# ACTIVE FAULT MAPPING AND VALIDATION USING GEOPHYSICAL AND TERRAIN ANALYSIS FOR ASSESSING SEISMIC HAZARDS IN PARTS OF HIMALAYA

ABHISHEK SAIKIA
March, 2015

SUPERVISORS:
Dr. P.K. Champati ray (IIRS, India)
Mr. S. Kannaujiya (IIRS, India)
dr. M. van der Meijde (ITC, The Netherlands)

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Specialization: Natural Hazards and Disaster Risk Management

SUPERVISORS:
Dr P.K. Champati ray, (IIRS, India)
Mr S. Kannaujiya, (IIRS, India)
dr. M. van der Meijde, (ITC, The Netherlands)

THESIS ASSESSMENT BOARD:
[Title, Initials, Name (Chair)]
[Title, Initials, Name (External Examiner, Name Institute)]
etc

*Dedicated to*

*My Mom and Dad, my Sister, my family, Fokir, Zoha, Pooja, Birbal, Tilai, Basu, Tappon, Rajashree, Shubhki (u-turners if there were any).*

*"All that is gold does not glitter,*
*Not all those who wander are lost."-*
*Poem by Bilbo Baggins in the Fellowship of the Ring*

*"It is our choices, that show what we truly are,*
*far more than our abilities."-*
*Albus Dumbledore*

*"It takes a great deal of bravery to stand up to your enemies, but just as much to stand up to your friends."-*
*Albus Dumbledore*

# ABSTRACT

The Himalayan region is one of the most tectonically active region and source of large magnitude earthquakes. The source of these large magnitude earthquakes may be due potential reactivation of the several large scale thrust faults that are present in the region. Active faults are the source of most of these seismic events. Hence the need to properly map and characterize active faults in the region. The Doon Valley lying in the northwest Himalaya is an area which is bounded by four major active fault systems: The MBT (Main Boundary Thrust), The HFT (Himalayan Frontal Thrust), the Yamuna Tear Fault (YTF) and the Ganga Tear Fault (GTF). These fault systems have many associated minor and major faults, many of which are still believed to be active. The aim of this research is to properly validate and map the active faults in the area by the use of geophysics and remote sensing. For this study all the major active faults are mapped from CARTOSAT high resolution imagery, LANDSAT ETM+ imagery and CARTOSAT DEM of the area using previous studies conducted on active tectonics in the area. A composite active fault map is prepared based on previous literature of the area. Geomorphic signatures of active tectonics such as fault scarps, topographic breaks, knee bends in rivers, sudden termination of alluvial fans, termination of structural features, sag ponds, steep escarpments and steep river terraces were observed in the field. Based on these field observations and also trenching sites mentioned in previous literature validation surveys were conducted. These surveys were conducted with the help of Ground Penetrating Radar (GPR). The profiles were taken to the transverse direction to the fault line as much as possible. Some of the faults such as Piedmont Fault near Roorkee, HFT near Mohand, Bharli Fault near MBT and a possible fault near Ibrahimpur give clear evidences of faulting in the GPR profiles. These profiles clearly show the dipping direction of the faults and the fault geometry. The Bhauwala and the Harrowala faults also show clear evidence of faulting. This research may be used in the future as a starting point to conduct more extensive geophysical surveys in the Doon valley. The GPR surveys can be augmented by other geophysical methods (e.g. resistivity) and trenching investigations. The combined results of the geophysical and trenching investigations can then be used to conduct paleoseismic investigations and also predict recurrence intervals of surface rupture in the active faults. The active faults can also be mapped properly and a composite database of active faulting in the area can be created which is lacking at present. This will in turn be hugely beneficial in conducting seismic hazard assessment of the region.

Keywords: Himalaya, Doon Valley, active tectonics, seismic hazard assessment, fault scarps, thrusts, Ground Penetrating Radar (GPR), geophysical methods, trenching, paleoseismic.

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# 1. INTRODUCTION

## 1.1. BACKGROUND

Active faults are defined as those faults which show evidences of movement due to crustal deformation in the recent geological past. These movements are generally correlated to past earthquakes or the present seismicity of the region. Any faults with manifestations of activity in the last 100,000 years are defined as active faults (Trifonov 1995). The active faults can be recognized as those occurring during the Late Quaternary and with possibility of deformation during the future (Malik *et al.* 2010a) .The fault displacement and earthquakes are both potential hazards. Studying active faults is useful for estimating seismic and other geologic hazards. Research on geodynamics and recent tectonics can also be carried out by studying these active faults (Trifonov 1995).

## 1.2. MOTIVATION AND PROBLEM STATEMENT

The Himalayan region is an area which is tectonically very active with the presence of large number of active faults. There are series of large-scale thrust faults such as the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT). Seismicity of the Himalaya is highly influenced and manifested by active tectonics at the mountain front, particularly involving HFT, MBT and recently postulated presence of minor faults in the piedmont region (Thakur 2004). In seismically active regions like the Himalaya, active faults are the cause of large magnitude earthquakes and paleoseismic investigations have confirmed the ability of these faults to create large magnitude earthquakes. Therefore precise mapping of active faults is the need of the hour particularly where previous information on the orientation, size and extension of these active faults are not readily known. Because without such information the hazard posed by these faults may not be assessed properly (Malik *et al.* 2010a, Malik *et al.* 2010b).

As reported by various authors the subsurface structural configuration cannot be inferred directly, although active faults can be recognized on satellite images and in the field. Although trench logging is used to confirm the presence of fault in depth, but due to limited depth of exposure trench logging information cannot reveal completely the subsurface geometry of the major faults at depth. Vegetation and sediment cover conceals the fault traces. Therefore it is imperative to carry out the geophysical surveys to validate and map these faults to determine the seismic hazard prevalent in the area (Fazzito *et al.* 2009).The main objective of carrying out active fault mapping is to determine the exact location and other characteristics of the active faults (Yalçıner *et al.* 2013). The location of active faults in the study area will be very useful for seismic hazard assessment in the region with respect to recurrence of great Himalayan earthquakes (Joshi and Hayashi 2008).

## 1.3. OBJECTIVES

The main objective of the present study is
"Identification, mapping and sub-surface characterisation of active faults using geophysical and terrain parameters"

### 1.3.1. SUB OBJECTIVES

The sub objectives of the present study is:

- To map the active faults of the study area.
- To carry out geophysical investigations (using GPR survey) to validate the presence of faults.
- Assessment of seismicity vis-a-vis presence of active faults.

## 1.4. RESEARCH QUESTIONS

The research questions that are to be answered from the study:

- Which are the prominent active faults in the study area?
- Whether geophysical surveys (GPR surveys) can confirm/validate the presence of fault extension in the subsurface?
- What is the relation between seismicity and active faults of the region?

## 1.5. THESIS STRUCTURE

The thesis work is prepared as follows:

*Chapter 1: Introduction*: The chapter introduces the basic concepts behind the research (active fault mapping) along with the research questions and objectives of the research.

*Chapter 2: Study Area and Literature Review*: It introduces the study area and gives a summary of the geology and tectonics of the Doon valley that have been published in previous studies of the area. It also discusses the previous GPR studies conducted in India for fault identification.

*Chapter 3: Materials and Methods:* This chapter describes the methodology and the different datasets, instruments and softwares used during the research period.

*Chapter 4: Results and Discussions:* This chapter discusses the results of the active fault mapping studies along with the GPR and seismicity results of the area. The results are introduced for each individual fault followed by a discussion on the significant observations of the research results.

*Chapter 5: Conclusions and Recommendations:* This chapter concludes the research with observations about the strong points and the limitations of the research along with recommendations for future studies in the same area.

# 2. STUDY AREA AND LITERATURE REVIEW

## 2.1. STUDY AREA

The study area extends from Roorkee to Mussourie covering the Doon valley and the Piedmont zone to the south of the Doon valley. The extension is roughly from Roorkee to Mussourie in Uttarakhand, India (Figure 2-1). This main Doon valley is bounded by the HFT (Himalayan Frontal Thrust) and the MBT (Main Boundary Thrust) with many minor faults also prevalent in the region. Most of the faults have already been identified and my objective was to validate and confirm the location of these known faults (the faults which can be identified from satellite image analysis and field observations) through sub surface characterization by using geophysical methods.

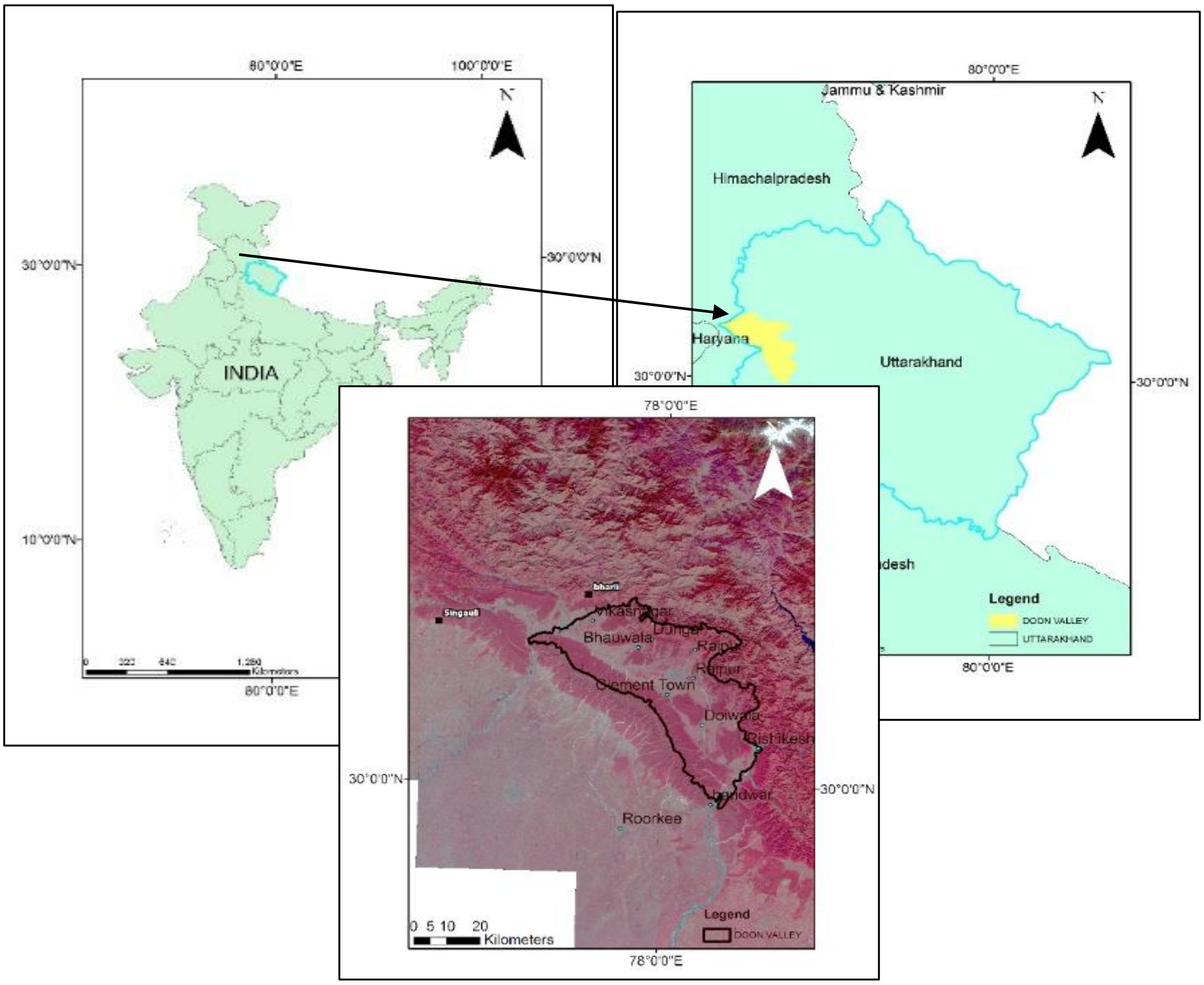



Figure 2-1: The map of the study area on a LISS III image of the area.

## 2.2. TECTONICS AND GEOLOGY OF DOON VALLEY

The Doon (Dehradun) valley is defined as a synclinal intermontane valley which lies within the Shiwalik group rocks in the NW Himalaya (Singh *et al.* 2001). The Main Boundary Thrust (MBT) separates the valley from the Lesser Himalayan formations and demarcates the northern part of the valley (Singh *et al.* 2001, Singh *et al.* 2007). The Shiwalik group of rocks which are of the Upper Tertiary age is separated from the Gangetic alluvial plains by the Himalayan Frontal Thrust (HFT) (Sahoo *et al.* 2000, Singh *et al.* 2007). The Shiwalik group of rocks mainly consists of fluvial sandstones, shales and conglomerates (Sahoo *et al.* 2000). The Doon valley lies between the Ganga and Yamuna rivers in the east and west respectively (Sahoo *et al.* 2000). The Doon valley being synclinal in nature is filled up with piedmont and other fluvial deposits called the "Dun gravels" due to the presence mainly "gravels" in these deposits (Singh *et al.* 2007). The "Dun gravels" are also shown as recent alluvium in some of the published geological maps (Singh *et al.* 2001, Singh *et al.* 2007). The Doon valley is formed by three major fans: the Dunga, Dehradun and Bhogpur fans. These fans extend from west to east. These fans are deposited by streams coming out of the Lesser Himalayas with the major relief provided due to the MBT and the related faults (Singh *el al.* 2001). The deposition of these fans took place roughly from 50,000 to 10,000 years ago (Singh *et al.* 2007). The Dun is divided into the following major zones geomorphologically from North to South: Lesser Himalaya (~2500 m amsl), Dissected Shiwalik hills (<1150 m amsl), Pedimented Shiwalik hills and Piedmont zone (900-300 m amsl) (Singh *et al.* 2001). These zones are generally bounded by faults. The Dun gravels overlies the dissected Shiwaliks. The younger Dun surface are formed by the pedimented Shiwalik hills with a thicker gravel cover which decreases in height from north to south. The isolated N-S trending hills in the Doon valley and the piedmont region rises above the younger Dun surfaces (Thakur *et al.* 2007). The Dun valley has two distinct slope and depositional regimes according to Thakur *et al.* (2007). The distinct slope and depositional regimes are divided by the Asan and the Suswa Song rivers which flow along the axis of the valley trending E-W towards the south of the MBT (Thakur *et al.* 2007). In the northern part of this depositional regime, the Dun principal fan is the central fan which forms the drainage divide between the Ganga and the Yamuna rivers (Thakur *et al.* 2007). The uplifted Nagsidh hill is a prominent feature in the southern part of this fan (Thakur *et al.* 2007). The Bhogpur fan has no uplifted surfaces and instead starts from the Lesser Himalaya and descends continuously to a lower elevation upto the Suswa-Song rivers (Thakur *et al.* 2007). The northern slope of this fan is highly entrenched with a height difference of 50-200m between the river floor and the surrounding Doon highlands (Thakur et al. 2007). The southern part of the Dun depositional regime is a hogback structure formed by Shiwaliks with smaller fans and washed up mountain slopes (Thakur *et al.* 2007) (Figure 2-2).

The piedmont region is formed by the fans deposited by the streams emerging from mountain front HFT (Thakur *et al.* 2004b). The fans are almost 15-25 km wide ranging from the HFT to the Gangetic plains towards the south (Thakur *et al.* 2004b). This region between the HFT and the Gangetic plains forms the piedmont zone. Two sets of piedmont zones have been identified between the Yamuna and the Ramganga on the basis of soil characteristics: the old piedmont zone (OPZ) and the young piedmont zone (YPZ) (Thakur *et al.* 2004b). The remnants of OPZ are seen in the form of dissected badlands and isolated hillocks almost ~20 meters above the surrounding floodplains (Thakur *et al.* 2004b). The NE-SW trending

Biharigarh ridge is one example of the old piedmont zone (Thakur *et al.* 2004b). To the east and the southeast of the Biharigarh ridge another 15-20 m high plateau is identified with highly dissected topography due to gully erosion representing the remnants of the old piedmont (Thakur *et al.* 2004b). The Solani River near Roorkee acts as the boundary where the Piedmont zone in which uplifted topography is observed terminates abruptly against this NW-SE trending river (Thakur *et al.* 2004b).

The geomorphological units of the Doon valley which have been described above are divided into clear units by some major E-W trending faults in the Doon valley more specifically in the NW Doon valley. The Santaurgarh Thrust (ST) acts as the demarcation between the dissected and the pedimented Shiwaliks lying parallel to the MBT (Thakur *et al.* 2004b). It is just to the south of the MBT. As such it is marked by a sharp topographical break and the bending of streams which can be clearly seen as a lineament on the satellite imagery (Thakur *et al.* 2004b, Singh *et al.* 2007, Philip *et al.* 1996). The ST has also been demarcated as Dunga fault by some authors like Philip *et al.* (1996). Just south of the ST lies the Bhauwala Fault (BF) which is identified from the southern termination of the N-S trending ridges of the Pedimented Shiwaliks and knee bending of the streams (Thakur *et al.* 2004b). It lies near the Bhauwala village and defined by the boundary which joins the southern end of the N-S trending remnant Shiwalik hills (Singh *et al.* 2007). According to Thakur and Pandey (2004a), the N-S trending isolated ridges of Dun gravels with the pedimented Shiwaliks as base terminates abruptly along the Bhauwala lineament. Also sections are seen along the Suarna river near Bhauwala village which shows the Doon gravel lying unconformably over the Shiwalik rocks (Singh *et al.* 2007). Thakur and Pandey (2004a) also mentions the sudden knee turn bend of the rivers further east into the Doon valley which proves the continuation of the Bhauwala lineament further east. Further there is a faint trace due to elevation changes which is described as probably being the trace of the Majhaun/ Bhelonwala Fault lying just north of the BF (Singh *et al.* 2007). Philip (1995) also described the Bhelonwala Fault as one of the prominent faults coming out of the study in active tectonics of the Doon valley by analysing remote sensing data and field investigations in the valley and its surrounding areas.

The boundaries of the three principal fans in the Doon valley are demarcated by the presence of N-S trending transverse faults (Singh *et al.* 2007). The subsidence and upliftment of the Bhogpur and Dunga fan respectively is due to the presence of these N-S trending transverse faults in the form of Nun and Song river faults (Singh *et al.* 2007). The MBT is disrupted by the presence of the N-S trending Baldi-Song fault, the Chandrabhaga Rao Fault and the Jakhan Rao Fault towards the northern end of the Doon valley near Rajpur and Bhogpur (Sahoo *et al.* 2000, Singh *et al* 2001, Singh *et al.* 2004, Thakur *et al.* 2007). An E-W trending blind fault is also mentioned by many authors along the Asan river and the Nagsidh hill which is called the Asan river Fault and it is delineated by the presence of uplifted scarp and the straight course of the river (Rautela and Sati 1996, Sahoo *et al.* 2000, Thakur and Pandey 2004a). The Suswa Song Fault is also an E-W trending fault which causes the anomalous uplift of the Nagsidh hill and uplift of the

Nagsidh ridge (Thakur and Pandey 2004a). There is also the presence of three major strike slip zones along the rivers Yamuna, Dhaulkhand and Ganga called the Ganga Tear Fault, the Yamuna Tear Fault and the Dhaulkhand Fault (Rautela and Sati 1996, Joshi and Patel 1997, Sahoo *et al.* 2000). The Ganga and the Yamuna tear fault bound the east and west of the Doon valley respectively and the Dhaulkhand Fault lies to the south of the Asan Fault just north of the HFT. Between the Doon valley and the alluvial plain is the HFT which is a zone of active deformation (Thakur 2013) (Figure 2-3).

In the piedmont region, the piedmont zone is demarcated to the south by the presence of a strong NW-SE trending lineament. This lineament lies just to the north of the Solani River and follows the course of the Solani River along with the termination of the piedmont fan along this lineament. This lineament has been demarcated as the Piedmont Fault which is the major E-W trending fault in the piedmont region of the Doon valley (Thakur and Pandey 2004b, Thakur *et al.* 2007).

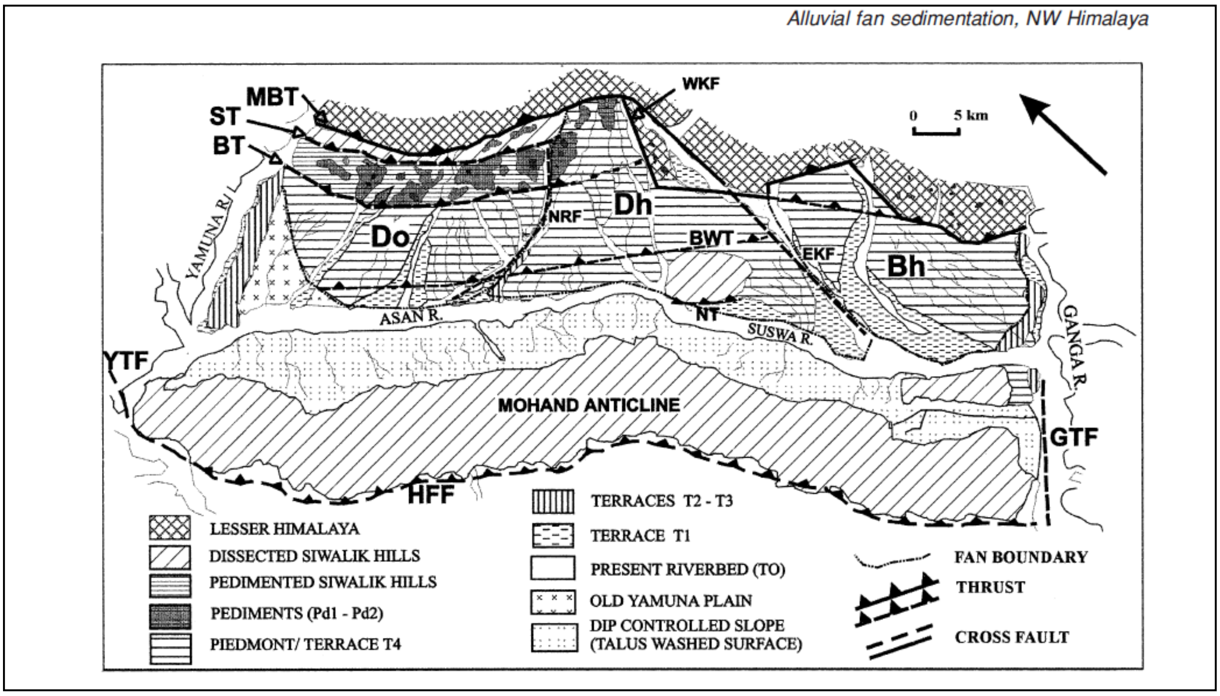



Figure 2-2: Geomorphological Map of the Doon valley taken from Singh et al (2001), Singh et al (2004). In the Figure- HFF: Himalayan Frontal Fault; GTF: Ganga Tear Fault; YTF: Yamuna Tear Fault; BWT: Bansiwala Thrust; NRF: Nun River Thrust; EKF: East Kalanga Fault; WKF: West Kalanga Fault; NT: Nagsidh Thrust; Do: Donga Fan; De: Dehradun Fan, Bh: Bhogpur Fan.

