5. Solid Earth Modelling Programme

During this year the group signed MOU with University of Kashmir and Indian Institute of Astrophysics for academic and scientific collaboration. Further, Major Lab project with a budget of ∼INR 3.5 crores was sanctioned to our group for seismic studies in Jammu, Kashmir and Ladakh region, On the research front, we majorly focused on the implications of crustal structure and crustal velocities on the seismic hazard of tectonically active northwest Himalaya. For the first time, we integrated the GNSS and Broadband data in Kashmir valley and adjoining regions and concluded that magnitude Mw ∼7.8 earthquake is over due in this region. We published the first high resolution (0.5 X0.5 degree) shear wave velocity structure of northwestern Himalaya extending from Hindu Kush through Kohistan-Nanga Parbat to Kashmir Himalaya, as well as the Pamirs in the north and Lesser Himalaya along with the foreland basin including the Hazara syntaxis in the south providing significant insights in to low and high velocity layers and Moho depth. We analysed the broadband seismic observation network data of Kashmir-Zanskar region to estimate the sensor orientation, seismic noise and their effect on seismic anisotropy. Microtremor measurements of Srinagar city were used to obtain the two and three dimensional subsurface geological features which in turn aid in mitigating the earthquake impact. We gave detailed crustal structure model of Gharwal Himalaya from foothills to south Tibet detachment. Further, composite analysis of strain budget using geodetic and seismic moment rates of Gharwal-Kumaun region of northwest Himalaya indicate high locked strain budget which has a potential to generate a megathrust earthquake (Mw 8). GNSS remote sensing studies yielded correlation between atmospheric opacity and water vapour for two decades at high altitude Indian Astronomical observatory at Hanle in northwest Himalaya. In addition, GNSS remote sensing studies gave significant insights in to the short and long term ionosphere variability over Indian subcontinent. For the first time we published the Impact GPS, Glonass and Combined GPS+ Glonass signals on the position and velocity estimates of Indian subcontinent. Our research yielded about 7 high impact SCI publications and about 300 citations during this year.

Inside:

- 3D-Shear wave velocity structure beneath North-Western Himalaya and adjoining areas
- Misorientation and Noise analysis of the Kashmir-Zanskar seismic network

- Imaging subsurface geological complexity (2D/3D) beneath Greater Srinagar region of Kashmir basin, Northwest Himalaya
- Nature of MHT in Garhwal Himalaya using shear wave velocity modelling
- Atmospheric opacity and water vapor trends over high altitude astronomical observatory at Hanle
- Evaluation of the Performance of IRI model VTEC using GPS TEC
- Implications of high GNSS rates in Kashmir Valley
- GNSS and its impact on position estimates in Indian subcontinent
- Seismic Potential of Gharwal-Kumaun Himalayas
- Estimation of Seismic strain rates in North-West Himalaya

5.1 3D-Shear wave velocity structure beneath North-Western Himalaya and adjoining areas

A detailed shear-wave velocity structure (Vs) is necessary for precise earthquake locations, modeling of earthquake hazard etc. Here we develop a high-resolution (0.5*0.5 degrees) Vs model of NW Himalaya utilizing data from Kashmir-Zanskar network and nearby national and international deployments. The model was obtained by inverting 2-D surface wave tomographic maps using a Bayesian approach. This method enables us to report robust errors on our Vs estimates unlike linear(ized) inversion schemes. The tomographic maps were also inverted for Moho depths and the obtained depths were compared with those reported by other workers. The results yield the first high resolution shear wave velocity structure of northwestern Himalaya extending from Hindu Kush through Kohistan-Nanga Parbat to Kashmir Himalaya, as well as the Pamirs in the north and Lesser Himalaya alongwith the foreland basin including the Hazara syntaxis in the south. The major findings are: a) a pervasive low velocity layer (3km/s) beneath the region at 30 km depth b) shallow high-velocity signature beneath the high-crystalline complexes of the NW Himalaya and gneiss domes of the Pamirs (Figure 5.1) c) high velocity root of the Nangaparbat syntaxis and d) shallow Moho beneath the NW Himalaya by 10 km compared to its adjoining regions.

