Chapter 1:

INTRODUCTION

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1.1. Statement of the Thesis:

During the last century our country have faced as many numbers of natural hazards such as earthquakes, Tsunami, Cyclone, storms and several other natural calamities. The Indian subcontinent has a history of devastating earthquakes. The major reason for the high frequency and magnitude of the earthquakes is that the Indian plate is driving into Asia at a rate of approximately 47 mm/year. Geographical statistics of India show that almost 54% of the land is vulnerable to earthquakes. In the Himalayan region four great earthquakes have cause a high damage to the life and property. The country's economic development is being greatly hindered due to the occurrences of earthquakes in it. The present research problem is focused on earthquake study in the NW Himalayan region. Understanding of earthquake genesis in the Himalayan region will be helpful not only for our country but also for the people living in other parts of the earthquake prone regions of the world. Before explaining details of the present research work it would be essential to understand about the earthquakes. Earthquakes caused due to the sudden release of energy from the earth's interior that produces ground shaking and displacement. This seismic wave energy causes damage with its propagation to the earth surface structures. In India the potential seismic zones for the great earthquakes lies in the Himalayan region. The recent seismic zoning map of India given in the earthquake resistant design code of India assigns four levels of seismicity for India in terms of seismic zone factors. The earthquake zoning map of India divides India into four seismic zones i.e. Zone II, III, IV and V). According to the classification, Zone V expects the highest level of seismicity whereas Zone II is associated with the lowest level of seismicity.

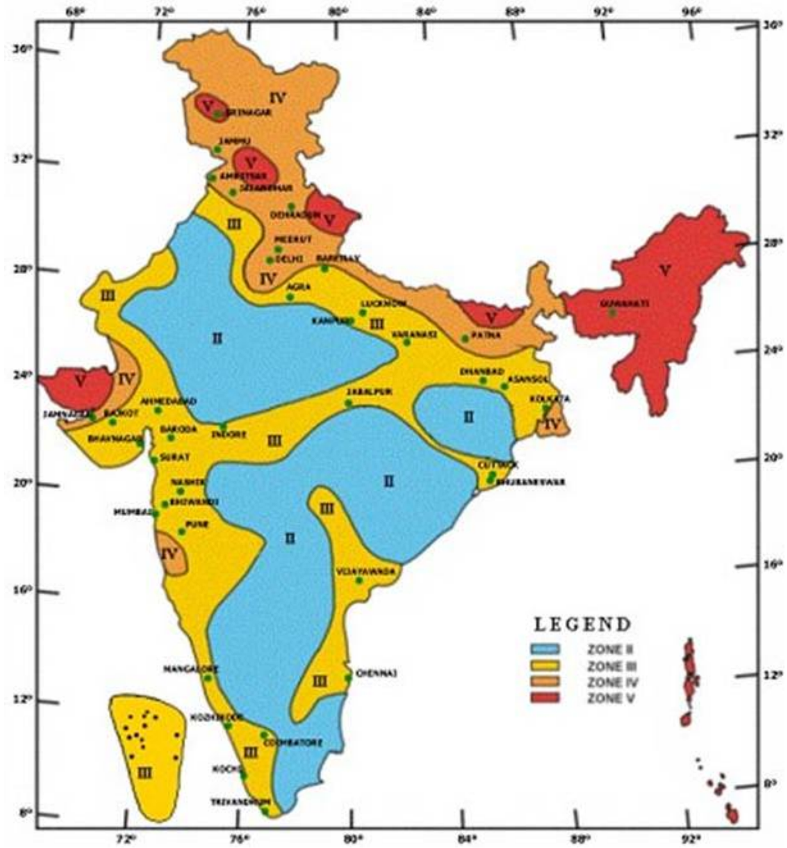

Figure 1.1: Seismic zonation map of India (http://nidm.gov.in/safety_earthquake.asp)

1.2. Motivation for the present Research

Strain is building along the Himalayan arc due to continued collision between India-Asia plates resulting large number of devastating earthquakes. In this part accumulating strains continuously triggering micro-earthquakes. It is necessary to understand the earthquake source processes and the medium characteristics which provide the basic tools for the assessment, mitigation and reduction of seismic hazards. Literature review of this region inferred that the tectonic setting in the Himalayan region is highly complex and the crustal and upper mantle structure varies within very few kilometres. The available velocity models which has applied for this region results high errors in hypocentral locations in latitude, longitude and depth. In this present work we have re-estimated the velocity models and refined the seismicity with reduced errors in geographic locations. It is also necessary to estimate the source characteristics of moderate to large earthquakes in NW Himalaya so that we shall be able to know the characteristics of earthquakes taking place along the tectonic faults or boundaries. With the high precision seismic data we also have estimated the stress accumulation and pattern of stress change in this region of the Himalaya. Using all the available and estimated information's it would infer the possible areas which may trigger the moderate to major earthquakes in near future.

1.3. Rationale of the Present Work

The Himalaya was formed due to a continent-continent collision between the Indian plate and Eurasian plate. This collision have made the whole Himalayan region as one of the most seismically active intra-continental region in the world and caused many devastating earthquakes in India and surrounding region. The NW Himalaya can be divided into four major tectonic sub-divisions in a transacted section directed in SW–NE direction. The divisions may be termed as Siwalik Himalaya (SH) segregated from Indo-Gangetic plain (IGP) by major fault structure named as Himalayan Frontal Thrust (HFT). The next major tectonic unit is the Lesser Himalaya (LH) and it's bounded by Main Boundary Thrust (MBT) to its south and Main Central Thrust (MCT) to its north. The third major tectonic zone is the Higher Himalaya (HH) bounded to its south by Main Central Thrust (MCT) and mainly consists of crystalline rocks named as Higher Himalayan Crystalline (HHC) rocks. Above all these the fourth tectonic regime named as the Indo-Tsangpo suture zone (ITSZ) bounded by south with South Tibetan Detachment (STD) and in the north with the Indus-Tsangpo suture zone thrust.

