Chapter 2

Literature Review and Methodology

The shaking of earth crust generally termed as earthquake. It is one most disastrous natural hazard, which has the capability to induce the huge loss of life and destruction on one big scale. Indian plate is one of the complexly deformed parts in the world which had also become the source of various devastating earthquakes on the past and percent also. (Rajendran and Rajendran, 2004). The existing zoning map has several limitations though it provides some basic information on the relative seismic potential of different regions of the country. The history of earthquake recording and the historical documentation itself are too short to represent the long-term activity of the faults. Earthquakes occur rarely in intra-plate settings and most of the archean cratons in the earth were earlier considered as stable (Johnston and Kanter, 1990). Considering the variable recurrence intervals on different faults in intraplate settings, earthquakes are occurring in unexpected locations.

Identification of the potential source zone or active faults in an area is the first step in the direction seismic hazard assessment. It becomes difficult, as the majority of the faults are either hidden, or don’t have produced recognizable deformation in recent geological formations. Peninsular India, having low rates of deformation coupled with the high erosional activity, as well as lack of reliable instrumental seismological data for strong earthquakes, is a challenge to the identification and characterization of active faults. However, there are instances that geomorphic analysis played an effective role in identifying the potential seismic source zones. In evaluation or classification of a fault in an area, as active/potential/inactive, fault geometry, geologic age, morphotectonic signature and relation with ongoing seismicity records plays a key role.

2.1 Active Fault Studies

The investigation and characterization of the active faults has started in 1916. The first definition of the active fault was given by Wood and termed it as “Living zones of geological faulting” (Wood, 1916). This definition was modified by Willis with the addition of two classes of fault, i.e., Alive and Dead (Willis, 1923). Louderback (1937; 1950) had come up with the characterizing the active fault which has shown deformation
in all the formations including the quaternary, induced changes in topography, and has a record of movement associated with earthquakes in the recent time. If these observations are negative it may be considered as inactive or dead. Schultz and Cleaves (1955) suggested that the fractures which have shown displacements in the marker beds within the historic times, and which also has the accurate seismic record, should be considered as active fault. If the underlying fault did not show any displacement in the overlying younger strata it should be considered as inactive.

Terefethen (1959) based on his studies done in the upper part of the crust in North America, has termed fault as live if the displacement has occurred within historic time. If there is no slipping observed, it should be considered as dead.

For the next half a decade the above definitions and classification have been used in the characterization of active faults. Further modifications in defining and characterizing the active fault were initiated by Sherard (1963). In his book “Earth and Earthrock Dams”, he defined that if any clear displacement or indication of displacement is observed along a feature in either historic or geological time, it should be considered as active fault. He also stated that if there is no sign of having been active in recent geological time, it should be termed as dead.

Cluff (1964) based on his studies carried out in dam foundations, suggested that if a fault has shown conclusive evidence of movement in the recent geological time by cutting recent sediments such as alluvium, alluvium fans or seismic record (epicentral plot along the fault) is called an active fault. In the same period Allen (1965) on the basis of the outcome of his study in southern California for the relationship between seismicity and geological structure supported the above definition for the active fault. He stated that in absence of historical seismic record, only geological criteria should only be taken into consideration.

Studies done by Albee and Smith (1966) on the earthquake characteristics and fault activity in southern California suggested that different faults show different extent of activity along them, and they classified the earthquakes into active, moderately active, slightly active. Based on the deformation associated surface features, seismic records and geodetic evidences, this classification is done. They emphasized that “geological
evidence monitors a fault over a time period 100 or more times as long as the accurate seismic and geodetic record”.

Studies were done on the surface rupturing associated with the faults in United States and Mexico by Bonilla (1967; 1970), and he first time attempted to fix the time period in geological time scale for characterizing the active fault. He stated that any fault which has shown activity in Holocene Epoch (10,000 years, approx.) should be considered as active. He also attempted to fix the criteria for the investigations related to active fault, i.e., accuracy in assigning a seismic event to a fault, identification of episodes of rupturing, elastic and inelastic strain evidences, and structural component.

