CHAPTER 5

NEOTECTONICS

The term 'neotectonics' was introduced by Obruchev (1948) who defined it as 'recent tectonic movements occurred in the upper part of Tertiary (Neogene) and in the Quaternary, which played an essential role in the origin of the contemporary topography'. Since then there has been debate on the time period which can be defined as to mark the distinct neotectonic activity. Some authors consider neotectonics to be basically synonymous with 'active tectonics', while others start the neotectonic period from the Middle Miocene. A general agreement has been emerging that the actual time frame may vary in every geological environment. Tectonic movement contemporaneous with the formation of the morphology of the modern river is referred to as "active tectonic movement" (Ouchi, 1985). Pavlides (1989) defined neotectonics as "the study of younger tectonic events which have occurred or are still occurring in a given region after its orogeny or after its last significant tectonic set-up." The neotectonic events are recent enough to permit a detailed analysis by specific methods, while their results are directly compatible with seismological observations. This approach has been accepted by many researchers. Later, the definition was widened to include all tectonic processes since the last major tectonic configuration change, and the establishment of the modern stress field (Hancock, 1986; Slemmons 1991; Stewart & Hancock 1994). The last tectonic event of a region may vary from the other region giving variation in the time span of the neotectonic events in different areas. The neotectonic study has great societal importance in the modern society. Knowledge of the neotectonics of an area is used for seismic hazard studies and to get hold of their mitigation measures, therefore attention is given in acquiring, processing and interpretation of the data. Field evidences of neotectonism are also supported by critical analyses of morphometric parameters. The neotectonic studies essentially calls for a multidisciplinary approach. The importance of multidisciplinary approach by combining structural, neotectonic and morphological data to study the setting of big river basins in relation to geological structures has been found useful in the study of geomorphological evolution of a region (Potter, 1978; Lanzhou and Scheidegger, 1981; Centamore et al., 1996; Scheidegger, 2004).

In the current context of Kachchh basin, the change in the stress regime from extensional to compressive seems to be most important event which is responsible for the present tectonic set up of the area and can be taken as distinct point of time to consider the neotectonic activities.

Kachchh basin has been under great tectonic disturbances since the rifting of the Aravalli-Delhi fold belt of the Gondwanaland in the Late Triassic-Early Jurassic Period (Biswas, 1985). There was reactivation of the pre-existing faults along the NE-SW trend of Delhi Fold Belt that swings to EW in Kachchh region. Several major faults resulted in the Kachchh Peninsula forming the Kachchh rift. According to Biswas (1987) the Indian Continental plate evolved by rifting from the Eastern Gondwanaland in Late Triassic-Late Cretaceous period, followed by northward drift along an anticlockwise path and collision with the Eurasian plate in late Mid-Eocene.

A number of normal faults can be observed in the Mesozoic horizons (Fig. 5.1) indicating the extensional regime up to the time of collision of the Indian plate with the Eurasian plate. Several syn-deformational features are very well preserved in the Mesozoic rocks of the area. A number of penecontemporaneous deformation (PCD) structures are recorded in the sections exposed along the Pur River near Rudramata area which comprise disturbed, distorted or deformed sedimentary layers. These features are supposed to have formed during or shortly after deposition of sediments. The main mechanism of formation of these deformational structures includes sudden sediment loading, gravity induced mass movement, storm impact and seismic shocks (Rossetti and Goes, 2000). They are very important indicators of past seismic activity (Sim, 1973, 1975; Allen, 1975; Sieh, 1978). Generally, such deformation features are of local character, being primarily confined to a single bed within undeformed layers. The PCDs observed in the area can be grouped into convolute beddings, ball and pillow structures and slump structures.

Convolute Bedding: Convolute bedding is a structure showing crumpling or complicated folding of the laminae of a rather well-defined sedimentation unit (Kuenen, 1953; Potter and Pettijohn, 1963). Thus, laminae of primary bedding, foreset laminae of a ripple bedding, etc. show convolutions. According to Rossetti (1999) the folds resulting from convolute bedding are defined as distorted stratifications that form laterally alternating convex and concave-upward morphology. Generally, convolutions show more or less sharp crests alternating with rather broad troughs. Convolute bedding is generally well-developed in fine-grained, non cohesive sediment, such as fine sand or fine silty sand. Several explanations have been proposed for their genesis. Williams (1960) suggested that convolute bedding is produced by differential liquefaction of a sedimentation unit. According to Reineck and Singh (1973), liquefaction of sediment is a most important factor in the genesis of convolute bedding. Liquefaction can be achieved by overloading, by seismic waves, or by some other shock, causing a disturbance in the sediment packing.

In the Pur River section at a locality near the Rudramata Dam, there are at least 6 units in Bhuj-sandstone horizon, each of nearly one meter thickness, showing convolute lamination, mud diapers and slump structures (Fig. 5.2, 5.3).

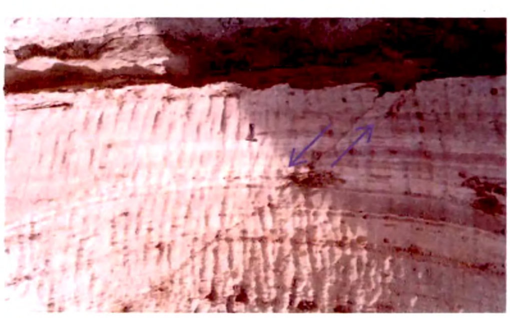

Fig.5.1: Normal fault in the Bhuj Formation.

Fig.5.2: Convolute lamination in Bhuj Sandstones, Pur River section, Rudramata.

Ball and Pillow Structures: The ball and pillow structure is a primary structure, well developed in the Bhuj Sandstone of the Pur River section. Sand layers lying above a muddy layer exhibit the ball-and-pillow structure (Fig.5.4). The sand layer is broken up into several pillow-shaped, more or less hemispherical, kidney shaped, ellipsoidal masses. In size these bodies range from a few centimeters to several meters. These pillows may be slightly connected, or sometimes even completely isolated, floating freely in a muddy matrix. Pillows are generally better developed in the lower part of the sand layer, grading upward into a more or less undisturbed sand layer. The underlying mud layer is usually involved in the deformation. It is partly broken and extends upward into the sand layer, between the pillows, in the form of tongues (Potter and Pettijohn, 1963).

Fig.5.3: Liquefaction induced structure in the Bhuj Formation. Mud is intruding into sand layer; Pur River Section, Rudramata.

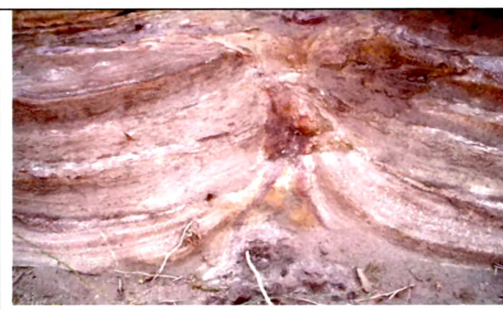

Fig.5.4: Ball and Pillow structure in the Bhuj sandstone; Pur River section, Rudramata.

Slump Structures: Slump structure is a general term which includes all the penecontemporaneous deformation structures resulting from movement and displacement of already deposited sedimentary layers, mainly under the action of gravity. Slump structures are generally formed due to rapid sedimentation. Such regions may be unstable because of greater slopes, type of sediment deposited, or other reasons. Slumping of sediment mass may result a chaotic mixture of different types of sediments, such as a broken mud layer embedded in a sandy mass.

Sand dykes: Sand dykes are recorded from various places around Jawaharnagar and Jhura villages cutting across the Mesozoic sequences (Fig. 5.5).

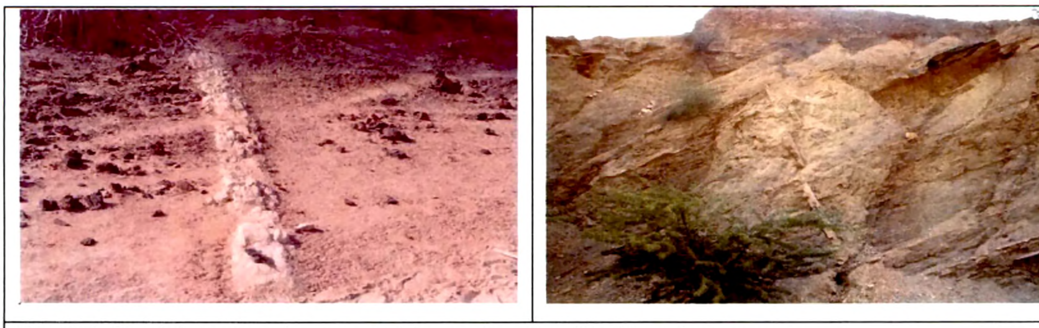

Fig.5.5: Sand dykes cutting across Mesozoics, South of Jawaharnagar.