All major and many local faults in the Himalaya are suggested to root into a low-angle northwards dipping detachment zone which is described as the Main Himalayan Thrust (MHT), (Schelling and Arita, 1991). There are many localized faults and lineaments in the present study region of NW Himalaya (Najman et al., 2004). Some of the most destructive earthquakes which have triggered in India in the past have their epicentral locations in the NW sector of Himalayan region. These earthquakes having epicentres placed in NW Himalaya along with their magnitudes are listed below.

Date	Time *(IST)* HH:MM	Location	Latitude *(°N)*	Longitude *(°E)*	Mag. (Mw)
April 4, 1905	01:19	Kangra, Himachal Pradesh	32.01	76.03	7.8
January 19, 1975	13:32	Kinnaur, Himachal Pradesh	32.46	78.43	6.8
October 20, 1991	02:53	Uttarkashi, Uttarakhand	30.73	78.45	6.8
March 29, 1999	00:35	Chamoli, Uttarakhand	30.408	79.42	6.8

Table 1.1: Major earthquakes with their recorded hypocentral parameters in the NW Himalaya are listed

Moderate to major earthquakes listed in *Table 1.1* triggered in the NW Himalaya, inferred that this part of the Himalaya region needed to be study with higher degree of accuracy so that all the people living in these regions can be aided against this destructive natural phenomenon. The NW Himalaya is seismically very active where a large number of people are living at present and this is the main reason for more attention is required in this region

1.4. Study Area

The North–western (NW) Himalaya is bounded at its southern ends by the northwest-southeast trending Himalayan Frontal Thrust (HFT) and to its north it is constrained by the Indus Tsangpo Suture (ITSZ). Broadly speaking the Himalayan orogeny in the studied sector can be divided in to four major lithotectonic units. These four major lithotectonic units can be named as Outer (Sub) Himalaya (Siwalik), Lesser Himalaya (LH), Higher Himalaya Crystalline (HHC) and Tethys Himalaya Sequence (THS) from south to north. The major tectonic divisions are segregated from each other by major tectonic boundaries namely the Himalayan Frontal Thrust (HFT) separating the Outer or Sub Himalaya from the adjoining Indo-Gangetic Plain (IGP), the Main Boundary Thrust (MBT) segregating the Sub or Siwalik Himalaya from the over thrusting Lesser Himalaya, the Main Central Thrust (MCT) separating the Lesser Himalaya from the over thrusting Higher Himalayas and the South Tibetan Detachment (STD) segregating the Higher Himalaya from the Tethys Himalayan sequence. The present study area i.e. the Garhwal- Himalayan region, the Kangra-Chamba and Kinnaur region in the NW Himalaya falls under all the mentioned seismotectonic units as shown in *Figure 1.2*

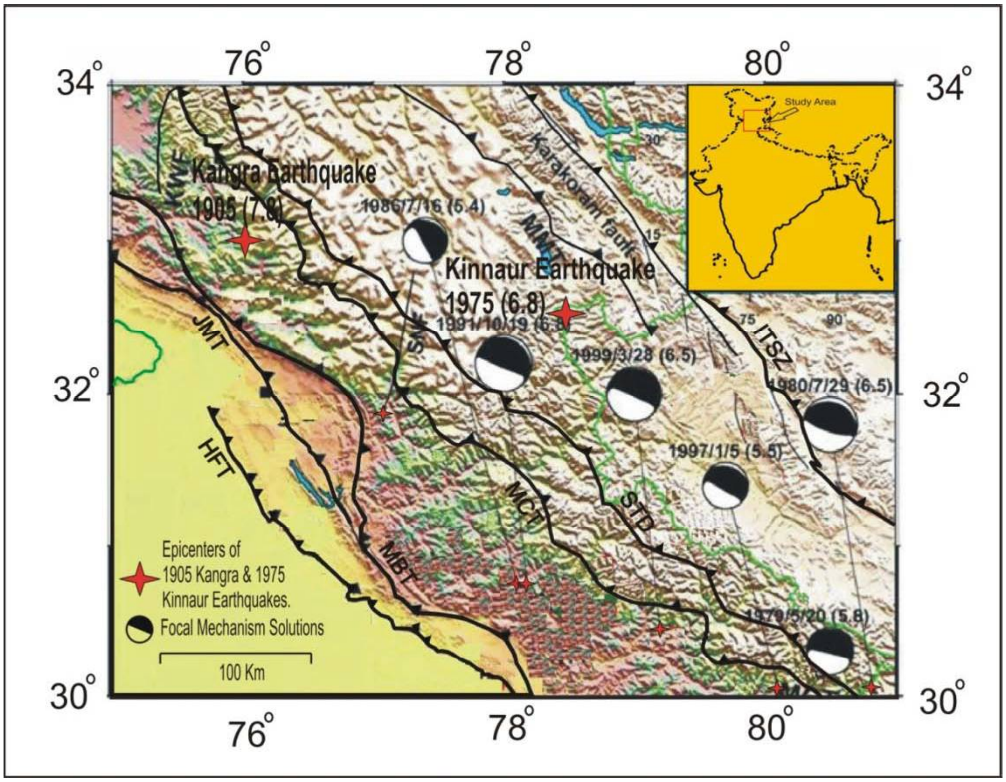

Figure 1.2: General tectonic map showing the epicentre of 1905 Kangra earthquake & 1975 Kinnaur earthquake, major tectonic breaks ITSZ: Indus-Tsangpo Suture Zone; MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan frontal thrust; JMT: Jawalamukhi thrust; KWF: Kishtwar fault; SNF: Sundarnager fault; MMT: Main Mantle thrust along with the topography as well as the focal mechanism solutions of some major earthquakes that occurred in the region in the past.(Modified after Tripathi et. al, 2014).

