# Chapter – 8

# DISCUSSION

Geomorphological and stratigraphic studies are crucial for delineating the nature and constrain the timing of neotectonic activity. The present study combines detailed field mapping of the landforms and stratigraphic studies on the exposed sedimentary sections followed by GPR studies to reconstruct the subsurface neotectonic behaviour of the KHF, an E-W trending intrabasinal fault of southern Mainland Kachchh. The Kachchh rift basin, located at the western extremity of India, opened during the Early Jurassic and became fully marine in Middle Jurassic which resulted in the deposition of more than 2000 to 3000 m thick Mesozoic and Cenozoic sediment succession (Biswas, 1977, 1987). The framework of the present fault controlled geomorphic configuration of the Kachchh was produced due to inversion of the basin in late Cretaceous time (Biswas and Khattri, 2002). Since Cretaceous period a large part of the Kachchh basin continued to suffer intermittent uplift along various E-W trending basin-bounding and intrabasinal faults, thereby maintaining first order structural control on the topography (Biswas, 1974; Biswas and Khattri, 2002). The post-rift (inversion phase) geological evolution of the basin is marked by periodic reactivation of various E-W trending intrabasinal faults like the Island Belt Fault (IBF), Kachhh Mainland Fault (KMF), South Wagad Fault (SWF), Katrol Hill Fault (KHF) and others (Figure 2.1), which are also responsible for recurrent seismic activity in the region (Biswas, 2005). It is therefore essential to characterize the active faults of Kachchh and document the successive tectonic events and related landform development during Quaternary. The present study focusing on the Katrol Hill Range located in the seismically active Kachchh palaeo-rift points to dominant role of Quaternary tectonic activity along the KHF in the deposition of Quaternary sediments and evolution of present day landscape.

Most part of the Mainland Kachchh is occupied by Mesozoic rocks which represent continuous deposition from Bathonian to Santonian (Biswas, 1977). The Katrol Hill Range is located to the south of KHF in the southern Mainland Kachchh. The range exposes rocks belonging to the Jumara, Jhuran and Bhuj Formations. To the north of the KHF, Bhuj Formation is exposed, which forms a gently undulating rocky plain. The E-W trending Katrol Hill Fault (KHF) is, therefore, a major range bounding fault that divides the Mainland Kachchh into northern and southern parts. The KHF originated as a near vertical fault in extensional regime during the rifting phase of the Kachchh basin (Biswas, 1987). Subsequently, the KHF alongwith other

E-W trending master faults have been involved in several episodes of basement involved uplift due to inversion since the Late Cretaceous (Biswas and Khattri, 2002).

Geomorphologically, the KHF is expressed as an E-W trending line of north-facing scarps that separates the rocky plain comprising sandstones of Bhuj Formation to the north and the rugged terrain of Katrol Hill Range made up of highly deformed Mesozoic rocks older than Bhuj Formation. The KHF, therefore, marks a sharp lithotectonic contact between the Bhuj Formation and older Mesozoic Formations like the Jhuran and Jumara Formations that form a narrow zone of domal structures along the KHF. To the south, the various Mesozoic Formations dip southwards and are overlain by the Palaeocene trappean basaltic flows, Tertiary rocks and Quaternary sediments extending up to the coastline of Gulf of Kachchh. Apart from the dominating E-W structural trend represented by the KHF and related faults, the NNE-SSW and NNW-SSE trending transverse faults also affect the Katrol Hill Range (Thakkar et al., 1999; Maurya et al., 2003a). The field investigations and mapping of the KHF carried out in the present study suggest significant variation in the dip of the fault plane. The dips is about $80^{\circ}$ in the eastern part, which reduces to about $45^{\circ}$ in the western part. Significant variations of the E-W trending strike of the KHF is also observed in the vicinity of transverse faults.

