Chapter 1
Introduction

1.1 General

Natural hazards have a disastrous effect on human lives, properties and serious economic, environmental and social impacts that greatly retard the development processes. Some of the well known natural calamities are flood, drought, cyclone, tornado, hurricane, volcanic eruption, earthquake, tsunami etc. Man has no power to control or stop the natural hazard to occur. But the knowledge of such calamities before its occurrence can save a large number of lives and properties. The growth of major cities, along with increase in population in hazard prone area are the real cause of concern regarding the steps taken against natural hazards, disaster mitigation, and disaster prevention. Among the major fields of hazards, the earthquake hazard stands out as one of the most intractable. The earthquake phenomenon is highly complex and unpredictable. However basic knowledge is available about levels of background risk, nothing yet exists for earthquakes comparable to the warning systems (for all their defects) currently available in respect of floods, hurricanes, and volcanic eruptions. As the earthquakes occur suddenly with devastating consequences, earthquake prediction is a matter of great interest among the research communities, public and emergency service officials. Numerous works on prediction of Earthquake has been attempted by various scientists from all over the world. The success over it has not been achieved remarkably. But each attempt and approach of study has unlocked some interesting facts, behavior and mechanics of Earthquakes occurrence. Each of the different approaches towards studying the processes leading different seismicity patterns can help in finding the new ways of understanding the earthquake mechanisms. Hence an applicable model for earthquake hazards zone may be of great helpful for the society. So far Earthquake prediction is concerned, it is not possible but the in-depth study can extract the most vulnerable zone or highly seismic hazardous zone. Such prior warning helps the society to get ready for facing the challenges and implementing mitigation process. Thus the present study of this thesis is an endeavor towards understanding earthquakes pattern of
occurrence leading to estimation of high seismic risk zone or in other words the most hazardous zones for future large event.

The present study region is one of the most geologically and tectonically complex one known as the Himalayas. The Himalayas are the largest and youngest of the mountain system of the Earth. This represents one of the few places on earth where continental crust is attempting to under-thrust continental crust. As the Indian plate under-thrusts the Himalaya, it warps down in response to an advancing orogenic load and keeps the entire Himalayan mountain arc seismically active. Even today the Himalayas continue to develop and change the structures by the movement between Indian and the Eurasian plates. Earthquakes in the region are generally due to the collision of these two plates. Earthquakes in India are mainly caused due to release of elastics strain energy created and replenished by persistent collision of these two plates. The Himalayas and the neighboring region are known for high seismic activity. Earthquakes of different (low to very high) magnitudes have clustered in the NW-SE trending Himalayan terrain of about 2500 km long and 240-320 km wide. The past and the present occurrence of earthquakes in the region indicate that the earthquake dynamics in this region is very complex and hectic. Moreover, the four Great Earthquakes in the past had produced huge losses to property and human lives in Himalaya and its surroundings. The Himalaya has witnessed nearly nineteen thousand deaths in the great 1905 Kangra (M 8.5) earthquake, loss of eleven thousand lives in the great 1934 Bihar (M 8.4) earthquake and about 1500 fatalities both in 1950 Assam (M 8.5) and 1897 Shilong (M 8.7) earthquakes. Recently, few moderate earthquakes with $6 < M < 7$ have also been seen viz., 1988 Bihar-Nepal ($M_{6.6}$); 1991 Uttarkashi ($M_{6.6}$) and 1999 Chamoli ($M_{6.5}$) events which led to huge losses. The huge disaster generated by this natural calamity (Earthquakes) can never be underestimated. In this context proper understanding of the complexity of the earthquakes sequence in the region is the need for future hazard estimation zone leading to help in preparedness and mitigation of earthquakes hazard.

Several researchers (Khattri and Tyagi, 1983; Khattri 1987) have classified the Himalayas as three zones of high seismic risk known as seismic gap where future large earthquakes are possible. According to the seismic gap of first kind, the great earthquakes are the phenomena whereby crustal stress gradually increases over a wide
range along with strain accumulation leads to, a rupture when it has reached the limit by spontaneous stress release and strain reduced. So the places where no great earthquake has occurred for a long time can be regarded as possible sites for the next great earthquake. Generally, earthquakes do not occur uniformly throughout the world but occur repeatedly in certain limited areas, particularly in belt-like active seismic zones. Omori (1907) and Imamura (1928) stated that where large earthquakes occur successively in such seismic zones the next earthquake will occur in the remaining area. Several cases in which earthquakes have actually occurred at the location cited as seismic gaps of first kind. McCann et al. (1979) have collated these examples into a table. The seismicity associated in the Himalayan region is mainly due to under-thrusting of plates (Molnar et al., 1973; Ni and Barazangi, 1984). The section west of the 1905 Kangra earthquake is referred as the Kashmir gap; the section between the 1905 Kangra earthquake and the 1934 Bihar earthquakes is the Central gap; the section between the 1934 and 1950 Assam earthquakes is referred as the Assam gap.