1.4.1. Garhwal Himalaya

The Garhwal Himalaya region (Yin, 2006) drained by the major rivers such as Bhagirathi and Alaknanda rivers has been less studied from seismotectonic point of view as compared further east, Nepal region. The foothill belt of the Garhwal Himalaya is marked with the presence of the foredeep sediments that are affected by the terminal phase of the Himalayan orogeny. The extremely complex high grade crystalline termed as Almora Crystallines, is delimited on either side by the North Almora Thrust (NAT) and South Almora Thrust (SAT). The major Thrust faults trending from south to north ranging from the Main Boundary Thrust (MBT) in south to Main central Thrust (MCT) in the north notably marks their presence in this sector of the Garhwal Himalaya. The lithotectonic unit marks its presence in the current Himalayan section is the Lesser Himalayan sequence (LHS). This Lesser Himalayan sequence (LHS) is further divided in to inner and outer lesser Himalayan sequences. The Higher Himalayan sequence (HHS) composed in the Higher Himalaya (Yin, 2006) are separated by the major topographic break called the Main central Thrust (MCT) is also seen in this Garhwal Himalaya sector. This Main Central Thrust (MCT) is the most active thrust fault is also divided in to two parts with the upper bound named as MCT-II (Arita, 1983), and as the Vaikrita Thrust (Valdiya, 1980) and the lower bound namedin Garhwal as the Munsiari Thrust/MCT-I, places the highly metamorphosed rocks of the GHC over the metasedimentary rocks of the LHS (Celerier et al., 2009). Observations in Garhwal of discontinuous exhumation cooling ages (Vannay et al., 2004) suggest that the Munsiari Thrust/MCT-I was active later than the Vaikrita Thrust/MCT-II (though similar observations in central Nepal have been fit by models of passive overthrusting without an activeMCT-I (Robert et al., 2011). The above paragraph completely describes the tectonic and the major geological units of the Garhwal Himalaya.

1.4.2. Kangra-Chamba

The Kangra-Chamba region consists of four major tectonic units marked from south to north directed namely; Sub-Himalaya (SH), Panjal

Imbricate Zone (PIZ) of the Lesser Himalaya, Chamba Nappe (CN) and Higher Himalaya (HH). The Himalayan Frontal Thrust (HFT) separates mainly the tertiary rock features of the Sub-Himalaya from the alluvium of the Indo-Gangetic plains. The Main Boundary Thrust (MBT) delimits the Tertiary rocks of the Sub-Himalaya from the Panjal Imbricate Zone (PIZ) of the Lesser Himalaya. The Panjal Imbricate zone that is composed of the Lesser Himalayan sequence (LHS) is placed in a narrow belt of this zone. These Panjal Imbricate zone made up of phyllite, slate and limestone (Rautella and Thakur, 1992; Thakur, 1998). The movement along the southern dipping of the Chenab Normal Fault (CNF) characterizes the northern boundary of the Chamba Nappe (CN).

The presently described tectonic unit i.e. Chamba nappe (Thakur, 1992; Thakur, 1998) the main geological feature of the Kangra-Chamba sector of our study area is said be composed of metamorphosed sediments (Khattri et al., 1978). These meta- sediments said to have intruded because of the southwestward sliding of the Tethys Himalayan sequence (THS) from north over the metamorphic Higher Himalayan crystalline (HHC) along the south dipping Chenab Normal Fault (CNF) that separates the Chamba Nappe (CN) from the Higher Himalayan crystalline (HHC). Another major tectonic feature is the Chamba Syncline (Klippen) that is a piggyback basin that's overlain by Higher Himalayan crystalline rocks (Thakur, 1998).

The Panjal Thrust (PT) and the Chamba Thrust (CT) are also the most important structural features of the Kangra-Chamba.Here, the Dhuladhar ranges, immediately north of closely spaced MBT and the PT, rise abruptly attaining an average altitude of 4000m and is characterized by intense seismicity. There are some other major fault structures in the Kangra-Chamba sector in the Sub-Himalaya that may be described as a single entity as MBT and distinctly speaking they may be described as Jwala Mukhi Thrust (JMT), Barsar Thrust (BT) in the Lesser Himalaya (LH). This Kangra-Chamba sector is tectonically and seismically one of the active zones in the NW Himalaya, India.