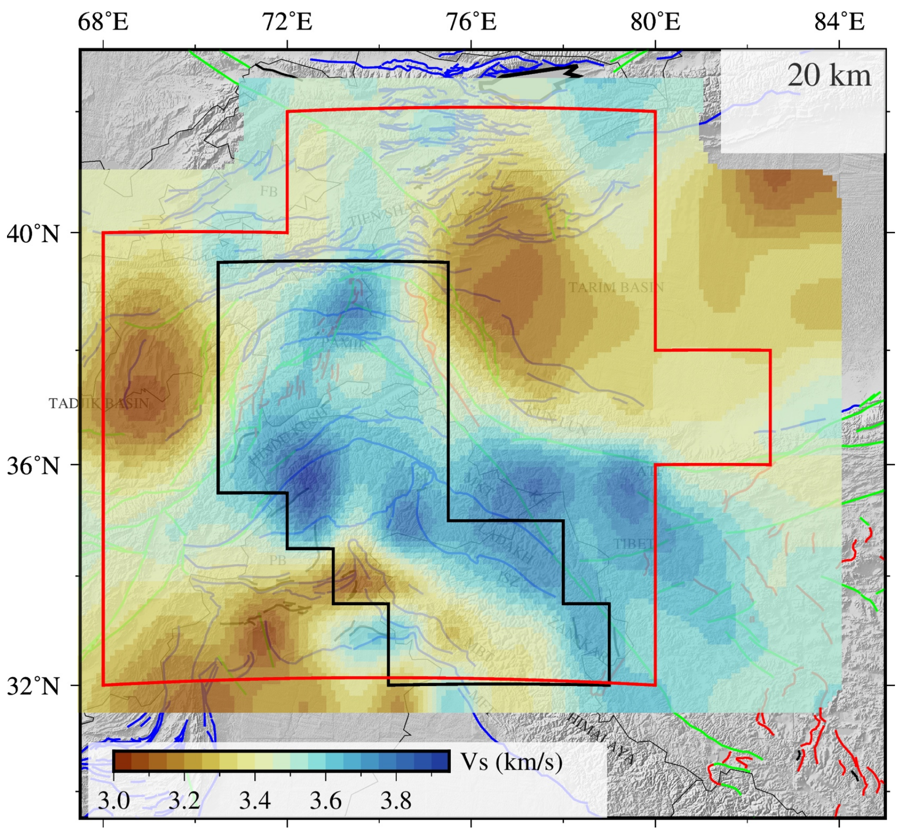

Figure 5.1: Shows the posterior Vs slice at the depth of 20 km. Red and black polygons respectively demarcate resolvable regions of resolution $1^0 \times 1^0$ and $0.5^0 \times 0.5^0$.

5.2 Misorientation and Noise analysis of the Kashmir-Zanskar seismic network

High quality data recording is first and foremost goal for all seismic networks preferably for temporary ones – owing to their shorter duration. Despite considering all factors like instrument siting on in-situ bedrock, less anthropogenic noise, well-marked geographic orientation, etc. still errors in sensor positioning and noise does affect or restrict the data usage for further analysis. Here for Kashmir-Zanskar network we estimate sensor misorientation (e.g. see Figure 5.2 for station KRG) as well as seismic noise at all broadband stations since their inception. The former is done by using global surface wave records of earthquakes (M>=5) and the latter use about a month-long continuous data, recorded at 100 samples per second, during summer season to estimate energy content of various recorded frequencies. We observe that obtained misorientations have a strong influence over seismic anisotropy measurements of the region, whilst having less influence over the crust-mantle boundary (Moho) depth estimates. Also, we found that within Kashmir basin the earlier reported microseismic events (ML $\sim$1) are well distinct due to less ambient noise of the recording stations.