Possibility of large earthquakes of magnitude > 8 due to the MHT (Main Himalayan Thrust) has been reported by several workers (Khattri and Tyagi, 1983; Khattri, 1987) on the basis of seismological evidence, where they mainly confirmed the existence of three seismicity gaps in the Himalayan plate boundary. Among the three seismicity gaps, the extent of the Central gap lying between the rupture zones of the 1905 and 1934 earthquakes is very long and has the potential for sustaining two future great earthquakes. Further seismic cycle evidenced by numerous studies (Molnar 1987; Bilham et al.1995; Gahalaut & Chander 1997) underlines the existence of a major seismic gap in western Nepal and surrounding region between the 1905 Kangra and the 1934 Bihar-Nepal earthquake areas. However, another major earthquake is yet to be recorded in this area over the past three centuries, and possibly since the 1255 event, which might be the last major rupture in this part of Nepal (Wright, 1877; Bilham et al., 1995). The 1934 Bihar-Nepal earthquake, that ruptured a 100-300 km long part of the Himalayan arc (Molnar & Pandey, 1989), seems to be the recurrence of some of these events (Bilham et al.,1995), whereas the 1803, 1833 and 1866 events could be related to the rupturing of a segment west of Kathmandu in central Nepal (Bilham ,1995). A 500- 800 km seismic gap which lies between 77ºE and 84ºE is yet to experience a great earthquake for more than two centuries (based
on reliable British historical seismicity) and perhaps since the huge 1255 earthquake (Jouanne et al., 2004). Bilham et al. (1995) has hypothesized that, based on the assumption of constant convergence rate of 20 mm yr\(^{-1}\) maximum slip deficit in the seismic gap may be around 15m, which may cause one or several magnitude > 8 earthquake. The scientific study made by various researchers (Sykes & Quittmeyer, 1981; McCann et al. 1979; Molnar, 1987; Bilham, et al., 1995; Gahalaut & Chander, 1997; Bilham, et al. 2001; Avouac et al. 2001; Jouanne et al., 2004 and Singh et al., 2010) suggest that the central seismic gap is more vulnerable for future large earthquakes. So proper study of the earthquakes occurrence and hence the hazard estimation zone for future large event is very much in need in this particular region for mitigation process. The location of the present study area lying within the central seismic gap is shown in Fig.1.
Fig. 1 The map shows the study region with Latitude 28°N-33°N and Longitude 76°E-82°E in the Himalayan region.
The concept of fractal was first introduced by Mandelbrot (1967) since then it has been used in many applications to study natural objects (Feder, 1988; Turcotte, 1997; Suteanu et al., 2000). The dynamic behavior of earthquakes occurrence and its fractal nature have been reported by various workers (Legrand et al., 1996, Teotia et al., 1997, Tiwari, et al., 2003). Fractal methods have been widely used in understanding the earthquake-related phenomena (Nakaya, S. and Hashimoto, 2002; Oncel, A. O. and Wilson, 2002; Roy and Mondal, 2009). The numerous results of seismicity study indicate that seismic hazard zone is a complex self-organized system with scaling laws of parameter distribution. The well-known Gutenberg–Richter law is a scaling dependence, which can be viewed as a manifestation of self organized critical (SOC) dynamics (Bak, 1997). Several researchers (Turcotte, 1997; Teotia, 2000; Roy and Mondal, 2009, 2012a) have applied the concepts of fractal in understanding earthquakes dynamics. Understanding the physical mechanism underlying the scaling laws in seismology is an enthralling research area, where its application can be of great help in seismic hazard estimation. Numerous studies have been carried out to examine the physics of earthquakes using scaling laws in seismology and their scale invariant properties. The application of fractal in earthquakes reveals so many important information regarding the nature of earthquakes occurrence. The results of several researchers show that the seismicity of spatial and temporal distribution reveals statistically self-similar properties in wide range of scales and can be treated as fractal or multifractal (Sadovsky et al., 1984; Okubo and Aki, 1987; Geilikman et al., 1990; Hirata and Imoto, 1991; Turcotte, 1997; Wangand, 1996; Lapenna et al., 2000). The results of the study of the fractal properties of seismicity and fault system suggest the method to be applicable for in-depth extraction of information related to earthquakes mechanism statistically in seismically active region (Turcotte, 1997; Sadovsky et al.1984; Wyss and Wiemer 2000).