International Atomic Energy Agency (1968) for the safety of the nuclear establishments from the active faults, had made a conclusive study and compiled all the information for the characterization of active faults. They emphasized on gathering the information on how the fault has moved recently and how often it had moved in the past. In addition to that, the regional seismological, geodetic and geological considerations should be taken into account for calling it as active. They further emphasized that along with the main fault, the associated branches of the fault should also be studied for a proper assessment.

Based on the observation made by Cluff and Bolt (1969) with their earthquake risk assessment study done in San Francisco Bay area, suggested that “A fault should be considered active if it has displaced recent alluvium or other recently formed deposits, whose surface effects have not been modified to an appreciable extent by erosions, which has earthquakes located in the near vicinity and whose recurrence of movement is expected”.

Wentworth et al. (1969) in their report made on the seismic environment around Ventura County, California, explained that the present tectonic settings are the cause for a fault to become active, and the fault can undergo repeated movement from time to time. It was further emphasized that understanding the regional tectonic settings only depends on the geologist’s efficiency (Wentworth et al. 1970).

US Atomic Energy Commission (1971), to make their nuclear establishments safe from active sources, has given three major guidelines for the characterization of active fault. It states that a fault which exhibits a) movement or surface rupture at least once in
35,000 years or more than once in the past 50,000 years; b) well determined macro seismic activity along it; and c) coherency between the a & b condition, then it should be considered as active.

Subsequently, the International Atomic Energy Agency (1972) concluded that if a fault is associated with creep movement and topographic evidences of surface rupture, offset and warping, then it should be considered as active. They have further divided the active faults into four classes on the basis of geomorphology, viz. a) class A- High rate of movement, greater than 1 m per 1,000 years; b) Clear evidences of topographic dislocation; c) Indistinct evidences of topographic dislocation; d) No evidence of amount or rate of dislocation on which quantitative assessment can be based, but the fault is considered capable of causing surface faulting.

Wesson et al. (1972), based on his seismic zonation studies carried out for San Francisco Bay area, attempted for refining the criteria for the identification of potential faults. The criteria includes historic or current seismicity, deformation in Holocene sedimentary deposits, structural geologic evidence of displacement in quaternary time and geophysical anomalies suggesting the displacements in buried bedrock coincident with anomalous distribution of surface deposits.

<table>
<thead>
<tr>
<th>Era</th>
<th>Geologic Age</th>
<th>Years Before Present</th>
<th>Fault Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Quaternary</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Historic (Calif.)</td>
<td>200</td>
<td>Active</td>
</tr>
<tr>
<td></td>
<td>Holocene</td>
<td>10,000</td>
<td>Potentially Active</td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>1,650,000</td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>Pre - Pleistocene</td>
<td>65,000,000</td>
<td>Inactive</td>
</tr>
<tr>
<td>Pre - Cenozoic time</td>
<td></td>
<td>4,500,000,000</td>
<td></td>
</tr>
<tr>
<td>Age of the earth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2.1 Classification of the Active Faults after California State Mining and Geology Board, (1973). (Keller and Pinter, 1996).
Based on the above time to time modifications in the definition and the characterization of the active faults, Association of Engineering Geologists, California (1973) had come up with a broad classification of active faults in which all the faults fall in three categories, viz. Active, Potentially Active and Inactive with respect to the geological time scale (Fig. 2.1). As per this classification, those faults which have shown historical activities along it will be considered as Active faults. Those faults which do not have any known historical or seismological record but having strong geological indication of recent faulting are considered as potentially active. This category is further divided into two. The first group incorporates those faults which have affected the Holocene deposits (age less than 10-11 ka), strong geomorphic expression, induced ground water anomalies, occurrence of micro seismic activity along them - these are termed as high potential. The second group incorporates those faults which have shown the activity same as the first group, except for occurrence of micro seismic activity along the feature and indication of movement in Pleistocene deposits (less than 1,650,000 years ago) - these are termed as low potential. Those faults which do not show any activity in Holocene and Pleistocene offsets are termed as inactive faults.