The DEM studies of the Katrol Hill Range clearly brings out the structural variations in the topography. The crest line comprising the highest summits of this range lies close to the northern edge whereas the drainage divide to the south also lies very close to the crestline. The DEM illustrates the narrow incised region between the crest line and drainage divide marked as backvalley trending E-W within south dipping Mesozoic Formations. The offsetting of the range front scarps of the KHF along various transverse faults is clearly seen in the DEM. The Katrol Hill Range forms the main watershed of Mainland Kachchh, the major rivers draining towards north are the Khari, Pat and Pur Rivers. Radial drainage patterns observed along Katrol Hill Range, are influenced by individual domes, where the drainages of eastern and western flanks which meet in the backvalley and follow the trend of transverse faults. Some of the drainages which arise from the crest line and flows towards south meet the backvalley between the crest line and drainage divide. The backvalleys are filled with Quaternary deposits, mostly by valley fill miliolites. The various rivers show narrow gorges of varying dimensions in Quaternary as well as in Mesozoic rocks. The Formation of gorges on both sides of the KHF is attributed to differential uplift under an overall compressive stress regime. However, site-specific tectonic conditions controlled the distribution, orientation and the nature of gorges formed. The geomorphic setup and the drainage of the Katrol Hill Range provide several lines of evidence for neotectonic activity along the KHF. The E-W trending line of north facing range front scarps, the conformity of the overall landscape with the tilt block structure, the E-W trending back valleys, the sharp division of the drainage system into south flowing and north flowing Rivers, the incising nature of the drainage, development of gorges, the mode of occurrence of Quaternary colluvial and fluvial sediments and their stratigraphic development testify to the continued uplift of the range in a tilted manner due to periodic tectonic movements along the KHF during the Quaternary period.

The Quaternary sediments of the area provide important stratigraphic evidence for delineating the major phases of neotectonic activity along the KHF. Quaternary deposits occur both within the Katrol Hill Range and to the north of the scarp overlapping the KHF. While the back valleys immediately to the south of the scarp line are dominantly filled with valley fill (fluvial) miliolites with patches of alluvium, the sediments to the north of the range front scarps show a scattered and restricted occurrence along the KHF zone. Though the deposits show patchy occurrences, a well defined sequence of depositional phases can be recognized. The sequence of the Quaternary deposits starts with the bouldery colluvium, aeolian miliolite, valley fill miliolite, alluvium and scarp-derived colluvium (Table 4.1). The Quaternary deposits are incised by various north flowing rivers. The bouldery colluvium contains large fragments of shale and sandstone and overlain by miliolites along the Katrol Hill Range. The miliolite deposits of the area are separated into two categories. The older miliolites occur on hill slopes which comprise well lithified fine grained miliolitic sand and is of aeolian origin. It also occurs as obstacle dunes and occupy topographic depressions and hollows in the slopes of high hills and ridges. The valley fill miliolite occur along incised cliffs and show stratification with pebble to cobble size clasts of Mesozoic rocks suggesting role of fluvial activity in their deposition. Valley fill miliolites are also found in the backvalleys created within the Katrol Hill Range between crest line and drainage divides. Since they are derived from carbonate rich sand from miliolite rocks these deposits shows varying degrees of compaction (Patidar et al., 2007). The fine grained alluvial deposits are found to overlie the miliolites and occur in patches within the Katrol Hill Range along various river valleys. The scarp-derived colluvium is the youngest Quaternary deposit of the area and is found at the base of the range front scarp. The deposit shows a maximum thickness of 2-3 m along various north flowing rivers. 230Th/234U ages of the miliolites occurring in the Katrol Hill Range varies from 130 to 30 ka, suggesting late Pleistocene age for these deposits. Significant amount of incision of exposed Quaternary sequences by lower order streams within the vicinity of the KHF indicates post depositional upliftment of the area.

Incision in the miliolites provides crucial evidence for constraining the timing of formation of the present day gorges. Chronologic data available on the miliolites suggest a rather prolonged time of miliolite deposition during the Late Pleistocene. The formation of gorges within the Katrol Hill Range, therefore possibly occurred during humid climate of the Early Holocene period, which may have provided the necessary runoff for vertical erosion of the landscape. The formation of gorges within the Katrol Hill Range therefore possibly occurred during humid climate of the early Holocene period, which may have provided the necessary runoff for vertical erosion of the landscape. This is in conformity with the recent studies on the coastal alluvial plain located to the south of the Katrol Hill Range that have provided geomorphic and stratigraphic evidence of fluvial incision during the early Holocene in response to southward neotectonic tilting (Maurya et al. 2003a). The scarp-derived colluvium is the youngest Quaternary deposit that occurs in the form of small aprons over the older sediments. The deposit varies from clast rich to matrix rich with gravel to cobble sized clasts mostly derived from the scarp faces subsequently reworked by debris and sheet wash processes. The E-W oriented trench indicates frequent lateral shifting of deposition with the top unit showing evidence of rilling and gullying. This colluvium is attributed to the youngest phase of neotectonic activity that occurred possibly during the late Holocene.