1.4.3. Kinnaur Himalaya

The Kinnaur Himalayas consists of a large number of N–S trending Faults that greatly affect the Precambrian-Palaeozoic succession of the Tethys Himalaya of Spiti (Hayden, 1904; Gupta and Virdi, 1975). There are intrusions of granites into the high grade metamorphosed sediments of the Vaikrita group which are quietly exposed in this region and these are again conformably overlain by low-grade metamorphics, e.g., phyllite, schist and quartzite (Haimanta group). The Palaeozoic succession comprising friable and splintery shale, quartzite and limestone is well exposed in the region of Lipak valley and was observed along Leo-Shalkhar-Sumdoh-Kaurik track. The Kinnaur region is also marked by the presence of a number of N–S trending active faults of which Kaurik-Chango fault that separates the spiti succession from the west. The region of this culmination has been crossed by numerous N–S faults. This fault is westerly dipping and has caused the erosion of the Tethyan sediments on the up thrown eastern block that is made up of metamorphics (Khattri et al., 1978). The Kinnaur Himalaya is characterized with a 10 km thick northeast-dipping amphibolite to migmatitic gneisses, is bounded by the Main Central thrust at the base and by the South Tibetan detachment at the top; these faults were contemporaneously active during the early and middle Miocene (Hubbard and Harrison, 1989; Burchfiel et al., 1992). To the south, in the footwall of the Main Central thrust, Lesser Himalayan Crystalline rocks, which constitute a portion of the lesserHimalaya (Valdiya, 1980), are exposed within the Larji-Kulu-Rampur window (Vannay and Grasemann, 1998). Timing of southward propagation of the Himalayan deformation front is not well constrained, but the Lesser Himalaya probably began thrusting onto the Sub-Himalaya along the Main Boundary thrust system during late Miocene (Huyghe et al., 2001, and references therein). The Kinnaur Himalaya is subjected to crustal shortening due to the tectonic subsidence of the Indian plate beneath the Eurasian plate and that has resulted in extensive seismicity and tectonism in the NW Himalaya, India. The NW Himalaya has a great heterogeneity and complexity in its formation as well as an active tectonic zone of the region due to the continuous collision of India and Eurasian Plate. In view of the present scenario in this region, the following main objectives were stressed in the present study.

1.5. Objectives

1) To relocate the seismicity in NW Himalayan region using local earthquakes recorded within the region with higher degree of accuracy in location and reduced errors in origin time, latitude, longitude and depth.
2) To estimate the source mechanism of earthquakes ($M_L \geq 3.5$) to understand the physics of the earthquake sources in the mentioned study region.
3) To infer the stress pattern scenario in the NW Himalaya that will help in identification of new earthquake potential zones having their epicentres in the above mentioned region.
4) Modelling of seismicity and source mechanism results with gravity data to explain the tectonics.

1.6. Geological and Tectonic Setting of the Himalaya

1.6.1. Geology of the Himalaya

Himalaya as we know stretches over 2400 Km between Namche Barwa (7782m) syntaxis in Tibet to Nanga parbat (8125m) in India. The formation of the mighty Himalayas can be credited to the ongoing continental-continental plate collision between the Indian and the Eurasian tectonic plates. Himalaya has also been subjected to higher amount of weathering and erosion by several forces of wind, water etc. The geomorphological and regional variation subdivided the entire Himalaya into western Himalaya having a longitude range of 66°– 81°E, central Himalaya between a longitude ranges of 81°–89°E and eastern Himalaya having longitudinal distribution ranges between 89°–98°E (Yin, 2006). Himalaya can be divided into east trending geographic belt that corresponds to the four geological domain and these geological units extends along the entire Himalayan orogeny. These lithotectonic units may be termed as Outer (Sub) Himalaya (Siwalik), Lesser Himalaya (LH), Higher Himalaya Crystalline (HHC) and Tethys Himalaya Sequence (THS) from south to north (Gansser, 1964; LeFort, 1975).

The Himalaya consisting of major tectono-stratigraphic units are segregated from each other by major tectonic boundaries. The tectonic units may be designated as the Sub or Siwalik Himalaya (SH) bounded in south by Himalayan Frontal Thrust (HFT) separating it from the adjoining Indo-Gangetic Plain (IGP), the Lesser Himalaya (LH) isolated from the Siwalik Himalaya (SH) by the major tectonic break called the Main Boundary Thrust (MBT). The Higher or Greater Himalaya separated from the lesser Himalaya by the Main Central Thrust (MCT) and the Trans Himalaya or Tethys Himalaya bounded by the South Tibetan Detachment (STD) in the south segregating it from the Higher Himalaya in the north bounded by Indo-Tsangpo suture zone (ITSZ) fault. The Tethys Himalaya consists of the Tethys Himalayan sequence of metamorphic rocks. The Indo-Gangetic plain (IGP) consists of sediments of Cenozoic age and the Siwalik Himalaya is composed of Neogene sandstone, mudstone and conglomerates sequences. The lesser Himalaya consists of low grade metamorphic rocks and had connections with the Higher Himalayan crystalline (HHC). The Higher Himalaya metamorphic rocks ranging in the age from Neoproterozoic to Ordovician with an increase in grade of metamorphism from the lower to the middle part and decreases till the upper part towards the South Tibetan Detachment (STD) (DeCelles et al., 2000; Lefort, 1996). All the NW–SE dipping thrust faults is said to have been rooted deep as splays of Main Himalayan Thrust (MHT) which is called as the Main Himalayan Detachment fault (Zhao et al., 1993). The southern limit of the Himalaya termed as the Indo-Gangetic Plain (IGP) is an active depression that receives a large amount of sediments from Himalaya. There are a number of basement highs underneath the Indo-Gangetic Plain (IGP) that are being subducted under the Himalaya along the Himalayan Frontal Thrust (HFT) and these are the controlling factors along the strike variation of seismicity below the Himalaya (Johnson, 1994; Pandey et al.,1999; Avouac, 2003). The Siwalik Himalayan sequence consists of the Neogene and Palaeogene to early Miocene strata with the former present in the Main Boundary Thrust (MBT) footwall and the latter is emplaced with the Main Boundary Thrust (MBT) hanging (Schelling and Arita, 1991; Burbank, 1996; De Celles et al., 1998a, b). The tertiary strata form below the Main Boundary Thrust (MBT) to the sub-Himalayan geographic and stratigraphic zone (Gansser, 1964). The lesser