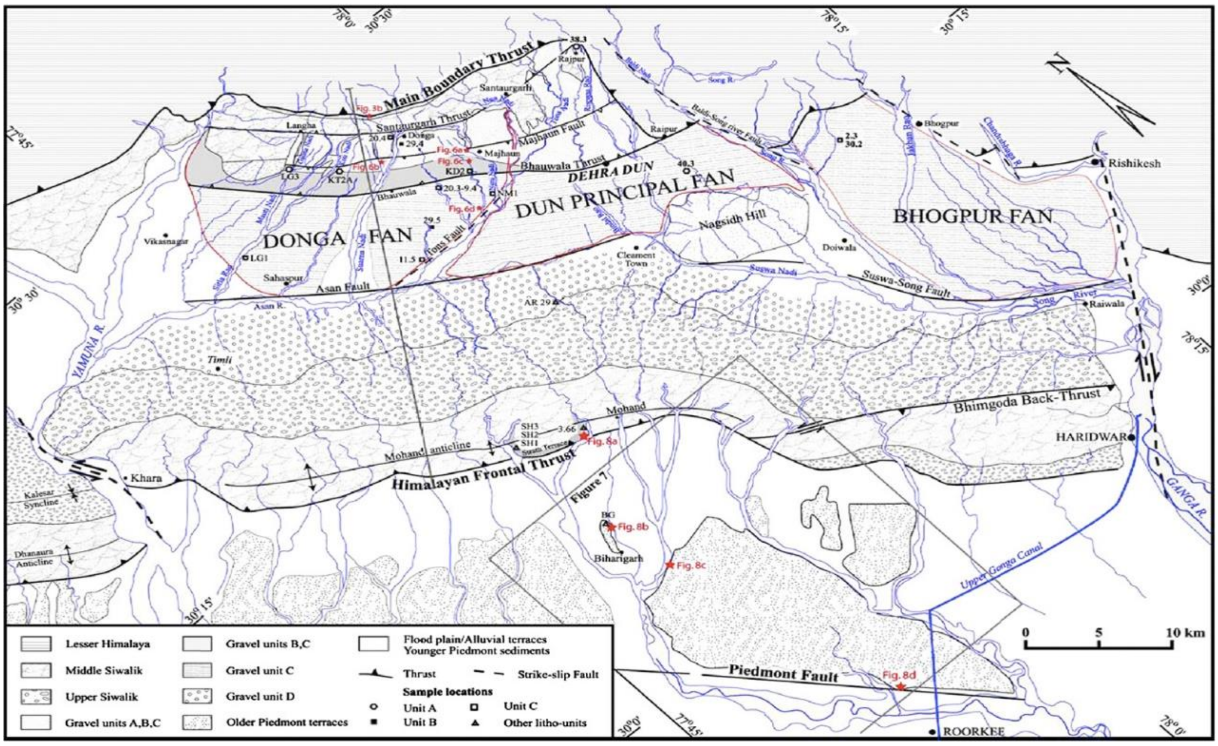



Figure 2-3: Tectonic map of the Doon Valley and its surroundings taken from Thakur et al 2007.

The Piedmont Fault is described as a branched out imbricate of the HFT and a low dipping thrust fault causing the uplift of the piedmont zone (Thakur 2004). The HFT is propagating southward which may have contributed to the upliftment of the piedmont zone (Thakur 2004).

The Duns and the surrounding areas are therefore regarded as sites of extensive neotectonic activities (Philip *et al* 2009). Also the ongoing deformation along the HFT means that the Duns experience recent tectonic activity along the active faults. The signatures of these active tectonics are visible in the form of tilted terraces, quaternary sediment deformation and also tectonic landforms visible on the surface. Some movements are found to be as recent as 800 yrs Bp along the Yamuna tear fault (Philip *et al* 2009). All these point towards the active tectonics of the Dehradun valley and its surrounding areas.

## 2.3. GPR SURVEY FOR VALIDATION OF ACTIVE FAULTS

Ground Penetrating Radar (GPR) survey is used to delineate the subsurface geology along with trenching to get more details on the neotectonic and the paleoseismic history of the surveyed faults (Maurya *et al.* 2005). In India GPR surveys for fault identification and confirmation are still in the nascent stage. Maurya *et al.* (2005) stressed on the need to conduct Ground Penetrating Radar studies for detailed subsurface analysis along faults and fault zones. The advantage of GPR over other methods is that it will help in obtaining high resolution images of the subsurface upto ~ 50 meters which is known as the 'blind zone'. The sediment exposures along faults are not sufficient for detailed stratigraphic and paleoseismic studies. The lack of exposures in most of the areas also makes it imperative to undertake detailed GPR studies.

Preliminary studies were conducted along the Katrol Hill fault (KHF) in Kachchh by Maurya *et al.* (2005). Profiles were taken in N-S oriented transects which were perpendicular to the E-W trending faults. A shielded 200 MHz antenna was used along the measured survey lines. Repeat measurements are taken until the best quality data is obtained along with the required fault profile. The KHF was identified about 800 meters away from the fault scarp. The distance of the scarp from the present location of the faults shows the usefulness of GPR in determining fault scarp retreat and locating the precise fault. Also 3D GPR surveys were carried out at other locations in the fault. 3D surveys can be used to resolve doubts about the changes in dip of the fault in the subsurface. Also the variable scarp retreats derived from the GPR study suggests that different parts of the fault were active during different times.

Malik *et al* (2014) conducted GPR surveys along the foothill zone of Kumaun sub Himalaya to study the active faults in the zone and its impact on landscape shaping and drainage evolution. The survey was conducted across the NW- SE facing fault scarp near Dhol in the Kumaun sub Himalaya. A common offset continuous mode is used in the GPR study with a 20 meter long profile taken across the fault trace identified from remote sensing images by visual interpretation. The frequency of the antenna used was 200 MHz. The distinctive georadar reflections in the hanging wall of the fault suggest folding within the sediment succession. These reflections are truncated along the fault wall which suggests the direction of the thrust movement.

Malik *et al* (2010a and 2010b) conducted studies along the Janauri anticline in northwest Himalaya to confirm the near sub surface faulting of an active fault (the Hajipur fault). A 200 MHz frequency antenna was used with a 22 meter long profile across the fault. 3D data was acquired to get a better cross sectional view of the fault in a 22 meter long and 10 meter wide grid. The fault strand was identified from the 3D fault profile by the presence of inclined reflections which marks a low angle thrust fault. The fault plane is identified to be dipping towards NW. Trenching and paleoseismic investigations were carried out after the GPR survey.

All of these above studies show the advantages of GPR to delineate faults in shallow subsurface environment. The GPR gives more direct and higher resolution images of the subsurface than any other geophysical methods especially in the blind zone ~ 50 meters depth. Further paleoseismic and detailed trenching studies can be carried out based on the results of the GPR studies.

# 3. MATERIALS AND METHODS

## 3.1. MATERIALS

The active fault map/ tectonic map of the area is the main necessity which was prepared with the help of previous literature with the help of visual image analysis performed on the satellite data. A tectonic maps was prepared showing the active faults in a LANDSAT pan sharpened satellite image. CARTOSAT high resolution panchromatic image of the area is also included in the analysis along with LISS III FCC.

## 3.2. DATASET

The dataset used is CARTOSAT 1 DEM which is freely available in www.bhuvan.nrsc.gov.in. The resolution of the DEM product is 30 meters. The satellite imagery used in the analysis is LANDSAT 7 ETM+ image of the year 2000. The image used is a pan sharpened image of the Doon valley and its surroundings. The CARTOSAT high resolution panchromatic image has a resolution of 2.5 meters. The images were acquired from 2009 to 2011. The LISS III FCC image has a resolution of 23.5 meters. Google™ high resolution imagery was also used in the dataset.

## 3.3. SOFTWARES

ARCGIS 10.1 and ERDAS IMAGINE 2014 were the GIS and image processing softwares used in the study. Hill shaded images were generated from the CARTOSAT 1 DEM images using the 3D analyst module in ARCGIS 10.1. Topographic profiles were also created by using the 3D analyst tool in ARCGIS 10.1. The final images were created by combining three or four scenes from the study area using the Mosaic function in Erdas Imagine 2014. GRED 3D viewer software was used for the viewing and the processing of the GPR profiles where the required corrections like move start time, migration and filtering were carried out and the profiles were also georeferenced.

## 3.4. EQUIPMENTS

IDS GPR with 100 and 200 MHz antenna was used in the GPR surveys. The 100 and the 200 MHz antenna to give optimum penetration along with good resolution. These two antennas were shielded antennas which caused less interference due to noise in the agricultural fields where there is the presence of surface objects. Garmin GPS is used to measure the location and the elevation of the profile points.

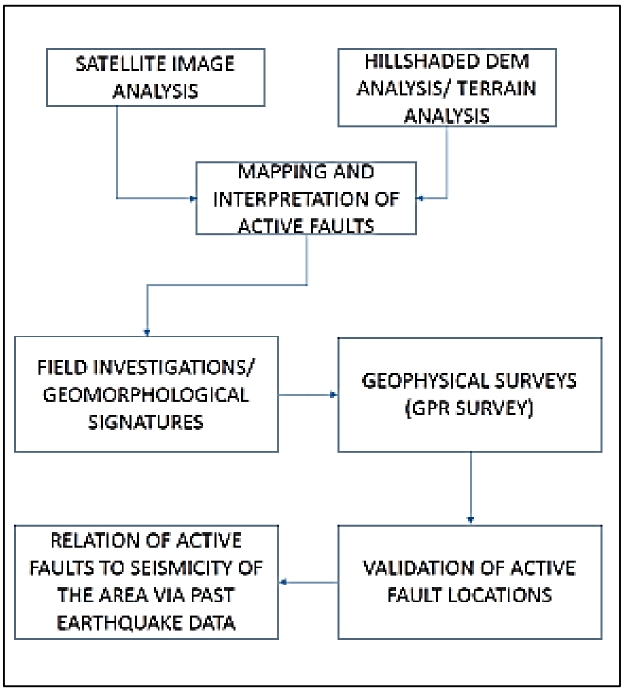



Figure 3-1: The flowchart of the methodology followed during the research.

## 3.5. METHODOLOGY

### 3.5.1. HILLSHADE CREATION

A hillshaded image was created from CARTOSAT 1 DEM. Hillshaded images created from high resolution DEM enhances lineaments while viewing with different orientations and numerous light conditions. According to Singh *et al.* (2007) the azimuth angle of 45° and an altitude angle of 52° of the light source are the best orientations to effectively delineate the lineaments in the Doon valley where the orientation of the main fault systems are in the NW-SE direction. The azimuth angle has to be kept nearly perpendicular to the general direction of the tectonic lines in the area as SRM has the property of enhancing the features which are perpendicular to its illumination direction and suppresses those which are parallel to it (Singh *et al.* 2007) (refer to Figure 3-1 for the flowchart of the methodology).

### 3.5.2. SATELLITE IMAGE ANALYSIS

The false colour composite (FCC) of the LANDSAT ETM+ Pan Sharpened imagery of the Doon valley was used to verify the faults based on the factors like colour, texture and pattern (Singh *et al.* 2007). The geomorphological units were established and demarcated based on the traditional visual interpretation techniques like tone, texture, knick points in rivers, sudden changes in river streams, straight courses of rivers and vegetation differences. The high resolution Google earth imagery of Doon valley was also used to identify and demarcate fault traces.

### 3.5.3. TOPOGRAPHIC AND TERRAIN ANALYSIS

During this part of the research, the topographic and terrain analysis was carried out in the study area. Lineament/ fault traces were first observed and digitised from previously existing tectonic/geological maps of the area Singh *et al.* (2007), Thakur and Pandey (2004a), Thakur and Pandey (2004b) and Thakur *et al.* (2007). The CATOSAT high resolution satellite data, LANDSAT ETM+ pan sharpened imagery, the LISS III dataset were then used to verify the previous fault traces. Some of the major traces like the Bhauwala fault, the Majhaun Fault, the Piedmont Fault and the Santaurgarh thrust were verified from previous literature based on the criteria of traditional visual interpretation techniques like sudden changes in the course of river channels, the knee turn bend of rivers, the knick points and the termination of alluvial fans (as in the case of Piedmont Fault). The abrupt termination of the geomorphological units (e.g. the Shiwalik units) was also used as a factor to determine traces of faults in the NW Doon valley. The sudden changes in elevation were then observed across the possible trace of the fault as a validation that there is a change in topography across that area. The fault scarps are visible in the form of an elevated area in a hillshaded image. The scarps were also traced and observed to validate the fault traces with the use of a CARTOSAT DEM product hillshaded image.

### 3.5.4. GPR SURVEY FOR VALIDATION OF FAULTS IN THE SUBSURFACE ALONG WITH FIELD OBSERVATIONS OF ACTIVE TECTONICS

The GPR is regarded as a technique which is non-destructive and detects shallow subsurface changes with the help of EM energy which range from 10-1000 MHz (Robinson *et al.* 2013). The main principle of GPR is to transmit high frequency EM waves into the subsurface and to detect changes in velocity of the waves. The velocity of the wave changes due to difference in electrical properties between the various materials in the subsurface (Robinson *et al.* 2013). The EM energy is transferred back to the receiving antenna of the GPR system due to changes in the dielectric constants of the subsurface materials (Robinson *et al.* 2013) (Figure 3-2 A).

The GPR survey suitability is dependent on the depth of the target to be surveyed. If the target is beyond the reach of GPR antenna of a certain frequency then the GPR survey is not suitable. As the resolution decreases with decreasing frequency but the depth of penetration increases, there is a balance to maintain in every GPR survey between resolution and depth of penetration (Robinson *et al.* 2013). Keeping this in mind, the surveys were done using 100 and 200 MHz antenna. Clay has the ability to attenuate signals and thus plays a major role in limiting the penetration depth (Robinson *et al.* 2013). Since many of the fields where survey was carried out had high clay content layers that acted as limiting factor of the penetration depth for most of the profiles. The depth of penetration has been observed to be upto 12 meters in case of 100 MHz antenna and upto 6 meters in case of 200 MHz antenna in the Doon valley and piedmont region which is also the penetration depth observed for the 200 MHz antenna in similar studies conducted in the NW Himalayan region by Malik *et al.* (2010a and 2010b). The fault was often traceable upto 5-6 meters and upto 3 meters for the 100 and 200 MHz antenna, respectively. Reflection profiling is the survey design for used the IDS GPR instrument where the antennas are kept at a fixed distance from each other and then traversed across the profile (Figure 3-2 B).

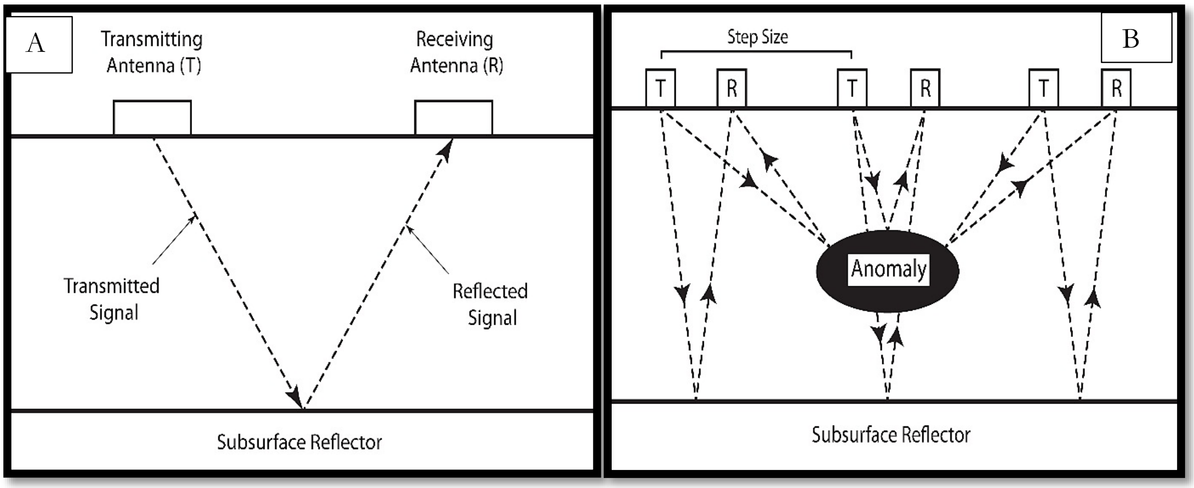



Figure 3-2 A: The EM wave propagation in the subsurface material; Figure 3-2 B: The fixed offset reflection profiling. (Both the pictures are taken from Robinson *et al.* 2013).

Antenna separation should be as small as possible based on the needs of the survey as antenna separation can reduce the resolution of the survey though the investigation depth increases (Robinson *et al.* 2013). The antenna separation is fixed for most of the GPR systems. The antenna separation is fixed at 50 centimetres and 1 meter for 200 and 100 MHz antennas resoectively for the IDS GPR system used in the survey. Shielded antennas were used to minimize the effect of tress and other noises present in the field.

The parameters for the GPR survey used are (Table 3-1):

Table 3-1: The GPR survey parameters.

| GPR PARAMETERS | SETTINGS |
|---|---|
| GPR ANTENNA FREQUENCIES | 100 and 200 MHz |
| RANGE | 256 ns (100 MHz) and 128 ns(200 MHz) |
| ANTENNA SEPARATION | 50 cm(200 MHz) and 1 m (100 MHz) |
| No. of Samples/scan | 512 |

The most important thing in processing is to keep it simple and not overprocess the data. Sedimentological environments require only minimal amount of processing (Robinson et al. 2013). Overprocessing can introduce bias and potential artefacts into the data.

The basic processing steps involved in the GPR processing in GRED HD software (Gred HD *v* 01.01-user manual, 2013) were:

1) Move start time: automatic.
2) Dewow filtering: automatically applied.
3) Time domain band pass filtering: 50 to 100 MHz for 100 MHz antenna and 100 to 200 MHz for 200 MHz antenna.
4) Background Removal: to a maximum depth of 5 meters for the 100 MHz and 4 meters for the 200 MHz antennas.

The standard (basic) processing steps were conducted automatically by the GRED HD software.

The processed GPR data is made available in the jpg and png format. The processed data is visualized in the form of a radargram with the depth in the vertical axis and the horizontal distance in the horizontal axis (Figure 3-3, taken from Robinson *et al.* 2013).

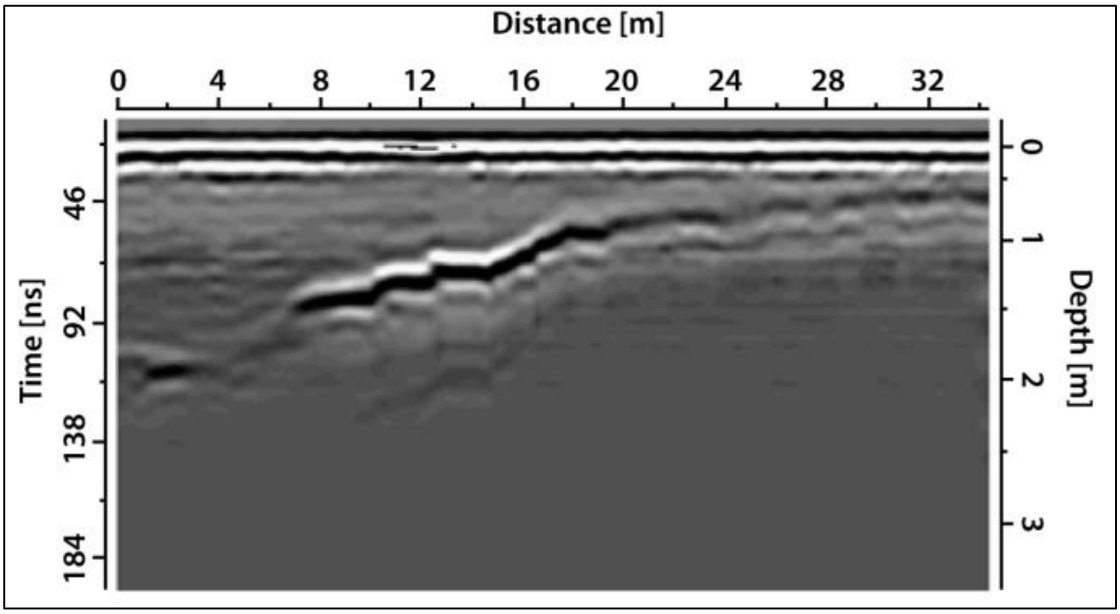



Figure 3-3: A radargram showing the depth and TWT in the vertical axis and the horizontal distance in the horizontal axis taken from Robinson *et al.* (2013).

Interpretation of faults is carried out by observing the sub surface reflectors and their dip (Figure 3-4, taken from Malik *et al.* 2010a) (Robinson *et al.* 2013). The breaks in reflection where it indicates a vertical offset is generally interpreted as a fault (Figure 3-5, taken from Robinson *et al.* 2013). Generally vertical offsets across GPR profiles dominate the profiles in case of a fault zone (Robinson *et al.* 2013). The dipping reflectors along with vertical offsets between reflectors are the major criteria used to determine a fault during this research (refer to Figure 3-4 and Figure 3-5 for the illustration). High amplitude reflectors giving way to lower amplitude reflections with a sharp contrast between them are also taken as signatures of faulting (Figure 3-6).

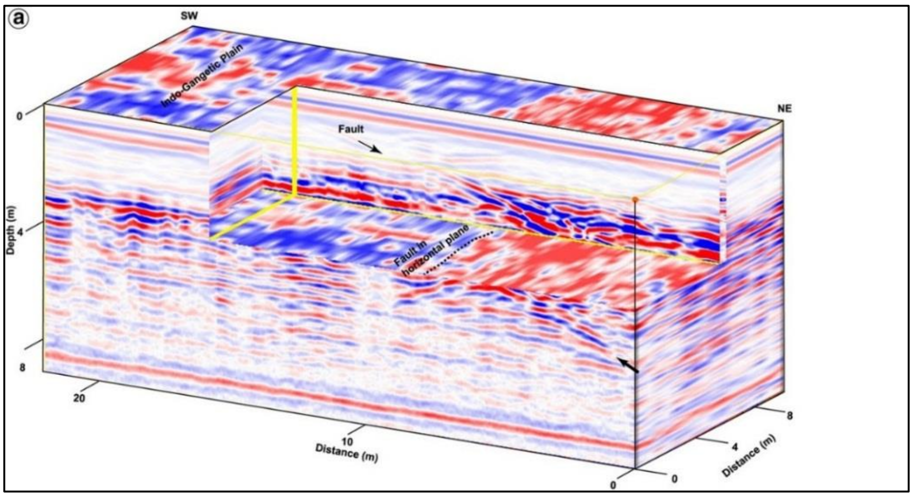



Figure 3-4: A GPR profile indicating a fault which is interpreted on the basis of dipping reflectors indicating a low angle thrust fault (adapted from Malik et al. 2010a).