Later the Division of Mines and Geology, California, had given a definition for the Active faults as: “Active faults are those faults which have had surface displacement within Holocene time (about the last 11,000 years). Such faults are considered as active and hence as constituting a potential hazard.” (Mines and Geology Department California, 1976). As per this definition any fault which has shown the signature of slipping in the present tectonic regime and likely to repeat it again in future is termed as active fault. The historical, geological, seismological, geodetic, and geophysical evidence of activity should also be taken into consideration.

During 1973 to 1976 many other researchers attempted to make modifications in the classification and the definition of active faults to provide a greater safety factor (Grant Taylor et al. 1974; Nichols and Buchananbanks, 1974; Wesson et al. 1975). However the 1973 classification given by the Association of Engineering Geologists, California and the 1976 definition given by the Division of Mines and Geology, California, are widely used to characterize the faults in the three categories of Active, Potentially Active and Inactive Faults.
2.2 Application of Geomorphic Analysis

The study of tectonic geomorphology increasingly in last few decades, has develop into a main tool in the evaluation of active tectonic elements (e.g. Keller and Pinter, 1996 and references therein). The morphology developed by the tectonic features or morphotectonics, in general, explores the interrelationship of climatic, tectonic, erosion-deposition process and other surfacial features (Caputo and Pavlides, 2008). Tectonic geomorphology indicates an amount of interaction between surfacial & tectonic processes and also the control of climatic conditions over them (Bull, 1991). Numerous geomorphic indices are formulated for quantitative assessment of the tectonically active area (Peters and Van Balen, 2007; Bull and McFadden, 1977; Keller and Pinter, 2002; Burbank and Anderson, 2001). Certain quantitative parameters have also been identified by the researchers which can be directly used in the categorization of an area as being Very Active, Moderately Active, or Inactive. This kind of classification will become more useful in figure out the locations in which more intense field activities can identify the active structure and also the prevailing rates. However identification of active faults in areas having low relief and low seismicity is very difficult and only a few applicable methods exist. In the present study both conventional morphometric parameters and geomorphic indices has been used for the evaluation of the study area.

2.2.1 Conventional Morphometric Parameters

The term Morphometry indicates the measurement of shape. Basin morphometry is the quantitative analysis of the drainage basin of a fluvial system. This method of quantitative analysis of drainage basin was first introduced by Horton (1945) followed by Strahler (1952) in the field of hydrology. Though four different systems of classifications for stream ordering are proposed by Jackson (1834), Gravelius (1914), Horton (1945), Strahler (1952) and Schidegger (1970), the one put forward by Horton was widely accepted. Horton (1945) system later had been modified by Strahler’s (1952) to make the classification simpler. In that system, the unbranched, smallest drainage is termed as 1st order. Two 1st order by joining will form a 2nd order drainage. Two 2nd order by joining will form a 3rd order drainage and so on. At the joining of two different order drainages, the higher order remains.
The basic principle behind morphometry is based on the points that landforms developed due to the physical processes and the control of such processes over their shape and geometry. A number of researchers have utilized this method throughout the world to study the Morphometric characteristics of various basins and sub basins (Kumar et al. 2000; Horton, 1945; Strahler, 1952; 1957; Leopold and Miller, 1956; Shreve, 1966; Abrahams, 1984; Reddy et al. 2004; Altin and Altin, 2011; Krishnamurthy et al. 1996;). Geomorphic variables like bifurcation ratio (Schumm, 1956), drainage density (Horton, 1945), constant of channel maintenance (Schumm, 1956), basin relief (Schumm, 1956), Ruggedness number (Schumm, 1956), Circularity ratio (Miller, 1953), relief ratio (Schumm, 1956), Elongation ratio (Schumm, 1956), Form factor (Horton, 1945), have been utilized to the quantitative and qualitative analysis of land forms.