These are the some of the well documented evidences which are of paramount importance as they provide valuable insight into the tectonism and palaeodynamics of the area.

NEOTECTONISM IN THE AREA

Kachchh region has been seismically active and has experienced number of large magnitude earthquakes in the historic past. Various evidences of neotectonic activity recorded from the area are discussed below.

I. Historical Seismic Records

Kachchh region falls within the seismotectonic zone-V in seismic zonation map of India (Fig.5.6). It has a long history of earthquakes of varying magnitudes ranging from M_L 3.5 to 8. The records of epicenters of earthquakes that occurred in the Kachchh from historic times to 2010 are compiled from various sources like USGS sites, Indian Seismological Research (ISR), IMD and various published literatures (Tables 5.1 and 5.2). They have been plotted over the tectonic map of Kachchh Peninsula (Fig.5.7). Some of the large magnitude earthquakes ($\geq$6) in Kachchh over a period of 182 years are Allah Bund earthquake (1819), Khavda earthquake (1940), Anjar earthquake (1956) and Bhuj earthquake (2001).

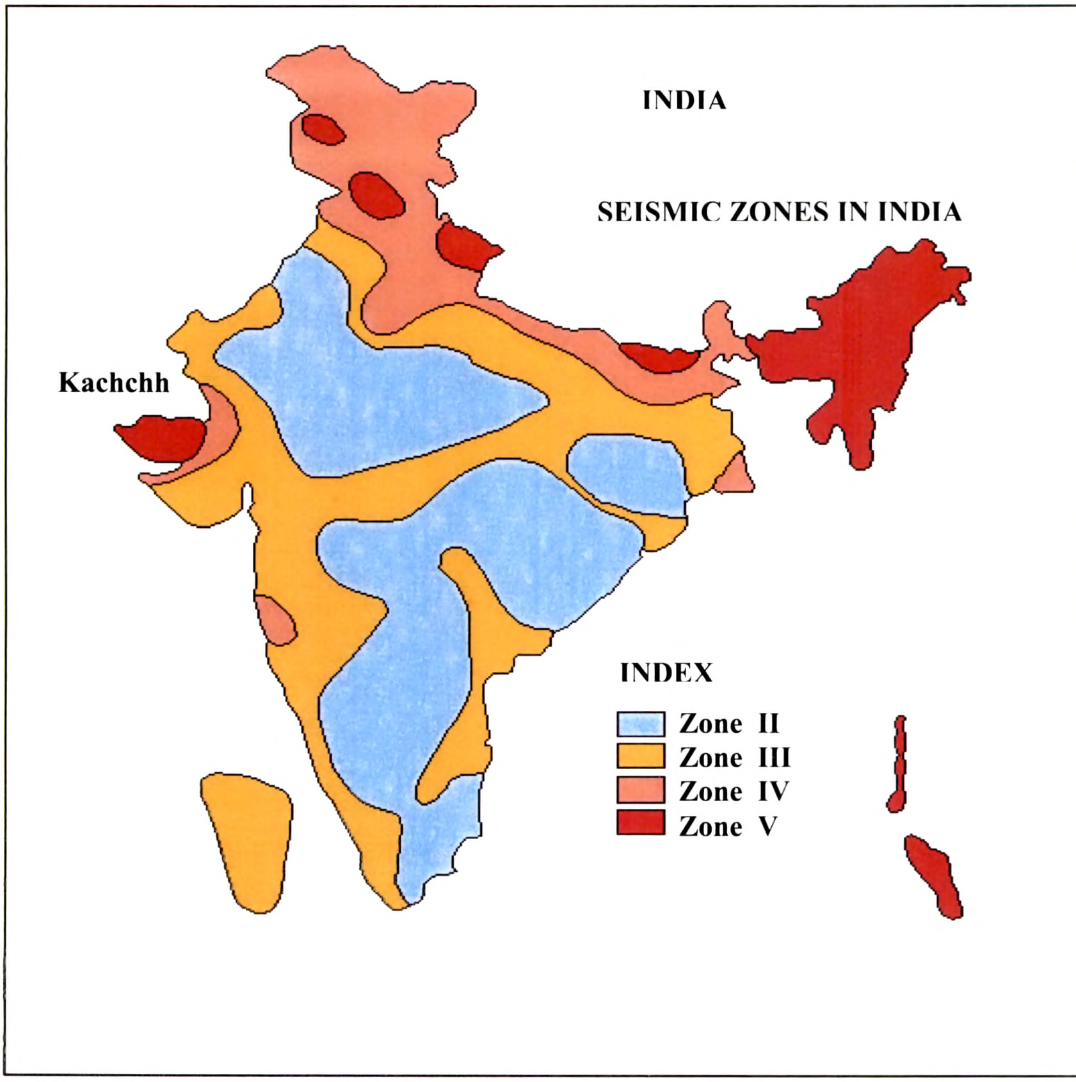

Fig 5.6: Seismic Zones in India (Source: Bureau of Indian Standard).

Table 5.1: Historical Record of Seismological History (modified after Malik, 2001)

Year	**Magnitude**	**Fault**	**Locality**
B.C. 325	>7.0	-	Gulf of Kachchh; tsunami waves partly destroyed Alexander's army anchored at the ancient mouth of the Indus River.
1030	>7.0	IBF	Ruined the city of Brahminabad.
1668	7.6	IBF/KMF	Indus delta in NW of Kachchh (Source: Historical accounts; Burnes (1835)
1819	8.0	IBF	NNW part of Kachchh near the international border
1821	5.0	KMF	Anjar
1828	4.3	KMF	East of Bhuj and Bhachau
1844	4.3	IBF	East of Lakhpat
1845	>5.0	IBF/NPF	East of Lakhpat
1845	6.3	IBF/NPF	East of Lakhpat
1864	5.0	IBF	Greater Rann, east of Rapar
1903	6.0	IBF	Greater Rann
1904	>4.0	KMF	Bhuj
1940	5.8-6.0	NPF	Northeast of Khavda
1956	6.1	KMF	Anjar
1965	5.3	IBF	North of Khavda
1966	5.0	NPF	Northeast of Khavda
1976	5.1	NPF/ABF	North of Allah Bund
1981	4.1	NPF	Greater Rann
1982	4.8	NPF	North of Khavada
1982	4.8	NPF	North of Mauvana
1985	4.4	NPF	North of Bhand
1991	4.7	NPF/ABF	Greater Rann
1991	4.7	NPF/ABF	Greater Rann
1993	4.3	NPF/ABF	North of Allah Bund
1996	4.5	KHF	South of Bhuj
2001	7.6	KMF	Bhachau (east of Bhuj)

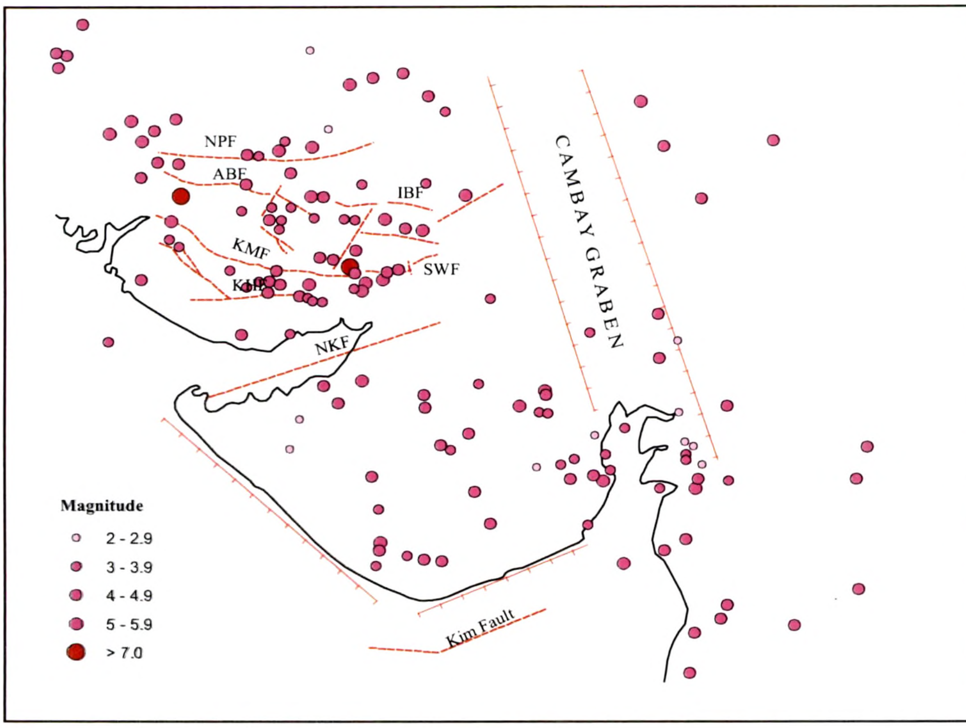

Fig.5.7: Earthquake records of Kachchh region from historic times through 2010 (Source: ISR, 2010).