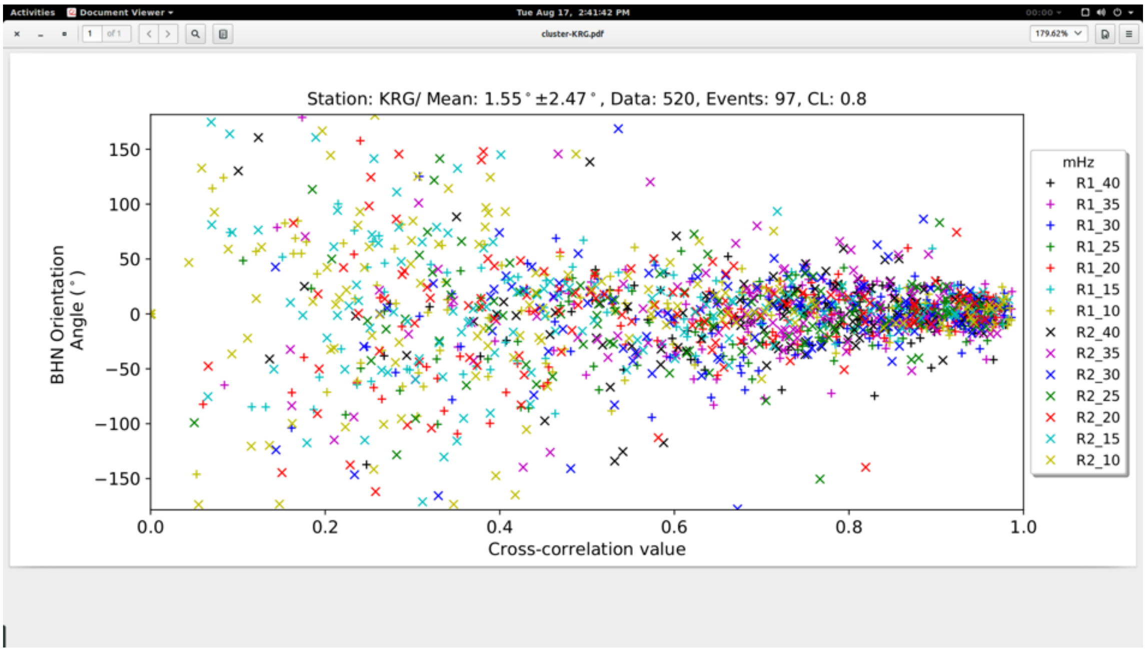

Figure 5.2: Final result at station Kargil having mean misalignment of 1.55^0 using 97 unique events. The individual measurements (‘+’ and ‘x’) are obtained for frequency range 10-40 mHz for both first-minor (R1) and first-major (R2) arcs.

5.3 Imaging subsurface geological complexity (2D/3D) beneath Greater Srinagar region of Kashmir basin, Northwest Himalaya

A high resolution microtremor measurement in Greater Srinagar city of Kashmir valley has been analyzed to image 2D and 3D subsurface geological complexities. This region falls under a highly seismogenic Himalayan belt and sits atop of deep sedimentary lake bed with laterally varying thickness of soft sediments. Srinagar region is a major economic center and capital city of Kashmir valley with 2 million inhabitants living at high seismic risk. To accomplish subsurface complexity beneath the city, we present: (1) High-resolution subsurface shear wave velocity Vs structure using the Horizontal to Vertical Spectral Ratio (HVSR) inversion, (2) time averaged shear wave velocity for top 30 meters of soil column (VS30) map with NEHRP site classification, and (3) azimuthal behaviour of HVSR peaks, all of which unravel the subsurface spatial heterogeneity and engineering efficacy beneath the study area (Figure 5.3). The presented potentiality of microtremor

HVSR (mHVSR) technique over Srinagar region which lies on the eastern edge of basin with significant topographic irregularities indicates uneven distribution of local site effects (primary and secondary) in case of strong ground motion. The novel comprehensive results can be promising in engineering analyses of local ground and structural responses in order to mitigate the impact of earthquake risk in the city and adjoining regions.

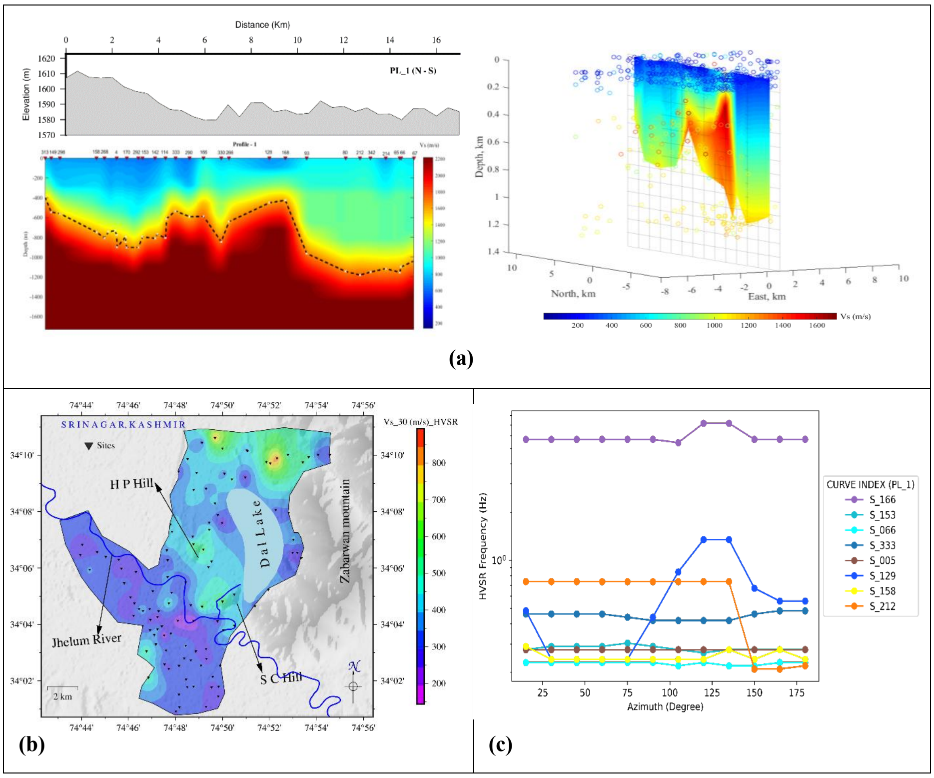

Figure 5.3: (a) The Vs profile (2D and 3D) cross-section with topographic variation, (b) V_{S30} distribution for Srinagar metropolitan region and, (c) azimuthal variation (at the interval of =15^0) of HVSR peak frequency across the Srinagar region and its suburbs.