Himalaya consisting of the metasedimentary rocks in the form of lesser Himalayan Sequence as proposed by Heim and Gansser (1939) and LeFort (1975) which comprised of fossiliferous low grade metamorphics. These overlain strata are often referred to as the Gondwana Sequence (Gansser, 1964) which consists of metasedimentary sequence ranging from Permian to Cretaceous in age. The Higher Himalaya consists of the Higher or Greater Himalayan complex (GHC) which are high grade metamorphic rocks. These High grade metamorphic rocks form a continuous belt along the east-trending axis of the Himalayan range, but they also occur as isolated patches surrounded by low-grade Tethyan Himalayan strata such as in the Zanskar and Tso Morari regions of NW India, along the North Himalayan Antiform (NHA), and in the Nanga Parbat massif of northern Pakistan (Honegger et al., 1982; Steck et al., 1998; Di Pietro and Pogue, 2004). The Tethys Himalaya consists of the Tethyan Himalayan Sequence that consists of Proterozoic to Eocene siliciclastic and carbonate sedimentary rocks inter bedded with Paleozoic and Mesozoic volcanic rocks (Baud et al., 1984; Garzanti et al., 1986, 1987; Gaetani and Garzanti, 1991; Garzanti, 1993, 1999; Brookfield, 1993; Steck et al., 1993; Critelli and Garzanti, 1994; Liu and Einsele, 1994, 1999). In this way the Himalaya along with its active structures lies under the compressional and extensional regime and accommodates the shortening across major thrusts due to the ongoing India-Eurasia collision.

1.6.2. Tectonics of the Northwestern (NW) Himalaya

The NW Himalaya which lies in the northern boundary of the Indian sub-continent has experienced major earthquakes in the past as it falls in the zone of continental collision of the Indian and Eurasian plates (Chandra, 1992). This region demonstrates high complexity pertaining to its geological and tectonic significance. The natural disasters in terms landslides and earthquakes are considerably high as compared to other regions existing in the country. The presence of maximum earthquake prone zones here can be due to the existence of major active tectonic faults that are having northwest–southeast trends. These major seismotectonic faults includes the Main Boundary Thrust (MBT), Main Central Thrust (MCT) and the South Tibetan

Detachment fault (STD) running parallel to Himalayas and some other local transverse faults across the area are also present (Mahajan and Kumar 1994). The study area of NW Himalaya is divided into three major tectonic zones on the basis of past and present tectonic deformations and seismicity scenarios. These zones include the Garhwal Himalaya region, Kangra-Chamba region and the Kinnaur region respectively. The stratigraphic division of the Lower or Lesser Himalayan sequence as stated by Heim and Gansser (1939) includes the nonfossiliferous low-grade metasedimentary rocks.

These rocks strata sequence is believed to have been overlain by the strata of having an age range from Permian to Cretaceous that are often referred as the Gondwana Sequence (Gansser, 1964). The main lithological units that can be attribute to the lesser Himalayan sequence of the Garhwal Himalaya are the metasedimentary rocks, metavolcanic rocks, and augen gneisses (e.g., Frank et al., 1995; DeCelles et al., 1998a; Upreti, 1999). The upper Proterozoic strata present in this tectonic province can be said to be in conformable contact with overlying Cambrian strata in NW Himalaya and possibly in Nepal (Valdiya, 1980; Brunel et al., 1984, 1985). Earlier two different tectonic models were proposed for Himalaya on the basis of seismicity analysis. These models include the Steady state model proposed by Seeber et al., 1981 and the Evolutionary model proposed by Ni and Barazangi 1984. The steady state model suggested a gently dipping Indian Plate beneath an overriding Eurasian plate and a tapering sedimentary wedge. This sedimentary wedge is believed to have decoupled from both the Indian and the Eurasian plates. This model also states for the reactivation of both the major tectonic faults the MBT and the MCT simultaneously. But the evolutionary model proposed by Ni and Barazangi, 1984 states that the MBT is still active and MCT is dormant in the region. The subduction of the India plate under the Eurasia plate resulted in the formation of a sedimentary wedge consists of a part of the Indian lithosphere called as 'Plane of detachment' decoupled from down going Indian plate.

The plane of detachment or the Main Himalayan Thrust (MHT) that enroots major tectonic breaks such as HFT, MBT, MCT and STD coincides with the high topographic gradient in the Garhwal Himalaya region (Zhao et al., 1993). The Garhwal Himalaya region is also characterized with ramping of major tectonic fault the MCT Plate (Schelling and Arita, 1991; Lyon-Caen and Molnar, 1983 and Cattin and Avouc, 2000). The most important structure of the area known as the MCT shear zone is characterized by well-documented inverted metamorphism. In this region both MBT and MCT are still active and produce recurrent seismicity in the region.