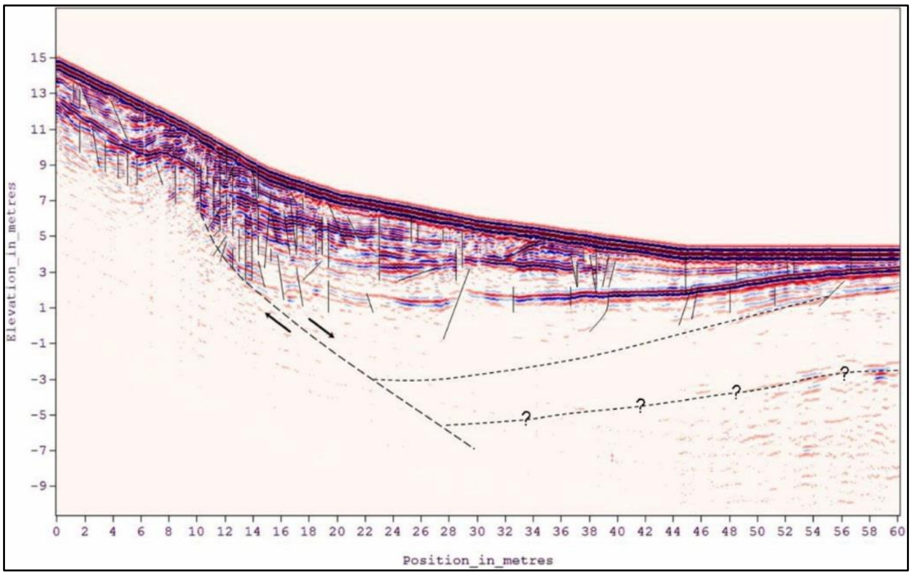



Figure 3-5: A normal fault interpreted on the basis of dipping reflectors and offsets between horizontal reflectors (adapted from Robinson et al. 2013).

The GPR survey was carried out transverse to the possible fault scarp or geomorphic expression of the fault. The DEM analysis, the satellite data analysis and the field observations were combined for identification of the best location for the GPR survey. Once the general area of the fault has been demarcated from satellite image analysis and hill shaded DEM analysis, field surveys were carried out across the fault. The field surveys takes into account locations of faults mentioned in previous literature along with new observations. The geomorphic expressions of active faults such as fault scarps, elevation changes, river terraces, bending of rivers and sag ponds are some of the features that are identified in the field which have also been mentioned in previous literature like Philip and Sah (1999), Malik *et al.* (2010a), Malik *et al.* (2010b). Once these are identified, the profile locations were determined for GPR studies. The profiles in this study were taken across the fault scarps but generally in areas of flat topography where the fault scarps have been flattened out by natural or anthropogenic activities to reduce the effect of topography on the fault profiles. 100-200 MHz antennas are used so that the profiles have optimum resolution along with reasonable penetration generally upto a depth of about 5-6 meters (Malik *et al.* 2010a, Malik *et al.* 2010b).

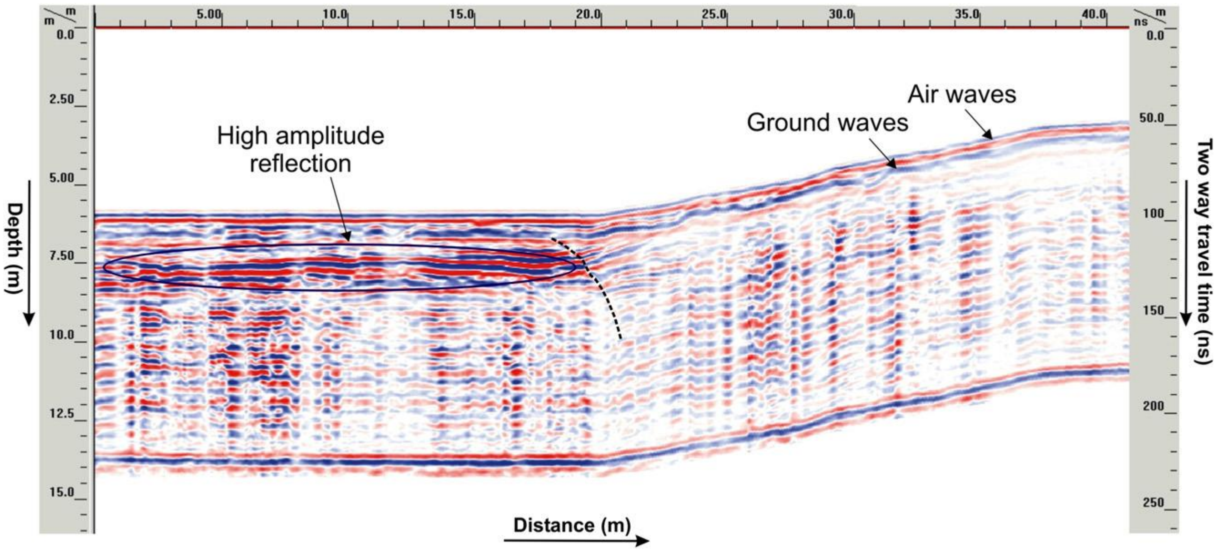



Figure 3-6: The GPR profile taken by a 200 MHz antenna. The figure is taken from Yeats and Thakur (2008).

### 3.5.5. SEISMICITY MAP OF THE STUDY AREA

A seismicity map of the Doon valley is prepared based on the almost 200 years of earthquake data along with some more historic data derived from different sources like USGS/NEIC, Indian Meteorological Department (IMD), CSEM/EMSC (Centre Seismologue Euro- Mediterranean / European Mediterranean Seismological Centre) and various publications depicting possible earthquake events. The earthquake epicentres are then plotted on a LISS III map of the Doon valley along with the GPR survey locations and the fault map of the Doon valley within and around the study area.

# 4. RESULTS AND DISCUSSION

## 4.1. ACTIVE FAULT MAP OF THE DOON VALLEY

A composite active fault map of the Doon valley is prepared on the basis of previous active fault maps. LANDSAT ETM+ pansharpened imagery was used in the preparation of the composite active fault map in the area. The active tectonics map prepared by Singh *et al.* (2007), Thakur and Pandey (2004a), Thakur and Pandey (2004b), Thakur *et al.* (2007) and Philip *et al.* (1995) was the basis for the preparation of the tectonic map. Active tectonics maps have already been prepared by these authors and thus the active tectonic composite map was prepared based on the available maps (Figure 4-1).

### 4.1.1. TECTONIC MAP OF THE DOON VALLEY BASED ON PREVOUS LITERATURE AND IMAGE INTERPRETATION

The major faults mentioned in Singh *et al.* (2007), Thakur and Pandey (2004a), Thakur and Pandey (2004b), Thakur *et al.* (2007) and Philip *et al.* (1995) were mapped (Figure 4-1). The main faults marked are ST- Santaurgarh Thrust, MF- Majhaun Fault, BF- Bhauwala Fault, N_TF- Nun Tons fault, SNF- Suarna Nadi fault, KF- Koti fault. The N_TF, SNF and KF are possible transverse faults which divides the Doon valley into its three principal fans: the Bhogpur, Dunga and Dun fans. These faults run along the course of the Nun, Suarna and the Koti rivers. Clear topographic breaks were observed on CARTOSAT high resolution images. Singh *et al.* (2007) states that river terraces were also seen all along these river sections with the Shiwaliks as the base and the Dun deposits lying unconformably on the Shiwalik rocks. Faint traces of the Bhauwala, Majhaun and the Dunga (Santaurgarh) Fault systems were also observed in the LANDSAT ETM+ pansharpened imagery. According to previous literature some authors have indicated the possibility of the Asan river fault (AF) and the Nagsidh Hill fault (NF) being the same extension of the fault with the AF being a blind fault with the NF surfacing as an extension of the AF. The Suswa Song fault (SSF) may also be an extension of the same blind AF-NF fault. The SSF after Thakur *et al.* (2007) is shown below on the pansharpened LANDSAT ETM+ image. There is a possibility that SSF is the manifestation of the same blind Asan fault and it extends from east to west throughout the entire Doon valley upto GTF (Ganga Tear Fault). The Chandrabhaga Rao (CRF) and the Jakhan rao faults (JRF) which supposedly disrupts the MBT. The faults were taken from Thakur *et al.* (2007). The faults in the Piedmont region from the earlier fault map are: the Piedmont fault (PF and PF extension), the N-S trending Biharigarh fault and the possible fault near Ibrahimpur village seen from the fault scarp. The figure below shows the major faults in Doon valley and its surrounding based on Singh *et al.* (2007), Thakur and Pandey (2004a), Thakur and Pandey (2004b), Thakur *et al.* (2007) and Philip *et al.* (1995) (Figure 4-1).

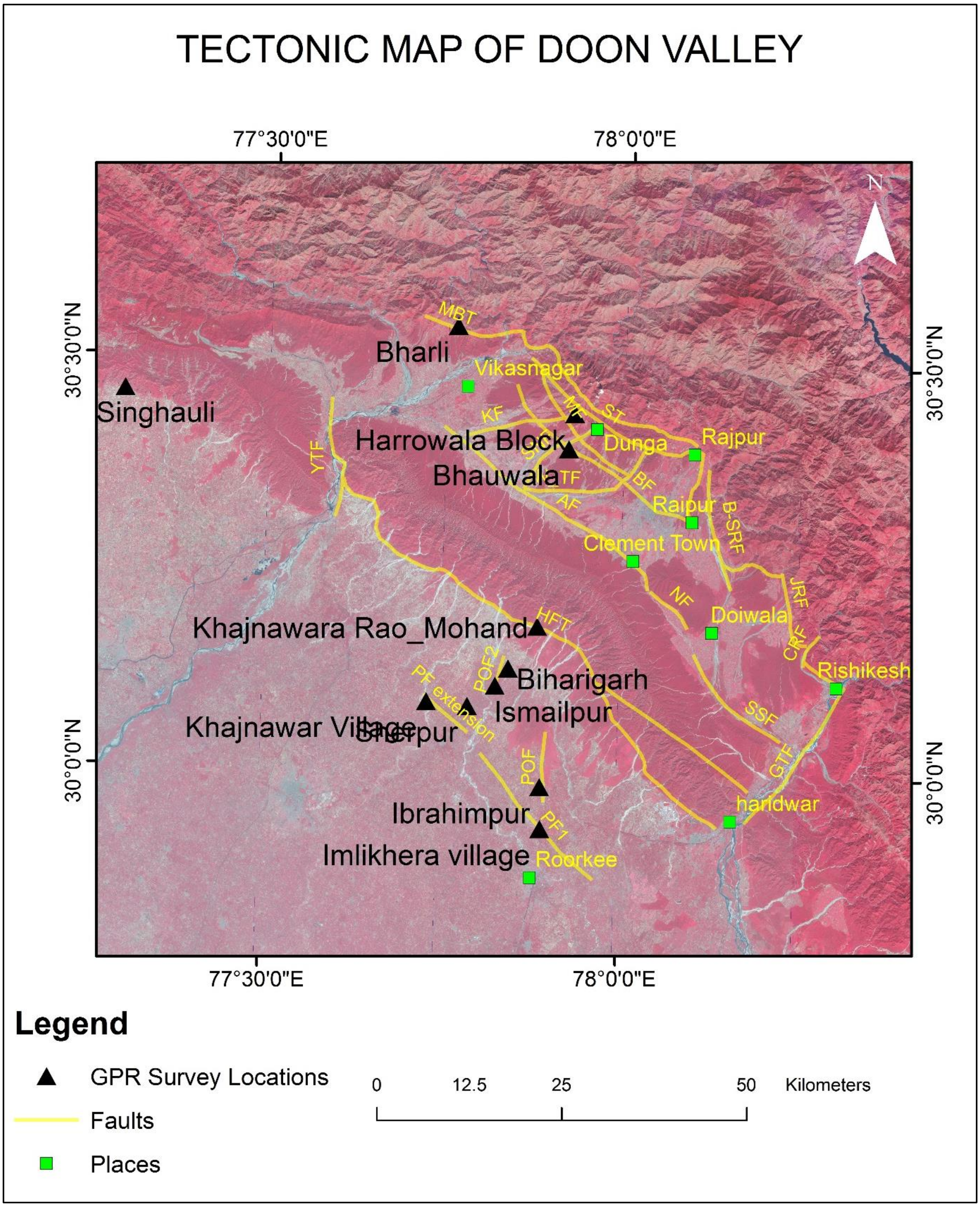



Figure 4-1: The active tectonic map of the Dehradun valley taken from Thakur and Pandey (2004a and 2004b). The fault map is prepared over a LISS III imagery. YTF: Yamuna Tear Fault, PF: Piedmont Fault, GTF: Ganga Tear Fault, ST: Santaurgarh Thrust, MBT: Main Boundary Thrust, HFT: Himalaya Frontal Thrust, Dalkhand fault, CRF: Chandrabhaga Rao fault, JRF: Jakhan Rao Fault, KF: Koti Fault, N_TF: Nun Tons Fault, SNF: Suarna Nadi Fault, SSF: Suswa Song Fault, NF: Nagsidh Hill fault, AF: Asan river Fault, B-SRF: Baldi Song river Fault, POF: Possible Fault (Ibrahimpur), POF2: Possible Fault (Biharigarh High). The GPR locations and the “places” of interest in the Doon valley are also shown.

## 4.2. GPR AND TERRAIN ANALYSIS RESULTS FOR MAIN DOON VALLEY

### 4.2.1. PIEDMONT FAULT

Detailed studies have been carried out in the piedmont zone near Roorkee previously. This area extends from the foothills of the Himalaya just south of the HFT upto a distance of 15-25 kms to the south. The Piedmont Fault was identified by various authors previously (Thakur 2004, Thakur and Pandey 2004a, Thakur and Pandey 2004b, Thakur *et al.* 2007, Thakur 2013) where the presence of a tectonic lineament is indicated in the form of knee turn bend of streams and the Solani river flowing from northeast direction to southeast.

Two sites (Imlikhera and Khajnawar villages) (refer to Figure 4-1) were selected in an effort to validate the presence of the northwest southeast striking Piedmont fault (PF). The Imlikhera profiles were taken with the help of 100 and 200 MHz antenna to get optimum depth and penetration. The profile location was selected to the south of the Imlikhera village in the northeast bank of the Sipla Nala stream about 200 meters to the west of the main road. The profiles were taken parallel to each other generally trending northeast southwest i.e. transverse to the strike of the piedmont fault (Figure 4-2 A and Figure 4-2 B). The trace of the lineament is drawn in CARTOSAT high resolution image of the area (Figure 4-2 A). The topographic profile drawn across the fault trace also shows a sudden elevation change (Figure 4-2 B and Figure 4-2 C). The possible scarp of the piedmont fault have been identified in these locations from field observations and previous literature. GPR surveys were carried out at these two locations transverse to the possible scarp of the PF. The Solani river has a sudden bend near Roorkee and it completely changes direction (Figure 4-3 A). The streams just to the north of Solani river also shows the same sudden changes in direction as observed in the satellite image (Figure 4-3 B) and this observation was also mentioned by Thakur *et al.* (2007).

The profiles clearly shows the presence of a possibly north dipping fault that is interpreted as a low angle thrust fault with the northern block uplifted. The dipping reflectors starts at a depth of about 1.5 meters and continues downwards (Figure 4-4 A and Figure 4-4 B). The scarp is also clearly observed in the field in 5-6 meters high about 200 meters in the east bank of the Sipla Nala (Figure 4-5 A and Figure 4-5 B).

The Khajnawara village profiles were taken across the south facing piedmont scarp at the southern lower end of the village on the east bank of the Chhacha Rao stream to the west of Biharigarh and Chhutmalpur townships in Roorkee district neighbouring Dehradun. The scarp is trending in north west-southeast direction and the profiles were taken in the direction of northeast southwest, across the fault trend. The profiles here too are taken across flat terrain to minimize the effect of topography on the GPR profile. The height of the south facing scarp is about 5-6 meters (Figure 4-6).

The profiles were taken on a road section leading into the lower end of the village which cuts across the south facing scarp just about 200 meters from the main road. Parallel profiles were also taken on both sides of the road in the flat topography where the scarp has been flattened due to human activities (refer to Appendix A (Figure A-1 and Figure A-2) for the GPR results of Khajnawar village).

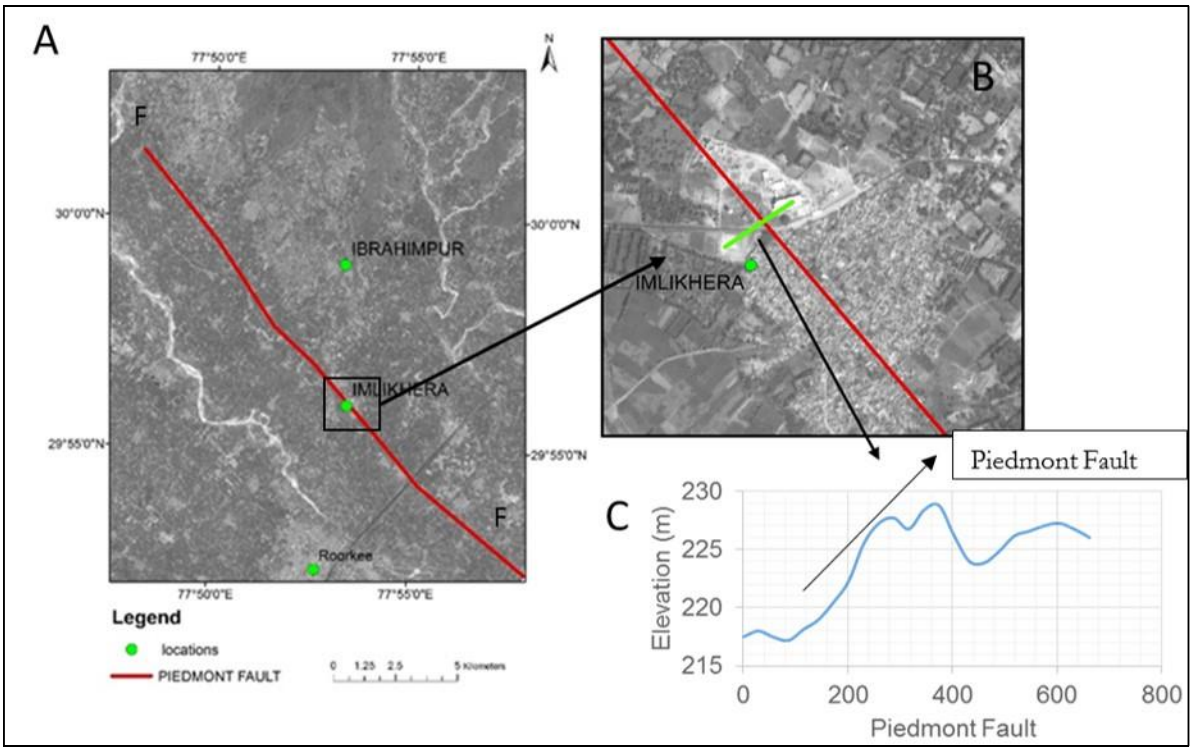



Figure 4-2 A: The trace of the Piedmont Fault (F-F) observed in the high resolution CARTOSAT imagery. Figure 4-2 B and Figure 4-2 C: The closeup of the scarp and the topographic profile drawn across the scarp.

All these analysis points towards the possible presence of a tectonic fault which have been identified as the possible Piedmont Fault by previous authors (Thakur *et al.* 2007, Thakur and Pandey 2004a, etc.) and also observed in the GPR studies.

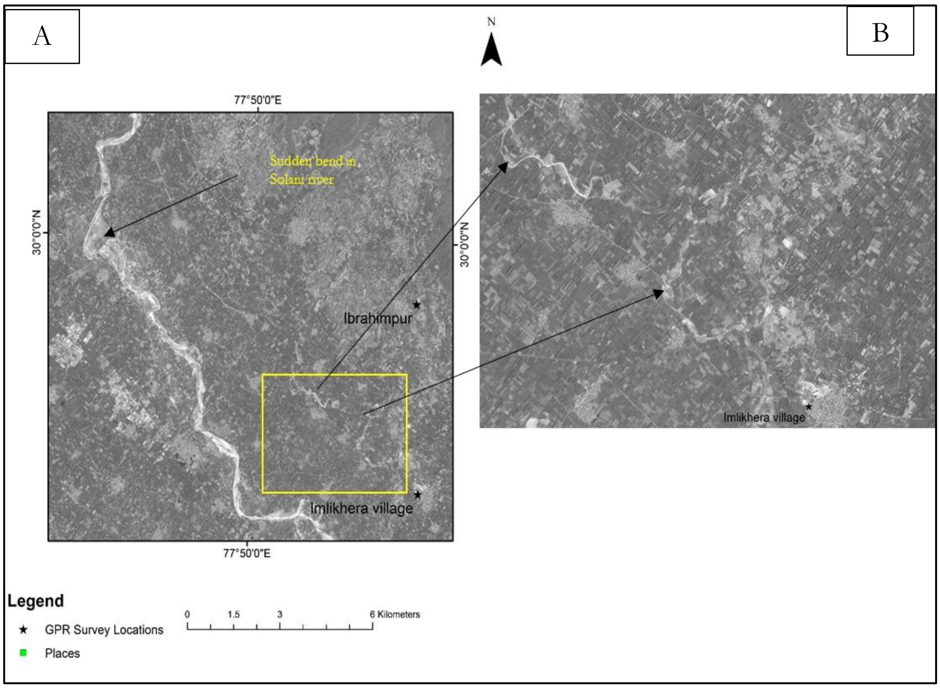
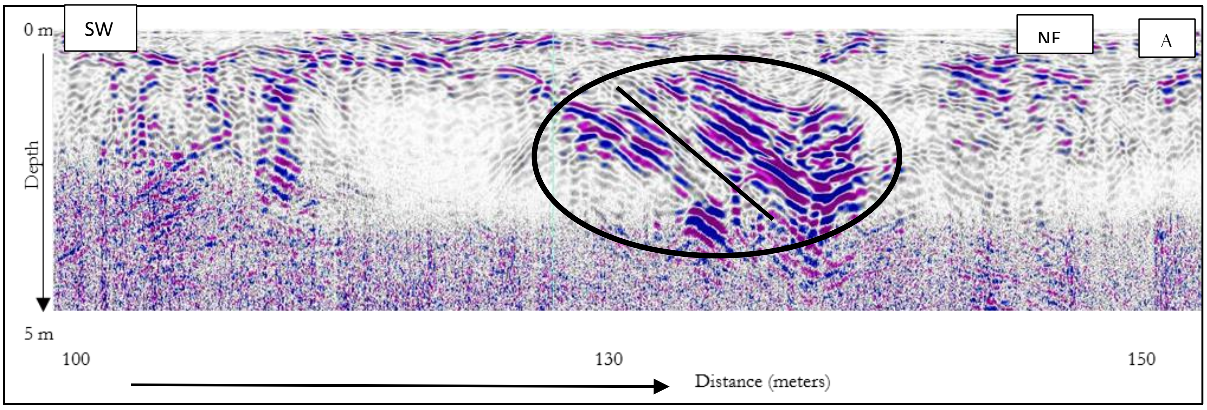



Figure 4-3 A: The sudden bending of the Solani river which is possibly due to tectonic control. Figure 4-3 B: The sudden changes in river direction along the streams to the north of Solani River near Imlikhera.