Table 5.2: Moderate and high intensity earthquakes in Kachchh (ISR, 2010)

Magnitude	No. of shocks Pre-2001 (200 yrs)	No. of shocks since 2001 (9 yrs.)
3.5 – 3.9	46	653
4.0 – 4.9	25	262
> 5.0	10	20

The number of seismic events seems to have increased in the last decade after 2000 as indicated in the Table-5.2. The better instrumentation facilities definitely increased the number due to proper recording of all the events after 2001, nonetheless in the second half of the 19th century most of the earthquakes were recorded. Even the number of earthquakes with magnitude more than 5 increased from 10 in 200 years to 20 in last 10 years. Some of the major earthquakes of the historical times have been described in next section.

The Allah Bund (1819) Earthquake

The 1819 earthquake in Kachchh is one of the most significant events to have occurred in the plate-interior setting (Rajendran and Rajendran, 2004). This is considered to be the second largest earthquake in the stable continental region, in magnitude (M 8), to the New Madrid Earthquake of 1811-12 (Johnston, 1989). Due to this earthquake about 90 km long ridge was formed with a present elevation of up to 4.2 m (Fig. 5.8). This feature is known as 'Allah Bund' meaning mound of God (Burnes, 1835; Baker, 1846; Lyell, 1857). This earthquake had an unprecedented societal impact in terms of destruction of man made structures which led to permanent migration of inhabitants. It not only damaged the flourishing township but also changed the land and fluvial systems, accelerating the desertification processes (Oldham, 1926). The earthquake caused shoaling of the Nara River (also known as Puran) and blocked its access to the sea which was connected to the Arabian Sea through the Kori Creek and used for river traffic (Burnes, 1835). The flourishing delta of the Nara River was transformed into a lifeless mud flat due to this tectonic event.

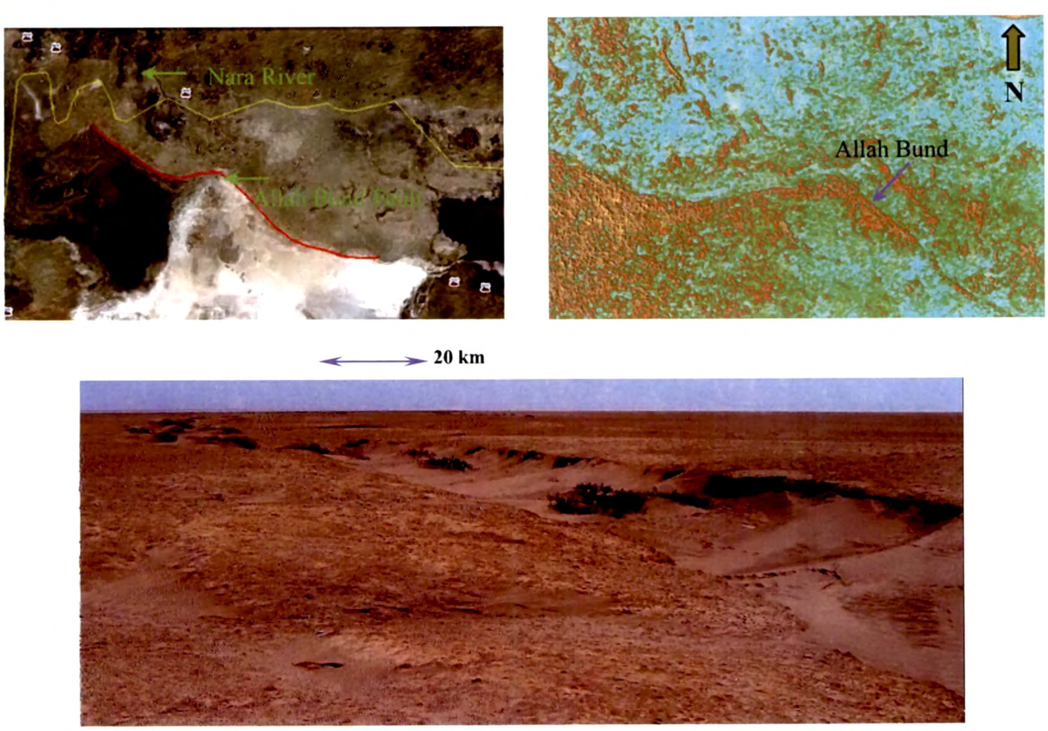

Fig. 5.8: Allah Bund Fault, over Google image (left), visible in the ASTER DEM (right) and field photograph (north of Dharmshala).

The 1819 earthquake induced intense and wide spread liquefaction. MacMurdo (1824) reported that "almost all the rivers have been filled to their banks for a period of few minutes...wells everywhere overflowed..., and in numerous places sports of ground in circles of twelve to twenty feet diameter threw out water a considerable height, subsided into a slough."

This earthquake caused significant changes in the fluvial systems. Frere (1870) reported that in the districts south of Hyderabad (Pakistan), flow in all the channels of the Fullalee River stopped for three days after the earthquake. Liquefaction effected places such as Porbandar, about 250 km south of the Great Rann.

The Anjar (1956) Earthquake

This was a major earthquake after the seismic instrumentation in India. This 6.1 magnitude earthquake, which killed 115 people and injured hundreds more, occurred on one of the boundary faults of the Kachchh rift. Fault plane solution indicates that it originated on a reverse fault dipping 45° N and striking NE-SW direction (Chung and Gao, 1995). No surface deformation resulting due to this earthquake was reported. Reverse faulting interpreted from seismograms of the 1956 Anjar earthquake suggests that ancient normal faults are now being reactivated (Chung and Gao, 1995). This reverse faulting was due to compressional stress regime in the area.

Bhuj earthquake (2001)

The Bhuj earthquake took place at 08:46 AM (local time) on 26th January 2001 during the 52nd Republic Day celebration of India. Indian Meteorological Department (IMD) gave the detailed information about the 2001 earthquake, measuring M_L 6.9 (M_W 7.7, USGS) on the Richter scale and its epicenter lying NNE of Bhuj town near Vondh village (23.40° N, 70.28° E) with a focal depth of 25 km (Kayal et al., 2002; Antoliok and Dreger, 2003; Bodin and Horton, 2004; Mandal et al., 2004; Singh et al., 2004). This was one of the most devastating earthquakes in the history of India which killed more than 19,000 and injured over 160,000 (Jain et al., 2001). About 600,000 were left homeless. The Gujarat State Government estimated loss of about 5 billion US dollars i.e. around Rs 22,000 crores (Jain et al., 2001).

Detailed macroseismic study was carried out in the region by various workers (Ravishankar and Pande, 2001; Wesnousky et al., 2001; Rajendran et al., 2001; Rastogi, 2001; McCalpin and Thakkar, 2003). The isoseismal map of the 2001 earthquake was prepared by Geological Survey of India, which shows the distribution pattern of the intensity of the earthquake (Fig. 5.9). Aftershock investigations were also carried out by various organizations like GSI (2003), India Meteorological Department (IMD) (2002), and National Geophysical Research Institute (2001). International organizations like USGS (Horton et al., 2001; Bodin and Horton, 2004) and ERI, Japan (Negishi et al., 2002), also carried out detailed investigations in the area. All these available data were analyzed to address the seismotectonic implications of the Bhuj (2001) earthquake.

Though, no surface rupture was reported due to this earthquake but coseismic ground fissures and cracks were developed at several places around the Kachchh Mainland Fault. Although the epicenter of the 2001 earthquake is spatially close to the well-exposed Kachchh Mainland Fault, its thrust type focal mechanism immediately ruled out any causal association with this normal fault (Rajendran et al., 2008).

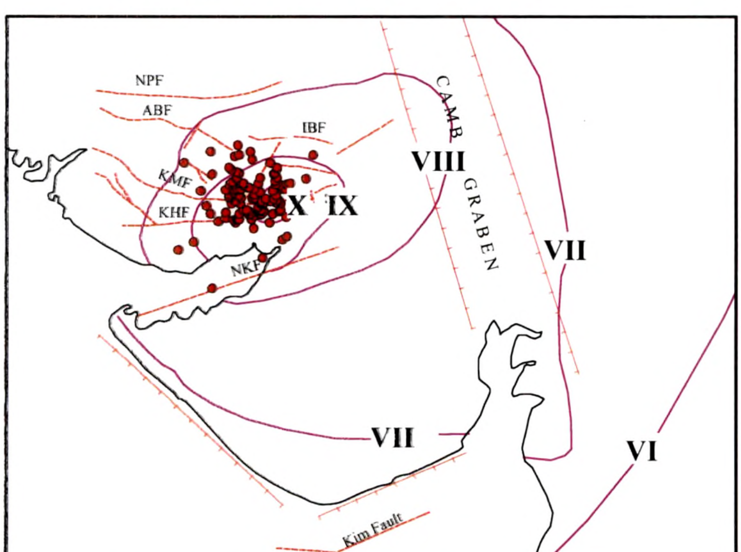

Fig.5.9: Map showing the Isoseismals of 2001 Bhuj Earthquake and the epicenters of the aftershocks in 2001 (after GSI, 2001).

