutions (FMSs) showing variable source mechanisms e.g. thrust, normal and strike-slip and the geological studies. But not much study has been attempted to understand the deformation pattern of the crust. The present study emphasizes on the crustal deformation pattern based on splitting analysis of *Ps* converted phase originated at Moho depth. The *Ps* phases are collected from the radial and tangential component of RFs. This kind of study is carried out in the region for the first time and results obtained from this study has significant importance in understanding deep deformation processes owing to the India-Asia collision.

This chapter summarizes the significant outcome of the thesis as well as the future scope of the study.

6.1.1 CRUSTAL STRUCTURE ALONG SATLUJ VALLEY

Receiver functions of ~3000 waveforms have been computed from ~300 teleseismic earthquakes recorded by 18 BBS stations established along the Satluj valley region. Iterative time domain deconvolution method of Ligorria and Ammon, (1999) is used for RF computation. Initially, H-*k* stacking method has been applied for analysis of selected RFs showing a clear record of *Ps* phases and its crustal multiples to obtain average crustal thickness and corresponding Poisson's ratio. Only data from 10 seismological stations are selected based on the data selection criteria. This study provides the first-hand information on the crustal thickness beneath the profile and provides a guideline for constructing initial model needed for inversion of RFs. The analysis shows relatively low Poisson's ratio (σ: 0.225 - 0.249) in Sub and Lesser Himalaya, intermediate (σ ~ 0.261) in the Higher Himalaya and high value (σ: 0.265 - 0.293) in the Tethyan Himalaya. The low and intermediate Poisson's ratio values beneath Sub and Lesser Himalaya are observed mainly due to local geology and compositions whereas higher values observed the Tethyan Himalaya is interpreted to be due to the occurrence of a fluid phase or a partial melt. This study reveals gradual thickening of crust from ~45 km underneath Sub Himalaya to ~50 km underneath Higher Himalaya, and ~62 km in the Tethyan Himalaya (Wadhawan et al., 2017).

The NA of Sambridge, (1999*a*, *b*) and CCP method are applied to the RFs for obtaining the shear wave velocity structure and tracing along profile variation of crustal structure. The results from NA inversion shows extremely low shear wave velocity of ~0.8-1.8 km s^{-1} in the upper most 3-4 km of the crust in the IGP and in the southern part of Sub-Himalaya suggesting an effect of sedimentary column existing beneath the stations. Both NA inversion and CCP image suggests gently dipping nature of MHT in the Sub, Lesser and Higher Himalaya (depth range of MHT ~16-27 km) that increases to ~38 km beneath the TH forming a ramp. The absence of ramp structure beneath the region between the Sub, Lesser and Higher Himalaya in contrast to reported ramp structure beneath adjacent Garhwal Himalaya region (Caldwell et al., 2013) suggests a significant variation in the structure of the MHT. The ramp on the MHT is, however, observed in the Tethyan Himalaya. The study shows ~44 km crustal thickness near the HFT that gradually increases to ~62 km beneath the TH (Hazarika et al., 2017).

6.1.2 SEISMICITY AND ITS TECTONIC LINKAGE

The spatial distribution of local earthquakes ($M \geq 3.0$) has been studied for the period 1964 –April, 2017 using ISC catalog to estimate the relationship between the crustal configuration and recent seismicity pattern in the study area. 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 KCF zone. The observed seismicity pattern is interpreted as due to the effect of arc-perpendicular continuation of DHR structure (Sastri et al., 1971; Valdiya, 1976). 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 the generation of clustered seismicity in the HSB.

6.1.3 SEISMIC ANISOTROPY IN THE CRUST

An effort has been made in the present study to understand deformation in the whole crust owing to the India-Asia collision with the help of shear wave splitting study of Moho converted *Ps* phases clearly visible on RFs of teleseismic earthquakes. A total of 137 splitting parameters (Φ, δt) have been computed from the best selected 124 teleseismic earthquakes recorded by 13 BBS stations by applying cross-correlation method (Bowman & Ando, 1987). Despite the variations of FPDs at single stations and between different stations, the average FPDs predominantly show NW-SE trend with the delay time range of 0.15 - 0.80 s. At few stations (e.g. DIGA, HURL and KAZA) wide variation of FPDs are observed indicating the complicated source of anisotropy formed due to the effect of upper crustal micro-cracks and lattice preferred orientation of lower crustal rocks. The average FPDs observed at RMPR, BNJR, SARA, PULG, TAPR, SPLO and MUDH station show predominantly NW-SE trend with average δt within the range of 0.40 - 0.47 s. The FPDs observed at RACK station shows NNW-SSE trend with an average delay time of 0.46 s. The obtained results at LOSR station shows FPDs oriented along E-W direction with average δt of 0.34 s. The northernmost station of the study area, KAZA and HURL are observed to have a wide variation in FPDs and majorly oriented in NW-SE direction with average δt of 0.57 s and 0.46 s, respectively. Despite the scattering of FPDs, in most cases, the average polarization direction of the faster split waves is parallel or sub parallel to surface geological features rather than following NE oriented compressive stress pattern suggesting structural anisotropy. 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 is mainly resulted from the LPO of anisotropic crustal minerals of the middle and lower crust caused by extensional deformation.