The Kangra-Chamba region of the present study area has witnessed a highly devastating earthquake of magnitude 7.8 on the Richter scale in 1905. This region is showing a characteristic plate deformation in the form of regular earthquakes due to the continuous accumulation of stress resulting from the subduction of the Indian plate beneath the Eurasia plate. This region is characterised with the presence of four major seismotectonic zone named as Sub-Himalaya, Panjal imbricate zone (PIZ), the extended Chamba nappe (CN) (Thakur, 1998) that separates the northern Higher Himalayan crystalline from the southern Lesser Himalaya and the Higher Himalaya. The CN is mainly composed of weakly metamorphosed sediments that are similar to the sediments present in the Higher Himalaya. The Panjal imbricate zone (PIZ) is another tectonic subunit which mainly consists of phyllites, slates and limestone (Rautela and Thakur, 1992; Thakur, 1998). The Chenab normal fault is yet another major tectonic feature present in the area carries these sediments resulting from the southward migration of the sliding Tethys Himalaya from the north over the Higher Himalaya. The other major tectonic breaks present in this study area are the Panjal Thrust (PT) and the Jwalamukhi Thrust (JMT) respectively. The Panjal thrust zone comprises of major formations such as the Shalkhala formations which are an imbricate of lesser Himalaya formations and the tertiary sediments of the outer Himalaya (Thakur et al., 1995). The Shalkhala formations are predominantly made up of mylonite gneiss which is clearly demarcated by the Panjal Thrust (PT). The lesser Himalayan formations that are predominantly demarcated by the Shali formations (Thakur, 1992) are mainly composed of limestone and black slate. The sediment evacuation of the Kangra region is said to have reactivated the Jwalamukhi Thrust (JMT) (Dey et al., 2016). Again moving to our second major tectonic region called as the Kinnaur region which has been less studied in terms of tectonics and seismicity in the past. Kinnaur is regarded as one of the most seismically active segment of the NW Himalaya region due to the fact that a major earthquake of magnitude > 6.8 occurred in this region in 1975. This seismic region lies in the Higher Himalaya and some parts of Tethys Himalaya between the two major tectonic breaks called as Main central thrust (MCT) and the Indo-Tsangpo suture zone (ITSZ) that marks the boundary between the India and the Eurasia plate. In this region a number of faults and thrusts are present that are characterised by the ongoing India-Eurasia collision. Some of the major faults that marks its presence in this particular area are the South Tibetan detachment system (STD), Kaurik Chango fault system (KCF), Karcham normal fault (KNF), Leo-pargil detachment zone (LPDZ) and the Tso-Morari fault (TSM). The most devastating earthquake of the region is the Kinnaur earthquake of 1975 which occurred due to the activation of the Kaurik Chango Fault and regarded as an N–S trending neotectonic fault. This region has experienced an extensional regime that is giving rise to earthquakes having a normal faulting mechanism. This tectonic region is comprised of rocks formations corresponding to Vaikrita and Haimanta groups respectively. These rocks are mainly of medium to high grade metamorphic in nature. The Vaikrita Group consists of psammatic gneiss with quartzite bands, banded gneiss, granite gneiss, quartz mica gneiss while the Haimanta Group comprises of grey-purple quartzite, black carbonaceous phyllites and quartz mica schist interbedded with amphibolites and calc schists respectively.

As crustal shortening in the NW Himalaya is observed along the southern mountain front and this region comprising of one of the major structural boundaries is characterized by major tectonic deformations along orogen-parallel and orogen-perpendicular normal faults (e.g., Le Fort et al., 1982; Burchfiel et al., 1992; Wu et al., 1998). In this regard the South Tibetan detachment system is associated with the normal faults in the study region that strikes parallel to the major thrusts in the Himalayas such as the Main Boundary thrust (MBT) and the Main central thrust (MCT). This major tectonic boundary also separates the high grade metamorphosed rocks of Higher Himalaya from the low grade metamorphosed rocks of the Tethys

Himalaya (Burg et al., 1984; Burchfiel and Royden, 1985; Burchfiel et al., 1992). There have been immense evidences from some studies (Hodges et al., 2001; Hurtado et al., 2001) that the South Tibetan detachment system has been reactivated recently during the Quaternary. Therefore this region can be significantly linked to active tectonism in the present context along with the Kangra- Chamba region. These three distinct tectonic units form the major part of the NW Himalaya should be studied in great particular for some major tectonic implications.

1.6.3. Seismicity of the Northwestern (NW) Himalaya

Seismicity in Himalayas is a very common phenomenon that can be seen from a number of historical records that shows how these regions have been subjected to a number of devastating earthquakes in the past. As stated earlier in this chapter this seismic activity in the NW Himalaya arises due to the ongoing collision between the Indian and the Eurasia plate at the northern boundary of the Indian sub-continent. Earthquakes that are a major hindrance to the life and property should be studied in detail in order to provide a clear picture of the potential hazard and risk associated with the phenomena for the study region. Historical records of seismicity depicts that the NW Himalaya is the active seismic zone in the Himalaya which has been hit by a number of earthquakes in the past. These three major tectonically disturbed regions which are mainly conducting our study covering the Garhwal Himalaya region, the Kangra-Chamba region and the Kinnaur Himalaya was hit by major earthquakes of higher magnitude on the Richter scale in 1905, 1975, 1991 and 1999 respectively. India-Eurasia continent-continent collision resulted in the assemblage of earthquake hypocenters in the form of interplate seismicity in the Garhwal Himalaya. *Figure 1.3*represents the earthquake epicenters recorded during the period using both the catalogues i.e. the WIHG catalogue and the ISC-EHB catalogue in the NW Himalaya.