Though, the early studies concluded that there was no primary surface faulting due to 2001 earthquake but McCalpin and Thakkar (2003) have described an 830 m long and 15-35 cm high, east-west trending thrust fault scarp near Bharodiya village (between

23°34.912' N, 70°23.942' E and 23°34.304' N, 70°24.884' E). In most of the scarps the Mesozoic bedrocks have been thrusted over the Holocene sediments. If the seismogenic fault plane is projected on the surface it would lie in the same area of Bharodiya village. But according to Bodin and Horton (2004) the 2001 earthquake did not generate a primary rupture. If the fault plane was to reach the surface; it would have resulted into 3 m of uplift. Since there is no accumulated topographic surface expression, they suggested that the 2001 Bhuj earthquake ''represents either a very slowly slipping or a very newly active fault''.

An array of stations operated for 77 days in Kachchh and recorded more than 3000 aftershocks of M≥1. Based on the aftershock investigation, the following inferences were drawn (Kayal et al., 2003).

i) The aftershocks are confined in a 60 km × 30 km zone around the epicenter of the main event.

ii) Maximum concentration of events is between the depths of 15 to 38 km; whereas the aftershock activity is less in the shallow depth (≤10 km).

iii) A conspicuous lack of aftershock activity is seen in a crustal slice between 10 and 15 km depth.

iv) The deeper earthquakes show NE-SW trend whereas the shallower ones cluster along NW-SE direction.

v) Composite fault plane solution for the aftershock events at a depth range of 25 to 38 km show reverse fault mechanism with a large left-lateral strike-slip component along a NE-SW trending plane.

vi) Composite fault plane solution of the shallower aftershocks (<10 km depth) gives a reverse fault mechanism with right lateral strike-slip component along a NW-SE trending plane.

vii) The aftershock observation also confirms that the NE-SW trend shows a SE dipping plane and the NW-SE aftershock trend indicate a SW dipping plane.

NGRI carried out soil-gas (Helium) emanation studies (Srinivasan and Reddy, 2001) along the suspected surface rupture zones around Budharmora and Manfara. The study has indicated absence of any Helium anomaly, suggesting that the deep seismic fault might have ended blindly without any opening at the surface.

Rajendran and Rajendran (2001) and Rajendran et al. (2008) inferred that the main rupture generated by the 2001 earthquake does not propagate to the surface, despite the fact that the epicenter lied close to the Kachchh Mainland Fault. They have concluded that the imbricate faults within the Kachchh rift may have the potential to be reactivated and another fault located north of KMF could be the causative tectonic plane.

Pande (2001) and Kayal et al. (2002, 2002b) are of the opinion that during Bhuj earthquake-2001, the KMF and some of the transverse faults got reactivated due to deep seated ruptures as a consequence of which the ground ruptured, upheaved, subsided or displaced in the area.

II. Geological Evidences of Neotectonism

The field study in the area suggests that it has repeatedly experienced tectonic disturbances from geologic past to recent times. The autoclastic intra-formational conglomerate, contorted bedding and laminations, warping, drag folds, faults and sand dykes provide ample evidence of neotectonism in the area.

(1) The compression of the sediments in the zone of KMF has resulted into the drag folds in comparatively incompetent beds. The Tertiary units comprising of shale with thin gypseous beds are suitable to preserve such type of structures. Drag folds and warps are recorded from the Miocene sediments in the north of Khirsara village. Thus they indicate a phase of neotectonism in the KMF zone (Fig.5.10). The axial planes of these folds are sub-horizontal, making it recumbent in nature.

Fig. 5.10: Drag fold in the gypseous shale of Miocene age, North of Khirsara village.

(2) Small scale normal faults are recorded from a river bed in the north of Khirsara village. These faults are small scale with throw of about 15 cm. These are accompanied with rejuvenation of stream channels showing headward erosion thus indicate the tectonic activity during Holocene times. The knick points in the long profiles of the rejuvenating streams fall very close to the KMF and are supported with newly developed coseismic fissures / cracks of Bhuj (2001) earthquake.

(3) Deflection in stream courses recorded in the north of Devisar and Khirsara along the KMF suggests the existence of a weak zone of KMF. The north flowing streams show a sharp westward bent along the KMF. After following the KMF for about 40-50 meters the streams flow in the regional slope direction towards north. (Fig 5.11). Further at Devisar a stream has abandoned the old course and taken a new course developed parallel to the KMF (Fig 5.11). New ground fissures are recorded along the present course developed during Bhuj (2001) earthquake. This indicates that the deflection was induced due to development of fissures during earlier earthquakes.

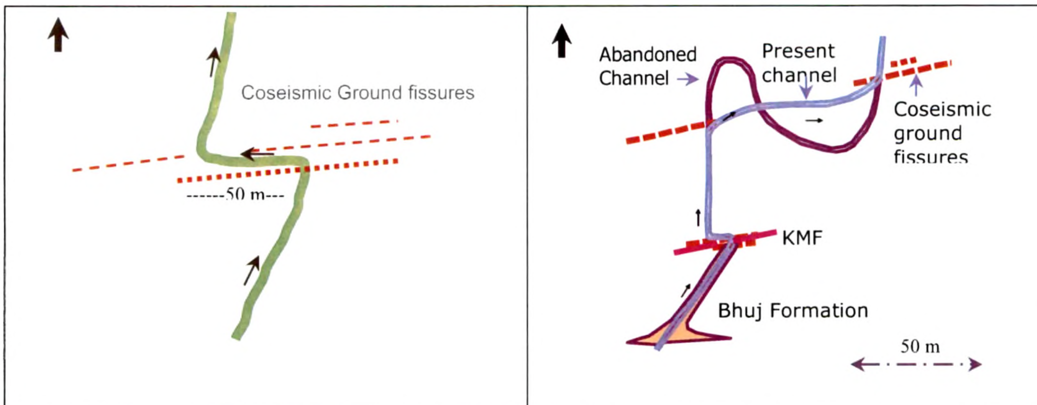

Fig.5.11: Schematic diagrams sowing stream deflection at KMF, north of Devisar.

(4) The contorted beddings / laminations bounded by undisturbed horizons are recorded from a nala terrace sequence to the north of Khirsara village. It indicates that the beds have experienced some disturbance / seismic-shaking during the period of their deposition / lithification during Holocene. The nala section is a part of alluvial fan comprising medium to coarse grained, loosely compact sand and silt admixture. The lowest horizon is about 10 cm thick with highly contorted laminae. There are three more such contorted beddings at different horizons in the same locality as shown in the Figure 5.12. Slump structures are recorded from Lodai area, south-west of Loriya and at Khirsara.

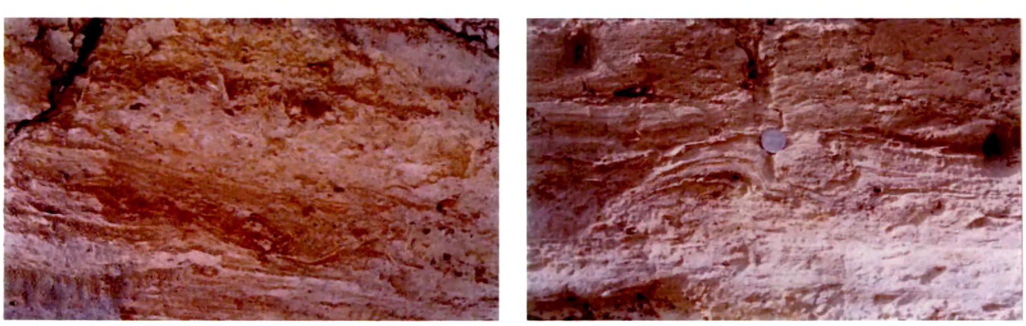

Fig.5.12: Contorted laminations in sandy horizons, north of Khirsara village.

Well preserved contorted bedding / penecontemporaneous structures are recorded from the miliolitic limestone horizon at the right bank of Dhrung River to the south of Dhrung dam (23°23.557'N / 69°48.628'E) (Fig. 5.13). The amplitude of the localized wavy structure ranges form 10 to 16 cms. This horizon is bounded by undisturbed horizontal laminae of same lithology i.e. miliolitic limestone. This is pertinent to mention that the miliolitic limestone is aeolian deposit in the area of Pleistocene age. These contorted beddings are accompanied with minor faults (Fig. 5.14). Thus, these structures indicate the neotectonic disturbances in the area during that period.