By studying the drainage system and its pattern qualitatively and quantitatively, a quick judgment is possible on active tectonics in an area (Keller and Pinter, 2002). Quantitative measurements of drainage network are also used as a reconnaissance tool to make inferences about relative tectonic activity (e.g. Cox, 1994; Keller and Pinter, 1996). Work done by many of the researchers such as Deffontaines et al. (1992) in Morocco, Simoni et al. (2003) in Northern Apennines, Delcaillau et al. (2006) in Siwalik foot hills, Ramasamy et al. (2011) in southern India, enumerates various methods of analyzing the drainage pattern and the associated anomalies as evidences of active tectonics. Various parameters of Morphometric analysis have also been employed to delineate the tectonic activities in Zaire basin (Deffontaines and Chorowicz, 1991), Wheeler ridge, California (Talling and Sowter, 1999), Northern Apennines (Simoni et al. 2003), Ladakh batholith, India (Jamieson et al. 2004), Arunachal Himalayas, India (Devi et al. 2011), Tibetan Plateau (Zhang et al. 2006), and Palaghat gap, India (John and Rajendran, 2008).

2.2.2 Geomorphic Indices
Various studies carried out throughout the globe have documented that the changes in geomorphology such as change in landscape and evolution of fluvial system induced by the tectonic activities, can be identified through careful evaluation of the geomorphic indices. The geomorphic indices Asymmetry Factor (AF) (Fig. 2.2 A), Transverse Topography Symmetry Factor (T) (Fig. 2.2 B), Mountain front sinuosity ($S_{mf}$) (Fig. 2.2C)
River sinuosity index (SI) (Fig. 2.3 D), Valley floor width Valley height ratio ($V_{f/w}$) (Fig. 2.2 E), etc. are some of the examples (e.g. Bull and McFadden, 1977; Seeber and Gornitz, 1983; Gregory and Schumm, 1987; Wells et al. 1988; Rhea, 1993; Demoulin, 1998; Burbank and Anderson, 2001; Keller and Pinter, 1996; McCalpin, 1996; Malik et al., 1996).
Attempts have been made by the researchers to classify the value of the $V_f$ and $S_{mf}$ in relation to the active tectonics. Based on their studies Bull and Macfadden (1977) have given a classification for the correlation of the values and the tectonic activity (Table 2.1). A number of researchers have used this classification and have proved its effectiveness in the evaluation of ongoing tectonic activities, in different tectonic settings eg. South west of United States of America (Bull and McFadden, 1977; Rockwell et al. 1984), Oregon Coast Range, USA (Rhea, 1993), Western India (Sohoni et al. 1999), southeast Spain (Silva et al. 2003), NW Himalaya, (Malik et al. 2007), eastern Betics, SE Spain (Giaconia et al. 2012), Aksehir fault,SW Turkey (Topal et al. 2016), Costa Rica (Wells et al. 1988). The studies carried out along the north and south of the Garlock fault found this $V_f$ ratio has got the values ranging from 0.05- 47 and the lower values was associated to the area where more vigorous activity was assumed (Bull and MaFadden, 1977; Keller and Pinter 1996). Studies carried out in the Pacific Coast suggests that the low $V_f <1.0$ along narrow valley across mountain fronts and $> 1.0$ along the broader valleys (Wells et al. 1988). The study done in the Betics in SE of Spain have suggested a classification i.e low $V_f$ values <1.0 indicates the active uplift, and high $V_f$ values >1.0 indicate major lateral erosion (Silva et al. 2003). This classification is being used recently for the quantitative assessment tectonic activity (e.g. Pedrera et al. 2009; Giaconia et al. 2012; Topal et al. 2016; Pérez-Peña et al. 2010).