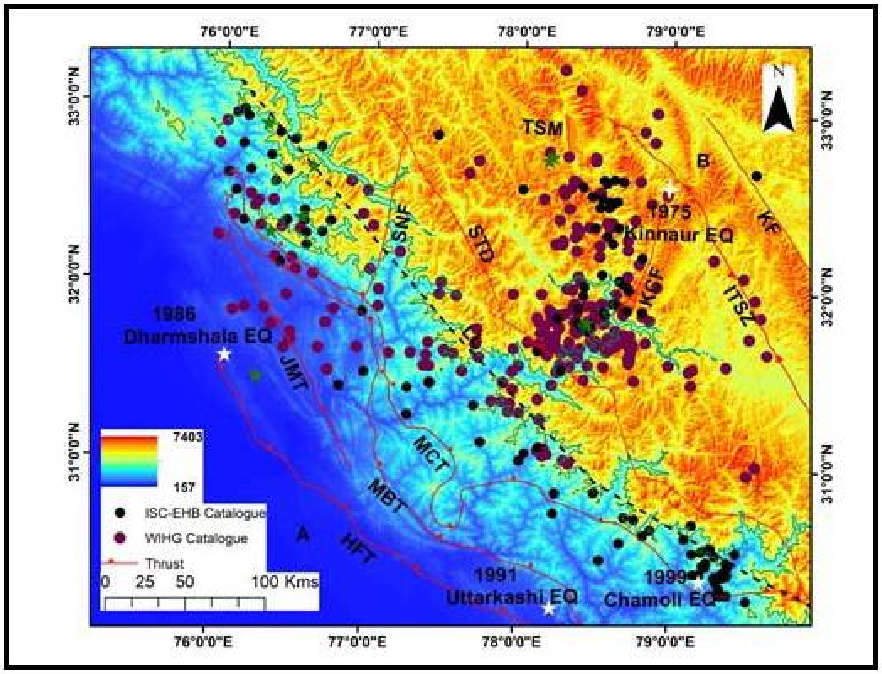

Figure 1.3: The seismicity recorded during the period using both the catalogues i.e. the WIHG catalogue and the ISC-EHB catalogue in the NW Himalaya along with major structural breaks (HFT: Himalayan Frontal Thrust; JMT: Jwalamukhi Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; LL: Locking line; SNF: Sundarnager Fault; STD: South Tibetan Detachment; KCF: Kaurik Chango Fault; TSM: Tso-Morari Fault; ITSZ: Indo-Tsangpo Suture Zone; KF: Karakoram Fault). It also signifies the four moderate to strong earthquakes in the form of white solid stars along with their year of occurrences. The earthquake epicenters recorded by WIHG seismic stations are denoted by red solid circles and the earthquake denoted by ISC-EHB stations are denoted by black solid stars. It also represents the earthquakes whose moment tensors are being determined as solid green stars that is discussed in particular afterwards.

The NW Himalayan collisional boundary demarcating the India-Eurasia convergence within the underthrusting of the Indian plate beneath the Eurasia upshot the earthquake occurrence of the Himalayan region in general and the Garhwal Himalaya in particular. The dipping of the Indian plate beneath Eurasia along the enrooted MHT plane is marked with the occurrence of moderate sized earthquakes as evidenced from fault plane solutions (Ni and Barazangi, 1984) The seismic activity as evidenced from the seismicity plot shows more confinement of earthquake hypocenters towards the north of MCT around the epicentral zone of the 1999 Uttarkashi earthquake that is associated with the MHT plane. This seismicity accountancy can be linked with the current deformations of the Indian plate at the collision boundary. More recently, moderate earthquakes, namely the Uttarkashi earthquake of 1991 and the Chamoli earthquake of 1999 have occurred in the Garhwal and Kumaun Himalaya region. Gaur et al., 1985; Khattri et al., 1989; Jain and Chander, 1991 carried out the seismic monitoring work in Garhwal-Kumaon Himalaya with a local seismic network and attributed an active seismic zone of about 150 km long and 30–50 km wide running almost parallel to the surface trace of MCT lying between Yamuna and Alaknanda valleys. Sharma and Wason (1994) attributed the occurrence of low stress drop events at shallow depths in the Garhwal Himalaya to the low strength of the crust to accumulate strain energy. The Kangra- Chamba region and the Kinnaur region have been studied earlier by some of the researchers in the past (e.g. Thien dam network and Salal dam network) using micro-earthquakes by utilizing seismic networks catering the needs for river valley projects in NW Himalayas. But these studies could not provide a clear picture for the seismicity of the region. They could not specify the accurate depth section of the layer that consists of most of the earthquakes. According to the above studies the earthquakes are mainly confined within a layer corresponding to less than 10 km. with an error of ±3 km in it. They inferred that most of the seismic activity in the Kangra-Chamba region is associated with the Main Boundary thrust (MBT) in the epicentral zone of the Kangra earthquake of 1905. The earthquake study carried out around the source zone of the 1905 Kangra earthquake demarcates the present seismicity to be associated mainly with the NW–SE trending MBT (Kumar and Mahajan 1991). The location of some of the earthquake hypocenters can be also linked with the presence of NNE trending transverse lineaments (Srivastava et al., 1986). The recent micro-earthquake seismic studies carried out by various researchers such as Kumar et al. 2009; Kumar et al. 2013; Chatterjee and Bhattacharya (1992) revealed high seismic activity associated with the MBT. The seismic activity in the adjacent regions, e.g. in the Kumaon and Garhwal Himalaya reported by Yadav et al. 2009 shows the seismicity clustered in the northern part of LH, close to MCT but as the MCT merges with MBT and described as PT in the Kangra–Chamba region (Thakur, 1998), the high seismicity is shifted to the north of MCT. The focal depth of majority of the earthquakes associated with the tectonic movement along MBT, PT (Panjal Thrust) and the Chamba Thrust (CT) are well above the detachment (Khattri et al., 1989).

