Executive Summary

The NW Himalaya (30°– 33°N, 76°–80°E) originated due to the continuing India-Eurasia continental convergence since Cenozoic time (~55 Ma) is largely believed to be multifaceted tectonic processes including earthquakes, landslides and other natural occurring disasters in different times, some on annual basis and others at unpredictable times . The complexity in the geodynamic evolution of the Himalaya region had experienced series of earthquakes of which 553 number of the earthquakes having an intensity range from II to X on Modified Mercelli (MM scale) occurred in the study region (30°– 33°N, 76°–80°E) in the last 50 years. This NW Himalaya region covering the two major states especially Uttarakhand and Himachal Pradesh of Northern India is placed in Seismic zone 4 and Seismic zone 5 in the hazard zonation map of India. Therefore the complexity involving different intensity of earthquakes, periodic seismic tremors reveal the continuous active tectonic process has been operational over the entire region covering an area of 1,09,156 sq. km. The present study using a combined geophysical techniques of both gravity and seismological tools is an attempt to unravel secrets of active tectonism. This research based on the methodological advantage of uninterrupted monitoring of active geophysical data, attained by the national institute of global importance, WIHG, Dehradun, is to support geophysical research investigations to a better academic and research.

This lateral and vertical growth in this Himalayan segment is accommodated along a series of NW-SE trending crustal fault systems. These major fault systems are categorised as the Southern Tibetan detachment, the Main Central thrust, the Main Boundary thrust, and the Himalayan Frontal thrust. The above defined series of fault systems separates the curved orogen into four principal lithological tectonic provinces, from south to north that can be named as the Sub-Himalaya, the Lesser Himalaya, the Higher Himalaya, and the Tethyan Himalaya (Gansser, 1964). These tectonic units bounded by major faults in the NW Himalaya can accommodate about ~30%–50% of

India-Eurasia plate convergence (Banerjee and Bürgmann, 2002; Zhang et al., 2004). The southward propagation of the major thrusts in the area symbolise the process of thrusting and shortening starting from the Main Central thrust (since 23–20 Ma; Hodges et al., 1996) to the Main Boundary thrust (since 11–9 Ma; Meigs et al., 1995) to the Himalayan Frontal thrust, which has been active since the Pliocene (Molnar, 1984; Wesnousky et al., 1999).

In the NW Himalaya mainly the resultant crustal seismicity are largely characterised by the occurrence of approximately 90 % of thrust events and the rest are associated with minor 10 % occurring due to the standard faulting motion of N-S trending normal faults present in the study region. These are mainly in the area of stress buildup marking the downdip end of the locked portion of the Main Himalayan Thrust (MHT) (e.g., Cattin and Avouac, 2000; Bollinger et al., 2004). The study carried out by Stevens and Avouac, 2015 in the present study area (i.e. NW Himalaya) also states the Inter seismic coupling on the MHT in the entire Himalayan arc and the rate of uplift to nearly equal to the topography that further concludes the interseismic strain to be an unending phenomenon. In the entire Himalayan arc there is an absence of aseismic barrier that could terminate the along strike propagation of ruptures (Stevens and Avouac, 2015). The present study area, in the NW Himalaya covering roughly, 0.1 million sq. kilometres, covering regions falling in the states of Uttarakhand and Himachal Pradesh, had experience of four strong to major earthquakes (viz. Kangra earthquake, 1905 (32.01°N, 76.03°E); Kinnaur earthquake, 1975 (32.46°N, 78.43°E); Uttarkashi earthquake, 1991 (30.73°N, 78.45°E) and Chamoli earthquake, 1999 (30.40°N, 79.42°E)) in the past. The magnitudes of these earthquakes range from 6.8 *(Ms)* to 7.8 *(Ms)* (https://earthquake.usgs.gov). The locking depth in the study region appears to follow closely the 3.5 km (Avouc, 2003; Bollinger et al., 2004) elevation contour as evidenced by a line of microseismicity that follows the transition from the locked to creeping upper surface of the Indian plate throughout the length of the Himalaya (Bollinger et al, 2004). The northern limit of great ruptures of the Himalayan earthquakes are bounded by the locking line. As there is a variation in distance between the locking line and the frontal thrusts of the Himalaya along the arc this greatly influence the steepness of the mountains with sharp topography as well as the total seismic moment release in the form of great earthquakes.

The present study titled 'Seismological and Geophysical studies of NW Himalaya: Tectonic Implications' carried out is taking an advantage of improved geophysical techniques integration, that is, seismological and gravity study to critically assess the lithospheric structure, source characterization, nature and behavior of the earth's subsurface and identification of the potentially seismic hazard beneath the NW Himalaya, India due to its maximum likelihood to earthquake occurrence in the recent past and also compare results obtained from earlier investigations that were poor in locating exact epicentres for the lack sophisticated techniques, tools and monitoring advantages.