The seismicity of a region described by fractal properties in time and space distribution of earthquakes may be measured by its fractal dimensions. This statistical tool may be used to quantify the dimensional distribution of seismicity clusterization and its randomness (Kagan and Knopoff, 1980; Ogata, 1988; Hirata, 1989a). The information about the stability of a study region may be gained from the application
of fractal dimension of the past and present activity of earthquakes. Further, a change in the fractal dimension may correspond to the dynamic evolution of the states of the system. The quantitative measure of the degree of heterogeneity of seismic activity in fault systems of a region may be reflected from the application of fractal dimension (Oncel et al., 1996).

Studies made by several researchers (Xie and Chen, 1988; Xie, 1993; Hirata et al., 1987) suggests that the damage evolution process from the small-scale (a microcracking in cm) to the large-scale (an earthquake in km) is a fractal. Therefore, the rocks burst which is damage due to fracture with an intermediate-scale (m) may also be fractal. The micro seismic event locations construct a spatial distribution of a point set in which a point corresponds to a cracking surface or volume element in physical space. Thus, the fractal dimension of the damage evolution process experienced by a rock burst can be directly measured from the distribution of the point set. The results on the distribution of micro seismic event locations were observed to have a fractal clustering structure. The degree of clustering of micro seismic events increases with the approach of a main rock burst that corresponds to decreasing fractal dimension. The lowest fractal dimension is generally produced near the occurrence of a rock burst. Thus, the fractal dimension has potential use as a rock burst predictor. Similarly, in seismology the fractal nature of rock bursts is consistent with the conclusion of a lower fractal dimension (or b-value) which is associated with the occurrence of a main earthquake. The fractal and physical mechanisms of rock burst are analyzed in theory using damage mechanics and fractal concept. A strong failure in rock burst or in an earthquake is observed as equivalent to a fractal cluster of cracking within the rock mass (Xie and Pariseau, 1993). So the application of fractal dimension in earthquakes distribution study may be of great help in getting information regarding the main-shock or in other words a signature before a large earthquake.

Spatial and temporal distribution of intermediate size earthquakes is important for understanding the future earthquake preparation process. The study made by several researchers in rock fracturing due to seismic clustering in small and large scale has witnessed the importance of seismicity clustering before the main shock (Zavialov and Nikitin, 1999; Mogi,1968; Scholz,1968a). The behavior of the
fractal dimension determined by the use of box-counting method of the continuum of earthquake epicentres of 23 strong events has been studied by Uritsky and Troyan (1998), where it was found that the pre-earthquake period was characterized by a lower fractal dimension in 16 cases. Furthermore, in search of the precursory signatures due to changes of multifractal characteristics of the seismicity distribution before the Hyougo-ken Nanbu earthquake has been undertaken by Goltz (1998).

The basic and important seismological parameter used to describe an ensemble of earthquakes is the b-value in the frequency-magnitude relation, which characterizes the distribution of earthquakes over the observed range of magnitudes. The earthquake sizes have a power-law distribution that can be expressed in terms of the Gutenberg-Richter relation (Gutenberg and Richter, 1944).

The equation is given by

\[ \log N = a - bM \] (1)

where \( N \) is the cumulative number of earthquake that exceed or equal to a given magnitude \( M \) in a chosen area for a chosen time interval. The constant ‘\( a \)’ depends on the overall seismicity, which may vary greatly from one region to the next. The ‘\( b \)’-value is normally 1, but it varies from 0.5 to 1.5 depending on the seismicity and tectonic setting of a seismically active region.