Fig.5.13: Contorted laminations in the miliolitic limestone; south west of Dhrung.	**Fig.5.14:** Fault in miliolitic limestone of Pleistocene age; south-west of Dhrung.

III. Morphometric indicators of Neotectonism in the area

Detailed morphometric analysis of the five river basins, with well developed drainage, has been taken up as described in the previous chapter. Various morphometric parameters of the river basins have been derived. The bifurcation ratios of the various basins indicate that the area is hilly which has high degree of tectonic activity as indicated by the higher values of bifurcation ratio for the lower order streams. The elongation ratio of the basins is high, in general. These indicate that the basins are elongated in shape which owes to the recent tectonism in the area. The drainage density is high and in the arid climate higher drainage density is also attributed to the active tectonics in the area.

The sinuosity indices for the Kaswali and Nirona Rivers show that the topographic sinuosity index is 100% in upper reaches whereas it starts decreasing in the middle portion of rocky plains. The high values of Topographic Sinuosity Index as compared to Hydrological Sinuosity Index for the Kaswali and Nirona Rivers indicate that the tectonic factors are dominating over hydraulic factors in shaping the course of the rivers. High texture ratio i.e. 23.087 for Nirona River is indicative of uplift of the basin. The ruggedness of the basins suggests high drainage density over comparatively low relief indicating towards active tectonism in the area.

Analysis of general trend of the lower order streams of the Kaswali and Kaila basins indicate that majority of the streams are oriented in the NNW-SSE direction and a quite few in the NE-SW to ENE-WSW direction. This analysis indicates that the lower order streams are governed by the tilting of the basins. The asymmetry factor calculated for the basins indicates that the river basins are tilted towards west. Since majority of the river basins are showing westward tilting, it is concluded that the mainland block has undergone westward tilting.

The prominent breaks in the long profiles of the rivers are the knick points which indicate rejuvenation of the streams (Hancock et al., 1996). The high PHI values are also indicative of rejuvenation of the streams. The Mountain Front Sinuosity indices of the east-west trending fronts, near the KMF, falls within the tectonic activity class I of Bull and McFadden (1977) indicating recent activity along these faults.

IV. Coseismic activities due to Bhuj (2001) earthquake

Various geomorphic and geologic changes have been recorded due to the devastating 2001 Bhuj earthquake. Some of them have been shrouded up to some extent due to a span of time, e.g. liquefaction sites, while some have been aggravated due to geomorphic agents working along them like ground fissures followed by stream channels. The important geomorphic and geological changes recorded from the area are discussed below.

Ground Fissures and Cracks

The coseismic ground fissures and cracks are recorded from various places from the area. Most of them are running parallel to the KMF. They are abundantly recorded just near the KMF and north of it but in the south of KMF a few are developed. Plotting of these fissures and cracks on the geological map give the spatial information about the location of active faults in the area which got activated due to 2001 earthquake. The fissures run for hundreds of meters to kilometers with a width of a few cm to 1.5 m. These features are more commonly developed in the area between Bhachau and Loriya villages. Fissures and cracks are recorded in the north of the Devisar and Khirsara domes in plenty. There are parallel fissures in a zone of about 300 m in the north of Devisar dome indicating a zone of activity.

Displacement in Manfara Transverse Fault

A transverse fault to the KMF from Manfara- Kharoi up to Vondh village extends for about 10 kilometers as conspicuous deep and wide coseismic ground fissures in the N15°W-S15°E trend. This fault is known as Manfara Transverse Fault (Fig.5.15). The ground fissures developed are up to a meter wide and more than a meter deep at various places. At some places they are developed in en-echelon pattern. This transverse fault shows 50 cm of dip slip and 20 cm right strike slip component near Kharoi village in a trench excavated during the study. The dimension of the trench was 3m (length) x 1.5m (width) x 2m (depth). The displacement is also recorded in the weathered felspathic sandstone below about a 2 m thick soil cover. The fault plane seems to be sub-vertical dipping westerly at very high angles.

Fig.5.15: Manfara Transverse Fault visible as coseismic ground fissures due to Bhuj (2001) earthquake, near Kharoi village.

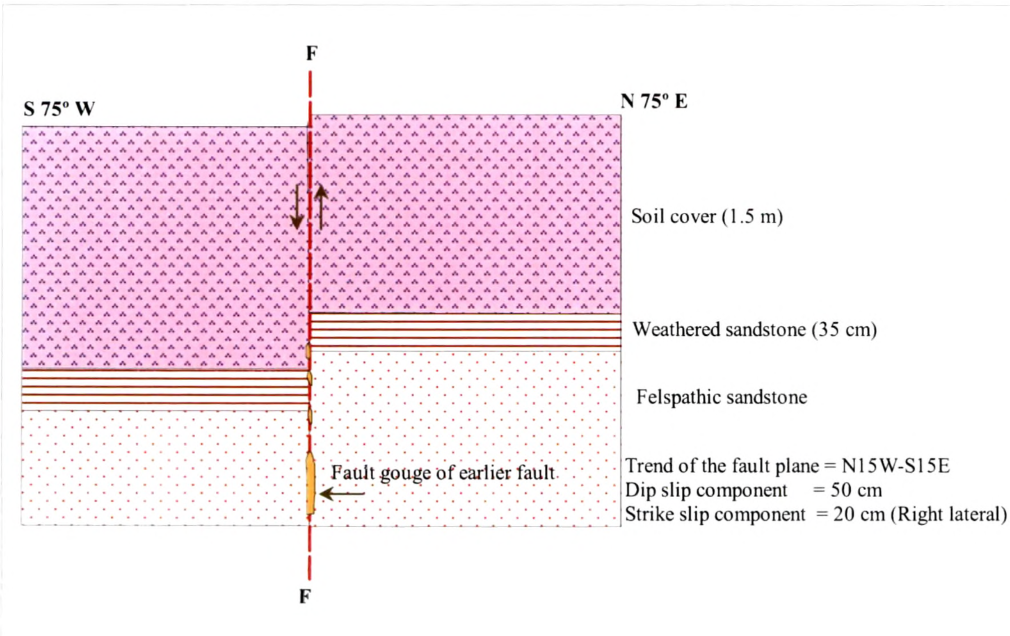

Fig.5.16: Litholog of the trench made across the Manfara Fault, near Kharoi.

During the trenching a greyish-white material was found along the newly developed fault plane (Fig.5.16). It has proved to be fault gouge of an earlier fault, which coincides with the current coseismic fissure. Materials from different horizons have been dated by Rajendran et al. (2008) to study the seismic events.

Table: 5.3: Data on Quartz Optically Stimulated Luminescence (OSL) dating from Manfara Fault (after Rajendran et al., 2008)

Material	Average Dose Rate, Gy/Ka	Equivalent Dose (Gy)	Estimated Age (Ka)
Sand	1.121 ± 0.046	0.77 ± 0.07	0.690 ± 0.069
Sand	1.732 ± 0.107	7.66 ± 1.03	4.424 ± 0.656
Sand	1.452 ± 0.053	7.44 ± 1.19	5.125 ± 0.840
Sand	1.770 ± 0.064	10.94 ± 2.31	6.180 ± 1.324

These dates indicate the different sandy horizons of the Manfara trenches. Age of 4.424 ± 0.656 Ka is of a sand fill in a previous fissure found in a trench. Rajendran et al. (2008) assume that the OSL date of 4424 ± 656 years to be the minimum age of the penultimate event. If the fissure and the fill had formed immediately after the faulting, then this age should be considered as contemporaneous. Thus, it is evident that the Manfara fault is a pre-existing fault which was reactivated due to 2001 Bhuj earthquake.

Loriya Transverse Fault and its Reactivation

During the imagery study of the alluvial fan of the Pur River, a lineament is found cutting the northwestern part of the fan (Fig. 5.17). This lineament is manifested by a sudden change in the vegetation and textural pattern on either side of the line and the alignment of a stream course along this lineament. During the fieldwork ground fissures developed due to 2001 earthquake were found along the lineament. This confirms the existence of an active fault, named 'Loriya Fault' (Singh et al., 2011). This fault was reactivated during 2001 earthquake. The fault is cutting the recent alluvial fan, pointing towards very recent activity along the fault. The ground fissures developed due to 2001 earthquake are found in clusters running parallel to the fault. They are situated about 4.5 km north of Loriya village. The trend of the fissures is N55°E-S55°W to N40°E-S40°W (Fig. 5.17). They make an en-echelon pattern in right lateral fashion. The dimensions of individual fissures vary. They run for a length up to 150 meters with maximum depth of 1.5 meters and width of 2 meters. They are 'V' shaped in cross section. Trenches were dug to study the nature of movement along the fault plane. The study of the trenches shows no dip slip component of movement along these planes. Since the ground fissures recorded from the area make an en-echelon pattern in the right lateral fashion, this suggests a left lateral movement of the blocks along the fault plane (Yeats et al., 1997). The length of the Loriya Active Fault is about 8 km which is a transverse fault to the Kachchh Mainland Fault. Ground fissures are recorded from the east of the Loriya village, which also follow the trend of the Loriya Fault. Some north flowing streams follow the fault for some distance and then take the general slope of the area, which is towards north.