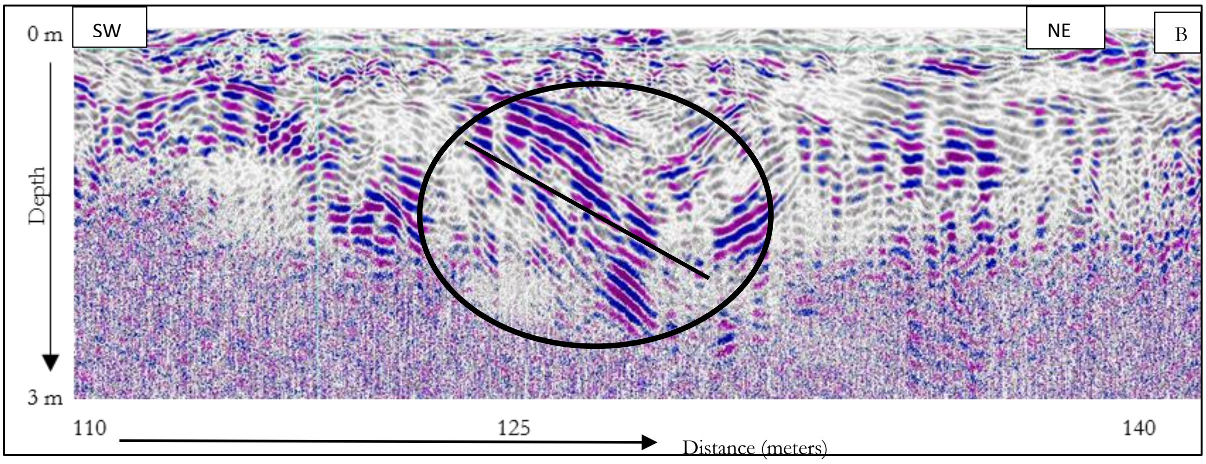




Figure 4-4 A: The 100 MHz profile in the Imlikhera village showing dipping layers upto a distance of about 5 meters in Imlikhera village. Figure 4-4 B: The 200 MHz profile observed in the Imlikehra Village with dipping layers upto a depth of 3 meters. Both the profiles were taken from SW to NE direction.


Figure 4-5 A: The scarp feature observed in the east bank of the Sipla Nala (stream) in the form of an elevated northern block. Figure 4-5 B: The closeup of the scarp feature.

Figure 4-6: The scarp feature observed in the Khajnawar Village.

### 4.2.2. PEIDMONT REGION

#### 4.2.2.1. IBRAHIMPUR

A NE-SW trending scarp was observed in the village of Ibrahimpur (refer to Figure 4-1) on both satellite imagery as well as during field observations just north of Imlikhera village (Figure 4-7 A, Figure 4-7 B). The scarp and the topographic break is also observed in the CARTOSAT image (Figure 4-7 C and Figure 4-8).

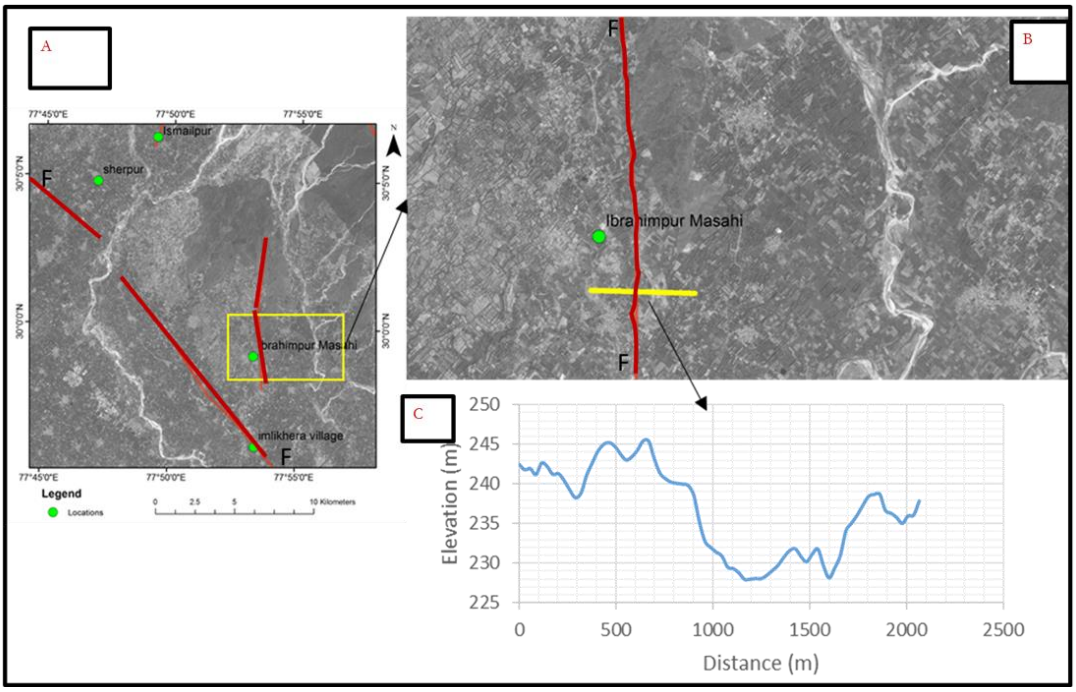



Figure 4-7 A: The trace (F-F) of the fault observed satellite image. Figure 4-7 B: A close up view of the satellite image. Figure 4-7 C: The topographic profile observed across the fault trace.

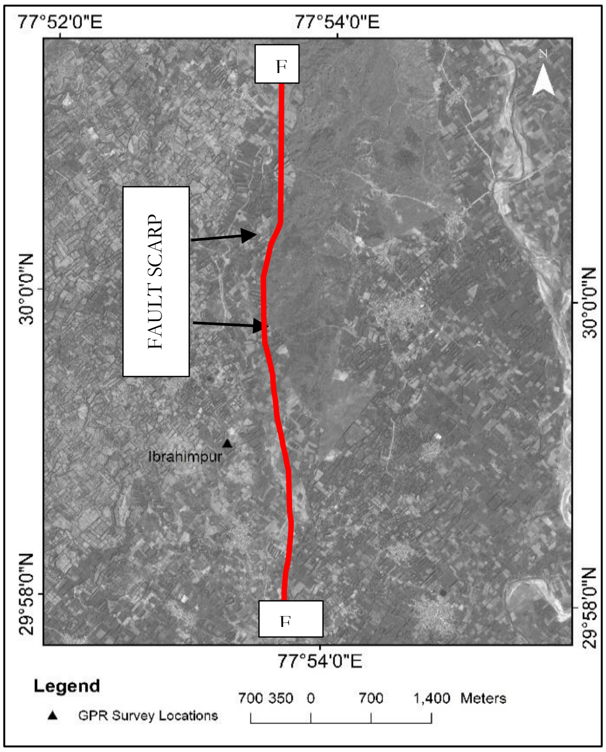



Figure 4-8: The fault scarp clearly observed in the CARTOSAT high resolution image. The fault trace (F-F) is drawn.

The profiles were taken in the W-E trending direction across the possible scarp feature. A possible N-S fault dipping towards the east was observed in the profiles clearly. Four parallel profiles were taken and the east dipping fault was clearly observed in them. One of the profiles is presented in this text (Figure 4-9).

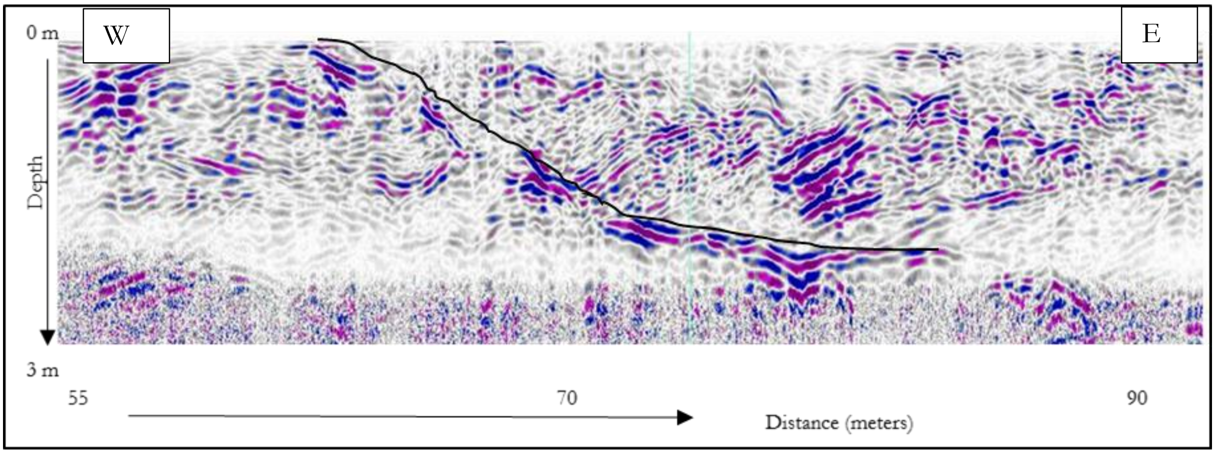



Figure 4-9: The east dipping fault observed in the profile taken from west to east.

The tectonic scarp was clearly observed in the field with a height ranging approximately from 3-4 meters and 15-20 meters at places (Figure 4-10 A and Figure 4-10 B).

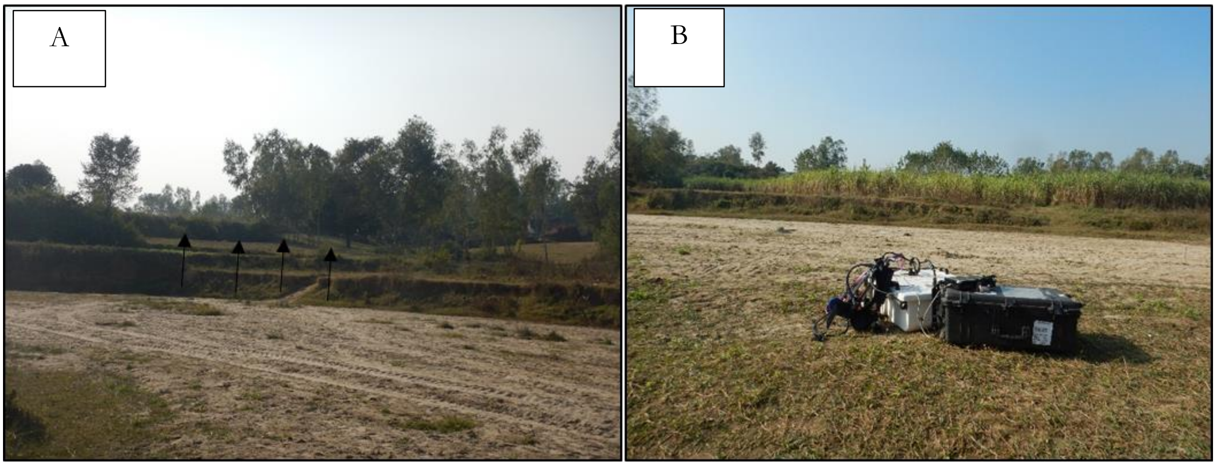



Figure 4-10 A: The scarp feature observed in Ibrahimpur with the photo taken facing west. The height is about 15 meters. Figure 4-10 B: The scarp of about 3 meters height with the scarp degraded due to human activities. Photograph taken facing west.

Some more GPR surveys were also conducted in other locations of the Piedmont region which did not to show any conclusive evidence of faulting and active tectonics. The locations are Biharigarh High, Sherpur and Ismailpur (refer to Figure 4-1).

### 4.2.3. NORTH WEST DOON VALLEY

#### 4.2.3.1. HARROWALA BLOCK (KOTI KATRA VILLAGE)

Towards the south of MBT (Main Boundary Thrust) in Harrowala Block (refer to Figure 4-1) there is a strong expression of a tectonic lineament which lies between the two identified E-W trending faults (the Santaurgarh and the Bhauwala fault) in the northwest Doon valley. The lineament is trending in the E-W direction with the expression traced in the high resolution satellite imagery (Figure 4-11 A and Figure 4-11 B and Figure 4-12). It may be a minor imbricate of E-W trending fault systems in the northwest Doon valley. The topographic break is also observed clearly in the CARTOSAT DEM (Figure 4-11 C). The profiles are taken in the general direction of S-N so that they are transverse to the fault.

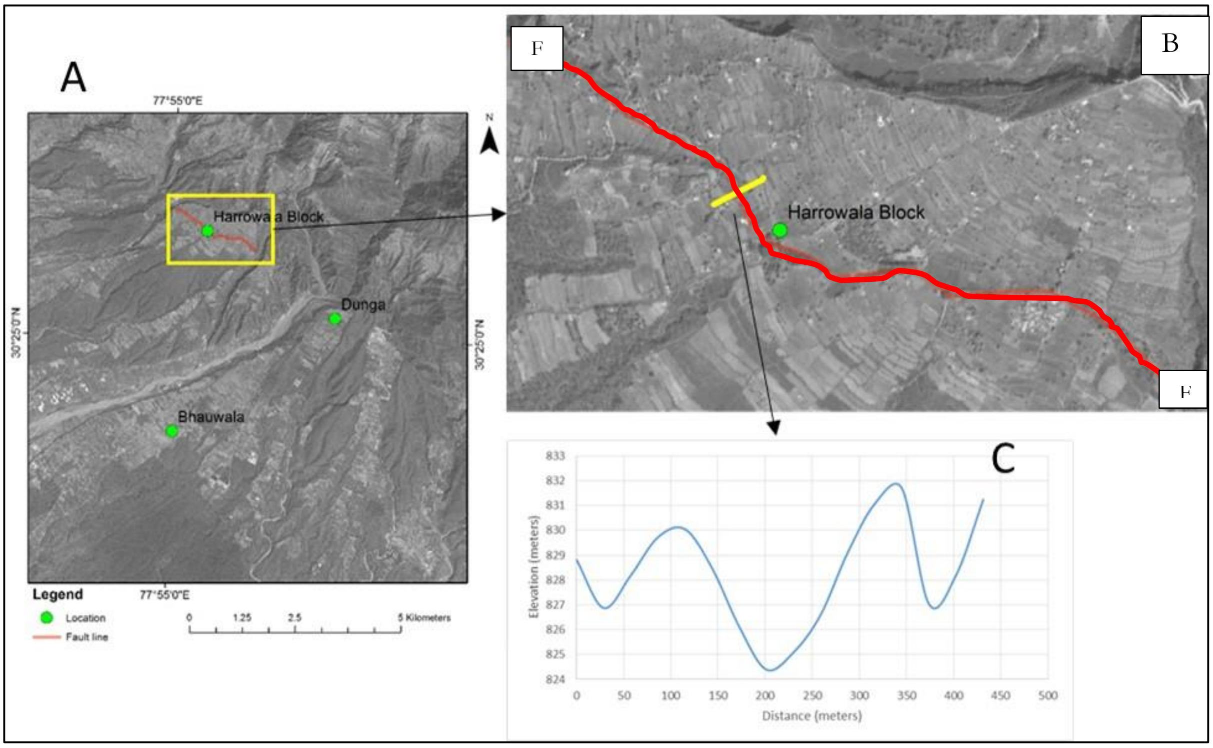



Figure 4-11 A: The trace of the fault can be observed in the CARTOSAT high resolution image of the area in the Harrowala block. Figure 4-11 B: The fault trace (F-F) being seen in the close up view of the CARTOSAT image. The trace is just south of the Narh village and the Koti village in the Harrowala Block in northwest Doon valley. Figure 4-11 C: The trace of the fault is clearly observed as a clear topographic break in the CARTOSAT DEM. The trace lies between the MF- Majhaun Fault and the ST- Santaurgarh Thrust signifying that it might be a southward extension of a minor imbricate of the ST.

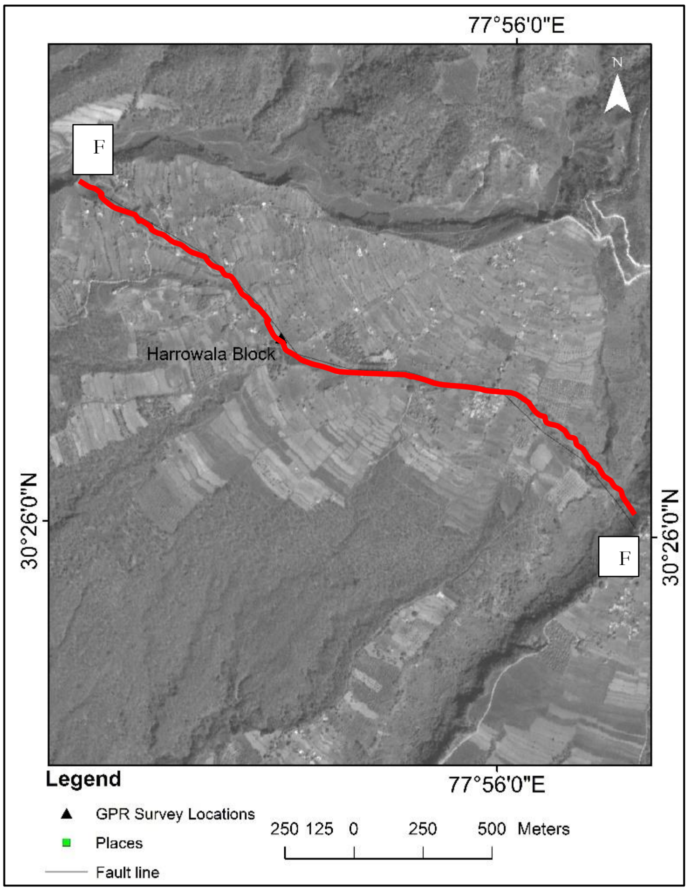



Figure 4-12: The trace of the Harrowala fault drawn on a closeup view of the image.

The northern block near is the elevated block while the southern part is the downthrown block. The profiles are taken across the main road which trends almost S-N transverse to the possible fault trace. As the fault is a possible southward extension of the Santaurgarh thrust fault system it is possibly a minor fault reactivated recently.

The 100 MHz GPR antenna was run along the main road trending in the N-S direction running through the village of Harrowala. The locations with active zones of deformation were observed. The GPR profile (Figure 4-13) gives a clear indication of the zone of deformation and the possible fault location with a possible north dipping fault observed during the survey.

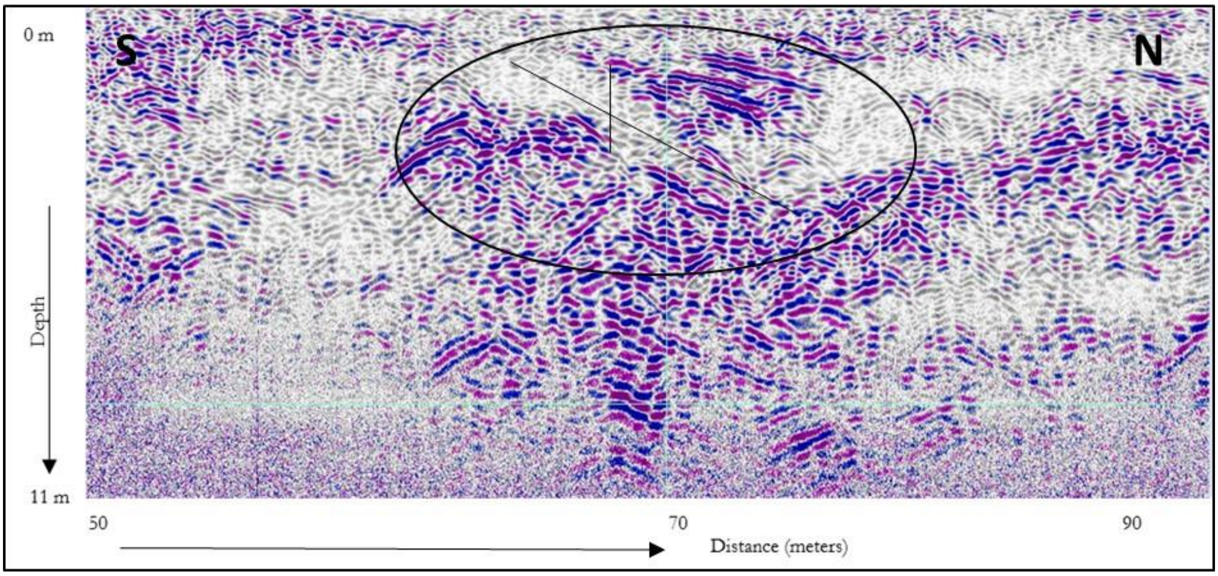



Figure 4-13: The 100 MHz profile showing the possible faulted zone. The profile is taken in the N-S direction from south to north.

The above profile (Figure 4-13) shows the 100 MHz profile from South to north. The possible faulted zone is clearly seen in the image and the dip direction and geometry of the fault is towards north. As can be seen clearly the layers towards the northern block are dipping southwards while the layers in the southern block are dipping slightly in the opposite direction which shows evidence of a possible faulted contact. The profile is taken in the main road leading towards the village (Figure 4-14 A) along with the scarp being clearly observed in the field observations in the village (Figure 4-14 B).


Figure 4-14 A: The main road leading into the village where the profiles were taken with Shiwaliks visible in the distance. Figure 4-14 B: The scarp feature trending NW-SE observed in the village that has not been modified by human activities.

#### 4.2.3.2. THE BHAUWALA FAULT

The Bhauwala fault is one of the major E-W trending faults in the N-W part of the Doon valley which has already been identified by remote sensing and satellite image analysis by previous authors during studies on the Doon valley. The fault have been identified by the trace of the lineament identified from satellite image analysis along with geomorphic signatures of the fault visible near the Bhauwala village in the North West Doon valley (Figure 4-15 A, Figure 4-15 B).The Bhauwala village Fault also shows a topographic break in the form of a sudden elevation change (Figure 4-15 C). The fault is faintly visible in the high resolution image in the form of the termination of Shiwaliks (Figure 4-16). The southward termination of the Shiwaliks and the sudden bending of rivers (Figure 4-17) in the area also points towards the presence of the Bhauwala fault. The presence of this fault has been well documented in various literature related to the active tectonics of the Doon valley as documented in the previous chapters.

The location of the profiles are taken parallel to each other with all the profiles transverse to the possible scarp of the fault. Four profile locations were selected near and around the village Bhauwala (refer to Figure 4-1) with each profile location roughly parallel to each other.