After carrying through literature survey for the spatial distribution of earthquake epicenters in the NW Himalaya region it has been observed that there is a higher error in epicentral location w.r.t latitude, longitude, depth and origin time of the earthquake epicenters. This problem is due to the non-availability of local crustal velocity model for the region. Therefore in order to have a better resolution to the spatial distribution of earthquake hypocenters in the region a local crustal one-dimensional (1D) velocity model for Himachal Pradesh, India has been developed by utilizing the P and S wave travel time data. This calculated 1 D velocity model will serve as a base velocity model for researchers for developing a 3 D tomographic velocity model in future for the study region. The 1D velocity model proposed for the study region has seven uniform layers with equal thickness of 5 km and having interfaces at depths of 0, 5, 10, 15, 20, 25 and 30 km with P wave velocity of 5.219, 5.314, 5.391, 5.392, 5.964, 6.071 and 6.073 km/s and S wave velocity of 2.998, 3.015, 3.134, 3.135, 3.441, 3.482 and 3.647 km/s, respectively. For P and S waves, the station correction ranges from −0.88 to 1.50 and −0.58 to 3.59 s, respectively. This low variation in station residuals could be for the reasons like, small lateral velocity changes that shows the accuracy and stability of the proposed1D velocity model (Kumar et al., 2009). As the data utilized here were acquired over a period of 10 years starting from 2004 to 2013 and the velocity model derived was in the year 2016. So utilizing this presently derived 1D velocity model, the earthquake epicentres were relocated and a shallow seismic activity in the region is observed at <30 km depth (Verma et al., 2015) that further characterizes that upper-most crust in the region is weak to withhold higher stress level and suffer brittle failure at lower stresses to produce small and moderate magnitude due to the ongoing convergence of the India-Eurasia plates in the study region. This study also infers a new, highly active seismic window in the latitude range of 31.8 °N to 32.8 °N and longitude range of 76.8 °E to 78.8 °E in the study region across the Kaurik-Chango fault, a causative fault for the1975 Kinnaur earthquake (Khattri et al., 1975). In order to test the accuracy of the derived 1 D velocity w.r.t earthquake epicenters distribution in the region the earthquake epicentres were relocated using the new derived 1D velocity model (2016), and a shallow seismic activity in the region with a maximum hypocenters placed at 30 ± 2 km depth has been observed for the study region.

The tectonics and seismic potential of the western Himalayan segment (30-33° N; 76- 80° E) of the Northwest (NW) Himalayan (India) region has been determined in this study in order to assess the potentiality of seismic hazard in the region. As the tectonic variations and potentiality of the region to produce great earthquakes are closely related to the earthquake hypocenter distributions in the study area, so it need to be constrained first with higher accuracy and lesser error. As evidenced from the previously carried out research work in the present study region by Khattri et al., 1989; Kumar et al., 2009, Mukhopadhyay & Sharma 2010, symbolise greater variations in spatial distribution of hypocentral locations due to some reasons such as non-availability of local crustal velocity model and lesser number of seismic stations operated and utilized for acquiring the seismic data, present study was attempted with an objective to reduce the variations in hypocentral parameters incorporating the current local crustal velocity model derived utilizing 20 seismic stations. This study have relocated 423 earthquakes in the NW Himalaya between 2004 and 2013 using more than 4495 P and 4453 S accurate P and S differential travel times. We have also determined moment tensors for 8 (Mw≥ 4.0) of these earthquakes using waveform inversion. The advantage of utilizing the waveform inversion technique is that because in this case the low frequencies are utilized and it makes modeling of waveforms less dependent on the inherently incomplete knowledge of the crustal structure. This method is highly advantageous in determining the exact fault plane characteristics pertaining to its Strike angle, Dip angle and rake or slip of the earthquake focus over other methods such as FPFIT, P-wave first motion polarization methods which require a greater number of stations and wide azimuthal coverage of earthquake hypocenter to determine the fault plane characteristics of the desired earthquake event.

The geometry of the MHT plane has also been deduced in this study which varies along the strike of the Himalaya in flat and ramp segments with a dip ranging from 4° to 19° below the HFT in south to STD in the north. There are also two new crustal ramps reported in this study having a depth range from 12 to 22 km below the MCT (31°N, 77.5°E) and 28 to 40 km beneath the STD (32.2°N, 78.4°E) respectively. The earthquake potential prevailing in the western Himalayan seismic gap lying between the epicentral zone of the 1905 Kangra earthquake and the 1975 Kinnaur earthquake has also been estimated utilizing the method of Kanamori, 1983 and the total amount of energy released since the last great event is estimated to be only a fraction (3-5%) of the accumulated energy (95-98%), This suggests that if an earthquake hits this NW Himalayan segment in future its magnitude might be equivalent to a Mw≥ 8.0.