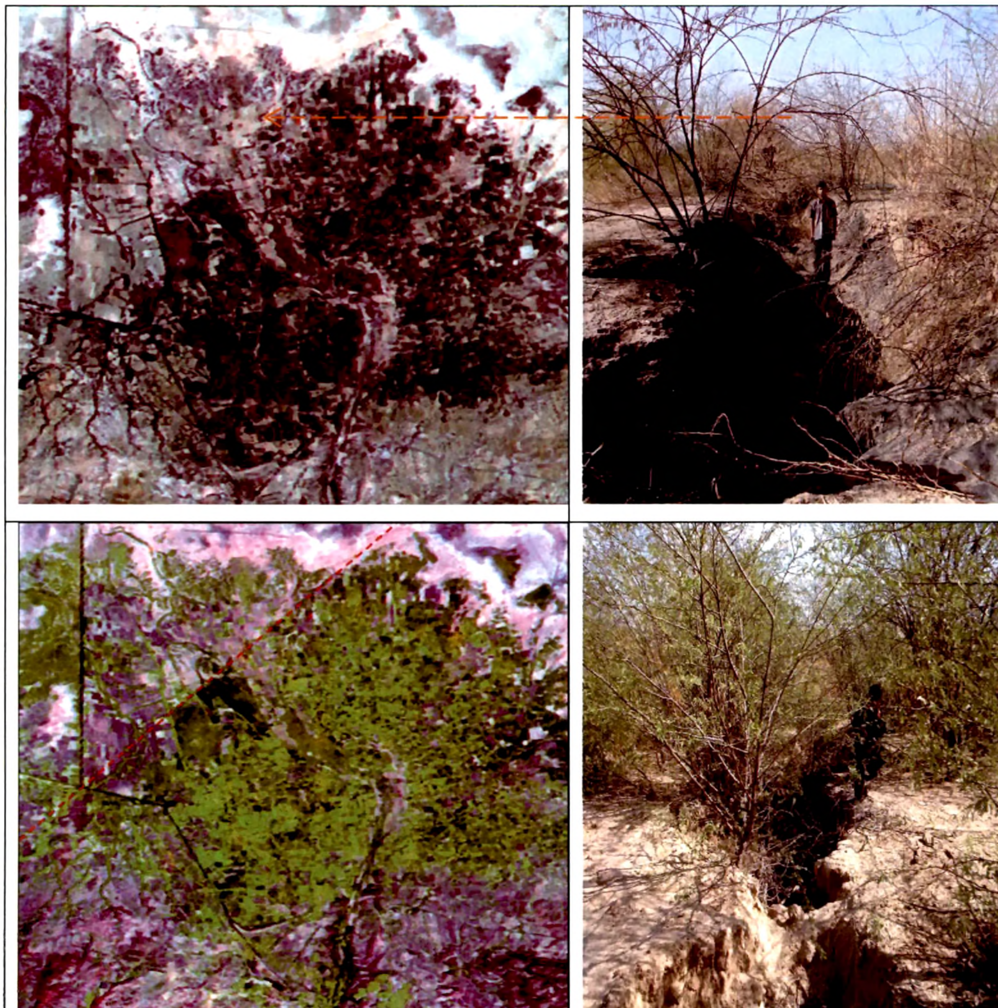

Fig.5.17: LISS-III imagery of alluvial fan of the Pur River showing lineament, which proved to be an active fault. The lower imagery is the enhanced one by PCA method and fault is better viewed in this imagery. Coseismic ground fissures (due to Bhuj (2001) earthquake), developed along the Loriya fault are shown to the right.

Digital elevation model of the alluvial fan is prepared using the SRTM data (Fig. 5.18). The asymmetrical profiles across the axis of the fan show steeper gradient in the north-western distal part of the fan cut by the fault. The asymmetric cross section of the Pur River fan, shown in figure 5.18, indicates the effect of the fault on the fan. The western side has steep constant slope while the eastern side is convex and gentler in slope. Since this asymmetrical feature is recorded in the alluvial fan of a present stream, it indicates neotectonic activity in the area.

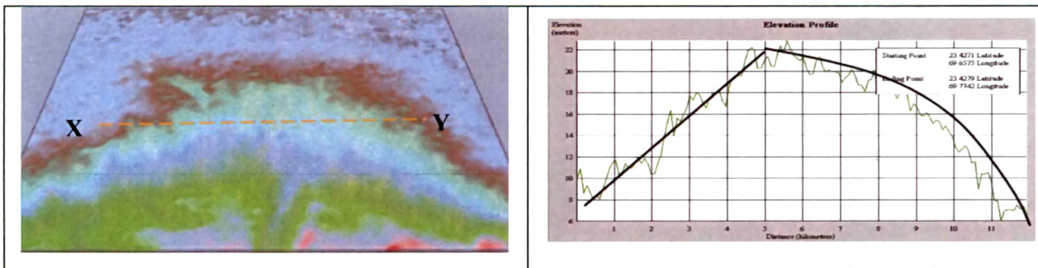

Fig. 5.18: DEM of alluvial fan of Pur River (left) and asymmetrical profile indicating the effect of Loriya fault (right). X-Y is the section line for profile.

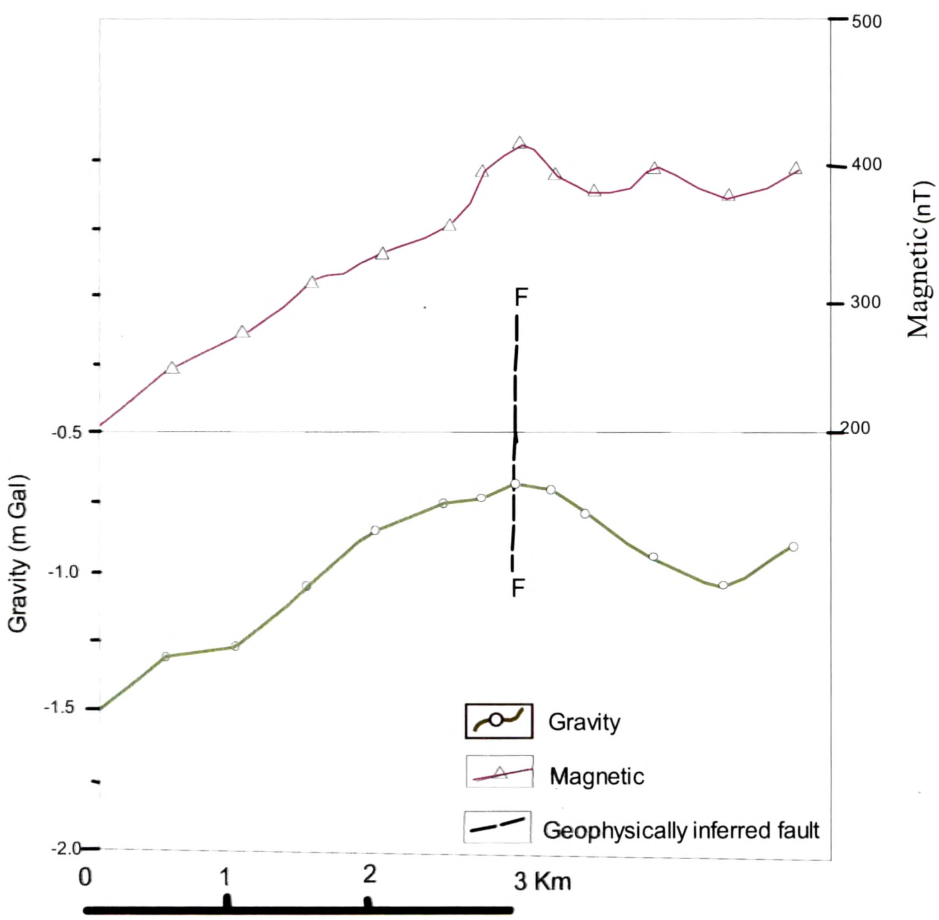

Fig.5.19: Geophysical profile across the Loriya Fault, signatures of gravity and magnetic anomaly is detected on the fault (after Singh and Lal, 2008).

The geophysical survey in the area across the Loriya Fault also indicates the signature in the form of gravity and magnetic variations. Increase in the magnetic and gravity values is demonstrated in the graph (Fig. 5.19).