5.4 Nature of MHT in Garhwal Himalaya using shear wave velocity modelling

The Himalayan range, formed due to continued subduction of the Indian plate beneath the Eurasian plate beginning about 55 Ma ago, is structurally dominated by various thrusts and detachment such as the Southern Tibetan Detachment (STD), the Main Central Thrust (MCT), Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). It is widely accepted that most of the thrust of the Himalayan range (MCT, MBT & MFT) are rooted into a common decollement termed the Main Himalayan thrust (MHT), which is a detachment between the base of Himalayan thrust wedge and the top of the subducting Indian plate.

We investigated crustal structure of Garhwal Himalaya using joint inversion of interpolated receiver functions along a NE-SW profile from 19 seismic stations and surface wave data with high resolution. The estimated velocity image highlights several important features of the crust in the region. The geometry of the Main Himalayan Thrust (MHT) along which the Indian crust under-thrusts is mapped as flat - ramp - flat structure across the Himalaya. The flat section is at a depth of about 8 km beneath the southern edge of the Himalaya and dipping at 3^0N. This geometry is inferred from the presence of low shear velocity (3.1-3.4 km/s) representing wet sediments dragged along the MHT and lying above the crystalline Indian crust with Vs of 3.6 km/s. At the front of High Himalaya, the dip of MHT changes significantly to about 35^0 – 40^0 representing the ramp, reaching to a depth of 20 km and continuing as a nearly flat structure beneath the High Himalaya and further north (Figure 5.4). The increase of dip to 40○ would significantly reduce the seismic decoupling zone width to about 33%, influencing the capacity to store elastic energy and hence the amount of slip deficit at the time of rupture. In the middle crust at a depth 20– 30 km we observe low velocity below the northern part of the Lower Himalaya. Thickness of the crust is ∼50 km beneath the Sub and lower Himalaya and increases abruptly in the front of High Himalaya to 60 km and remains so till the southern part of Tethys Himalaya. The observed thick crust with lower seismic velocity (and rigidity) beneath the High Himalaya could be responsible for its high topography.

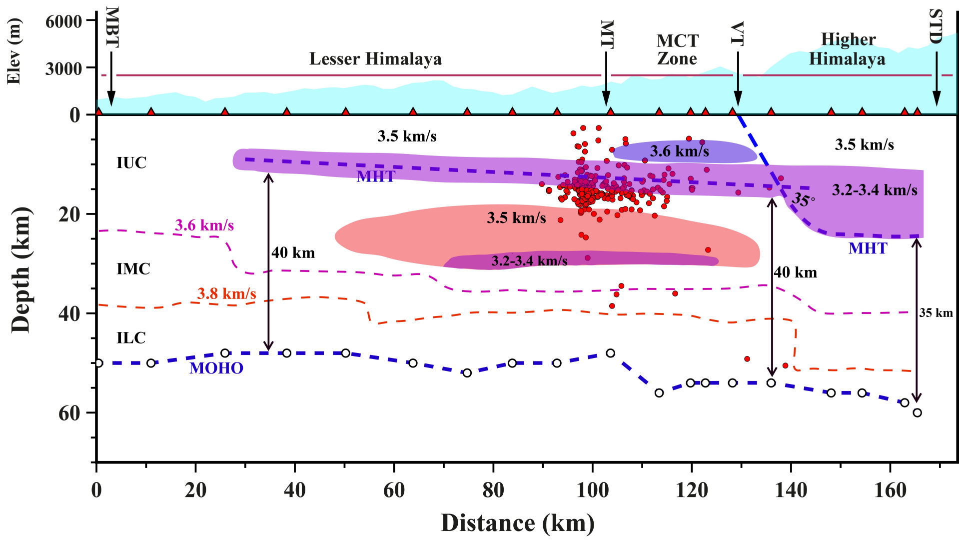

Figure 5.4: A schematic representation of velocity structure model of the crust along a NE-SE profile in Garhwal Himalaya from HFT to STD. IUC- Indian Upper Crust, IMC- Indian Middle crust, ILC, Indian Lower crust.

5.5 Atmospheric opacity and water vapor trends over high altitude astronomical observatory at Hanle

Atmospheric opacity at 220GHZ over Indian Astronomical Observatory (IAO) at Hanle is estimated using Radiometer data from 2006 to 2018 and compared with high temporal resolution GPS-PWV (Global Positioning System- Precipitable Water Vapor). The results indicate linear correlation (Figure 5.5) with a correlation coefficient of 0.8. Opacity at Hanle increased 44% during this period due to the dynamics of regional and global hydrological cycle. Water vapor at nine high-altitude astronomical observatories spatially spread across the globe using satellite and reanalysis data indicate increasing trends pointing to non-uniform dynamic hydrological cycles. This study was carried out to identify future sites for establishment of infrared and sub-millimeter astronomical facilities.