Seismic attenuation study is carried out in the NW Himalaya utilizing the earthquake data of 82 local earthquakes recorded during the period from 2004 to 2006. This analysis characterizing the coda quality factor Q_c is done utilizing the single back scattering model of Aki & Chouet, 1975. This single back scattering model is utilized because using this model the coda window can be analyzed just after the S-wave arrival. This model assumes that the elastic energy is radiated spherically, scatterers are distributed homogeneously and randomly, and single scattering is isotropic in the media. The earthquake hypocenters analyzed during the process are having a hypocentral distance <240 km and a magnitude range of 1.2–4.9 (M_l). The $Q_C$values were estimatedat 10 central frequencies: 1.5, 3, 5, 7, 9, 12, 16, 20, 24, and 28 Hz using starting lapse-times of 10, 20, 30, 40, 50, and 60 s and coda window-lengths of 10, 20, 30, 40, and 50 s. The estimated values for a lapse time of 10 s vary from 91 to 225 at1.5 Hz and from 1537 to 4795 for 28 Hz with coda windows ranging from 10 to 50 s. An average frequency dependent power law fit for the study region may be given as $Q_C = 116.716f^{0:9943}$. Q_C value obtained seems to increase both with respect to lapse time and frequency, i.e., the attenuation decreases as the quality factor is inversely proportional to attenuation. The low Q_C values or high attenuation at lower frequencies and high Q_C values or low attenuation at higher frequencies suggest that the heterogeneity decreases with increasing depth in the study region.

The static stress change due to the four major earthquakes namely the 1905 Kangra earthquake, 1975 Kinnaur earthquake, 1991 Uttarkashi earthquake and 1999 Chamoli earthquake that occurred in NW Himalaya, India are studied utilizing the Coulomb 3.1 application. Coulomb stress change was calculated utilizing the presumed three factors. These factors are defined as

1) The earthquake source to be acting as a receiver fault.
2) Recent earthquakes occurring in the aftershock zone of the major earthquakes acting as receiver for the source earthquake.
3) Receiver as a major fault system of Himalaya where no much seismicity is reported in past.

These factors are assumed based on the facts that change in stress can cause either a delay or an advance in the occurrence of future earthquakes (Rajput et al., 2005). So in order to quantify the seismic hazard associated with the past major earthquakes in the NW Himalaya in terms of its recent aftershocks, such factors are assumed. The study carried out shows that due to the occurrence of the 1905 Kangra earthquake a maximum stress associated with the MHT detachment and some of the previously shadow zone has been reactivated . For the 1975 Kinnaur earthquake we observed the reactivation of the previously seismic shadow zone. For 1991 Uttarkashi earthquake the high seismic stress was observed over the lesser and Higher Himalaya and major structural discontinuities like MBT and MCT both getting activated and triggering aftershocks. In case of 1999 Chamoli earthquake a significant stress shadow is observed in some parts of the lesser Himalaya and a significant high stress is noted on the rest part of the NW Himalaya. All the above results shows that the tectonic stress in NW Himalaya is quite high and the region is near to failure chancing major earthquakes in future.

The seismological modelling results could only constrain the lithospheric structure up to a shallow depth of 50 km as the hypocenters distributed in the sub surface were in maximum up to that depth. Therefore the seismological model could only resolute the shallow features of the Indian plate beneath the NW Himalaya region. Therefore in order to have a detailed image of the lithospheric structure of the Indian plate up to greater depth and also characterize the exact Moho depth beneath the study region modelling of Bouguer gravity anomalies for the study area has been carried out. Bouguer gravity anomalies which is derived from global gravity model (e.g. EGM2008) have been utilized to derive a lithospheric model beneath the NW Himalaya. This model has been constrained utilizing both seismological and gravity studies. The 2D density modelling of Bouguer gravity anomaly carried out along the SW–NE profile accounts for a large wavelength gravity anomalies which are interpreted due

The subsequent high density within the low density arising between the MCT and STD can be attributed to the presence of extended surface structures in to the subsurface (Tiwari et al., 2010). This feature can be attributed as the Main Himalayan Thrust (MHT) plane that characterizes the rooting of the major thrusts such as HFT, MBT, and MCT beneath the NW Himalaya subsurface. A density of 2.7 g/cm^3 is observed towards the western side of the Kaurik-Chango Fault that is resulted due to the soft-sediment deformation taking place within different lacustrine sedimentary bodies present in the

The present Seismological and Geophysical study provide major constraint to the lithospheric structure of the NW Himalaya, India region.