Table 2.1 Classification for Values for Mountain Front Sinuosity

<table>
<thead>
<tr>
<th>S. No</th>
<th>Range</th>
<th>Status</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1-1.4</td>
<td>Tectonically Active</td>
</tr>
<tr>
<td>2</td>
<td>1.4-3</td>
<td>Less Activity</td>
</tr>
<tr>
<td>3</td>
<td>3-5</td>
<td>Inactive</td>
</tr>
</tbody>
</table>

The method of quantitative assessment of sinuous pattern of drainage courses was introduced by Leopold et al. (1964). Zamyoli et al. (2010) have identified the neotectonic features by making a comparison of sinuosity distribution, in the Hungarian plate. In addition to ‘AF’ and ‘T’ have also been used effectively by John and Rajendran,
(2008), for the identification of the structural feature inducing the basin tilt and drainage migration.

2.2.2.1 Pattern Study

The changes in the fluvial systems in an area occurred in the past can be identified from proper understanding of the present day drainage pattern; it also helps in better understanding of deformational events occurred in the past along the mountain fronts (Friend et al. 1999). Many researchers, based on various conceptual models followed by their field investigations, have proposed that evolution or change in the landscape and fluvial system in a tectonically active area is directly controlled by the fault growth and associated deformations (Delcaillau et al. 1998; Friend et al. 1999; Burbank and Anderson, 2001; Van der Woerd et al. 2001; Gupta, 1997; Champel et al. 2002; Hitchcock and Kelson, 1999;).

Fig. 2.3 A) In Natural Setting the River Tend to Keep the Channel Slope Constant (Ouchi, 1985; Timar, 2003). B) Possible Model for Channel Pattern in Case of Normal Faulting. C) Possible Model for the Channel Pattern in Case Of Reverse Faulting. D) Possible Model for Channel Pattern in Case of Strike Slip Faulting.

Geomorphic evaluation is the a possible method for the analysis of alluvial river dynamics for identification of active faults (Ouchi, 1985). Studies suggest that even the smallest changes in topography affect the sinuosity of low gradient rivers (Holbrook and Schumm, 1999), and can help in the identification of ongoing topographic changes at
micro levels also. Under a given set of stable tectonic conditions, alluvial rivers tend to evolve as single meandering channels (Zámolyi et al. 2010). If this behavior is influenced by tectonic movements, it is expected to be reflected in river channel parameters. Within a given range of channel gradients, the meandering pattern changes, as vertical tectonic movements influence the valley slope. This process is largely independent of river size, once the fluvial system enters the meandering stage (Zámolyi et al. 2010). Such kind of geomorphic features can be utilized to know about the tectonic history of an area (Be´s de Berc et al. 2005).

In general the fluvial system responds to the tectonic activities and reflects either by the change in longitudinal or cross section profiles. The effect can also be seen either as the change in the drainage pattern or load discharge of the river. Numerous studies done over the alluvial river e.g San Joaquin River, California, The San Antonio and Guadalupe Rivers in Texas have documented the change in the channel pattern as an effect of the vertical crustal movements (Ouchi, 1985; Jogensen, 1990; Hollbrook and Schumm, 1999). Whenever the change in the slope of the valley crosses the equilibrium conditions, it results as the change in channel pattern, meandering, irregular, linear channel pattern. Studies done along the gangetic plains for the channel pattern suggest that if condition allows a meandering stage in a river, change in intra pattern result in the enhancement of its sinuosity. (Friend and Sinha, 1993).

In a tectonically active area, growth of fault and its propagation indicates the complex accumulation of the slip occurred in several major earthquakes on fault planes (Walsh et al. 2002), as a result of which changes in the fluvial system occur such as drainage deflections. Alluvial rivers, in general, tries to keep its slope in the equilibrium but if any tectonic activity such as fault folding etc influences; it may result in the change of sinuosity (Fig. 2.3 A). There will be an increase in the linearity of the channel in upstream across a normal fault while in downstream down throwing of faults induces the increased sinuousity (Ouchi, 1985; Keller and Pinter, 1996; Hollbrook and Schumm, 1999; Timar, 2003; Bridge, 2005) (Fig. 2.3 B). In case of reverse fault the upstream direction causes the increase in meandering while downstream faults results in the straightening of the channel (Fig. 2.3 C). While in the strike slip faults in general slope of the river remained unchanged in either block, but the offsetting or straitening of the
channel occurs along the lineament, fault or controlling tectonic unit, till the drainage flow along it (Fig. 2.3 D). All these features influence the river course and that changes can be investigated as a change in the river sinuosity.