Based on the geomorphic and stratigraphic data presented in this study, at least three major phases of tectonic uplift of the Katrol Hill Range have been delineated during Quaternary. The oldest being the pre-miliolite phase (middle Pleistocene) followed by a prominent post-miliolite phase (early Holocene) which resulted in fluvial incision with formation of gorges and the last one during late Holocene that continues at present. The uplift of the range in well marked phases during Quaternary took place in response to differential uplift along the KHF under an overall compressive stress regime.

Geomorphologic data and the offsetting in Quaternary sediments provide unequivocal evidence for reactivation of KHF in the recent past. Offset and deformation of Quaternary sediments recorded at three sites located exactly above the KHF fault line conclusively proves its active nature. The site I demonstrates that the observed deformation and offset is the cumulative effect of multiple events along the KHF. The total vertical offset within Quaternary sediments is about 7 m. At least three events are discernible as described earlier. The events can be tentatively bracketed in geologic time based on the correlation of the affected sediments with the available stratigraphic set up (Table 4.1). Event 1 occurred sometime in late Pleistocene while the Event 2 occurred during early Holocene. The Event 3 is younger than 2 ka. It is significant to note that the KHF propagated up to the surface during each of the three faulting events.

The GPR has been widely used for delineating shallow subsurface discontinuities, depositional facies variations and seismotectonic features. The trench data in combination with GPR profiles provide significant results in active fault research and palaeoseismological investigations. The present study and previous literature suggest that GPR performed better in the sediments having low electrical conductivity where as the materials with higher conductivity restrict the penetration due to absorption of radar signals. The technique of surveying and modes of data collections also controls the quality and resolution of the data. Some important data collection methods including 3D data acquisition and the processing steps are briefly described in appendix at the end part.

Investigations carried out in the present study indicate that the Katrol Hill Fault (KHF) is a south dipping reverse fault, the fault plane dip varying from steeply dipping in the east to moderate to steep dips in the western part. The GPR profiles show that the KHF is a steeply dipping reverse fault in the shallow subsurface that becomes vertical at deeper levels. An important feature of the KHF is its segmented nature as evidenced by right-and left-lateral offsets along the NE-SW to NW-SE trending transverse faults. The effect of neotectonic tilting of the southern block due to vertical movements along the KHF in shaping of the landscape of the Katrol Hill Range is implicit from the evidence documented in the present study. The general reverse nature of the fault in the shallow subsurface points to neotectonic activity in response to accumulation of compressive stresses along the fault. The occurrence of gorges on both sides of the KHF is in conformity with the available information on tectonic set up of the KHF.

However, the upward extension of the KHF in Quaternary sediments observed at sites I and II show gentler dips (Figures 7.3, 7.6). The KHF has been identified as a growth fault during the Quaternary deposition and the splaying of the main fault strand is also noticed at both sites discussed above during its upward propagation. The results of ground penetrating radar (GPR) also point to the changes in the nature of the fault during its upward propagation in Quaternary sediments. The splaying nature of the fault is also obvious in the GPR images. The reverse movements along the KHF and its splaying nature in Quaternary sediments indicate its neotectonic reactivation in compressive stress regime. The reverse movements along the KHF and its splaying nature in Quaternary sediments indicate its neotectonic reactivation in compressive stress regime.

At present no unambiguous relationship can be discerned between the nature of the KHF and the available epicentral data of earthquakes in Kachchh. This may be attributed to incompleteness of the historic record of the earthquakes. However, the segmented nature of the KHF delineated in the present study has implications for the accumulation and distribution of tectonic stress accumulating along it presently. Detailed studies on discontinuous faults elsewhere have shown that such faults may show clustering of earthquakes in the vicinity of transverse faults offsetting them. This can also significantly affect the aftershocks and earthquake swarm activity (Bakun and McEvilly, 1979; Eaton et al., 1970; Hill, 1977; Johnson and Hadley, 1976). A similar scenario appears to be applicable to the KHF also as all sites showing clear evidence of active faulting, where KHF ruptured the topography several times, are located very close to the transverse faults. This suggests that future earthquake nucleation along the KHF is most likely to be in the zones of transverse faults where the KHF has been ruptured repeatedly in the very recent past. The KHF is therefore characterized by a heterogeneous stress field and that the other parts of the KHF are possibly gaps of lower stress. A recent study of earthquakes in San Andreas Fault by Parsons 2008 has shown that although, the lower stress gaps are not immune to earthquake slip, they are less likely to be nucleation sites for future earthquakes.