5.6 Evaluation of the Performance of IRI model VTEC using GPS TEC

The empirical model International Reference Ionosphere (IRI) is developed under the joint sponsorship of the Committee on Space Research (COSPAR) and the International Union of Radio Science

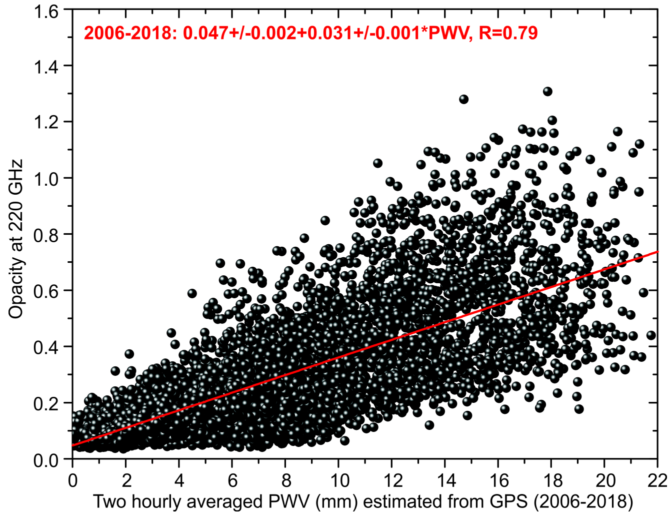

Figure 5.5: Scatter plot between 2 hourly opacity and GPS-PWV over IAO-Hanle.

(URSI) is the worldwide most used model for ionospheric parameters. Using worldwide a network of ionosondes, incoherent scatter radars, different topside sounders, and in-situ instruments IRI model provides the electron density, electron temperature, Vertical TEC (VTEC), and so on. TEC

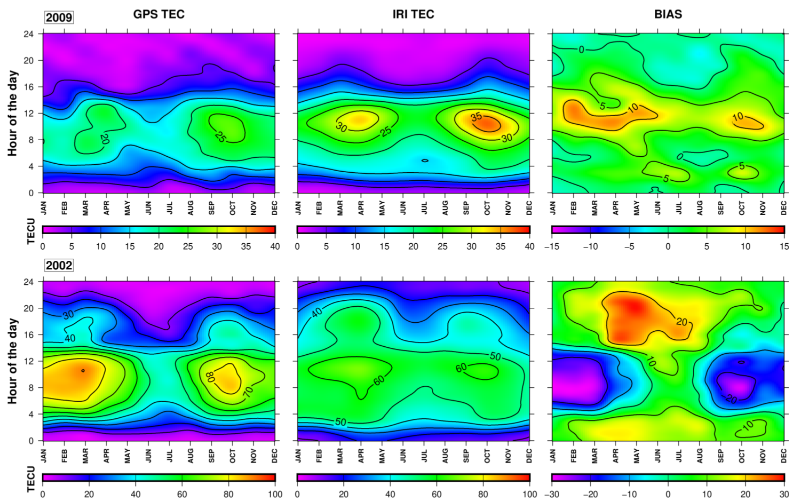

Figure 5.6: Diurnal monthly mean contour plots of IRI and GPS TEC, bias at IISC in 2002 and 2009.

variations are high in the equatorial and low latitude regions due to Fountain effect associated with the Equatorial Electro Jet (EEJ) current, plasma fountain, and Equatorial Ionization Anomaly (EIA). The long-term validation of the IRI model VTEC on Indian low latitude and equatorial regions are studied using Global Positioning System derived TEC (GPS TEC) calculated from dual-frequency GPS signal observables (L1, L2, P1, and P2) recorded in ground stations. Figure 5.6 shows the contour plots of diurnal monthly mean IRI model VTEC, GPS TEC, and bias in the year 2002 (high solar activity year) and 2009 (low solar activity year) at low latitude station IISC, Bangalore. This study will help to improve the IRI model performance for PNT applications in the Indian region.