2.3 Delineation of Lineaments

The concept of lineaments was first proposed in Great Britain during 19\textsuperscript{th} century for systematic mapping fractures. Hopkins (1841) was first who prepared a lineament map that described the relation between the structural and topographical features. This systematic mapping of fractures was incorporated in topographic maps during geological mapping (Daubree, 1879) and also in geomorphological maps of south and central Norway (Kjerulf, 1880). The outcome of the study by Kjerulf (1880) was reinterpreted by Hobbs (1912), who had come up with a definition of the lineament i.e., “Significant lines in the landscape which reveal the hidden architecture of the basement”. Time to time this definition has been refined on the basis of the length, spatial density, distribution and contacts (Hills, 1972; Hobbs et al. 1976; Ramsay and Huber, 1987). Oleray and Friedman (1978) reviewed the past works for characterizing the lineaments and came up with a classification of lineaments. In this classification the linear features have been divided into three classes, i.e., Lineaments, Alignment and Line.

Though the accuracy of the lineament maps made using the conventional field mapping techniques has improved, there were limitations. It is very difficult to demarcate all the lineaments in an area of larger extent using conventional field mapping techniques (Süzen and Toprak, 1998). Aerial photo was first utilized by Latterman (1958) for mapping of the lineaments. He noticed that the resolution of the structure and the area covered in photo plays a key role in the demarcation of the lineaments. However, due to lack of continuity, an aerial photographic survey is also unable to define the continuity of the lineaments having regional/ larger extent (Süzen and Toprak, 1998). Since the satellite images have relatively high coverage and resolution than any other data/method, they are utilised in the lineament analysis (Süzen and Toprak, 1998).

Identification of the lineaments is the preliminary information required in the field of active fault studies and have been employed globally in different tectonic setups such as around NW-SE extension of Pambek-Sevan – Syunik fault Armenia (Ritz et al. 2016),
Weihe Graben, Central China (Lin et al. 2015), Geuondeok fault, South Korea (Choi et al. 2015), South Wagad Fault, Kutch India (Kothyari et al. 2016), Weihe Graben, Central China (Rao et al. 2015), Eastern Betic Cordillera, Jumila fault zone, Spain (Balén et al. 2015), Aksehir fault, SW Turkey (Topal et al. 2016), Western Gangetic planes, India (Bhosle et al. 2007), California Volcanic table land (Geothals et al. 2016), SE Portugal (Silveira et al. 2009), Palghat gap, Peninsular India (John and Rajendran, 2008), Baikal rift system Siberia (Lunina et al. 2008), Eastern Beltics, Spain (Giaconia et al. 2012), Southern Italy (Bucci et al. 2013), Northern Italy (Naccio et al. 2013), Gowk fault Iran (Fattahi et al. 2014), Italy (Cultera et al. 2015), Turkey (Gürbüz et al. 2015) etc.

Generally the method for identification of lineaments using remote sensing can be divided into two categories, viz., visual extraction and automatic extraction. Though many of the authors advocate the automatic extraction method, lineament analysis using visual extraction method is still more reliable (Ricchetti and Palombella, 2005). This method is more efficient in discriminating human precipitation from geological lineaments in urbanized areas. (Ricchetti and Palombella, 2005). In the present study visual extraction method has been applied for the delineation of the lineaments.