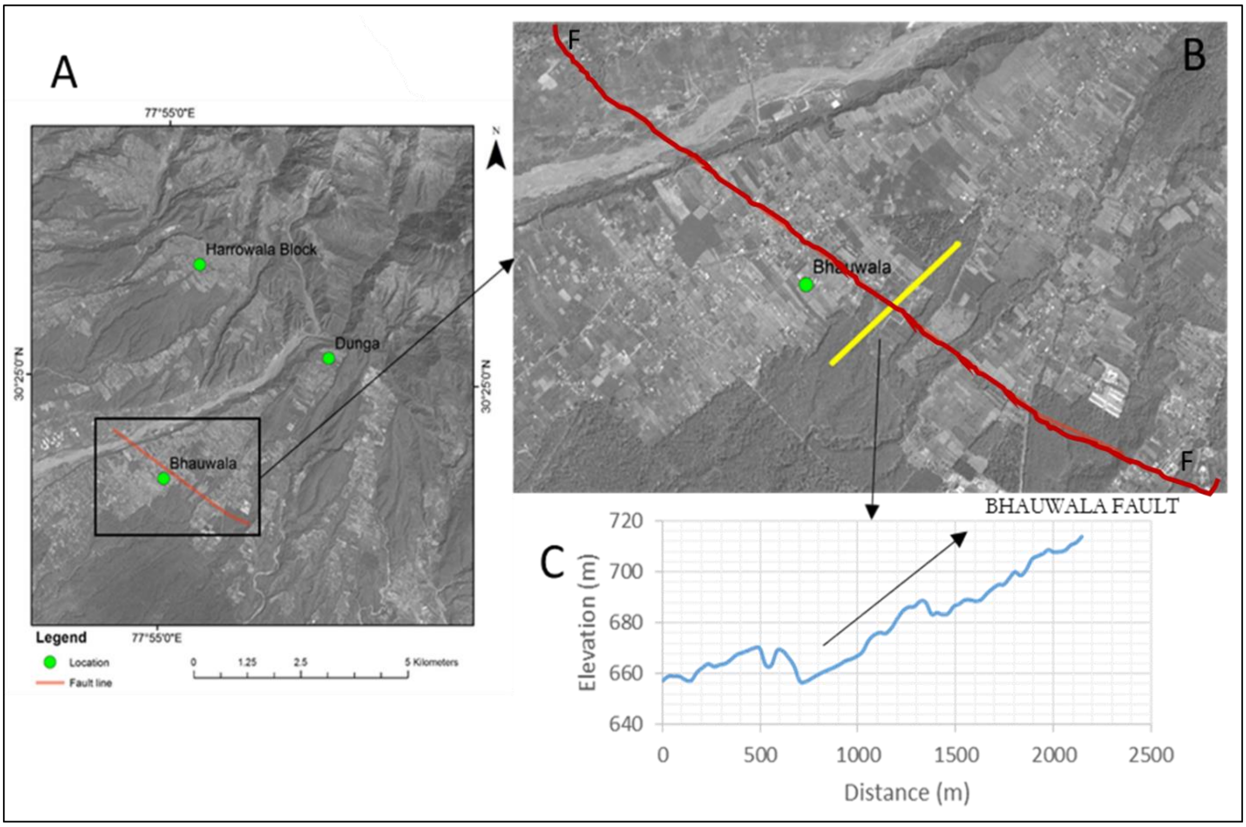



Figure 4-15 A: The location of the Bhauwala village on a CARTOSAT high resolution imagery. Figure 4-15 B: The trace of the fault (F-F) as seen in a close up of the image. Figure 4-15 C: The sudden change in elevation in the topographic profile.

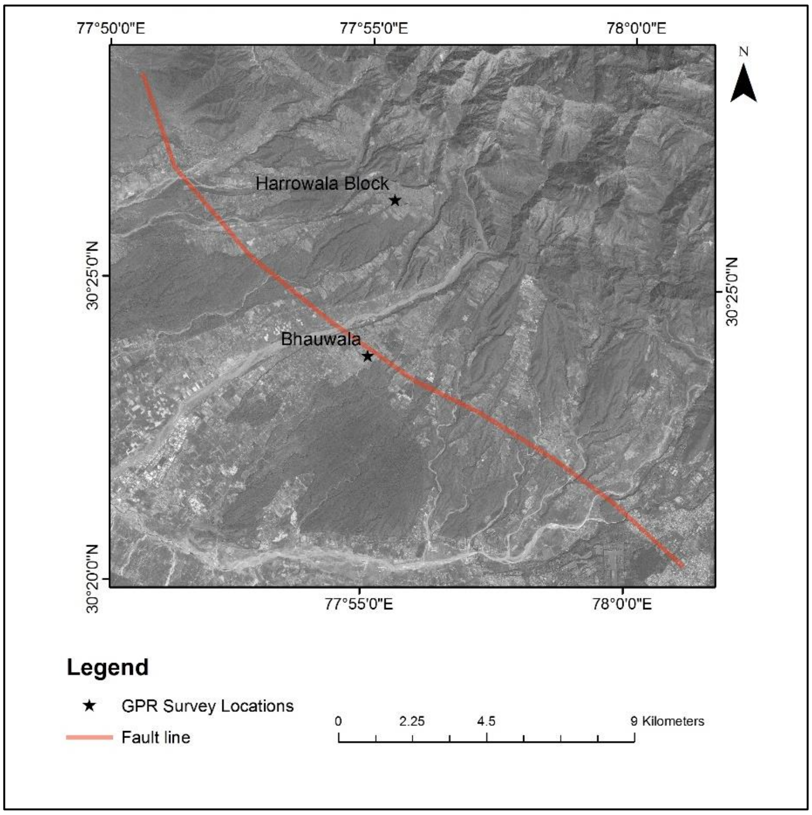



Figure 4-16: The close up of the Bhauwala Fault observed in the CARTOSAT image shown by the abrupt termination of the Shiwaliks.

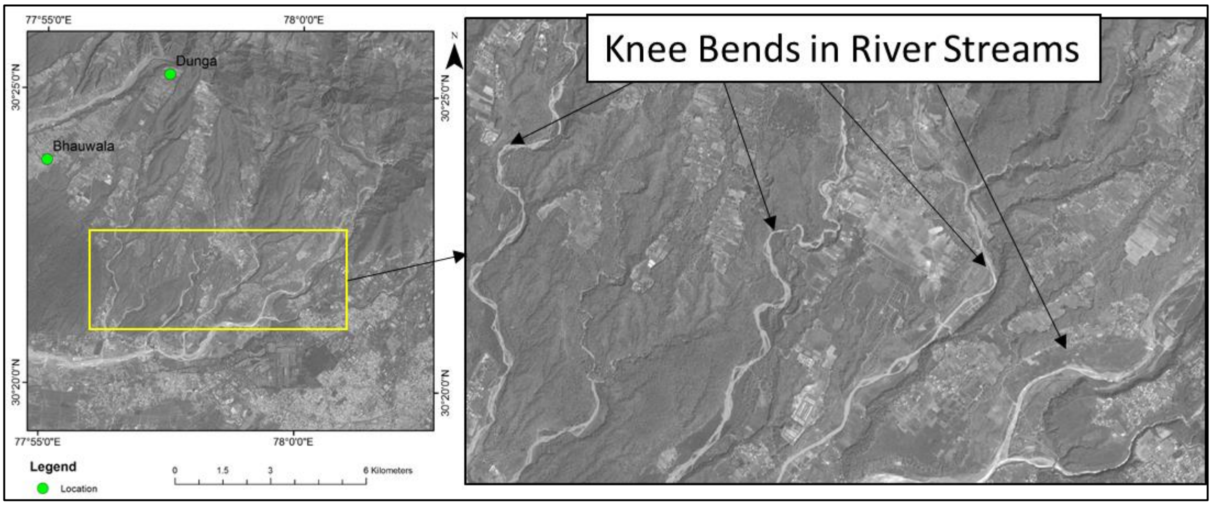



Figure 4-17: The sudden knee bend of the rivers also shows the existence of the Bhauwala tectonic lineament.

The profiles are taken in parallel to each other (Figure 4-18 and Figure 4-19). A possible north dipping fault can be observed in the profiles. The profiles with possibly some signatures of interest are shown below in Figures 4-18 and 4-19. (Refer to Appendix A, Figure A-3 for more results of Bhauwala village).

The scarp feature is degraded due to anthropogenic activities in Bhauwala village (Figure 4-20 B). The northern block is elevated as seen from the field photographs (Figure 4-20 A). Due to the degradation of the scarp only a faint trace of the lineament is seen from satellite images.

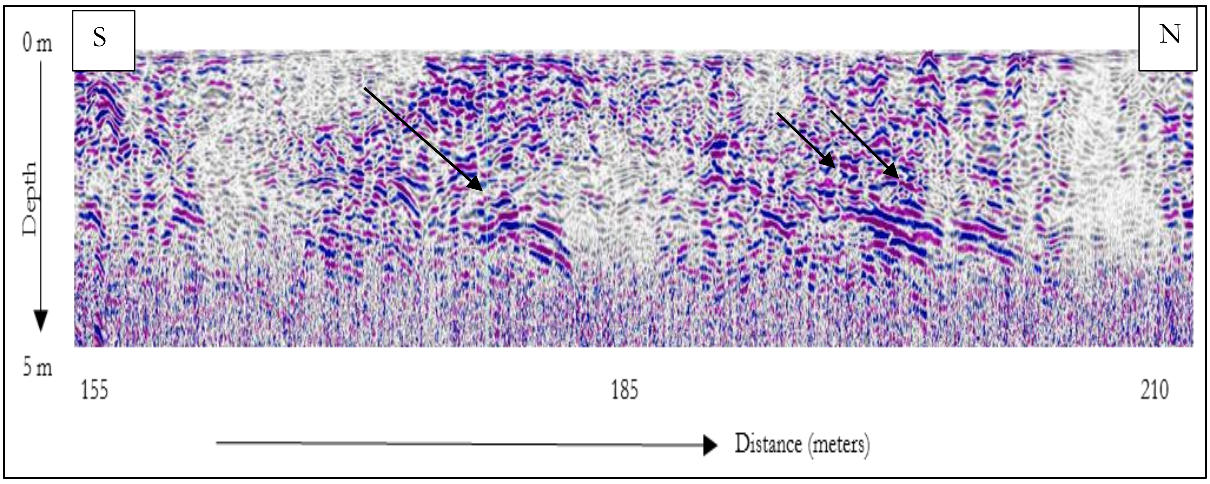



Figure 4-18: The profile shows dipping layers towards the north raising the possibility that the Bhauwala Fault might be a north dipping thrust fault. Though no conclusive evidence can be derived from GPR profile. The profile is taken from south to north.

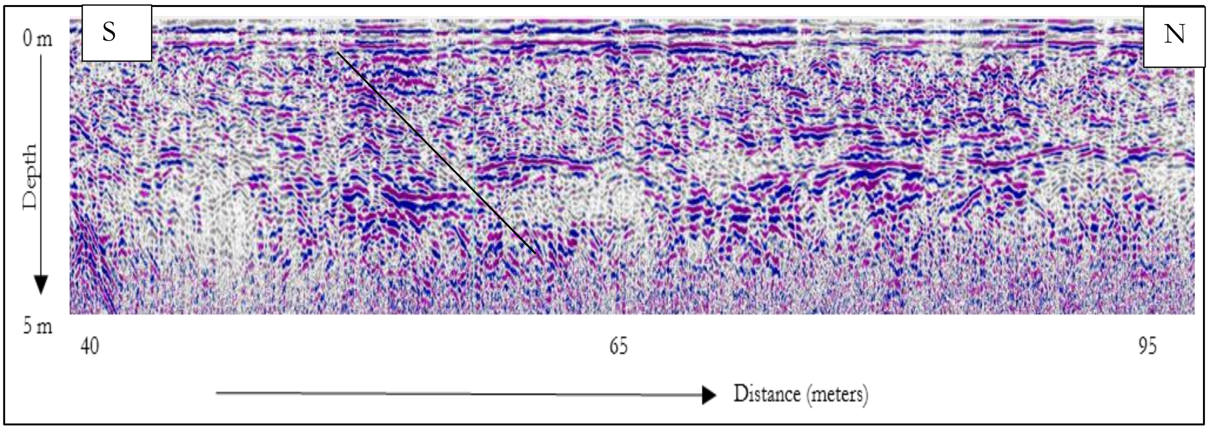



Figure 4-19: The profile shows a possible faulted feature with offsets between the layers being observed. The profile is taken from south to north. Again no conclusive evidences are found.

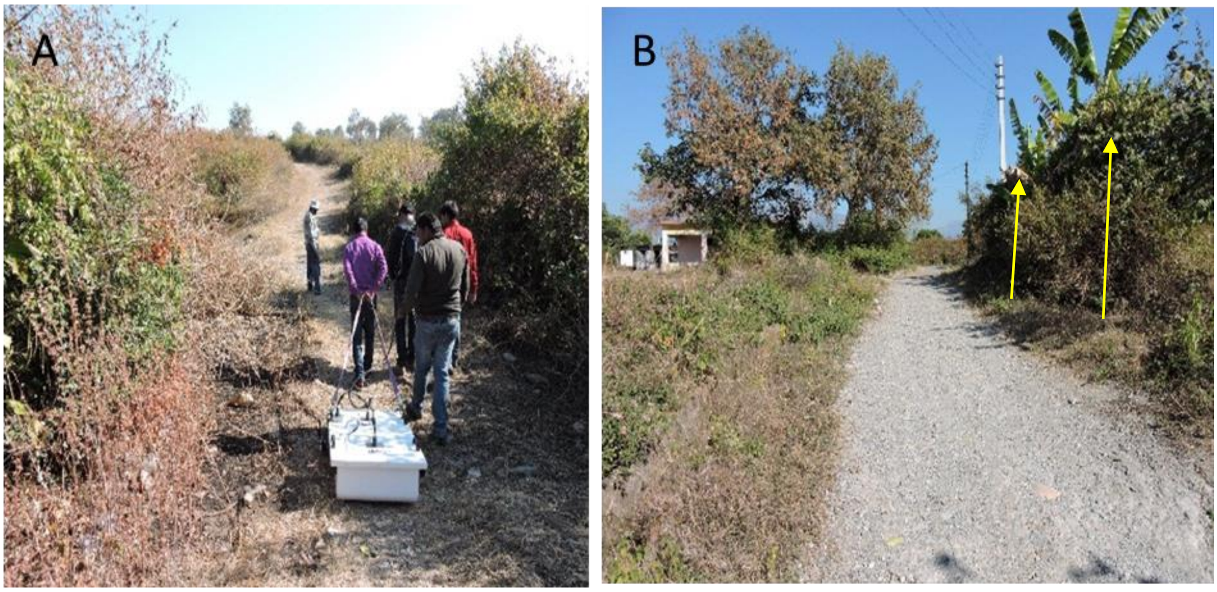



Figure 4-20 A: The GPR survey locations with the uplifted block being seen towards the north. The photograph is taken facing north. Figure 4-20 B: The degraded scarp being seen in the field near Bhauwala village.

The location of the Bhauwala fault (BF) as inferred from satellite imagery is observed to be quite closely located to the Majhaun fault (MF) as seen in the satellite image (Figure 4-21). This raises the possibility that the Bhauwala Fault (BF) is a southward extension of the Majhaun Fault (MF). There is also a possibility that it is a minor imbricate associated with the main Bhauwala Fault (BF) just as there is a possibility that the fault inferred in Harrowala block may be a southward imbricate of the Santaurgarh Thrust (Figure 4-21). Thus it appears there are a series of NE-SW trending major and minor faults in this part of the NW Doon valley.

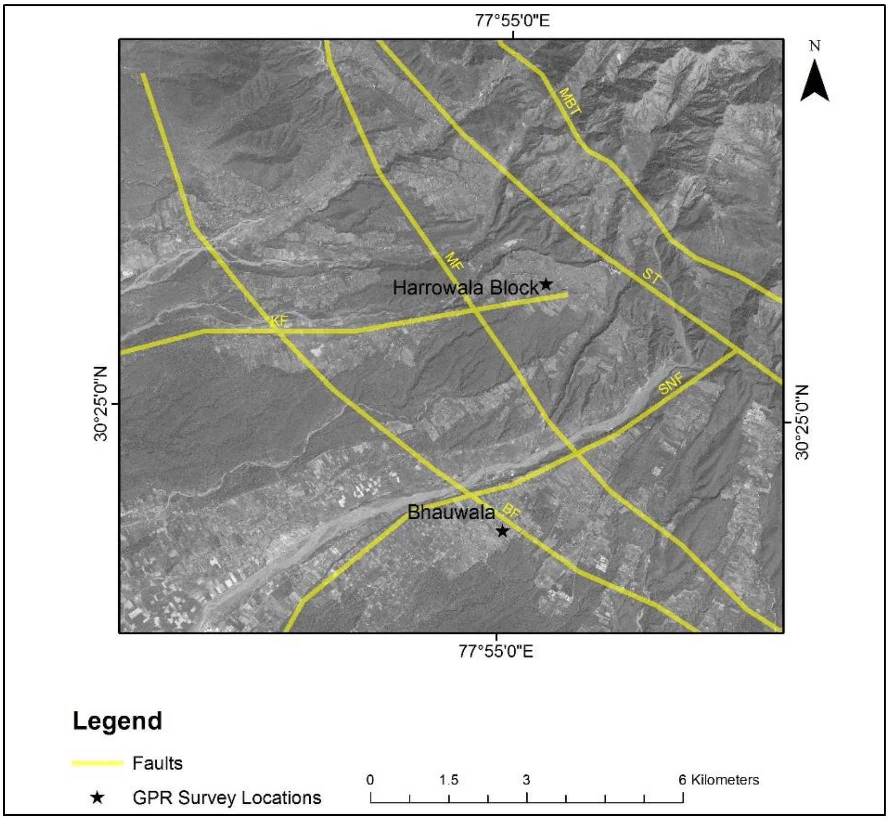



Figure 4-21: The image showing the location and traces of the faults in the NW Doon valley. MF: Majhaun Fault, ST: Santaurgarh Thrust, BF: Bhauwala Fault

### 4.2.4. OUTER DOON VALLEY

The Doon is not strictly restricted to the Ganga Tear fault and the Yamuna tear faults in the east and west respectively. Some of the surrounding valleys (duns) and areas can also be considered a part of the broader Doon valley like the Panduni basin and the Kiarda Doon which further extends to the west of the Yamuna river into the Bata river valley (Philip *et al.* 2009). As a result some GPR studies were also conducted across some previous trench locations which were not strictly a part of the Doon valley but a part of the active tectonic regime of the valley. Two such locations were the Singhauli village near Kala Amb which is a major fault displacing the Shiwaliks and the Bharli village in the outer north west Doon valley which has the Bharli active fault running through it.

#### 4.2.4.1. SINGHAULI VILLAGE (HIMALAYAN FRONTAL THRUST)

The site was selected based on evidences of active faulting reported by Philip *et al.* (2012). The trenching is done near the HFT near the Kala Amb transverse fault by Philip *et al.* (2012). The trenching results indicate the presence of two distinct faults which are reported to be due to the reactivation of the HFT by Philip *et al.* (2012). Field observations indicate the active deformation along the HFT which is indicated by the presence of modified fault scarps. Also three main river terraces were observed above the stream bed by Philip *et al.* (2012). Philip *et al.* (2012) conducted trench investigations across the faulted and deformed terrace near the Singhauli Nala (stream) located in the Singhauli village (refer to Figure 4-1). Philip *et al.*

(2012) on the basis of trenching identified three thrust faults from south to north. Liquefaction features comprising entirely of a large scale sand injection was also observed by Philip *et al.* (2012). These faults have been identified on the basis of severity of faulting, folding and displacement of the various lithological units.

The trace of the HFT is easily visible passing near Singhauli in satellite imagery (Figure 4-22 A, Figure 4-22 B and Figure 4-23) along with the topographic break also seen in the CARTOSAT DEM due to the presence of the HFT (Figure 4-22 C).

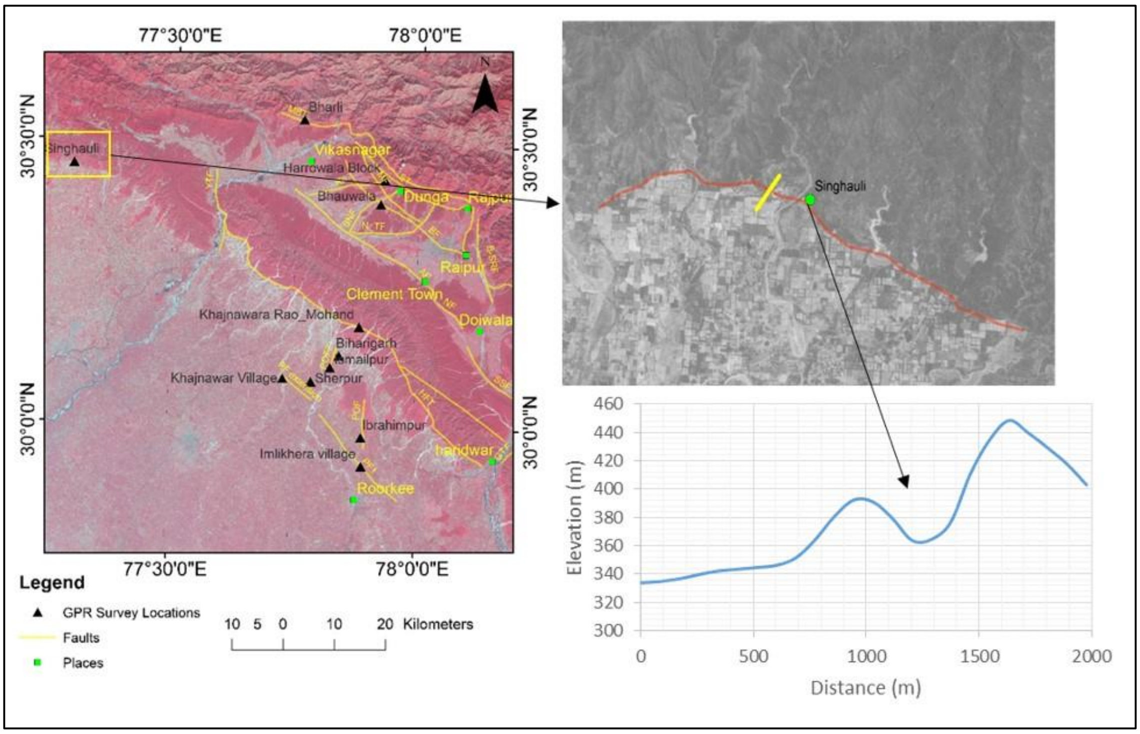



Figure 4-22 A: The Singhauli village location near the Himalayan front as seen form a LISS III image. Figure 4-22 B: The front of the HFT observed from the CARTOSAT high resolution imagery of the area. Figure 4-22 C: The topographic beak observed across the profile.