Liquefaction induced structures

Liquefaction induced structures are most important besides the ground fissures and cracks in the area. They are manifested in the form of numerous craters, sand-mud sprouts, sand blows, ground subsidence and slumping. Liquefaction has occurred mostly in the marshy area of Rann where the ground water table is shallow (4-5 m below ground level). The liquefaction phenomenon was recorded from the areas near Amrapar, Amardi, Devisar, Lodai, Khengarpar, Wanthra and north of Jawaharnagar (Fig.5.20). The linear array of some of the liquefaction centers indicates existence of some buried channels which have sandy beds with more water holding capacity. Due to shaking of the ground they have given rise to liquefaction craters.

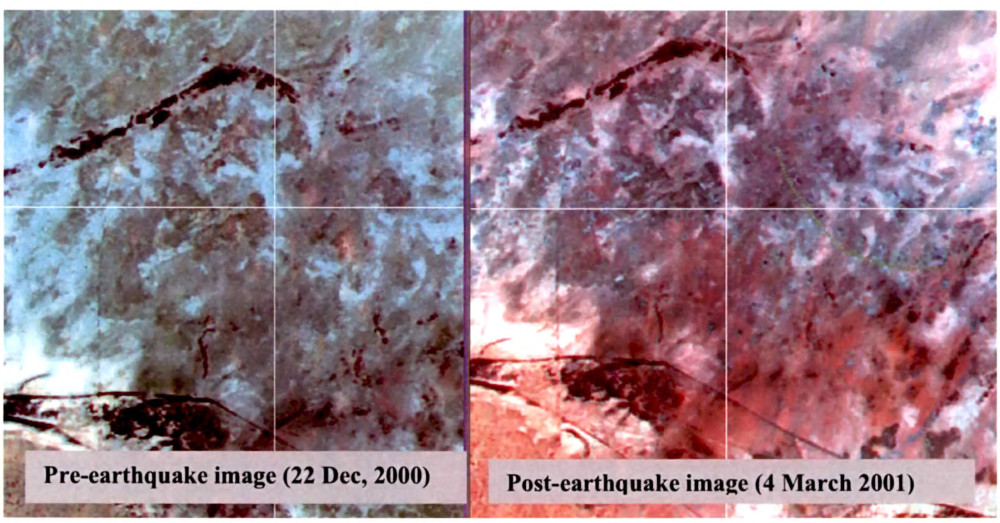

Fig. 5.20: Pre- and post- Bhuj (2001) earthquake images showing the liquefaction centers.

To study the liquefaction features there are different techniques. Making trenches across the craters is the most commonly used methods but Ground Penetrating Radar is now an established tool to study the shallow sub-surface features with high resolution imaging. Though, the application of GPR in the study of the liquefaction features is still in juvenile stage, Maurya, et al. (2006) investigated two large, closely spaced sand blow carters of different morphologies using GPR to study the subsurface deformation, identify the vents and source of the vented sediments. It imaged the subsurface nature of the craters based on the contrasting lithologies up to 6.5 m depth. GPR also detected three vertical vents of ~1 m width. Though, it has a limited utilization in detecting the features with no lithological changes and the features at depth.

Rejuvenation of streams

Rejuvenation of streams flowing north of Devisar is recorded with deep head ward erosion and knick points. Such features are also recorded near Khirsara, Jawaharnagar and Wanthra village near the KMF. This phenomenon suggests relative base level changes due to neotectonic activity.

Modification of stream courses

Change in stream courses has been recorded in the areas which are affected severely by the earthquake. Shifting of stream courses and abandoning the original stream, is clearly seen near Kharoi village and Devisar area (Fig. 5.11). Reversal of slope due to upheaval of land mass resulted into change in the stream direction near Budharmora village.

Faults in Quaternary sediment

Small scale faults are recoded from various places in the area. One vertical fault with 10 cm dip slip component is observed in the stream channel deposit in south of Dhrung village (Fig.5.14). Various small-scale faults are also recorded from the miliolitic limestone deposited along the slopes of the hills near Dhrung village. Another fault of mesoscopic size is recorded in the left terrace sequence of the Dhrung River just near the Dhrung dam (Fig. 5.21). It is a reverse fault in nature. The fault plane dips about 30° due north. This fault cuts the Mesozoic rocks below and the goes up to the Quaternary miliolitic limestone. A splay of the main fault plane is also developed.

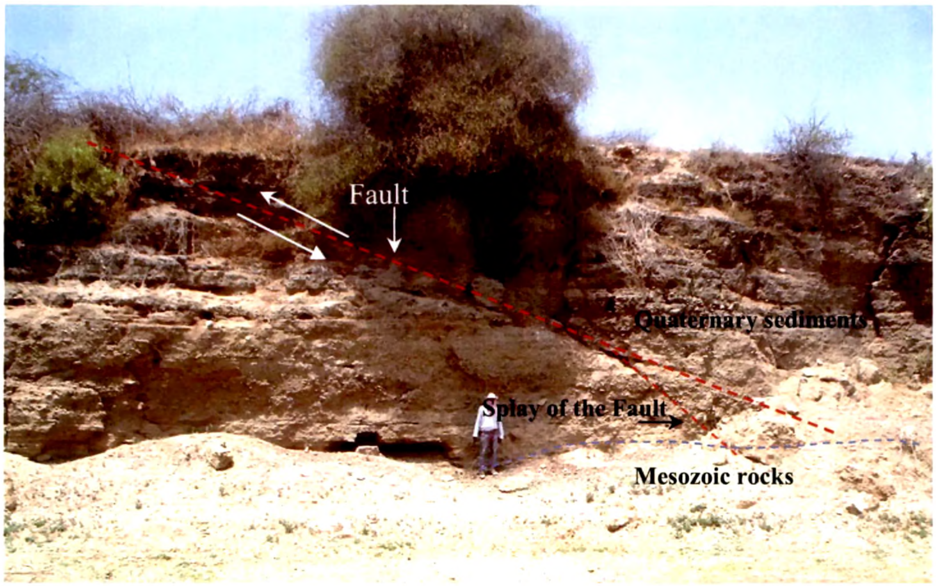

Fig. 5.21: View of the eastern terrace of the Dhrung River, near Dam, showing a Quaternary reverse fault.

Upheaval of land

About 350 m long East-West trending upwarp was formed about 1 km north of Budharmora village due to Bhuj (2001) earthquake (Fig.5.22). The maximum recorded height of the upwarp is ~65 cm. Parallel ground cracks are found in the north and south of this upwarp. The soil in the area consists of brownish silty sand. A trench of dimension 2m (length) x 1m (width) x 1.70 m (depth) was excavated across the upwarp. The trench logging shows about 25 cm top soil of light colour underlain by residual soil of brownish sandy composition of about 1 m thickness. Below the residual soil, deeply weathered felspathic sandstone of Bhuj Formation was encountered. This sandstone has turned into a non-cohesive sandy horizon with white weathered feldspar. The ground water table was encountered at a depth of 1.5 m.

The plane of the upheaval is not very distinct but the southern block appears to have overridden the northern block with a southerly dipping plane. The north flowing streams prior to the upheaval were, thus blocked and the flow direction changed along the strike direction of the upwarp. The upwarp is located at the Kachchh Mainland Fault and resulted due to reactivation of the KMF.

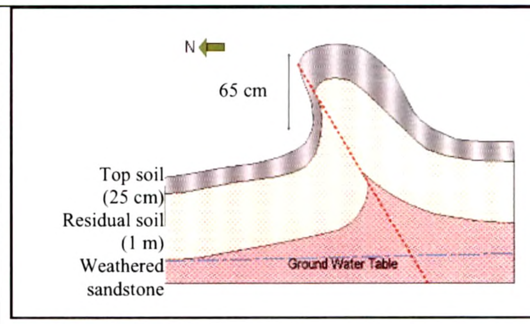

Fig.5.22: Budharmora upwarp (developed due to Bhuj earthquake) and the schematic diagram of a trench made across it.

Change in ground slope

Change in the local ground slope is recorded near the Budharmora upwarp and Kharoi village (near Manfara Fault). This has resulted into change in stream direction. The streams flowing northerly near Budharmora were obstructed by the upwarp created due the Bhuj (2001) earthquake. The stream course got deflected in the direction of the upwarp and then followed the general slope towards north.

Development of new streams

Various new streams are taking shape along the coseismic ground fissures. This phenomenon is very common in the area north of Devisar and Khirsara villages. The soil in the area is sandy, which is easily eroded with rain water resulting into new streams. The new streams are also developing along the Manfara and Loriya Faults, where maximum ground fissures were generated during the earthquake.

Emergence of buried channels

The study of pre- and post- Bhuj earthquake imagery of the area reveals emergence of various stream channels due to the 2001 earthquake (Fig. 5.23). These channels are noticed mostly from the Rann areas. In part of toposheet no 41 I/2, a number of small streams got filled up with water due to the shaking of the ground during Bhuj (2001) earthquake. These streams are distinctly seen in the post-earthquake LISS III imagery of the area (5th March 2001 imagery) while they are not visible in the pre-earthquake imagery (Fig.5.24). During the earthquake, strong shaking produced liquefaction in the silt and sand below the water table in the Rann of Kachchh. This caused the sediments to settle and expel their interstitial water to the surface. Field investigations have found abundant evidences of mud volcanoes, sand blows, and fissures from which salty ground water erupted over a large area.