2.3.1 Visual Extraction

Initially satellite images were studied through hard copies. In later stages images were studied in digital form through image processing software. Plenty of studies carried out at different places have done extraction of the lineaments from the satellite images and aerial photos by manual extraction/digitization, e.g., Benue valley and Jos plateau, Nigeria (Koopmans, 1986), Cambay basin, India (Majumdar et al. 1988), Northern Territory, Australia (Mah et al. 1995), engineered underground structures, USA (Kane et al. 1996), NW Peninsula, Malaysia (Mat Akhir and Abdullah, 1997), Central Turkey (Süzen and Toprak, 1998), Greece (Novak and Soulakellis, 2000). The image processing software provide many image processing tools to enhance the image for interpretation. These methods also involve the directional (Principal Component Analysis) and non directional filters such as, contrast stretching, Laplacian, and Sobel to visually enhance the lineament data. After image enhancement, the lineaments can be extracted through manual digitization.
Recently, the availability of multispectral data provided a unique way to study at least three spectral bands of choice to study by making a false color composite. Along with enhancement of the data, manual extraction of lineament method is still being widely followed, such as the studies done in Duero basin, Spain (Cortes et al. 2003), Coastal Cordillera, Northern Chile (Leech et al. 2003), ground water exploration in developing countries (Minor et al. 1994), Boktukola Mountains (Williamson, 2003), Northern Vietnam (Won-In and Charusiri, 2002).

The above methodologies have also been used in locating brittle deformation zones, for recognition of the type of fault and for identification of tensile fractures, by many researchers (Ramsay and Hubert, 1987; Keller and Pinter, 1996; Burbank and Andersson, 2001; Nur, 1982).

2.3.2 Automatic Extraction
There are many studies which utilized the automated method for extraction of the lineaments from the remote sensing images. Hough Transform, Haar Transform, START, Canny, EDISON, Segment Tracing Algorithm and Rotation Transformation – these are being utilized for the enhancement of lineament data (Wang and Howarth, 1990; Majundar and Bhattacharya, 1988; Koike et al. 1995). Automatic extraction of lineaments can be cost-effective and time-saving when investigating large areas (Tiren, 2010). Such programs basically work for shape recognition and lineament extraction. There is the possibility of extracting man-made linear features as lineament while using the automatic extraction technique. Thus, it is very necessary to test the efficiency of this methodology for extraction of lineaments in the study area (Tiren, 2010). In the present study this method has not been used for the extraction of lineaments.

2.4 Fault Zone Characterization
In crystalline terrains, in upper part of crust (depth up to 11 km), the fault related deformation is dominated by cataclasis, which involves the brittle fragmentation of mineral grains with rotation of grain fragments accompanied by frictional grain boundary sliding and dilatancy (Fig. 2.4). Attempts have been made by the researchers to identify such potential faults in the shield areas with the incorporation of bed rock geology (e.g. Dawers and Seeber, 1991; John and Rajendran, 2009). Brittle fault zones generally develop by the
progressive incorporation and amalgamation of newly formed and pre-existing subsidiary shears and fractures of varying size and orientation (John and Rajendran, 2009). Due to the rupturing along the rocks during faulting, first it will produce breccias and then a fine grained material, which is the part of rock itself and called as gouge.

The mineralogy of the source rock is remains as preserved though the gouge get changed to clay obliterating the relation between chemical and mechanical processes in different environments (e.g. Anderson et al. 1983; Mawer and Williams, 1985), and this provides clues for distinguishing the all the changes that gouge undergoes as it is produced. In brittle faults movement and principal stress directions can be determined from a careful study of slickensides (Marshak and Mitra, 1988). Wells and Coppersmith (1994) work out an empirical relationship from 167 earthquakes, between moment magnitude (Mw) and surface rupture length, average displacement, etc. Several studies used these relations to find out earthquake potential from field based data (e.g., John and Rajendran, 2009). Such studies further show that the amount of fault movement and surface rupture length can be determined from fault related field data (Engelder, 1974; Scholz, 1990).

The brittle fault zones in crystalline bedrocks, in general consists of a major slip plane bounded by a zone of fractured rocks, and thus three types of lithologies can also
be distinguished in the exposure, namely, 1) protolith or host rock, 2) damage zone, and 3) fault core (Fig. 2.5) (John and Rajendran, 2009).

