6.1 Overview of the studies undertaken

The studies undertaken in this thesis provide quantitative information of the earthquake site, source and attenuation mechanism in the crust beneath Kumaon Himalaya. The important tectonic features of the Kumaon Himalaya include the Southern Tibetan Detachment (STD), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). The region between the MFT and the MBT is widely referred as the Sub-Himalaya, between the MBT and the MCT as the Lower Himalaya, between the MCT and the STD as the Higher Himalaya and further north as the Tethyan Himalaya. With the presence of complex geological regimes, the seismicity patterns and other natural calamities, the study region creates a scenario for hazard analysis. A dedicated approach is used for the study of the effects of the earthquakes, from their causative origin to their final target area on the surface, and assessment of the possible seismic hazard potential, both qualitatively and quantitatively, required for proper mitigation measures. The three parameters needed for crustal and seismic hazard analysis are; to first measure the site response of the shallow portions of the study region; secondly, to estimate the source parameters and scaling relations of small earthquakes to characterize the source properties in this region; and thirdly, to estimate the attenuation relations of the study region using seismic coda waves, and body waves. With relevance to the different studies conducted, the respective results are summarized in the thesis.

6.2 Site Response using HVSR method

In chapter two of thesis, the HVSR method has been applied on extended records of ambient noise, and earthquake data. As the robustness of the estimates is desired, we have employed the statistical measure of 90 % confidence interval. Results based solely on short periods of ambient noise may not be reliable, and the use of earthquake recordings, wherever possible, is advised to avoid ambiguity. In our study, the results are consistent for both the
data sets. The major outcome is about natural frequencies or site characteristic frequencies, wherein our results show that the natural frequencies obtained from the HVSR method are mostly in the frequency range 1-5 Hz. The discernible implication is a potential risk for residential structures, mostly up to two storeys. The sites which have shown high H/V peaks or significant site response are identified, which are good candidates for ground motion like ALI, KSP, GHT, JLM etc. Ground motion can cause some types of soils (clay-free soil deposits, primarily sands and silts) to liquefy, which means they temporarily lose strength and behave as viscous fluids rather than as solids. The younger and looser the sediment and the higher the water table, the more susceptible a soil is to liquefaction. When the soil supporting a building or some other structure liquefies and loses strength, large deformations can occur within the soil, allowing the structure to settle and tip. Large blocks of ground may move laterally because of liquefaction in a subsurface layer. As some of the sites are on slopes, ground shaking may also trigger landslides, and other types of ground failure, which can also cause extensive damage.

Apart from the inference on possible ground motion and interactions with structures, HVSR method in our study also provides further information on the layering in sub-surface structure. The peaks in the HVSR curves refer to the sub-surface layer structure. This is sometimes used for obtaining the velocity structure beneath the station, as done in the receiver function technique. The results are thus useful for site characterization, identification of natural frequencies of near surface soil that might interact adversely with nearby structures, and development of response spectra for engineering purposes. The need for the expensive testing and seismic recording equipments is reduced to some extent.

6.3 Earthquake Source Parameters and Scaling relations

In this part of study of the thesis, the earthquake source parameters are studied and estimated using Brune’s $\omega^2$ circular model in the frequency range from 0.2 to 20 Hz. To achieve reliability in the methodology, the displacement spectra of both the P- and S-waves are analyzed. The agreement between the seismic moments from P- and S-waves and good fitting of theoretical Brune spectra to the observed spectra justifies robustness of the methodology. A number of important observations have been made in this study. A phenomenon of corner frequency shift has been observed in the region which is consistent
with the similar studies of other active regions. Our estimates indicate that the static stress drop (or Brune stress drop) is not constant with seismic moment in the range $1.6 \times 10^{13} - 5.8 \times 10^{15}$ N-m in the region, implying a breakdown of constant stress drop scaling. Moreover, the static stress drops are mostly observed to be less than about 10 bars, implying the partial stress-drop mechanism proposed by Brune (1986). A similar kind of decrease of stress drop with decreasing seismic moment has been found to be a scaling relation for the small earthquakes for several studies (e.g. Archuleta et al., 1982; Haar et al., 1984; Dysart et al., 1988; Abercrombie, 1995; García et al., 2004). The estimated corner frequencies and source radii are found to be uncorrelated with the seismic moments for the small earthquakes analyzed here. The increase of stress drop with increasing moment and non-correlation of source radius with seismic moment shows that the stress drop is the dominant scaling factor for moments considered here.