6.1.4 SEISMIC ANISOTROPY STUDY IN THE LABORATORY

The measurements of seismic velocities of 23 core samples (5 slates, 8 gneisses, 5 granites and 5 quartzites) have been done using ULT-100-Ultrasonic velocity testing system at room temperature and pressure conditions in the laboratory. Seismic velocities (Vp and Vs) of cylindrically core samples were estimated in two directions i.e., along and across the foliation plane using 'time of flight' ULT technique (Birch, 1960) and the seismic anisotropy coefficients of *P*-wave (Ap) and *S*-wave (As) for all cores samples are also measured. The obtained seismic velocities results for slates are found to very low. In the case of slates cores, *Vp* is varying from 2266 m/sec to 3459 m/sec and *Vs* from 1261 m/sec to 1597 m/sec, along the foliation and for across the foliation, *Vp* is observed to vary from 1927 m/sec to 2877 m/sec and *Vs* is 1114 m/sec to 1373 m/sec. The gneisses core samples exhibit highest *Vp* and *Vs* in both directions. For gneisses, the average *Vp* is varying from 4370 m/sec to 5181 m/sec and *Vs* is from 2004 m/sec to 2359 m/sec along the foliation and for across the foliation, *Vp* is varying from 1973 m/sec to 2879 m/sec and *Vs* is 1043 m/sec to 1544 m/sec. The granites cores are also observed to exhibit highest velocities. The *Vp* is varying from 4267 m/sec to 4811 m/sec and *Vs* is from 2059 m/sec to 2529 m/sec measured along the foliation and across the foliation, *Vp* is from 2400 m/sec to 2980 m/sec and *Vs* is from 1662 m/sec to 1852 m/sec. For quartzites core samples, *Vp* and *Vs* are observed to very high; *Vp* is varying from 4205 m/sec to 5436 m/sec and *Vs* is 2151 m/sec to 2855 m/sec along the foliation and across the foliation, *Vp* is varying from 3309 m/sec to 4521 m/sec and *Vs* is 1885 m/sec to 2493 m/sec.

The seismic anisotropy coefficients are estimated for all core samples and it is observed that gneisses and granites are exhibit highest coefficients values; for gneisses, average Ap is 79% and As is 71 % and for granites, average Ap: 61 % and As: 29 %. The anisotropy coefficients are found lowest for quartzites and slates. For quartzites, average Ap is 12 % and As is 10 % and for slates, Ap is 16 % and As is 12 %. These results show that quartzites are more anisotropic in nature than gneisses and granites and show a clear anisotropy in the ultrasonic velocities in both *P*-and *S*-waves traveling along the foliation are faster than those traveling across the foliation.

6.2 CONCLUSIONS

In order to fulfill the research objectives of the thesis, different passive seismological techniques like RF analysis and its modeling, H-*k* stacking analysis, CCP migration and seismic anisotropy in the crust have been adopted. The present study provides constraint on the geometry of the intra-crustal features and the crustal structure in the Satluj valley region. Major conclusions of the present thesis are listed below:

1. The crustal thickness obtained from H-*k* stacking, NA modeling and CCP stacking shows similar results. The depth of Moho shows gradual dipping trend starting from ~44 km at the stations south of the Himalayan Frontal Thrust to ~62 km beneath the Tethyan Himalaya. This observation is in conformity with under-thrusting of the Indian plate beneath the Himalaya and Tibet.
2. The NA modeling and CCP image infers that the MHT is gently dipping towards north from Sub Himalaya (at ~16 km depth) to Higher Himalaya (at ~27 km) unlike the reported ramp structure in the Garhwal Himalaya and Nepal Himalaya. However, the ramp structure is identified further north (~180 km from the HFT) of the profile beyond the STD. The depth of the MHT increases from ~27 km near the STD to ~38 km beneath the TH.
3. The significant along strike variation in the structure of the MHT is attributed to the effect of underthrusting Delhi-Hardwar Ridge which is a transverse structure to the Himalayan arc. The subsurface structures in the Himalayan region are controlled by topographic ridges on the underthrusting Indian Plate. Underthrusting bathymetric features like the DHR can change the crustal configuration and geometry of the MHT as observed in this study.
4. The shear wave velocity models obtained from NA modeling reveal extremely low shear wave velocity (~0.8-1.8 km s^{-1}) in the upper most crust in the IGP as well as in southern part of the Siwalik Himalaya indicating a ~3-4 km thick sedimentary column beneath the stations. These sediments are the deposits eroded from the higher topography of the Himalaya into the foreland basin. The results are in conformity with the previous studies carried out in the IGP as well as other sedimentary basins elsewhere.