2.3.3 Host Rock (Protolith)
Protolith is the undeformed host rock (charnockite) surrounding the fault rock and the damaged zone. The relative movement between the hanging wall and footwall will be reflected on the offsets, if there exists any marker bed/s (John and Rajendran, 2009).

2.3.4 Damage Zone
The damage zone consists of a network of fault-related subsidiary structures that bound the fault core. The fault-related subsidiary structures in the damaged zone include small offsets, veins, fractures and cleavages (Bruhn et al. 1994; John and Rajendran, 2009). The damaged zone will be characterized by fractures of varying orientations. These fractures can be filled with secondary minerals depending on the age of the fault close to the gouge zone, the material may also be injected into fracture zone. It should be noted that occurrences of similar veins were reported in Nagano Prefecture, Central Japan (Lin, 1997)

![Fault Zone Architectural Components](image)

Fig. 2.5 Model of Fault Zone Architectural Components, after Craine (1996).
where the gouge veins are interpreted to have been formed by rapid injection during seismic slip. This injection might have resulted from the fluidisation of fault gouge during seismic faulting (Otsuki et al. 2003; John and Rajendran, 2009). The slicken lines within damage zones can indicate the sense of movement (Fig. 2.5). From the complex array of movement planes deduced from the slickenlines, the principle stress directions during the time of faulting can be determined (Anderson, 1942; Marshak and Mitra, 1988).

2.3.5 Fault Core

Fault core is the portion of a fault zone where much of the displacement is accommodated (Caine, 1996; John and Rajendran, 2009) (Fig. 2.5). Within the principal slip plane, the host rock will be pulverized to become gouge and the original bulk fabrics completely disrupted. The occurrence of narrow zones accommodating large slips are reported from San Gabriel Fault (Chester et al. 1993) and Punchbowl Fault (Chester and Chester, 1998) of USA and in Nojima fault of Japan (Boullier et al. 2004). The thickness of the gouge zone with in the core can indicate the amount of displacement too (Engelder, 1974; Scholz, 1990; John and Rajendran, 2009).

2.4 Methodology Adopted in the Present Study

Based on the literature review, the present study formulated a methodology for evaluation of active fault, which can contribute efficiently to the characterization of active zones or fault (Fig 2.6). The adopted methodology is represented as a flow chart. In order to investigate the tectonic influence on landforms of the study area, first the lineaments are delineated from multispectral Landsat images. In the initial stages, remote sensing studies had been carried out for identification of the lineaments and other geomorphic anomalies. Geocoded Landsat Thematic Mapper (TM) images (Spatial resolution 30 m), SRTM Data (Spatial resolution 90 m), ASTER GDEM Data (Spatial resolution 30 m), Liss III Data, monochromatic (Spatial resolution 23 m), Cartosat images (Spatial resolution 2.5 m) were utilized for geomorphic analysis of the area. Lineaments are identified by using the visual image interpretation technique like spectral enhancement, band combination and band ratio methods. Image characteristics like tone, texture, shape, size and pattern are also considered for understanding the terrain. Subsequently, the area is divided into sub basins based 3rd and 4th order streams for the morphometric studies. A number of
morphometric variables have been calculated for identification of the anomalies in the fluvial system, which may reflect any subtle deformation in the area. Further, various geomorphic markers, change in which reflects the ongoing tectonic activity, are also analyzed. All basic measurements during the morphometric and geomorphic analysis have been carried out using ARC GIS 9.3.

Based on the anomalies identified in the morphometric and geomorphic studies, field studies have been carried out in those anomalous regions. The field investigations were focused for identification of the structural component responsible for inducing anomalies in the morphometric and geomorphic data. With the collection of all the data, a critical synthesis has been done for identification of the potential seismic source in the study area. Field investigations focused on identification of brittle faults which represent the youngest deformation in the area. The slickensides observed have been used to understand the relative movement of faults as well as the principal stress directions across them.