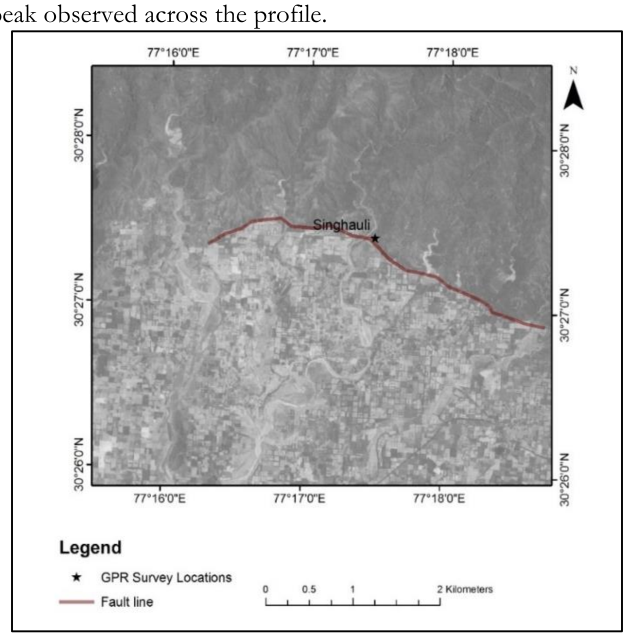



Figure 4-23: The close up of the HFT front in the CARTOSAT high resolution image of the area.

Middle Shiwalik sandstones overlain by Holocene deposits have been observed during field investigations (Figure 4-24). Though the fault scarp and the trench site have been severely modified, during recent field observations the thrusting of the middle Shiwalik sandstones over the Late Pleistocene sediments is observed (Figure 4-25) indicating faulted contact.


Figure 4-24: The Shiwalik sandstones thrusted over the Late Pleistocene deposits showing a possible fault.

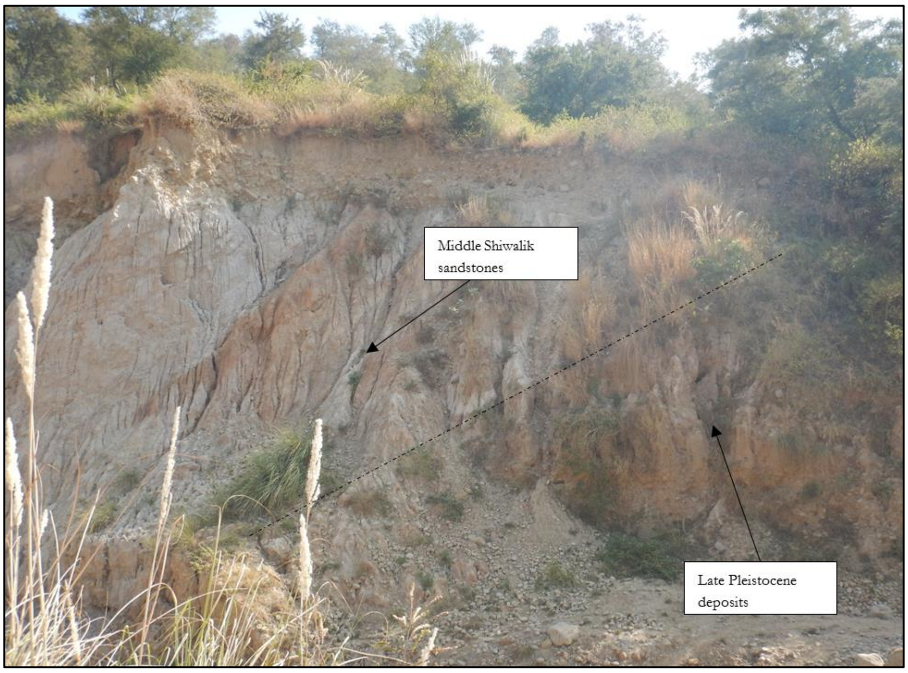



Figure 4-25: The scarp showing the Middle Shiwalik sandstones overlain by the Holocene deposits.

GPR PROFILES:

The profiles were taken across the three identified faults. The three faults are all thrust faults in the direction from southwest to northeast. The GPR was used to validate the presence of these faults in the subsurface. An attempt was also made to determine the sand injection feature which was reported previously.

The penetration of GPR was found to be slightly less at the location. This maybe due to the large scale attenuation in signals due to the presences of boulders, pebbles and alluvium in the stream bed. The stream bed running parallel to the scarp was the only flat topography in the area where the survey was feasible.

Though significant offsets and deformations were not clearly observed, there were offsets between the layers and possible deformation which indicates some faulting. The strong attenuation of GPR signals in the river bed limits the penetration a bit. The profile is from north to south.

Though the evidences are not conclusive, the signatures of faulting are seen in the profile below (Figure 4-26). This profile indicates a possible fault dipping towards the north.

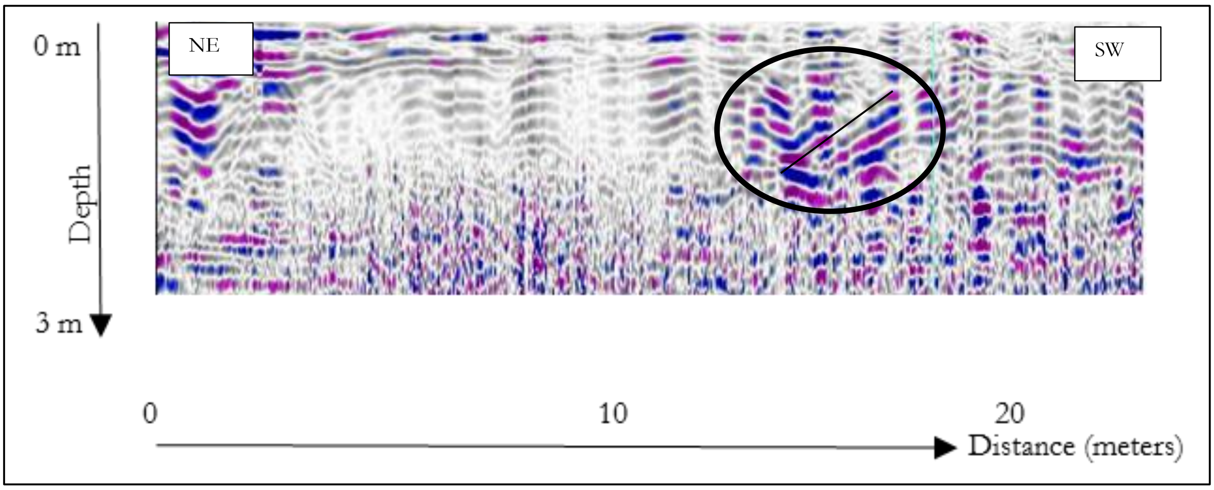



Figure 4-26: The profile showing the possible north dipping fault with the profile taken from north to south.

The profile shows a possible fault trace with a dipping direction towards the north which coincides with the dip direction determined from trenching studies. The GPR thus validates the trenching results of the previous studies.

The liquefaction feature described by Philip *et al.* (2012) as a sign of previous seismic event in the area was traceable on one profile which indicates a possible sand injection feature (refer to Appendix A, Figure A - 6).

#### 4.2.4.2. KHAJNAWARA RAO (MOHAND RANGE: HIMALAYAN FRONTAL THRUST)

Kumar *et al.* (2005) carried out trenching investigations at various sites in the Doon valley and its surrounding areas. One such area was Khajnawara Rao seasonal stream near the Mohand town (refer to Figure 4-1) and two levels of fluvial terraces are observed in this area, one uplifted and the other truncated by Kumar *et al.* 2005. According to the trenching carried out at the stream bed of Khajnawara Rao by Kumar *et al.* (2005), the HFT is quite close to the surface just covered by a thin layer of river alluvium (Figure 4-27). The results of the trench investigations shows that the highly sheared Shiwalik bedrocks are thrust over the older alluvial deposits of the surrounding floodplains and both these layers are overlain by the thin layer of river bed gravels as shown in the trench log determined by Kumar *et al.* (2005) (Figure 4-27). The front of the HFT passing through Khajnawara Rao and the topographic breaks were also clearly observed on the CARTOSAT high resolution imagery and CARTOSAT DEM imagery (Figure 4-28 A, Figure 4-28 B and 4-28 C).

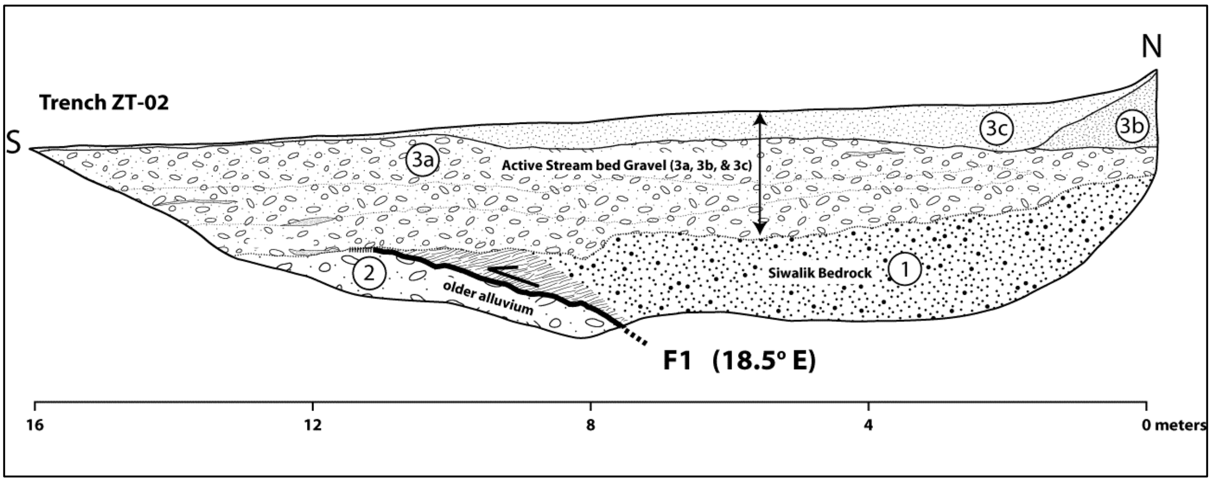



Figure 4-27: The fluvial terrace deposits and the location of the trench site along with the strike of the HFT (taken from Kumar *et al.* 2005). The contours are at 20 m intervals in the figure. The Shiwalik bedrock (1) is the oldest unit which is thrust over the older alluvium along a low angle thrust fault (F1) and is overlain by stream bed gravels (3a) and 3b and 3c represent a deposits from the nearby hillside and overbanks (Kumar *et al.* 2005).

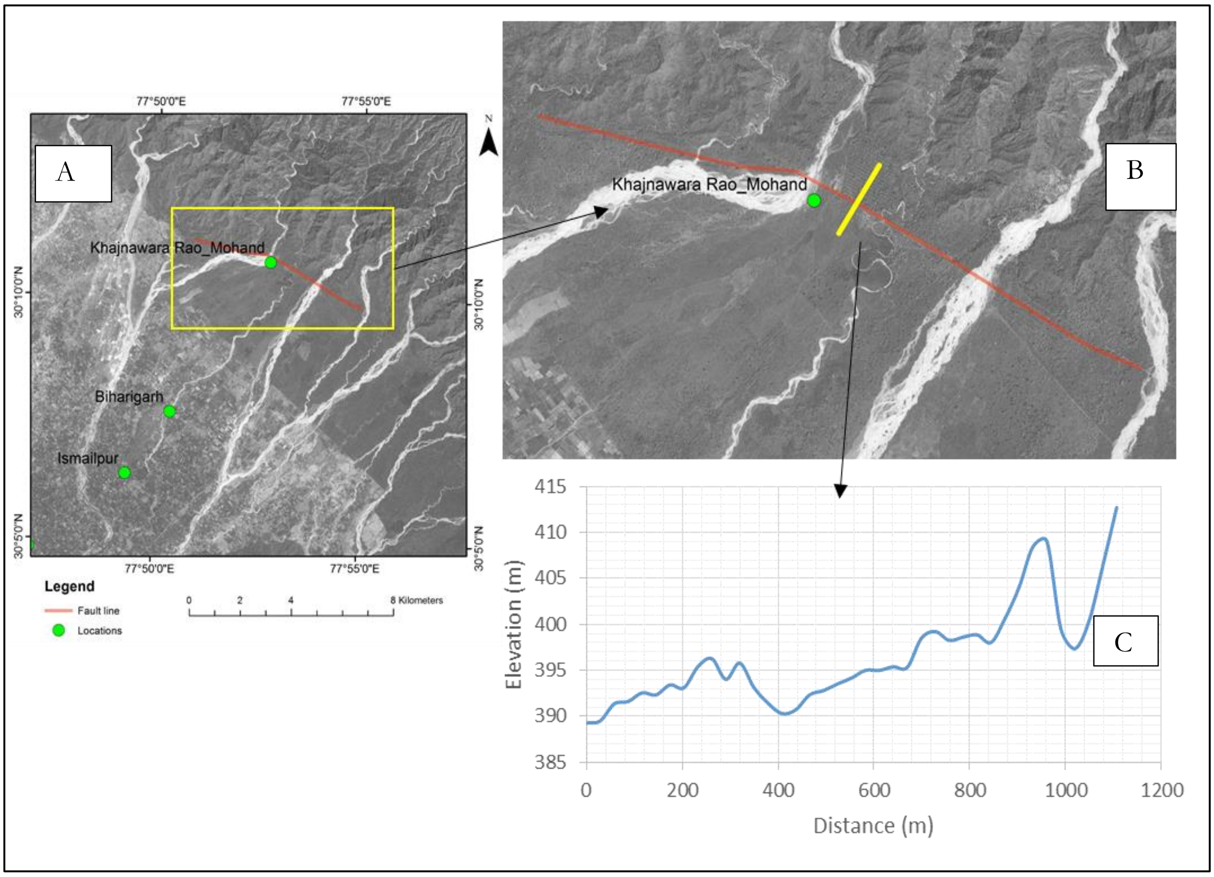



Figure 4-28 A: The location of the Khajnawara Rao GPR site in a CARTOSAT high resolution image. Figure 4-28 B: The closeup of the HFT observed in the CARTOSAT high resolution image. Figure 4-28 C: The topographic break observed across the profile.

The terraces are as high as 20-30 meters above the stream beds in these areas (Figure 4-29 A and Figure 4-29 B). These along with the presence of abrupt and steep escarpments in the area (Figure 4-30) was the reason to conduct GPR investigations in the area near the trench location to validate the trenching results of Kumar *et al.* (2005)


Figure 4-29 A: The 20-25 meter steep terrace being observed in Khajnawara Rao. Figure 4-29 B: The steep escarpment observed in the area about 15-20 meter in height.


Figure 4-30: The abrupt scarps observed along the HFT in Khajnawara Rao. Height about 15-20 meters. The picture is taken facing north. The trench site location of Kumar *et al.* (2005).

INTERPRETED PROFILE:

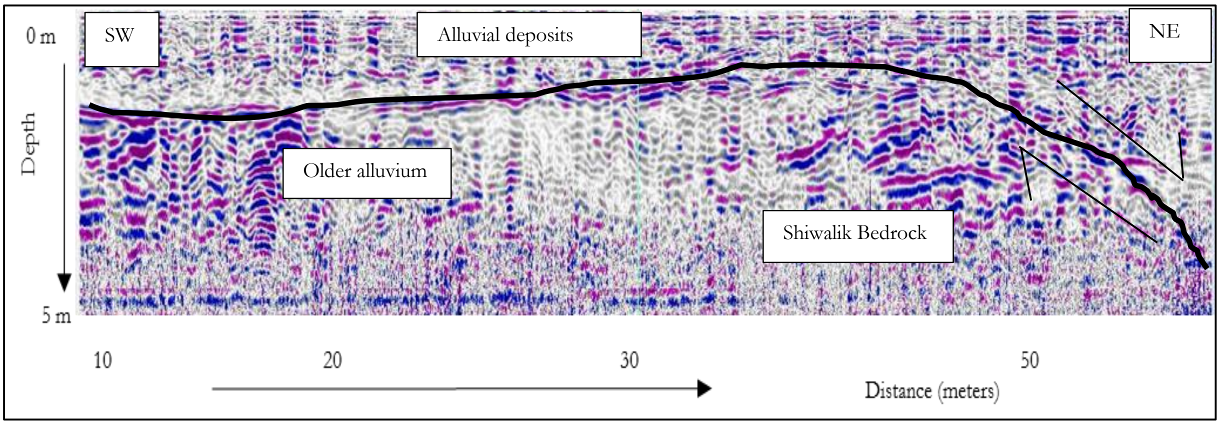



Figure 4-31: The interpreted profile clearly shows the low angle thrust fault along with the different sedimentary layers as observed in the trench log by Kumar *et al.* (2005). The profile is taken from southwest to northeast

The GPR profiles taken with 100 MHz antenna is used to validate the presence of the thrust fault and the sedimentary layers as shown in the trench log by Kumar *et al.* (2005). The interpreted profile (Figure 4-31) clearly shows the low angle thrust fault with a clear difference in layers between the alluvial gravels (river deposits) overlying the older alluvium with the Shiwalik bedrock being thrust over the older alluvium along the low angle fault. The continuation of the same profile validates the presence of this low angle thrust fault with associated minor faults in the vicinity which are observed in the GPR profiles (for GPR results and observations please refer to Appendix A, Figure A-5). All these results validate the presence of a low angle emergent thrust fault (HFT) as observed during the trenching studies of Kumar *et al.* (2005). The Shiwaliks are highly sheared and both the Shiwaliks and the older alluvium are capped by the recent alluvial deposits thus validating the results of the trench log by Kumar *et al.* (2005).

#### 4.2.4.3. BHARLI VILLAGE

The Bharli, Dhamaun and Sirmurital faults are some of the major fault systems in the outer northwest Doon valley and are described as part of the Trans-Yamuna active fault system by Oatney *et al.* (2001). The Bharli fault passes through village Bharli (refer to Figure 4-1) across the main road leading to the village. The Trans Yamuna active fault system is parallel to the Main Boundary Thrust (MBT) in the outer Doon valley in the northwest Himalaya.

Based on from satellite observations (Figure 4-32 A, Figure 4-32 B and Figure 4-33) and field observations location of the Bharli Fault could be confirmed. The topographic break is also observed in the CARTOSAT DEM of the area in the form of a sharp elevation change (Figure 4-32 C). The Bharli fault lies quite close to the MBT just to the north of it (Figure 4-32 B and Figure 4-33). The fault scarp has been found to be significantly degraded in the field due to road building activities. But strong expressions of active tectonics are observed in the field. Two sag ponds were observed in the field which are also clearly visible from satellite and Google Earth imagery (Figure 4-34 A, Figure 4-34 B, Figure 4-34 C, Figure 4-34 D and Figure 4-35).

These geomorphic features along with the presence of scarp topography confirms the presence of the active fault system in the area. GPR survey was conducted at this location for validation. The terrain was hilly and it made it very unsuitable for GPR survey and hence the survey was conducted on the main road leading into the Bharli village just to the south of the village.

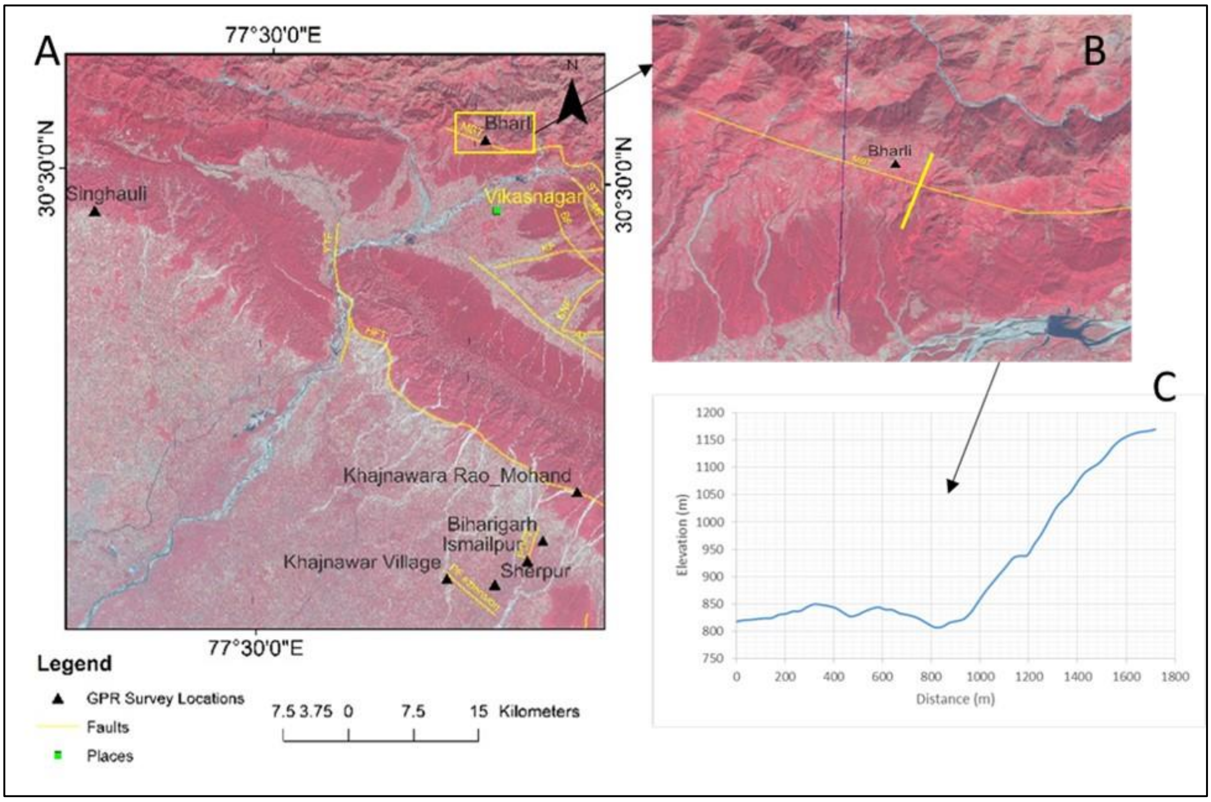



Figure 4-32 A: The location of Bharli in the LISS III image. Figure 4-32 B: The close up of the trace in the LISS III image. Figure 4-32 C: The topographic break depicted by sudden elevation changes as observed across the Bharli Fault.