5.7 Implications of high GNSS rates in Kashmir Valley

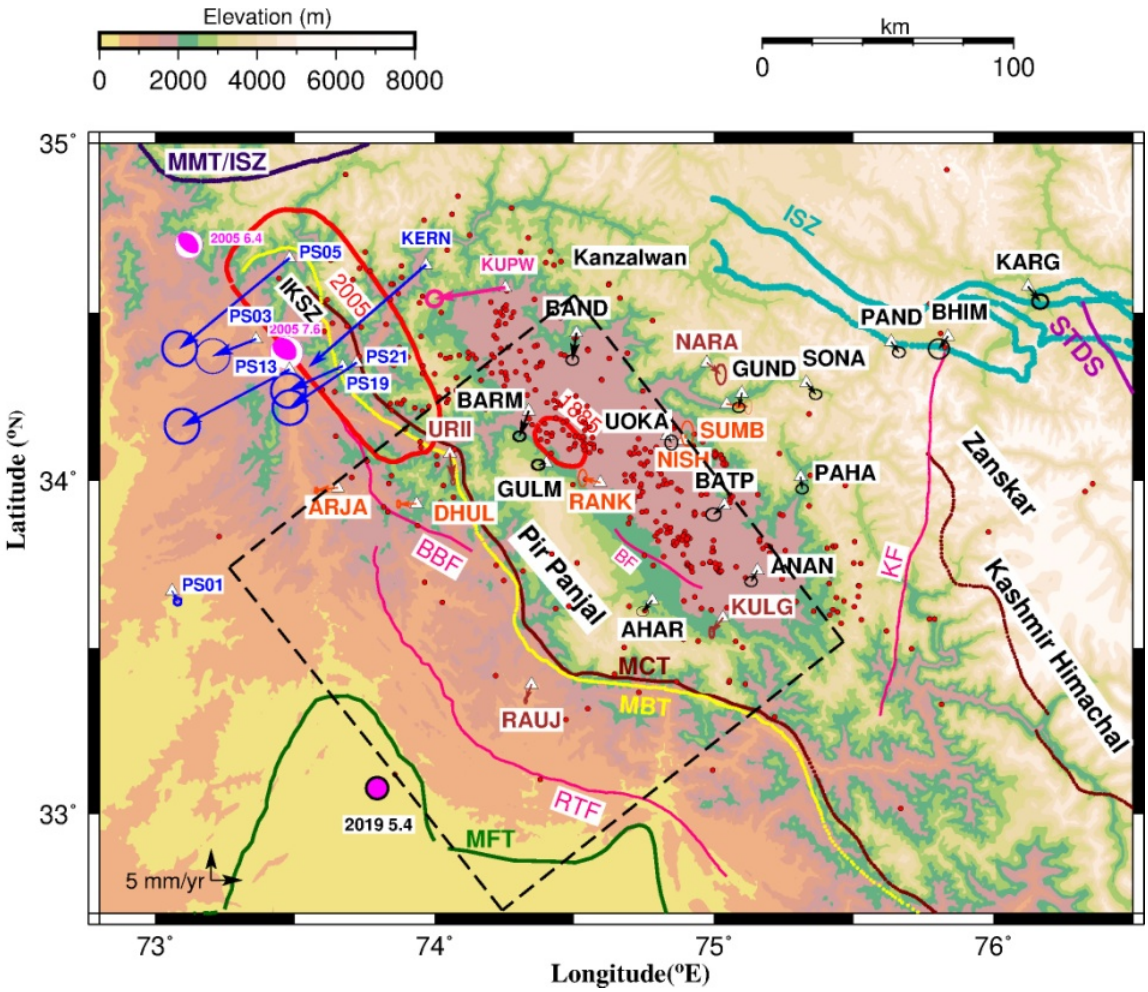

Figure 5.7: Topographic Map of Kashmir valley and adjoining regions along with surface projection of dislocation plane (dashed box) with residual velocities of the cGPS sites Solid red circles denote seismic events of M≥1 from collocated broadband network. India fixed velocity (bold Pink) is plotted at KUPW GPS site to the extreme northwest of Kashmir valley. Blue velocity vectors at Pakistan GPS sites denote post seismic displacements of October 2005 Muzaffarabad earthquake during March 2007 to August 2009 and Indian GPS site KERN soon after the earthquake.

Crustal deformation rates using Kashmir cGNSS (Continuous Global Navigation Satellite System) observation network (2008-2019) indicate oblique surface deformation of about 16mm/yr in Kashmir Valley and adjoining regions. Inverse modeling of surface crustal rates give slip of 16mm/yr at a depth of 15km (Figure 5.7) along the 145km wide Main Himalayan Thrust (MHT). High geodetic strain rates observed to the north of Kashmir valley and south of Zanskar ranges is consistent with northern edge of locked MHT mapped using seismic activity and inverse models. Since there was no earthquake since 1555, the total slip during the intervening 465 years is 7.6m which is capable of generating Mw 7.8 earthquake in Kashmir valley which is corroborated by the high scalar geodetic moment accumulation rate and micro-seismicity recorded in Kashmir valley.

5.8 GNSS and its impact on position estimates in Indian subcontinent

This study evaluates the impact of multi-GNSS (Global Navigation Satellite System) signals on the estimation of precise position with millimetre accuracy. Compared to standalone satellite system like Global Positioning System (GPS), multi-GNSS improves start-up time, performance, satellite visibility, accuracy, spatial geometry and reliability but on the flip side it increases the noise, signal interference, hardware complexity of receiver, inter-system interference and computation complexity which may degrade the performance. Our pilot study indicates that multi-GNSS does not significantly improve the positional accuracy but it eliminates the dependency on a particular satellite system in the long term.