There are many factors responsible for the deviation of b-value from normal value of 1. The increase in the material heterogeneity or crack density results in high b-values (Mogi, 1962) and an increase in applied shear stress (Scholz, 1968a; 1968b), or an increase in effective stress (Wyss, 1973) decreases the b value. A lower value of ‘\( b \)’ infers that the region is under higher applied shear stress and a higher value indicates that the area is already gone through the tectonic events. The b value gradually decreases before a major fracture, even under a constant load Mogi (1981). So it is possible that there is a gradual decrease in the b value before a large earthquake even if there is no increase in stress, which is thought it occurs as a precursory change of the forthcoming major fracture. No matter whatever, the mechanism may be, it is generally recognized that there is a tendency for the b value to decrease prior to a large earthquake, so undoubtedly this provides a clue in predicting earthquakes. But this does not necessarily mean that a large earthquake will occur when there is a decrease in the b value.
On the basis of seismicity pattern, some very positive result was noticed by Rundel et al., (2000) on the possibility of earthquake prediction. As the seismic activity reflects the physical condition of Earth’s crust, any information relating to forthcoming, potentially damaging earthquakes is of great importance. Moreover temporal variation of b-values and its relation to the future damaging earthquakes have been studied and discussed by several researchers. In many case studies, the decreases in b-value before a large earthquake have been reported. Wyss and Lee (1973) reported a decrease in the b-value before four out of five California earthquakes with magnitude of 3.9 to 5.0. Smith (1981, 1999) observed that the increase in the b-value was present for several years before the occurrence of large earthquakes and then it decreased to normal in the short interval before the large event itself. Li et al. (1978) observed a decrease in the b-value before the Tanshang earthquake and Imoto (1991) reported a decrease in the b-value before several earthquakes that occurred in inland Japan. Hirose et al. (2002) studied the temporal variation of b-values in asperities of subduction zones and noticed that a decrease in the b-value occurred in an asperity. Based on the increase in mean earthquake size (equivalent to a decrease of the b-value), Imoto (2003) developed a testable model and found a probability gain of two to four fold in the Kanto area, Japan. Several researchers (Yamashita and Knopoff, 1992; Hainzl et al., 2003) noticed the decrease in b-value prior to large earthquakes in numerical simulations and also in laboratory experiments (Scholz, 1968b; Ohnaka and Mogi, 1982; Sammonds et al., 1992; Lei et al., 2004). All these work helped in the realization of several well-founded properties of seismicity, such as Gutenberg-Richter’s magnitude-frequency relation (Gutenberg and Richter, 1944) and modified Omori’s law (Utsu, 1961). Recently decrease in b-value prior to the M 6.2 Northern Miyagi, Japan, earthquake was reported by Tsukakoshi and Shimazaki (2008). Extensive work over the application of b value in understanding the seismicity pattern of different region have been done by various researchers (Kellis-Borok, and Kossobokov, 1990; Wiemer and Wyss, 1994, 1997; Wiemer and Benoit, 1996; Wiemer and Katsumata, 1999; Schorlemmer et al., 2004; Parsons, 2007).

Faults and spatial distribution of earthquakes epicentres, statistically obey a power law distribution which is quantified by a fractal dimension. The application of
fractal analysis for fault system characterization is exercised. The study of fault system is done as it plays an important role in releasing the accumulated energy in the form of Earthquakes. Their fractal distribution of structural elements (faults, thrusts, lineaments etc.) is necessary for understanding the earthquakes occurrences. Generally, the active faults are considered to be the source for earthquakes in the seismically active zones of the world. Fractal analysis of complex fault system of the present study region is studied through the box counting method. The quantization of complex fault system in a single value of fractal dimension of fault system traced on surface lead us to understand the fractal distribution of fault system. Such distribution helps to understand the complexity of the tectonic elements in a region thereby leading to understand the cause of earthquakes occurrence in a region. The technique box-counting helped in the characterization of the fault system present in the area where the area was subdivided into 25 blocks of 1° × 1°. The calculation of fractal capacity dimension (D0) of each block provided the different numerical values of low and high. The indication of minimum and maximum coverage of structural elements in a region was identified with lower to higher capacity dimension value. This type of fractal analysis of the faults system shed a new light leading to identification of seismic hazard zones followed by the study of spatio-temporal pattern of earthquakes occurrences.

Various researchers applied the method of box-counting method for fault system in various parts of the world (Hirata, 1989b; Idziak and Teper., 1996; Angulo-Brown et al. 1998; Sunmonu and Dimri, 2000; Ram and Roy, 2005). Using the same tool the present work has been successfully done in this thesis and where significant results were observed (Roy et al, 2012b).