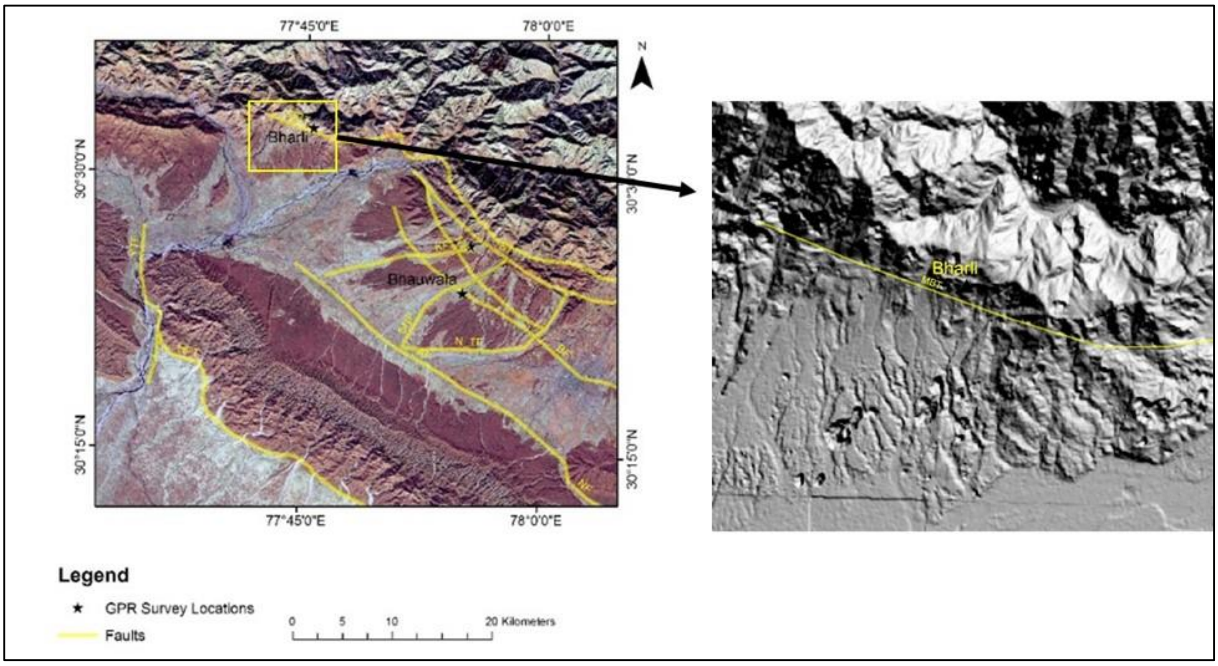



Figure 4-33: The Bharli village which is located quite close to the MBT as seen from the LANDSAT pansharpened image. A close up of the trace is also provided in CARTOSAT hillshaded image.

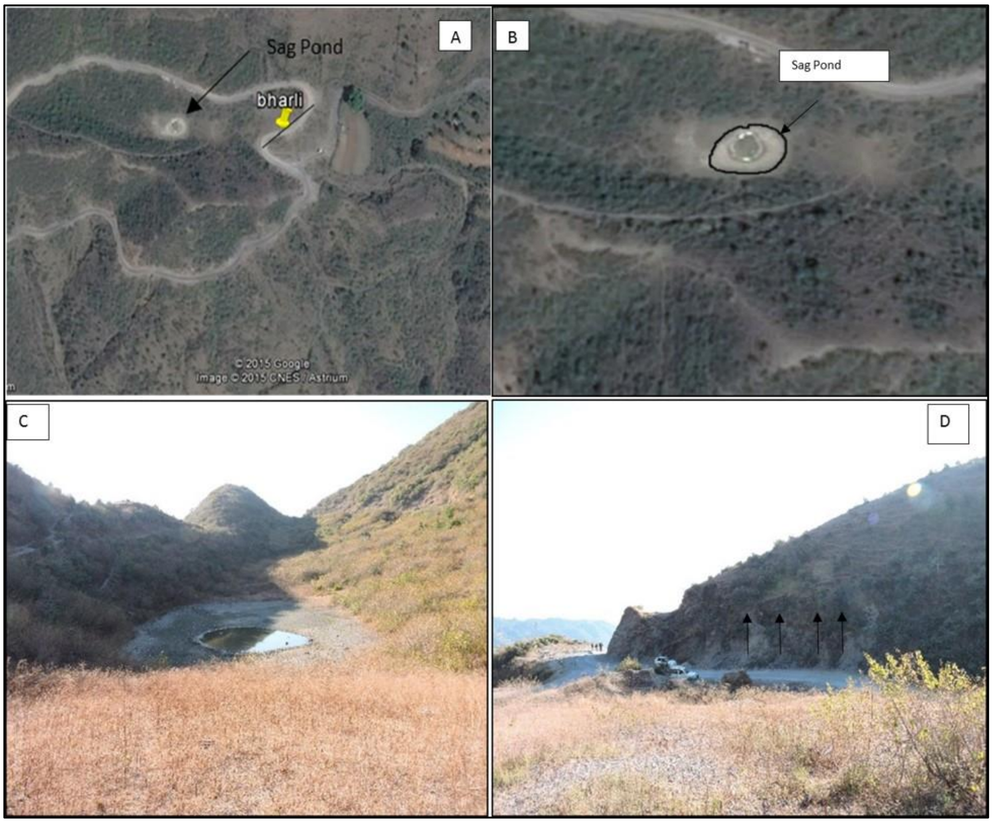



Figure 4-34 A: The location of the Bharli GPR profile SW of the Bharli village along with the fault scarp and sag pond visible in the Google Earth imagery (CNES Astrium 2015). Figure 4-34 B: The close up of the sag pond feature observed from the Google Earth imagery. Figure 4-34 C: The field photograph of the major sag pond which is clearly visible in the satellite imagery. Figure 4-34 D: The arrows indicate the degraded scarp due to road building activities in the area.

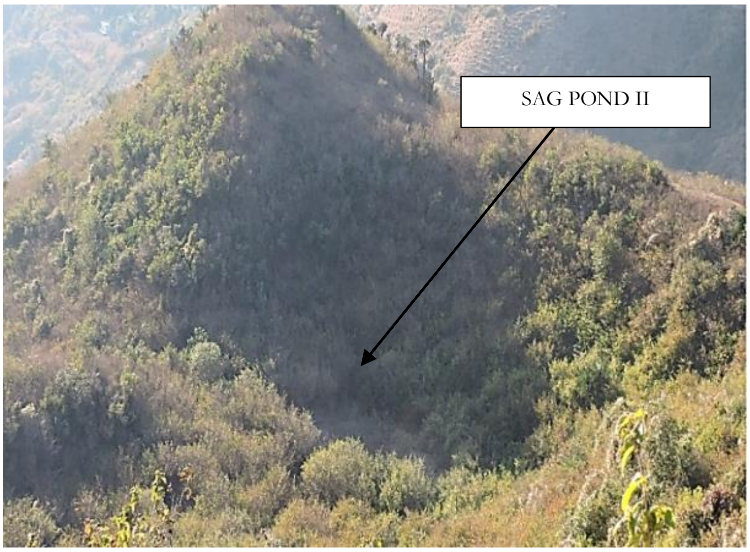



Figure 4-35: The sag pond II observed to the south of the Bharli village also occurs along the trace of the fault

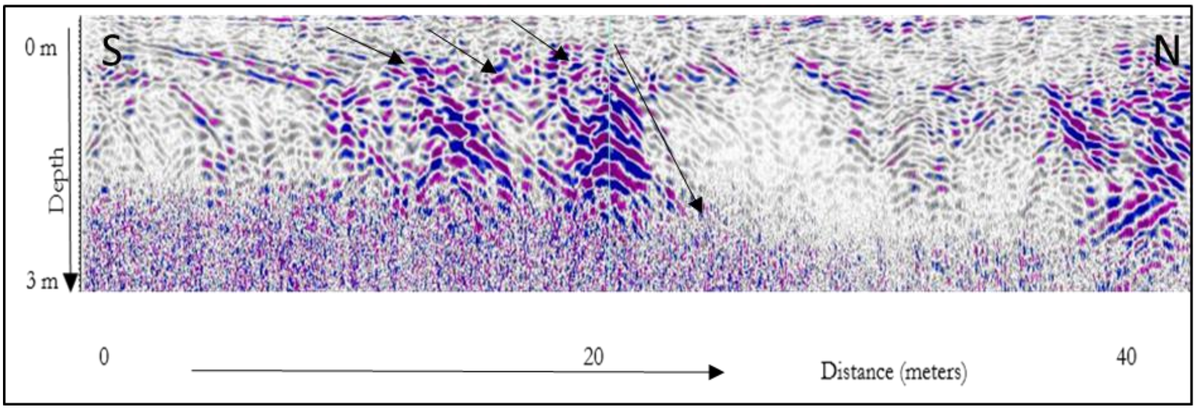



Figure 4-36: The dipping reflectors in the GPR profile taken in the south north direction showing the possible north dipping Bharli fault of the Trans Yamuna Fault system. Profile taken from south to north.

The GPR profiles were taken in the general direction of N-S or in the reverse direction on the main road. Due to the terrain conditions the road was the only feasible option where the GPR survey could be done. The arrows in the profile indicate the dipping and deformed high amplitude reflectors (Figure 4-36). The dip direction is in to the north. This may be a high angle reverse fault along with the presence of a strike slip component. A reverse profile is also taken from the direction of north to south to validate the results of the previous profile and a possible north dipping fault is also observed in this GPR profiles (for results refer to Appendix A, Figure A-4).

## 4.3. SEISMICITY OF THE REGION

The seismicity map showing the epicentres of the earthquakes from 1800 to present day shows some earthquake epicentres lying in the Doon valley and some lying extremely close to the Doon valley (sources derived from USGS/NEIC, IMD and previous publications, refer to Appendix A, Table A-1). Some of these epicentres show a close proximity to the major active fault systems of the Doon valley. There are 5-6 earthquake epicentres extremely close (within 20 kilometers) to the MBT and its related E-W trending fault systems in the NW Doon valley like the Bhauwala, Majhaun and Santaurgarh thrust (Dunga Fault) systems. There are also a couple of epicentres in the piedmont region of the Doon valley with close proximity to the Piedmont fault system near the towns of Roorkee and Saharanpur.

The map (Figure 4-37) clearly shows the vulnerability of reactivation of these active faults and that could experience major rupture during a possible large magnitude seismic event in the region including the piedmont region and NW Doon valley (For the table of earthquake data, refer of Appendix A, Table A-1).

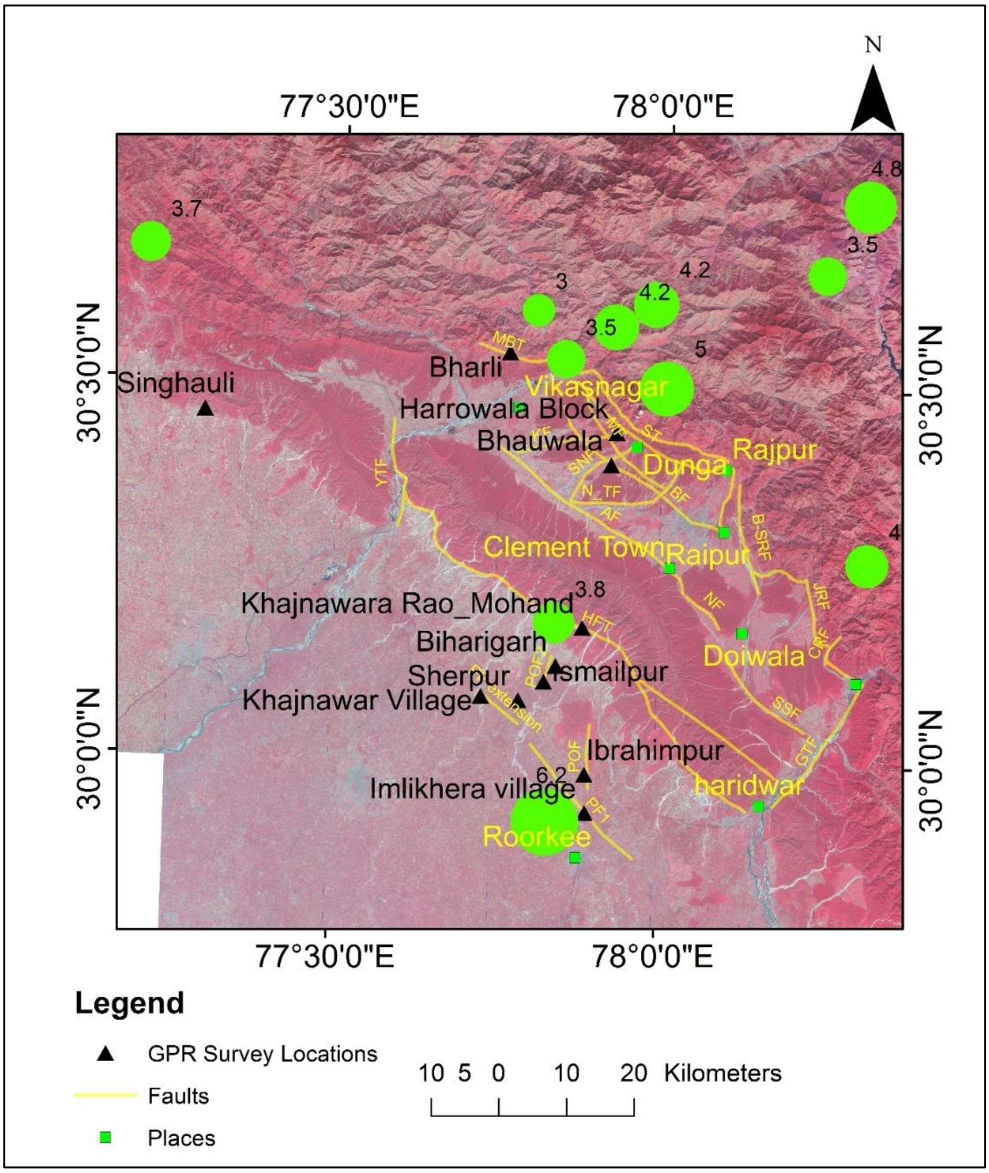



Figure 4-37: The seismicity map according to the magnitude of the historical earthquakes in the Doon valley in a LISS III image.

The potential reactivation of these faults even though they appear dormant now is one of the major concerns of the Doon valley. The 1905 Kangra earthquake (magnitude> 8) had its epicentre almost three hundred kilometers away from Dehradun in Himachal Pradesh (Thakur *et al.* 2000). Though the earthquake happened at such a distance, historical records prove that the earthquake mainly affected two regions: the local Kangra region and the Dehradun region. According to Thakur *et al.* (2000), the microseismal zone of Kangra earthquake extended from Kangra to Dehradun between the MBT and the HFT. This shows the potential of the faults of the Doon valley to reactivate even during far off seismic events. This shows that the faults in the Doon valley are still active seismically and has the potential to cause tremendous damage to life and property in case of any seismic event nearby. Thus the parallel faults located in the NW Doon valley (Bhauwala fault, Majhaun fault, Santaurgarh thrust, HFT and the Piedmont fault) are at most risk of reactivation.

## 4.4. DISCUSSIONS

The GPR results shows up clear evidences of faulting in several of the places where faults have been inferred and selected at places proved by trenching. The GPR results carried out in Imlikhera near Piedmont Fault shows the presence of north dipping layers. These north dipping layers may be due to the presence of the Piedmont Fault which is one of the most prominent tectonic feature identified in the region. The Bhauwala and Harrowala faults are part of the system of parallel faults in the NW Doon valley. Offsets were observed in Harrowala with a possible north dipping fault. The Bhauwala Fault on the other hand, is one of the prominent tectonic feature of Doon valley and traces of faulting dipping north are also observed in the Bhauwala profiles. The possible N-S trending fault near Ibrahimpur is one that is most clearly observed in the GPR profile of the area. The layers are dipping towards the east with the hanging wall block on the east also observed due to the bending of the hanging wall layers. The Bharli Fault was clearly observed in the profiles as thrust fault north of the MBT. North dipping layers were clearly determined from the GPR profiles of Bharli village.

GPR surveys were also conducted in Singhauli and Khajnawara Rao which were previous trenching sites and faulted contacts were conclusively observed. The GPR results were used as a validation tool to determine these faults. At the same time trench evidences were also used to validate GPR results and provide explanations where the GPR signals are not conclusive. The Khajnawara Rao results show that the HFT is a low angle thrust fault as was determined in the trenching studies. The HFT is found to be very close to the surface. Though there is a possibility that the dipping layers observed is a filled up erosional feature of the Khajnawara Rao river bed, the combination of the previous trench log and GPR results verifies the presence of the low angle thrust of the HFT. The signal attenuation has impacted the results in Singhauli village to some extent. The Singhauli Village profiles were taken in trench sites where faulted contacts have been conclusively proved. The GPR survey validated the presence of a north dipping fault (HFT) near the Singhauli village though signal attenuation limited the depth of penetration of the signals. The presence of boulders and pebbles in the stream bed also caused scattering of signals. The GPR thus proved to be hugely beneficial in validating the results of trenching at both the Singhauli (HFT) and Khajnawara Rao (HFT) sites.

Some major fault systems in the Doon valley are along rivers (e.g. the Asan River Fault, the Nun River Fault). This meant that these faults could not be verified by GPR surveys. The processing of the GPR results also had a drawback as topographic corrections were not available in the software. This might have caused us to miss some signatures of faulting. The effect of topography has been tried to be minimized by conducting surveys across flat profiles as much as possible. The surveys were conducted in reasonably flat terrains which meant that the scarp feature has been degraded and strongly influenced by human activities causing the disturbance of the soil upto a few meters underneath. The terrain of the Doon valley also showed up challenges (due to the hilly terrain in Doon valley and agricultural fields and plantations in piedmont region) due to which the Santaurgarh Thrust, the MBT (Main Boundary Thrust), the Nagsidh Hill faults could not be attempted. The elevation of these sites along with the rough terrain makes it very difficult to conduct GPR surveys in these areas, however geological evidences confirm these faults.

The GPR surveys were also used to determine the best possible antennas for geological studies especially in subsurface conditions similar to Doon valley. 25, 40, 100 and 200 MHz antennas were tested in the region. The best results have been observed in 100 and 200 MHz antennas. In optimum conditions the GPR was observed to penetrate the soil upto 12 meters and 7-8 meters in case 100 and 200 MHz antennas while normally the penetration was observed upto a depth of 6 meters and 4 meters in the case of 100 and 200 MHz antennas respectively in relation to subsurface conditions of the Doon valley. This depth of penetration along with the resolution of these two antennas makes these two the most suitable to conduct geological studies. The surveys also proved that for validation of the results reverse surveys should be carried out along the same profiles and parallel to the profiles. The results of the reverse profiles can then be used to validate the results of the previous profiles.

The seismicity data of the Doon valley and its surrounding reason shows that the area is seismically very active. The main faults which are candidates for displacement are the Piedmont Fault, the HFT and the MBT. There were a couple of historical earthquakes in and around the HFT (near the Mohand and Singhauli GPR profile locations). These earthquake epicentres prove that the HFT is reasonably active. Also the presence of a medium high intensity earthquake epicentre (6.2 magnitude) right near the piedmont fault shows the active nature of this fault. The largest concentration of historic earthquakes appear within 20 kilometers of the MBT. Even though the lack of seismic activity in the other faults though may suggest that these are dormant or not active but these are also potential candidates for deformation in the event of an earthquake. Also the data considered for historic earthquakes is only from the year 1800 AD onwards. This leads to the conclusion that there might have been historic earthquakes before 1800 AD in the Doon valley that might have contributed to reactivation of the Doon valley faults. Also the field observations support the theory that the faults in the Doon valley are active. Far off seismic events of sufficient magnitude have the capability to activate any of the faults of the Doon valley as the aftermath of the 1905 Kangra earthquake shows. There is also a larger trend observed that though the active front of the Himalayas is progressing southwards continuously the major seismicity concentration is still in the Lesser Himalayas near the MBT and the MCT.

## 4.5. SUMMARY OF THE RESULTS

A list of names and location of the faults which were surveyed during the research:

Table 4-1: The table showing the names and locations of the faults surveyed.

| FAULT NAME | LOCATION |
|---|---|
| THE PIEDMONT FAULT | IMLIKHERA AND KHAJNAWAR NEAR ROORKEE |
| POSSIBLE N-S TRENDING FAULT IN THE PIEDMONT REGION | IBRAHIMPUR VILLAGE (NORTH OF IMLIKHERA VILLAGE) |
| BHAUWALA FAULT | NORTHWEST DOON VALLEY (BHAUWALA VILAGE) |
| HARROWALA FAULT | NORTHWEST DOON VALLEY (HARROWALA BLOCK) |
| BHARLI FAULT | OUTER NORTHWEST DOON VALLEY (BHARLI VILLAGE) |
| HIMALAYAN FRONTAL THRUST | SINGHAULI VILLAGE |
| HIMALAYAN FRONTAL THRUST | KHAJNAWARA RAO (MOHAND) |

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1. CONCLUSIONS

### 5.1.1. RESEARCH QUESTIONS AND THEIR ANSWERS

- **Which are the prominent active faults in the study area?**

The prominent active faults in the area have been mapped through visual image interpretations and by referring to fault maps from previous literature. Also signatures of active tectonics like the displacement/uplift of river terraces, fault scarps, topographic breaks entrenched streams and sag ponds confirmed by field observations and satellite image interpretation. The prominent active fault systems in the area are observed in the NW Doon valley. There are a series of NW-SE trending fault systems along with associated minor faults which have been interpreted and confirmed during GPR surveys. The whole system appears to be a southward migration of the MBT. The major fault systems mapped in this area include the Bhauwala Fault, Majhaun fault and the Santaurgarh Thrust (Dunga Fault). The GPR results and the terrain analysis via DEM shows there are some associated fault systems with these major faults which are also trending more or less in the general direction of NW-SE. The piedmont region has one major E-W trending fault which is clearly discernible in the satellite imagery due to the sudden bending of river Solani and the break in topography observed due to the termination of the Old Piedmont Zone against this lineament just to the north of the Solani river. The Doon valley is bounded by four active thrusts clearly observed on the satellite images of the area which are also the four most prominent active faults in the area: the Ganga Tear Fault, the Yamuna Tear Fault, the Himalayan Frontal Thrust and the Main Boundary Thrust in the east, west, south and north boundaries of the Doon valley respectively. There are also prominent transverse faults across the Doon valley like the Koti Fault, the Suarna Nadi Fault and the Nun Tons fault along the rivers by the same names which divides the Doon valley into its major geomorphological divisions. Another active fault system is the the Asan Fault, Nagsidh Hill Fault and the Suswa Song Fault which are part of the same fault system marked by the lineaments discernable from satellite images.

- **Whether geophysical surveys (GPR surveys) can confirm/validate the presence of fault extension in the subsurface?**

The validation and the determination of faults can be carried out quite clearly with the help of GPR surveys as proved by the results. The results of Imlikhera (Piedmont fault), Harrowala and Bhauwala fault, Singhauli and Khajnawara Rao (HFT) and the Bharli village (Bharli fault) clearly show the GPR surveys can determine dipping reflectors and offsets between reflectors which are then be correlated to fault traces identified from satellite image analysis and field observations to validate the location and presence of a fault. Trenching results can also be validated with the help of GPR surveys. Also GPR can exactly pinpoint and confirm the fault extension in the subsurface and the also the geometry (dip direction) of the faults in the subsurface.

- **What is the relation between seismicity and active faults of the region?**

The seismicity map of the Doon valley and its surrounding areas shows number of historical earthquakes in the Doon valley and possible impacts from far off earthquakes. The recent seismic data along with the the active nature of the HFT, the MBT and the Piedmont Fault makes the area more vulnerable. The other faults in the Doon Valley though dormant can be reactivated in the event of a major earthquake. The Doon valley is still surrounded by active thrusts like the MBT and the HFT which shows the high seismic risk of the valley due to presence of minor and major faults and thick pile of sediments at the center. The Doon valley faults are at real risk of reactivation in the case of a high magnitude earthquake along the HFT or the MBT.