In the Kinnaur region the seismic activity can be attributed mainly around the South Tibetan detachment (STD) and the Kaurik-Chango fault that is having an N–S orientation. This fault is mainly inferred as a neotectonic fault (Joshi et al., 2010). The most devastating earthquake that hit this region is the Kinnaur earthquake of 1975 of magnitude 6.8 is associated with the activity across the Kaurik-Chango fault. In this region the fault-plane solutions demarcates pure normal faulting showing an E–W extension at shallow as well as at a greater depths km (Molnar and Chen, 1983; Molnar and Lyon-Caen, 1989). This region is characterized by shallow depth events having a depth $\leq$ 15 Km between the Tso Morari dome and the Main Central Thrust (MCT) and the Kinnaur earthquake region that is close to Leo pargil gneiss dome (*Hintersberger et al.*, 2010). The seismic activity recorded in the past and present is higher and is having N–S-striking structures in the Himalayas as compared to the micro-seismic activity observed in the similar type of structures in Thakkola graben in Nepal (Pandey et al., 1999). In this way the tectonic as well as the seismic activity in these three major seismic zones should be studied with great importance in order to provide some most valuable seismotectonic implications for the NW Himalaya region.

1.7. Chapter Scheme:

This Ph.D thesis entitled 'Seismological and Geophysical studies of NW Himalaya: Tectonic Implications' can be completely summarised in the form of six chapters. A brief summary of each chapter is given below:

Chapter 1 deals with an introduction to the research problem, description about the study area and the seismic activity scenario of the NW

Himalaya region.

Chapter 2 has a general description to the various methodologies utilized for the study. It includes the estimation of the 1 D crustal velocity model for the NW Himalaya, Double-difference relocation of seismicity, Seismotectonics for the NW Himalaya, Stress pattern scenario of the NW Himalaya, Seismic attenuation characteristics estimation of the NW Himalaya and Gravity study of the NW Himalaya.

Chapter 3 presents a detailed procedure about the estimation of 1 D crustal velocity model for NW Himalaya. The 1 D velocity model proposed for the study region has seven uniform layers with interfaces at depths of 0, 5, 10, 15, 20, 25 and 30 km with P-wave velocity of 5.219 km/s, 5.314 km/s, 5.391 km/s, 5.392 km/s, 5.964 km/s, 6.071 km/s, 6.073 km/s and S-wave velocity of 2.998 km/s, 3.015 km/s, 3.134 km/s, 3.135 km/s, 3.441 km/s, 3.482 km/s and 3.647 km/s, respectively.

Chapter 4 presents the significant implications on the Seismotectonics as well as potential estimation for future seismic events in the region. The geometry of the MHT plain varies along the strike of the Himalaya in flat and ramp segments and its dip varies from 4° to 19° below the HFT in south to STD in the north. The depth of the mid crustal ramp and great Himalayan ramp below the MCT and STD varies from 12 to 22 km and 28 to 40 km depth respectively. The earthquakes associated with these above tectonic subdivisions are having focus distribution depth of 2 to 47 km that infers the upper as well as lower crust deformation. The earthquake focus exhibits a bimodal depth distribution characterizing the seismogenic nature of the entire Indian crust. The earthquake associated with the major tectonic breaks shows a wide variation in focal mechanism solutions. The moment tensor solutions obtained for the study region shows a complex tectonic setting. The brittle – ductile transition zone is inferred at a depth range from 15-20 km in the study area. The above explained seismotectonic setting depicts the multifaceted nature of the NW Himalaya tectonic regime.

Chapter 5 deals with the current seismic stress pattern scenario in the NW Himalaya and the associated hazard. The static stress change due to the four moderate to major earthquakes namely the 1905 Kangra earthquake, 1975

Kinnaur earthquake, 1991 Uttarkashi earthquake and 1999 Chamoli earthquake that occurred in NW Himalaya, India were studied utilizing the Coulomb 3.1 application. Coulomb stress change was calculated utilizing the presumed three factors. 1905 Kangra earthquake shows 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.

Chapter 6 discusses the entire seismological and Geophysical study carried out in the NW Himalaya with major tectonic implications obtained from various studies. This clearly shows the fact that the current seismotectonic scenario prevailing in the region is near to failure in future and major earthquakes are likely to occur. The estimated seismic potential for the region considering all the microseismicity in the region shows that only a fraction of energy (3–5 %) that has accommodated in the region due to underthrusting has been dissipated through occurrences of Great earthquakes and the remaining (95–97 %) can give rise to number of devastating earthquakes in future and cause a great loss to the socio-economic condition of the country.

Chapter 7 concludes the entire work presented in this thesis and also the future directives.

1.8. Contribution made by the Scholar

The following outcomes of the thesis are original and claimed to be the contribution of the scholar:

1) A preliminary 1 D velocity model for Himachal Pradesh, India has been developed by utilizing the P and S-wave travel time data.

2) The double-difference earthquake location algorithm was applied for the relocation of 466 earthquake hypocenters in NW Himalaya, India and the relocated seismicity shows a bimodal depth distribution upto a depth of first layer up to 20 km and a second layer from 20 to 50 km.

3)Source characteristics of the region shows a mixture of thrust mechanism dominant in the Kangra-Chamba and a normal fault mechanism in the Kinnaur region.

4) The low QC values or high attenuation at lower frequencies and high QC values or low attenuation at higher frequencies estimated, suggest that the heterogeneity decreases with increasing depth in our study region.

5)The gravity highs are observed for the Indo-Gangetic Plain (IGP) and the Siwalik Himalaya (SH) and the significant lows are observed over Higher Himalaya and mostly in the collision zone of Tethys Himalaya.

6) An estimated EET as 53 km along with observed and best fitted coherence curve is obtained for NW Himalaya.The residual anomaly plotted corresponds to shallow sources of the crust. Thus topography and tectonic load correspond to presence of low density rocks in parts of Higher and Tethys Himalaya and high density rocks at some parts of Indo-Gangetic Plain, Siwalik and Lesser Himalaya.

7) This implies that in the NW Himalaya the higher tectonic provinces are characterized with shallower crustal seismicity as recorded with seismological modelling and supplemented with the gravity observations.