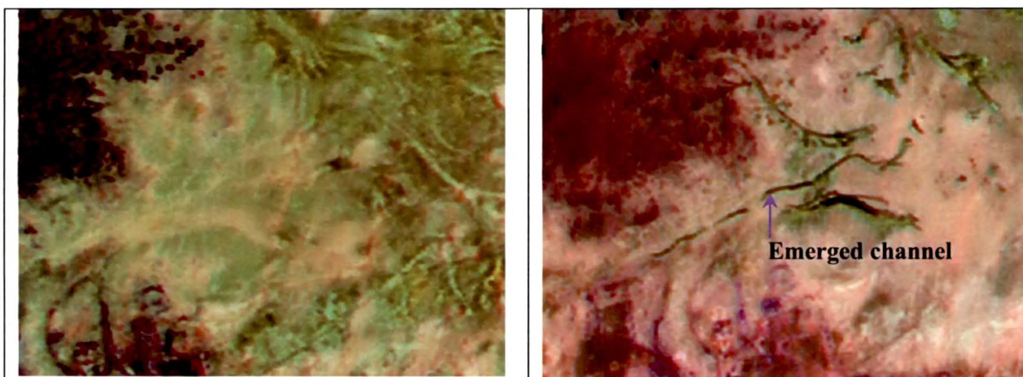

Fig.5.23: Emergence of buried channels, north of Amrapar. In Pre-Bhuj earthquake no channel is seen but in the post-Bhuj earthquake imagery channels are visible.

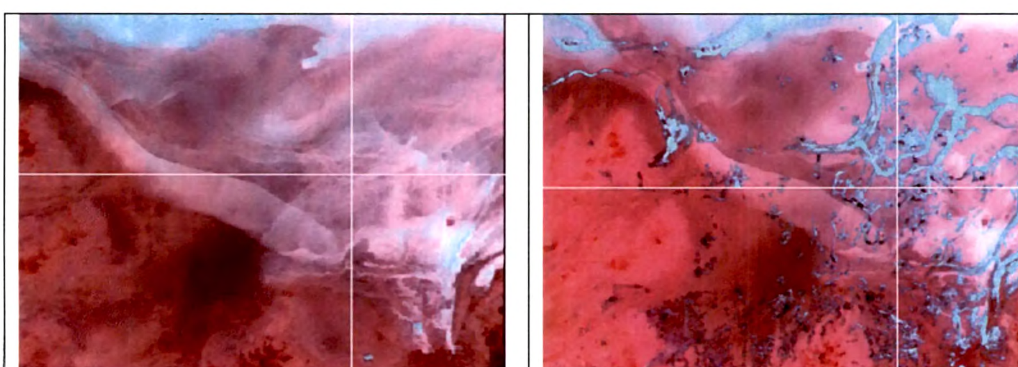

Fig. 5.24: Oozing of water in the channels in marshy region of Rann of Kachchh, (Pre-Bhuj earthquake imagery to the left and post-earthquake imagery to the right).

Transverse faults to the KMF and their active nature

Numbers of transverse faults have been reported across the Kachchh Mainland Fault which are very active and play an important role in the recent seismic activities. The KMF appears to be laterally displaced by several NNE-SSW to NNW-SSE trending transverse faults. These transverse faults have an important role in the evolution of Kachchh Mainland. The implications of these faults in the geomorphic evolution will be discussed later. Several transverse faults have been marked studying the imagery of the area along KMF. These are cutting across the various domes along the KMF (Fig.5.25, 5.26, 5.27 and 5.28). These faults coincide with dykes at several places and suggest their syntectonic origin in the region.

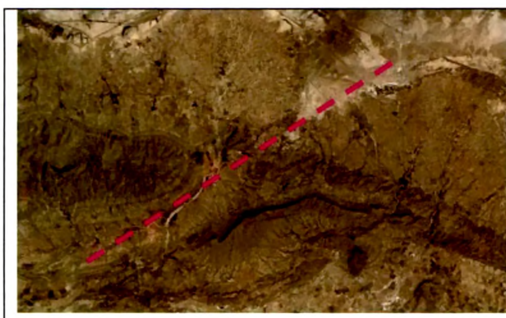

Fig.5.25: Lodai Transverse Fault.

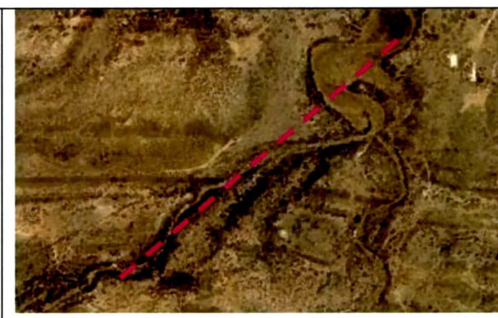

Fig.5.26 Dhrung Transverse Fault.

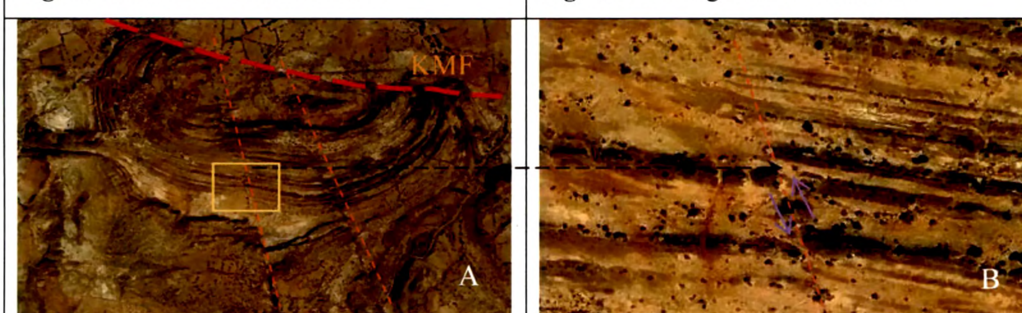

Fig.5.27 A: Distant view and, B: close view of transverse faults cutting the Jara dome to the SW of Lakhpat.

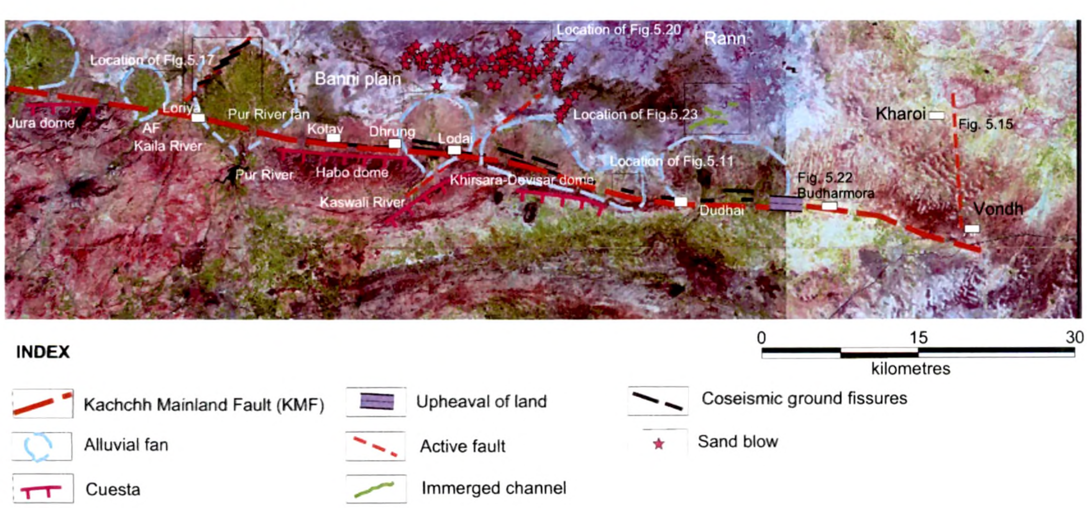

Fig. 5.28: Neotectonic map of the area along KMF between Loriya and Manfara Faults.

Thus, it is evident from the various evidences elaborated and discussed, that the Kachchh Mainland Fault is an active fault which has been causative factor for many seismic activities in the Kachchh region. Various transverse faults to the KMF along with the Master fault make a system and determine the configuration of the Kachchh basin. The recurrence of the seismic activities in the region points to the fact that active faults have the potential to rupture in future. Thus, the disaster prevention, mitigation, preparedness and relief, which contribute to the implementation of the sustainable development policies, should be made keeping in mind the vulnerability of the area.