The information regarding main features of seismicity and inner dynamics of seismotectonic activity can be analyzed through the spatio-temporal variation of earthquakes. Spatial correlation dimension (Dc) is a measure of spatial clustering and also indicate about the seismicity of the region. The fractal dimension (Dc) of the past earthquakes sequence using correlation integral approach indicate about the clustering of earthquakes in a region. The highest clustering of earthquakes is observed with lowest fractal dimension value (Dc). Further these clustering have been indicated as highly stressed zone and are the expected areas where nucleation for large earthquake
may finally appear. The observation of low fractal dimension before a large earthquake in different parts of the globe was observed and reported by several researchers (Roy and Ram 2006, Roy and Nath 2007; Roy and Padhi 2007, Roy and Mondal, 2009,2010). The fractal dimension of the spatial distribution of data set is calculated from the correlation integral approach in the present work. A number of subsets (say 50 or 100 or 200 events windows) of earthquakes were considered and $D_C$ value was determined. This leads to a number of $D_C$ value ranging from low to high. A unique property of $D_C$ value fluctuation has already been noticed before the large earthquake globally (Roy and Nath 2007). Such variation of $D_C$ value was observed in post-analysis of large events. The application of similar methodology has been attempted in this work. Furthermore, the correlation between parameters b-value and $D_C$ is also studied which provide very crucial information.

Multifractal analysis is needed for understanding the heterogeneity of fractal structure of the seismicity and existence of complex interconnected structure of the Himalayan thrust systems. Multifractals provide a more complete characterization of both the spatial and the temporal properties of seismicity distribution than do monofractals (Kagan, 1994). Since multifractal components provide additional information about the irregularities and complex dynamics of seismotectonic processes. Multifractal characterization is achieved by measuring the so-called generalized dimensions $D_q$. The multifractal index gives a quantitative measure of irregularities (or regularities) in the spatial distribution patterns. The results so obtained allow classifying different elements based on their multifractal indices. The multifractal dimension $D_q$ is a parameter representing the complicated fractal structure or multi-scaling nature. Multifractal study using correlation integral approach is necessary in order to quantify the spatial distribution with the help of generalized fractal dimension. The spatial multifractal dimension ($D_{q}$) provides a quantitative measure of the spatial clustering of events and hence it determines the crustal deformation in space and time of a region (Aki, 1981, 1984; King, 1983; Main, 1996; Nakaya and Hashimoto 2002; Öncel & Wilson 2006; Roy & Nath 2007). The physical laws underlying the multifractal structures are scale-invariant in nature. The occurrence of earthquakes is causally related to fractures that have multifractal structure in their space, time and magnitude distributions. Several researchers have utilized the
multifractal approach of study in different tectonic region on earth (Hirata and Imoto, 1991; Li et al., 1994; Dimitriu et al. 2000; Teotia et al., 1997; Telesca et al., 2005; Roy and Padhi, 2007; Teotia and Kumar, 2007, 2011; Roy and Mondal, 2012c). Multifractal study is very important to understand the heterogeneous characteristics of seismicity in a region. Such study may become important in understanding the preparation zone of large size earthquake in various tectonic regions.

Several researchers have applied the multifractal pattern of study in various seismic regions to examine the temporal variation of heterogeneity in seismicity. Recent studies show that the parameters which describe seismicity in a region show a spatial and temporal evolution which may be associated with the process of generation of large size earthquakes. The generalized dimension $D_q$ and $D_q$ spectra of the seismicity reflects the change in seismicity pattern for the region. Therefore, the study of temporal variation $D_q$ and $D_q$ spectra may be used to study the changes in the seismicity structure before the occurrence of large earthquake, which may be very helpful in understanding the preparation zone of large size earthquakes (Teotia and Kumar, 2011).