**ADDITIONAL QUESTIONS**:

- **What are the best frequencies of GPR antenna for conducting geological studies in the study area?**

The optimum penetration to resolution trade off can be obtained by using 100 MHz antenna. Though 200 MHz antenna can also be used in the surveys, due to limitation in penetration depth of the 200 MHz antenna, the 100 MHz antenna can be the best solution for conducting geological studies in the area.

- **What is the best survey plan in conducting GPR studies to determine fault extension in the subsurface?**

The best way to validate the presence of a fault is to conduct multiple surveys in the same location. Multiple surveys can be conducted by taking the reverse surveys along the same profiles which shows evidences of faulting. Also profiles parallel to the main profile should be taken to validate the exact location and extension of the fault in the subsurface.

## 5.2. RECOMMENDATIONS

The project highlights the necessity to conduct detailed fault analysis in the Doon valley along with reconstructing of paleoseismic history of the faults to determine the possible reactivation potential of the active faults. GPR has given very good results in validation of faults namely Imlikhera, Khajnawara Rao, Bharli and Ibrahimpur. The fault traces are clearly observed in the GPR profiles. The dipping of the layers and the offsets between the layers have proven the existence of faulting activity in these areas. This shows that the GPR is a vital tool to be used to validate and confirm the presence of faults in an area. The advantage of GPR over other methods is that it is a technique which can be used in different kinds of terrains and is a very efficient and time saving method to carry out subsurface geological investigations.

The advantage of GPR over other traditional methods like trenching is that trenching requires a huge amount of resources and a lot of time to come up with results. The GPR on the other hand is efficient in cutting down on resources and time and also to conduct multiple investigations at a single site to validate faults. Different antennas can also be used according to different target depths and also the resolution required, which is one of the significant advantages of this method observed during this study. The GPR results can also be used efficiently to determine potential trenching sites. Crustal deformation information can also be gathered with the help of these surveys as they clearly show the deformed layers in the subsurface.

The results of this research can be used to conduct seismic hazard assessment in the Doon valley and determine its past earthquake history. Paleoseismic investigations can be carried out of the basis of this study. Further geophysical and trenching investigations can also be carried out based on the results of these studies. This will in turn help create a proper active fault map of the Doon Valley and also to conduct proper seismic hazard assessments in the valley.

# LIST OF REFERENCES


Fazzito, SY, Augusto, ER, José, MC and Carla, MT 2009, 'Characterization of Quaternary faults by electric resistivity tomography in the andean Precordillera of Western Argentina. *Journal of South American Earth Sciences*, vol. 28, no. 3, pp. 217-228. DOI: 10.1016/j.jsames.2009.06.001.

GRED HD *v* 01.01- User Manual, 2013, GRED HD SOFTWARE, INGEGNERIA DEI SISTEMI S.p.A (IDS), Pisa, Italy, N doc: MN/2013/002 - Rev. 1.0.

Joshi, GR and Hayashi, D 2008, 'Numerical Modeling of Neotectonic Movements and State of Stresses in the Central Seismic Gap Region, Garhwal Himalaya'. *Journal of Mountain Science*, vol. 5, no. 4, pp. 279-298. DOI: 10.1007/s11629-008-0237-2.

Kumar, S, Steven, GW, Thomas, KR, Richard, WB, Vikram, CT and Jayangondaperumal, R 2005, 'The Himalayan Frontal Thrust of India is not blind.' *Journal of Geophysical Research*.

Malik, JN, Shah, AA, Sahoo, AK, Puhan, B, Banerjee, C, Shinde, DP, Juyal, N, Singhvi, AK and Rath, SK 2010a, 'Active fault, fault growth and segment linkage along the Janauri anticline (frontal foreland fold), NW Himalaya, India.' *Tectonophysics*, vol. 483, no. 3, pp. 327-343. DOI: 10.1016/j.tecno.2009.10.028.

Malik, JN, Sahoo, AK, Shah, AA, Shinde, DP, Juyal, N and Singhvi, AK 2010b, 'Paleoseismic evidence from trench investigation along Hajipur fault, Himalayan Frontal Thrust, NW Himalaya: implications of the faulting pattern on landscape evolution and seismic hazard.' *Journal of Structural Geology*, vol. 32, no. 3, pp. 350-361. DOI: 10.1016/j.jsg.2010.01.005.

Malik, JN, Shah, AA, Naik, SP, Sahoo, S, Okumura, K and Patra, NR 2014, 'Active fault study along foothill zone of Kumaun Sub-Himalaya: influence on landscape shaping and drainage evolution.' *Current science*, vol. 106, no. 2, pp. 229-236.

Maurya, DM, Patidar, AK, Mulchandani, N, Goyal, B, Thakkar, MG, Bhandari, S, Vaid, SI, Bhatt, NP and Chamyal, LS 2005, 'Need for initiating ground penetrating radar studies along active faults in India: an example from Kachchh.' *Current Science*, vol. 88, no. 2, pp. 231-240.

Oatney, EM, Virdi, NS and Yeats, RS 2001, 'Contribution of Trans-Yamuna active fault system towards hanging wall strain release above the décollement, Himalayan foothills of Northwest India.' *Himalayan Geology*, vol. 22, no. 2, pp. 9-27.

Philip, G 1995, 'Active tectonics in Doon valley.' *Journal of Himalayan Geology*, vol. 6, pp. 55-61.

Philip, G 1996, 'Landsat Thematic Mapper data analysis for Quaternary tectonics in parts of the Doon valley, NW Himalaya, India.' *International Journal of Remote Sensing*, vol. 17, no. 1, pp. 143-153.

Philip, G and Sah, MP 1999, 'Geomorphic signatures of active tectonics in the Trans-Yamuna segment of the western Doon valley, northwest Himalaya, India.' *International journal of applied earth observation and geoinformation*, vol. 1, no. 1, pp. 54-63.

Philip, G, Virdi, NS and Suresh, N 2009, 'Morphotectonic evolution of Parduni Basin: An intradun piggyback basin in western Doon valley, NW Outer Himalaya.' *Journal of the Geological Society of India*, vol. 74, no. 2, pp. 189-199.

Philip, G, Bhakuni, SS and Suresh, N 2012, 'Late Pleistocene and Holocene large magnitude earthquakes along Himalayan Frontal Thrust in the Central Seismic Gap in NW Himalaya, Kala Amb, India.' *Tectonophysics*, vol. 580, pp. 162-177. DOI: 10.1016/j.tecto.2012.09.012

Rautela, P, and Sati, D 1996, 'Recent crustal adjustments in Dehra Dun valley, western Uttar Pradesh, India.' *Current science*-Bangalore, vol. 71, pp. 776-780.

Robinson, M, Bristow, C, Mckinley, J and Ruffell, A 2013 'Ground Penetrating Radar.' British Society of Geomorphology: *Geomorphological Techniques*, Part 1, Sec. 5.5. ISSN 2047-0371.

Sahoo, PK, Kumar, S and Singh, RP 2000, 'Neotectonic study of Ganga and Yamuna tear faults, NW Himalaya, using remote sensing and GIS.' *International Journal of Remote Sensing*, vol. 21, no. 3, pp. 499-518. DOI: 10.1080/014311600210713.

Singh, AK, Parkash, B, Mohindra, R, Thomas, JV and Singhvi, AK 2001, 'Quaternary alluvial fan sedimentation in the Dehradun valley piggyback basin, NW Himalaya: tectonic and palaeoclimatic implications. *Basin Research*, vol. 13, no. 4, pp. 449-471.

Singh, AK, Parkash, B and Manchanda, ML 2004, 'Tectonic geomorphology of the Dehradun valley using digital terrain models and optically stimulated luminescence dating.' *Himalayan Geology*, vol. 25, no. 1, pp. 59-78.

Singh, AK, Parkash, B and Choudhury, PR 2007, 'Integrated use of SRM, LANDSAT ETM+ data and 3D perspective views to identify the tectonic geomorphology of Dehradun valley, India.' *International Journal of Remote Sensing*, vol. 28, no. 11, pp. 2403-2414. DOI: 10.1080/01431160600993397.

Thakur, VC, Sriram, V and Mundepi, AK 2000, 'Seismotectonics of the great 1905 Kangra earthquake meizoseismal region in Kangra–Chamba, NW Himalaya.' *Tectonophysics*, vol. 326, no. 3, pp. 289-298. DOI: doi:10.1016/S0040-1951(00)00126-8.

Thakur, VC 2004, 'Active tectonics of Himalayan frontal thrust and seismic hazard to Ganga Plain.' *Current science*, vol. 86, no. 11, pp. 1554-1560.

Thakur, VC and Pandey, AK 2004a, 'Late Quaternary tectonic evolution of Dun in fault bend/propagated fold system, Garhwal Sub-Himalaya.' *Current science*, vol. 87, no. 11, pp. 1567-1576.

Thakur, VC and Pandey, AK 2004b, 'Active deformation of Himalayan Frontal Thrust and piedmont zone south of Dehradun in respect of seismotectonics of Garhwal Himalaya.' *Himalayan Geology*, vol. 25, no. 1, pp. 23-31.

Thakur, VC, Pandey, AK and Suresh, N 2007, 'Late Quaternary–Holocene evolution of dun structure and the Himalayan Frontal fault zone of the Garhwal sub-Himalaya, NW India.' *Journal of Asian Earth Sciences*, vol. 29, no. 2, pp. 305-319. DOI: 10.1016/j.jseaes.2006.02.002.

Thakur, VC 2013, 'Active tectonics of Himalayan Frontal Fault system.' *International Journal of Earth Sciences*, vol. 102, no. 7, pp. 1791-1810. DOI: 10.1007/s00531-013-0891-7.

Trifonov, VG 1995, 'World map of active faults (preliminary results of studies).' *Quaternary International*, vol. 25, pp. 3-12.

Yalçıner, CC, Altunel, E, Bano, M, Meghraoui, M, Karabacak, V and Akyüz, HS 2013, 'Application of GPR to normal faults in the Büyük Menderes Graben, western Turkey.' *Journal of Geodynamics*, vol. 65, pp. 218-227. DOI: 10.1016/j.jog.2012.05.011.

Yeats, RS, and Thakur, VC 2008, 'Active faulting south of the Himalayan Front: Establishing a new plate boundary'. *Tectonophysics*, vol. 453, no.1, pp. 63-73. DOI: 10.1016/j.tecto.2007.06.017.

# APPENDIX A

KHAJNAWAR VILLAGE

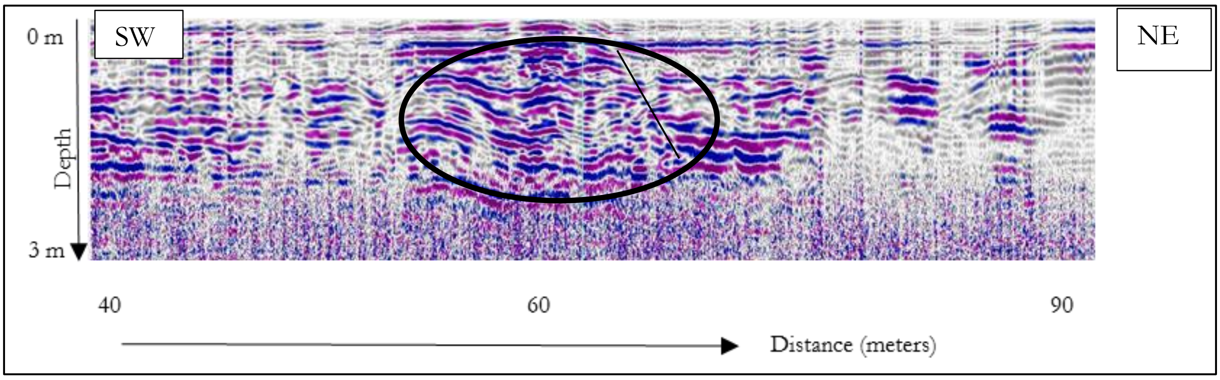



Figure A-1: The high amplitude reflectors with a sudden break/offset. The profile is from south west to north east.

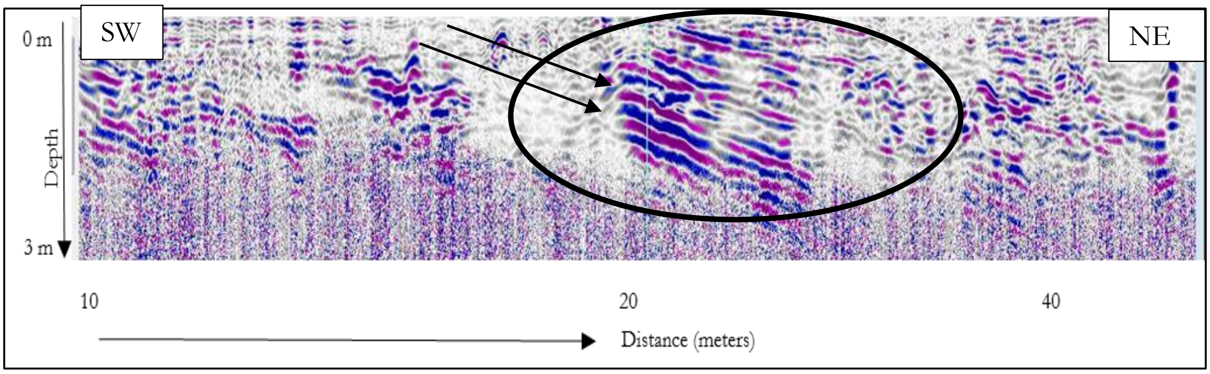



Figure A-2: The possible north dipping layers observed in a 200 MHz antenna in the Khajnawar village. The profile is from south west to northeast.

BHAUWALA

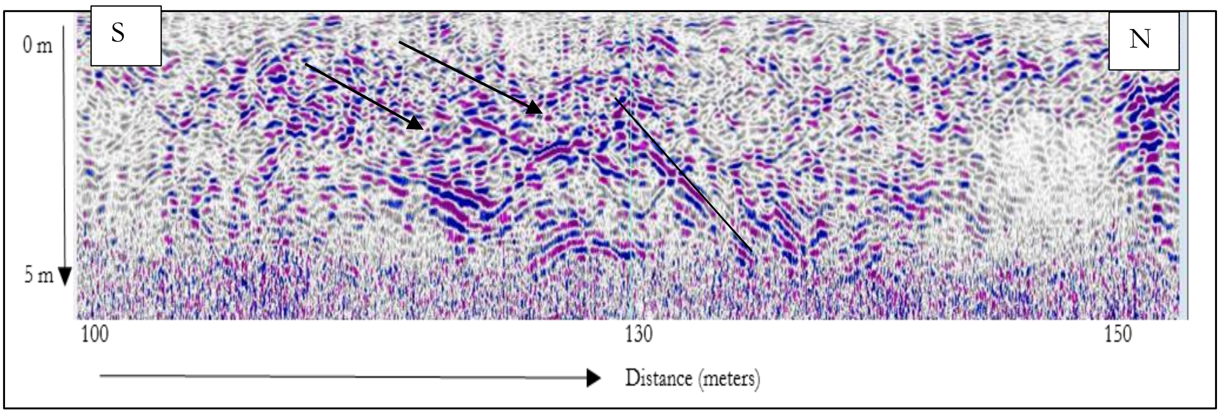



Figure A-3: The Bhauwala profile taken from south to north. Though some north dipping signatures are found, it is not conclusive evidence of any faulting.

BHARLI

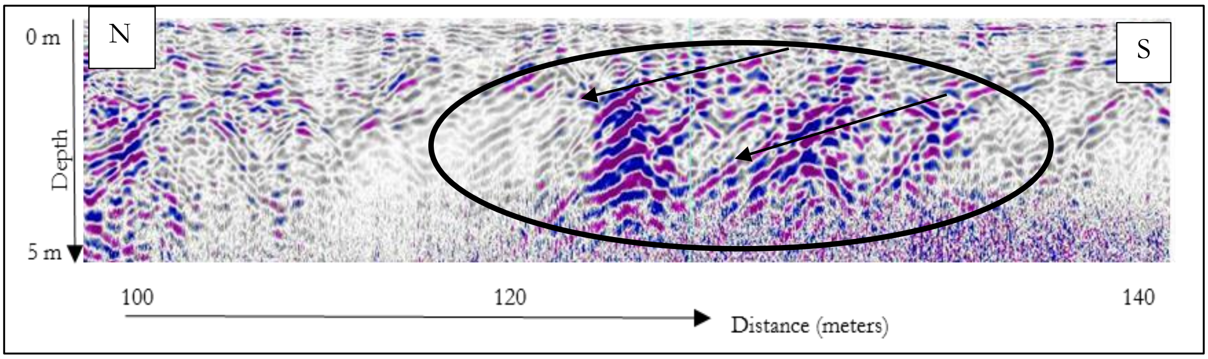



Figure A-4: The dipping reflectors also observed in the reverse profile taken from north to south indicating a north dipping fault

KHAJNAWARA RAO (HIMLAYAN FRONTAL THRUST)

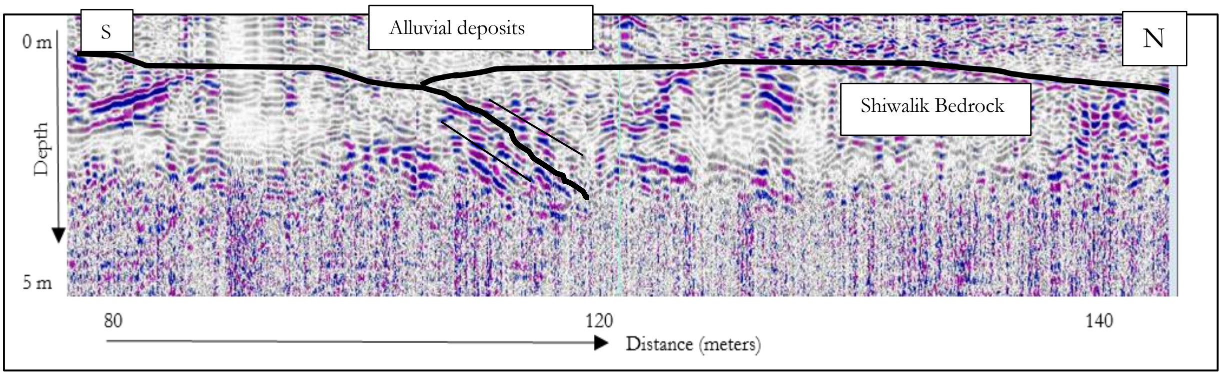



Figure A-5: The possible minor imbricate of the HFT which is north dipping observed along the profile with the alluvial deposits overlying the Shiwalik Bedrock.

SINGHAULI

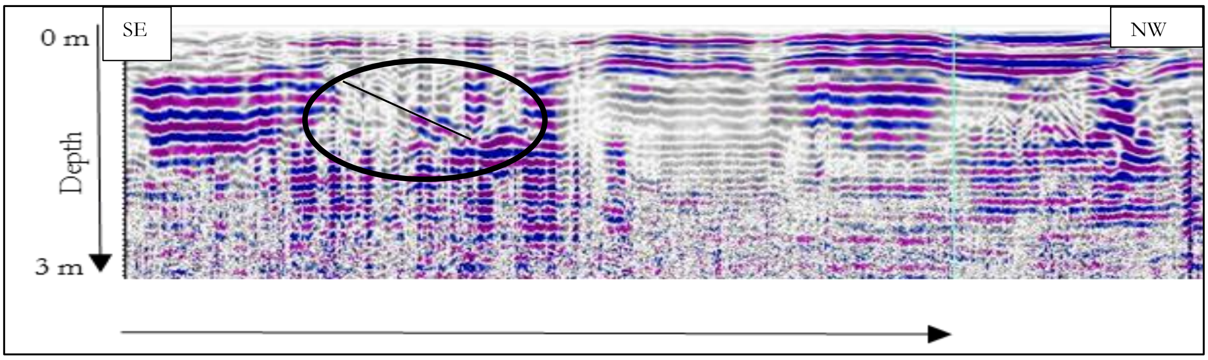



Figure A-6: The possible liquefaction feature observed due to the break in the reflectors at Singhauli.

PAST EARTHQUAKE CATALOGUE (WITH REFERENCES OF) THE STUDY AREA USED TO PREPARE THE SEISMICITY MAP

Table A-1: The table shows the past earthquake data in and around the study area.

| Date | Latitude | Longitude | Depth | Magnitude | Type | Region | Source |
|---|---|---|---|---|---|---|---|
| **2/1/1997** | 30.536 | 77.844 | 33 | 3.5 | Mb | HARYANA - UTTARANCHAL REGION, INDIA | USGS/NEIC |
| **3/5/2010** | 30.27 | 78.314 | 13.5 | 4 | Mb | UTTARANCHAL, INDIA | USGS/NEIC |
| **5/7/2013** | 30.6 | 77.8 | 9 | 3 | Ml | CHAKRATA (DEHRADUN), UTTARAKHand | IMD* |
| **9/14/1996** | 30.748 | 78.307 | 33 | 4.8 | Mb | UTTARANCHAL, INDIA | USGS/NEIC |
| **8/16/2008** | 30.185 | 77.836 | 10 | 3.8 | Mb | HARYANA - UTTARANCHAL REGION, INDIA | USGS/NEIC |
| **2/20/2005** | 30.655 | 78.243 | 25 | 3.5 | Mb | UTTARANCHAL, INDIA | USGS/NEIC |
| **11/26/2004** | 30.676 | 77.2 | 42.1 | 3.7 | Mb | HARYANA - UTTARANCHAL REGION, INDIA | USGS/NEIC |
| **12/26/1988** | 30.611 | 77.981 | 33 | 4.2 | Mb | HARYANA - UTTARANCHAL REGION, INDIA | USGS/NEIC |
| **26/12/1988** | 30.58 | 77.92 | 0 | 4.2 | Ml | Chakrata, dehradun-uttarakhand | S.T.G. Raghukanth (2010) |
| **25/03/1869** | 30.5 | 78 | 0 | 5 | Ml | tehri-Uttarakhand | Oldham, T. (1883). |
| **31/03/1852** | 29.92 | 77.83 | 0 | 6.2 | Ml | Roorkee, haridwar-Uttarakhand | W. M. Szeliga (2010) |

IMD*: Indian Meteorological Department.

REFERENCES:

Raghukanth, STG 2010, 'Estimation of seismicity parameters for India.' *Seismological Research Letters*, vol. 81, no. 2, pp. 207-217.

Oldham, T 1883, 'Catalogue of Indian Earthquakes from the Earliest Time to the End of AD 1869.' Geological Survey of India.

Szeliga, WM 2010, 'Historical and modern seismotectonics of the Indian plate with an emphasis on its western boundary with the Eurasian plate.' PhD diss., UNIVERSITY OF COLORADO AT BOULDER.