5. An Intra-Crustal Low Velocity Layer is detected beneath the study profile at most of the stations with variable depth and percentage of velocity reduction. Origin of IC-LVL at shallow depth at stations south of the STD is most likely due to presence of aqueous fluid expelled from underthrusting sedimentary rocks. On the other hand, presence of partial melt and/or aqueous fluid might be the possible cause of IC-LVL at deeper depth in the TH (e.g. at HURL station).
6. The Poisson's ratio estimations beneath the Satluj valley shows low value of σ in Sub and Lesser Himalaya (σ: 0.225-0.249), intermediate in Higher Himalaya (σ : 0.261) and high in the Tethyan Himalaya (σ : 0.265-0.293).
7. The low and intermediate Poisson's ratio values at stations to the south of the STD is possibly due to local geology and compositions, extremely high Poisson's ratio to north of STD (at HURL station) is interpreted as due to the presence of fluid/partial melt in the crust rather than change in bulk composition.
8. The shear wave splitting study provides important information of the crustal deformation. The NW-SE oriented average polarization direction of the faster split waves are parallel or sub parallel to surface geological features rather than following NE oriented compressive stress pattern suggesting structural anisotropy.
9. The observed strength of anisotropy (delay time: 0.15-0.80 s) suggests primary contribution of anisotropy from middle and lower crust. The coincidence of FPD 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. Coherent NW-SE trend of FPDs at all the stations suggest widespread and relatively uniform strain existing in the region in response to crustal shortening and extension along the Himalayan Arc.

10. The laboratory measurements of seismic wave velocities for different rock samples shows that velocities of *P*- and *S*-wave are higher along the foliation than across the foliation. This observation is much prominent for gneisses, which have a very well defined tectonic fabric/foliation. For quartzites, which have a very weak tectonic fabric, the variation in *Vp* and *Vs* along the foliation to across the foliation is not strong.
11. The quartzites, being a monomineralic rock, show the lowest seismic anisotropy coefficient which indicates its isotropic nature. The gneisses which are highly folded and foliated shows high coefficient of anisotropy signifies its anisotropic nature.

6.3 LIMITATIONS

The present study carried out RF analysis in a profile consists of 18 BBS stations along the Satluj valley spanning ~200 km from the IGP to the TH. The average spacing of the stations is ~18 km which is too high to obtain high-resolution RF image. The modeling of RFs provides subsurface information limited to a volume beneath a single station. Therefore, to obtain a lateral variation of subsurface structure, the sufficient number of stations is needed. The resolution of RF image also depends on frequency. The broadband waveform data provides an opportunity to compute high-frequency RFs for obtaining high resolutions images; however high-frequency waveforms are usually contaminated by scattering effects. In this study, the modeling is carried out considering the assumption of layered half space model for mathematical simplification. Such simplification/assumptions often cannot explain real earth's structure. The obtained shear wave velocity models can be further modified considering the effect of anisotropy, dispersion of seismic waves and dipping layers. This study also exploits the shear wave splitting of Moho converted *Ps* phase to investigate the crustal anisotropy and deformation in the entire crust. Although the *Ps* phase splitting parameters bear the anisotropic information of the whole crust, it is difficult to ascertain the contribution from upper crust, middle and lower crust separately. The shear wave splitting of *S*-wave of local earthquakes is helpful in ascertaining the contribution from micro-cracks developed in the upper crust due to tectonic force.

6.4 FUTURE SCOPE

The present study can be improved by combining the joint inversion of RF data and surface wave data. The RFs are quite sensitive to any impedance contrasts beyond the layer. On the other hand, absolute values of the shear wave velocities can be obtained from the surface wave data. These two complementary data sets can be readily used to develop better-constrained velocity models by means of joint inversion technique with the advantage of minimizing the limitations of non-uniqueness in RF inversion (Ammon et al., 1990) and a well-constrained surface low-velocity layer. The intra-crustal features like the MHT and IC-LVL observed in this study can also be well constrained by other geophysical investigations like magnetotelluric study. The crustal structure study carried out in this thesis can be extended to investigate the geometry of deeper discontinuities like Lithosphere-Asthenosphere boundary (LAB) and other mantle discontinuities (at ~410 km and ~660 km depth). Investigation of such deeper structure can be done with the help of joint inversion of *P*- and *S*-receiver functions.

Seismic anisotropy in the crust can also be studied by analyzing group velocity and phase velocity of the split waves in anisotropic media. The study of seismic anisotropy can further be extended with the help of shear wave splitting analysis of core refracted phases e.g. SKS, SKKS and PKS to investigate anisotropy in the upper mantle. The deformation pattern as observed by the shear wave splitting study can be combined with earthquake source mechanism study using moment tensor analysis of local earthquakes to investigate the average stress prevailing in the region. The study of seismic anisotropy of rock samples can be improved by analyzing the samples in controlled pressure and temperature conditions.