We provide arguments for the observations on low stress drops in our study. The authors Allman and Shearer (2007) suggest that earthquake source parameters, especially stress drops are mainly controlled by rock properties at depth and that strong heterogeneities of the stress field persist along the fault over the seismic cycle. However, there is also widespread evidence of earthquakes induced in stressed crust by the presence of fluids (Sibson 1992, Hardebeck and Hauksson 1999, Sibson 2009). It is speculated in this study that occurrence of low stress drops and possible predominance of partial stress drop source mechanism is attributed to the presence of complex fault structures and also partly the presence of fluids beneath the crust in Kumaon Himalaya. It is suggested that the presence of fluids facilitates low stress drops, and the interaction of the fluids with the fault zone may delay the healing process after the passage of the rupture front. Thus, the role of the fluid pressure should be further investigated under combined methods of study of geochemistry, petrology and geophysics. However, this study and its results have an important bearing on the estimates of seismic hazard in the region as the stress drop controls the high frequency ground motions.
6.4 Attenuation Studies using Seismic Coda and High Frequency Body waves

In this study, the seismic wave attenuation is investigated in the high frequency range 1-20 Hz, using the concept of the quality factor, Q. The attenuation characteristics of the crustal structure beneath the Kumaon Himalaya have been studied by considering smaller sub-regions according to distinct geological characteristics, namely, Block 1, Block 2, and Block 3, as mentioned in Chapter 1. Seismic coda waves and body waves from parts of the of three component seismograms from about 250 local earthquakes are analyzed. As attenuation mechanism is a combination of intrinsic and scattering processes, the quality factors for intrinsic absorption (Q_i) and for scattering (Q_s) have been estimated using the Wennerberg (1993) formulation using coda wave Q, and S-wave Q. The quality factor Q_c (of coda waves) is estimated using the single isotropic scattering model in the frequency range (1-20 Hz) at the central frequencies 1.5, 3, 6, 8, 12, 18 Hz using several lapse times 20, 30, 40, 50, 60, and 80 s. Similarly, body wave attenuation is estimated by Q_α, and Q_β using the coda normalization and the extended coda normalization methods. Our results show the frequency dependent nature of seismic attenuation in the considered frequency range. The attenuation related Q fit the frequency power law as $Q = Q_0 f^n$. The Q_c estimates vary both block-wise as well as on the basis of lapse time. For each Block, the factor Q_0 (Q_c at 1 Hz) is observed to increase from 20 s lapse time to 80 s lapse time, and the exponent of the frequency dependence law, n varies decrease from 20 s lapse time to 80 s lapse time. Similarly, the other quality factors, using body waves, namely, Q_α, and Q_β, vary for the three Blocks. There is a variation of power law relations for estimated Q, namely Q_c, Q_α, and Q_β, which are summarized in Chapters 4 and 5.

The first impression from this study is that the increasing trend of estimates of Q_c with lapse times indicates that the upper crust is more heterogeneous than the deeper parts, i.e. heterogeneity decreases with depth. Similarly, the exponent of the frequency dependence law, n decreases with lapse time, similar to those values obtained for active regions. Zeng’s (1991) study reveals that the effects of intrinsic and scattering attenuations combine in such a way that Q_c is more than Q_β. The second inference is that the crustal attenuation structure seems to adhere to the Zeng’s (1991) model for the considered frequency range (1-20 Hz). The other implications of this study point to the possible varying levels of rock saturation, as the ratio $Q_\beta / Q_\alpha$ varies for the three blocks (Vassiliou et al., 1982). On the basis of this ratio, we infer that
the seismogenic zone above and below the MCT zone (i.e. Block 2 and upper parts of Block 1) is inhabited by pore fluids in the crustal rocks. Further, the existence of fluids above and below the seismogenic zone can influence the activity of the nearby fault system, in terms of the long-term structural, compositional evolution and local stress regime of the fault zone (Sibson, 1992). As the fluids enter the active faults in the crust (such as the MCT zone), fault zone friction decrease, enhance the stress concentration in the seismogenic layer.

From our studies in this thesis on source parameters and seismic attenuation, and a growing body of other studies suggests that fluids (water, magma, and gases such as CO₂, SO₂, etc.) are intimately linked to a variety of earthquake faulting processes. These include the nucleation, propagation, arrest and recurrence of earthquake ruptures, fault creep or slow earthquakes (Zhao et al., 2002). It is suggested that fluids also play important roles in the dynamics and evolution of the Earth, such as lowering the melting temperature of the mantle, transporting elements, enhancing diffusion and creep. These pieces of evidence as mentioned above suggest that the generation of earthquakes in the crust beneath Kumaon Himalaya is not a pure mechanical process, but is closely related to the physical and chemical properties of materials in the crust and upper mantle, such as pore fluids, especially when addressing the MCT zone, in Block 2 this study. Also, it is inferred that attenuation quality factor Q is influenced not only by scattering, but also significantly by intrinsic environments. However, to contribute to the mitigation of earthquake hazards, it is preferred to conduct combined seismological studies with geological, geochemical and geophysical investigations which would certainly provide us with a better understanding of the earthquake generating and attenuation process.