The temporal distribution of earthquakes has been applied to characterize the main features of earthquakes occurrences and to highlight on the inner dynamics of seismotectonic activity in a region (Wang and Lee, 1997; Telesca et al., 1999, 2007; Enescu et al., 2005). The time series study of the region is done in order to quantify or characterize the temporal distribution, further multifractal distribution is undertaken with the help of correlation integral method. The temporal fractal correlation dimension ($D_2(t)$) is obtained from inter occurrence time of events. The variation of $D_2(t)$ value is noticed with low to high depending upon the clustering of earthquakes in time domain. The low value also suggests that they are temporally clustered. The temporal clustering implies that the strain of the region is concentrated due to tectonic stress field with the typical fault structure as the centre of the clustering. Such ideal clustering marked with low value temporally may be used as large earthquake forecasting tool. Further, multifractal dimensions are more efficient to reflect complex geodynamic processes which take place in active tectonic regions (Hirata and Imoto, 1991; Sunmonu et al., 2001 Telesca and Lapenna, 2006, Roy and Padhi, 2007; Roy and Mondal, 2012c).
Advent of GPS (Global Positioning System) technology for the measurement of tectonic plate motion in the level of high accuracy has given a new dimension in the field of geosciences. The millimeter rate accuracy in the observation of crustal movement plays an important role in determination of strain in a region that helps in understanding the earthquakes activity. The crustal deformation study derived by GPS measurements is the need of the present study and a source of vast information in the field of earthquakes assessments. GPS geodesy is an integral component for understanding surface strain due to tectonic motion and earthquakes. Moreover it is a sophisticated instrument and has become one of the most widely used tools to acquire geodetic measurements for crustal deformation study. The horizontal velocity vectors measurement helps to determine the pattern of strain accumulation in the region under study. The precise measurement from GPS has made it possible to understand the dynamics involved in the process of earthquakes occurrence.

Since long time GPS derived site velocity in different parts of the world has been reported (Bilham et al, 1997; Chen et al., 2000; Banerjee and Burgmann, 2002; Bettinelli et al., 2006; Reddy and Prajapati, 2008; Mukul et al, 2010). The continuous and campaign mode GPS data collection and analysis helps in the determination of plate motion. This study indicates about the accumulation of strain in a region thereby giving the important information about the crustal activity and knowledge about the seismicity. According to the hypothesis made by Bilham et al (1995), constant convergence rate of 20 mm yr$^{-1}$ were taken due to which maximum slip deficit in the seismic gap may be estimated to be 15m, which may cause one or several magnitude $> 8$ earthquake in the study region. GPS derived velocity in Himalayan region shows that India moves in the northeast direction at the rate of 50–55 mm/year (Paul et al. 2001; Jade 2004; Banerjee et al. 2008). As Himalayan region seismicity is mainly due to the collision of Indian plate with that of Eurasian plate. The crustal shortening in the area is known to absorb a large fraction of the plate convergence (Larson et al. 1999). The study made by Lave and Avouac (2000) shows that the geological shortening rate due to active thrust-faulting on the Main Himalayan Thrust (MHT) fault is about $21 \pm 1.5$ mm/yr. GPS measurement of crustal deformation highlights on the geometry of the locked portion of the MHT and helps in estimation of strain variation in the region. GPS technique is an effective and unique tool to precisely
measure the crustal deformation along individual faults and hence the strain accumulation in the region is observed. Observation of strain variation is an outstanding ingredient for identification of high seismic risk zone along with the study of other important seismotectonic parameters as discussed above.

**1.2 Importance of the present work**

Scientists have been trying to predict the future location and time of destructive earthquakes. There are several theories that try to predict earthquakes deterministically from the information about for some example like grounding tilting, humidity change, electrical currents, and magnetic field variations (e.g. Geller 1997, Kagan 1997a, Kirschvink 2000) or seismicity patterns (e.g. Feng et al. 1997, Eneva and Ben-Zion 1997, Li and Vere-Jones 1997). Similarly other approaches use features of observed seismicity to make probabilistic predictions. As an example, it is tried to estimate the probability of a large earthquake following precursors (e.g. Rhoades and Evison 1993) or seismic quiescence (e.g. Ogata 1988). But in this present study, the goal of the work is to apply the fractal in seismicity in the study region and measurement of GPS strain to delineate the most hazardous zone for probable future large earthquake. The main objective of the present study is to not to predict earthquakes but forecasting earthquakes in the central seismic gap. In other words, it can be said that studying the past seismicity associated with active tectonic elements, correlatable results of various researchers, application of fractal approach, GPS derived strain for the period of three years have been utilized to extract or identify the most hazardous zones in the study area. Some blocks of 1°×1° have been identified as the zones for future large earthquakes in Kumaun Himalaya and its adjacent region.