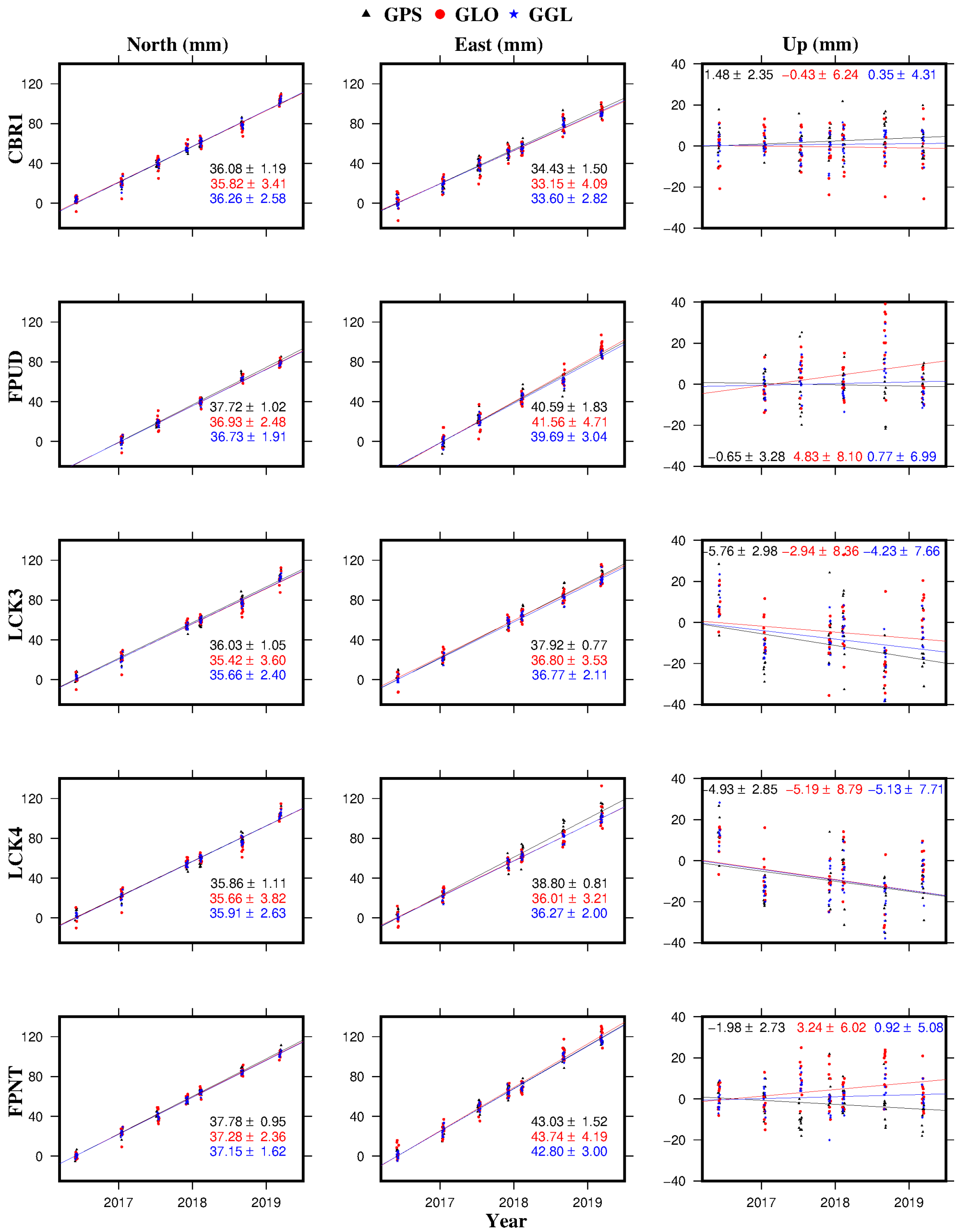

Figure 5.8: Multi-year time series of N.E and U positions/velocities using stand alone and combined GPS and Glonass observations.

Position time series (Figure 5.8) of multi-GNSS is much more stable than single GNSS with errors. For Indian subcontinent, GPS solution gives precise estimates of position and rates (Figure 5.8) compared to Glonass and combined GPS-Glonass solutions. This is due to poorly resolved additional ambiguity terms in GLO and GGL solutions for long baselines and also due to poor spatial spread of IGS sites equipped with multi-GNSS receivers.

5.9 Seismic Potential of Gharwal-Kumaun Himalayas

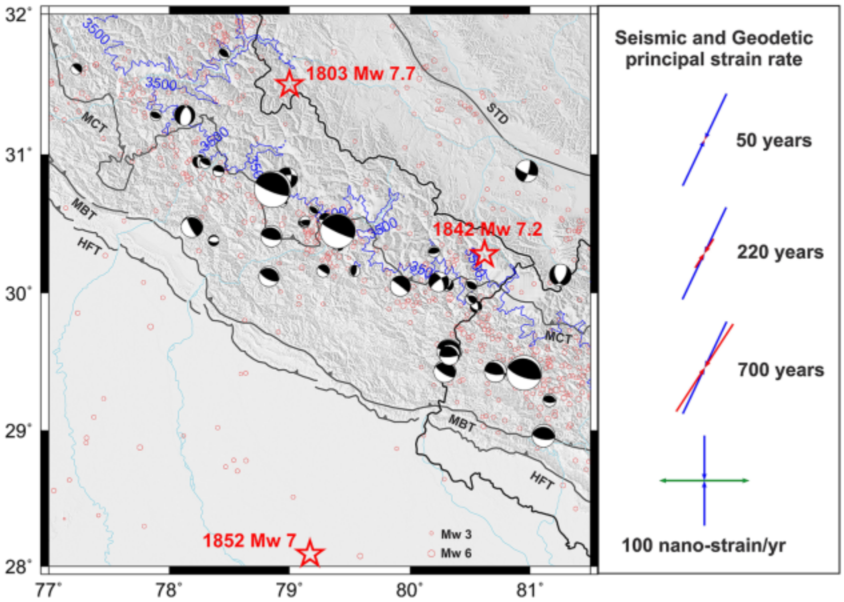

Figure 5.9: Seismicity and major faults in Kumaun-Garhwal region. The rightmost plot represents the comparison of amount and orientation of principal strain rates derived from geodetic and seismic data.

Composite analysis of past 20 years of GPS strain rates and seismic strain rates from 50, 220 and 700 years earthquake catalogue was carried out to estimate the seismic potential of Gharwal-Kumaun (GH-KU). Results indicate geodetic compression rate of 113 nano strain/year towards NNE in the Higher Himalaya. Seismic strain rates estimated are about -10ns/yr for 50 years, -38ns/yr for 220 years and -115ns/yr for 700 years of earthquake catalogue (Figure 5.9). This indicates that the length of seismic catalogue used for seismic strain analysis should be comparable to the recurrence period of megathrust earthquakes for the released seismic strain energy to be equal to the stored elastic strain energy. The orientation axes of the principal strain rates derived from geodetic and seismic strain rates from catalogue of different duration point to N25^0 to N35^0 compression (Figure 5.9). Analysis of strain budget using geodetic and seismic moment rates of GH-KU indicate high strain accumulation with locked strain budget of $\sim$ 5E + 21 Nm in the past 700 years which has a potential to generate a megathrust earthquake (Mw $\geq$ 8) in the present scenario.

5.10 Estimation of Seismic strain rates in North-West Himalaya

Seismic strain rates in North-West Himalayan are calculated using compiled earthquake catalogue of International Seismological Centre (ISC) for instrumental period (1964 to 2020). Magnitude completeness, seismogenic thickness and cumulative seismic moment are derived using ZMAP tool

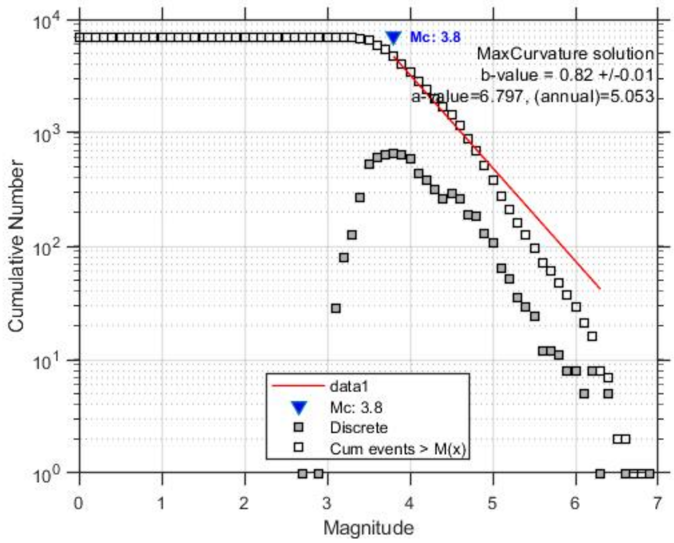

Figure 5.10: b-value estimation using magnitude completeness from maximum curvature method. The square and shaded square shows the cumulative and non-cumulative number of different size of events respectively.

and plotted in Figure 5.10 which gives magnitude completeness as 3.8. Hence, we utilized the fault plane solutions of the earthquakes Mw≥3.8 from Global Centroid Moment Tensor (GCMT), USGS catalogues and also from the earlier studies in this region to estimate the seismic strain. The focal mechanisms of earthquakes reveal the orientation of stress/strain in this particular region. Therefore calculation of seismic moment (Mo) with known fault plane solutions gives the deformation caused by the earthquake. Total seismic moment of the region is the sum of seismic moment of each event which is converted in to seismic strain using kostrov formulations. This study provides the knowledge about seismic hazard assessment in the North-West Himalayan region.