**1.3 Objectives of the proposed work**

The proposed work of this thesis is to estimate the large earthquake potential in Kumaun Himalaya and its adjacent Fault zone using the GPS strain measurements and multi-seismotectonic parameters study. The main and important parameters studied in this thesis are as follows.
[1] To quantify or characterize the tectonic elements (faults, lineaments etc) in the study region using box-counting method.

[2] To quantify or characterize the spatial and temporal clustering of events and its variation with time with the help of fractal and multifractal analysis using correlation integral approach.

[3] To obtain the b-value of consecutive hundred events window and observe the variation of b-value with time.

[4] To apply the campaign and continuous mode GPS field of three years 2008 to 2011 in Kumaun Himalayan region to estimate the strain accumulation in the region.

[5] To observe the low fractal correlation dimension ($D_2$) of earthquakes distribution.

[6] To identify the high seismic risk zone for future large events in Kumaun Himalaya with analysis of all the above parameters.

In this piece of work, a number of seismotectonic parameters have been analyzed to study the geologically highly complex Himalayan region for the identification of high seismically active zones for future large earthquakes. The present work discusses about the capacity dimension ($D_0$) of the fault system, spatial fractal dimension ($D_C$) of past earthquakes distribution sequence, correlation of b value with $D_C$ value, multifractal dimension ($D_q$) analysis of earthquakes distribution in space and time domain with temporal fractal correlation dimension ($D_2(t)$) and GPS strain measurements of the active region. The study was focused on the variation of fractal correlation dimension ($D_C$) with time. Since fractal dimensional value indicates about the clustering of earthquakes and hence the physical state of the stress distribution of the region is identified. Importance of study on the distribution of fault system has also been carried out because the earthquakes occurrence is related to fault system. Discussion of the generalized fractal dimension was done and interpreted as to how the multifractal analysis is well suited tool for quantifying the heterogeneity found in the seismicity. The strain measurement derived from GPS field data has well been correlated with other parameters to find out some of the very important activity
of tectonic features. Finally, an attempt has been done using these techniques to get the interrelationship between seismo-tectonic variables and GPS strain, which is first of its kind in segregating the high risk zones for large events. The earthquake potential is evaluated for the region and hence the high risk zone for future large events has been demarcated. The output of the thesis work will help in proper hazard estimation and provide crucial information for government to plan to save property and life.

1.4 Organization of the thesis

More explicitly chapters of the thesis are organized as follows:-

Chapter 1 is introductory, in which importance of earthquake study and more interestingly in the study region of the Himalayan is explained. A brief overviews of the different parameters used in this thesis is presented. Reviewed literatures are summarized that explain about the importance in this proposed work.

Chapter 2 deals with tectonic setting of Himalaya and more specifically the region of Kumaun Himalaya is reported. The tectonic plates that are responsible for majority of the seismicity in the region are discussed. Major thrust faults and other structural elements (viz. lineaments, surface faults, gravity faults etc) with their different aspects of seismicity are analyzed. The motion of Indian plate is reported as study made by several researchers on the basis of GPS data collected.

Chapter 3 clearly describes about the box counting technique for determination of capacity dimension ($D_0$) of the structural elements present in the study area. The area is subdivided into number of blocks of $1^\circ \times 1^\circ$ and $D_0$ of each is calculated through the box counting method. The variation of $D_0$ values so obtained in each block is shown.

Chapter 4 perform the fractal and multifractal analysis of the past earthquakes sequence. Determination of spatial correlation dimension ($D_2$) and generalized multifractal dimension ($D_q$) have been done using the correlation integral approach. The chapter deals with all the aspects of $D_C$ value variation with time and its important towards earthquakes clustering for future large events is explained.
Multifractal dimension of the study region in space and time domain is explained and its basic behavior for heterogeneity of crust.

**Chapter 5** explains the utility of GPS (Global Positioning System) technology in the field of crustal deformation study has been explained. The three years data collected in the Kumaun Himalayan region is processed and analyzed for absolute velocity measurement. Based on these sites velocity measurement the strain development in the region is obtained. The important correlation between fractal dimension and strain development in the region is demarcated.

**Chapter 6** deals with the summary of the work on the basis of the results so obtained with the application of multi-parameters approaches in the study region for understanding the future large earthquake. Finally the conclusions of the work are elaborated at the end of the chapter. Moreover, some of the seismic hazard zones in the study region have been identified. The future scope of the work is also introduced in this chapter. Appendices and bibliography is listed at the end of the last chapter.