CHAPTER 7

SUMMARY AND CONCLUSIONS

Geomorphological parameters developed for the study of alluvial system have been used extensively as a valuable tool to explore various aspects of the tectonic influences on the tectonically active areas. Studies related to long-term dynamics of fluvial systems and their responses to external controls provide important clues to geomorphic evolution of an area. Though tectonics plays the most important role in carving the landscape of an area (Burbank, 1992) but climate and sea level changes also play their role in the process of sedimentation (Blum et al., 1994).

A multidisciplinary approach involving geomorphic studies, geological, stratigraphic and tectonic evidences supplemented with palaeoseismic and coseismic features of the recent activities along with geophysical sub-surface data have been assimilated for detailed study of the neotectonism in the area. In the present study emphasis has been given to the application of detailed morphometric analysis of the river basins, study of the coseismic data of the Bhuj (2001) earthquake and other important historical earthquakes and study of the alluvial fans of the rivers flowing across the Kachchh Mainland Fault. The study provides insight into the nature of neotectonic movements along the Kachchh Mainland Fault. The features developed due to the recent seismic activities provide explicit data for the approval of the derived evidences from various procedures. The present study reveals more coherent evidences that KMF has been tectonically active throughout the Late Quaternary and has played important role in the geomorphic evolution of the Kachchh Mainland.

The Mainland Kachchh is characterized by arid climate and the tropic of cancer passes through Kachchh. The monsoon prevails for a very short period (June-August) with

a meager and erratic rainfall. Summers are scorching hot. Kachchh Peninsula comprises east-west trending hill ranges i.e. the Island Belt, the Kachchh Mainland and the Wagad Highlands. The hill ranges in each of these areas are separated by large tracts of low lands. All hill ranges and the intervening low grounds run almost parallel, a characteristic feature indicating that the topography has been controlled to a large extent by the geological factors of folding, faulting and lithology. Kaladongar (Δ 465 m) in the Pachchham Island is the highest peak of Kachchh whereas Nanadongar is highest among several peaks in the Kachchh Mainland.

Kachchh, the northwestern region of the state has been divided into four main physiographic units from north to south, viz; the Rann, the low lying Banni Plain, the Hilly Region, and the Southern Coastal Plains, taking into consideration the factors of altitude, slope and ruggedness of relief. The above four units show considerable diversity within each of them, depending on the gross lithology and structural elements. The area along the Kachchh Mainland Fault exhibits a series of elongated domes with roughly east-west trending axes bounded by Rann of Kachchh to the north and pediplain to the south. The KMF has significantly controlled the physiography of this part of the terrain. The north flowing streams, originating from the northern slopes of the Central Highland, join the streams originated from the Northern Hill Range and pour their water into the Chhari, Bhukhi, Nirona, Kaila, Pur (Khari), Kaswali and other rivers and these streams debouch into the Rann making conspicuous alluvial fans crossing the KMF. The streams of the Kachchh region are ephemeral and carry water only during monsoon. The relatively well carved valleys which now have very little water is the characteristics of the drainage of Kachchh Mainland which indicates that the area had experienced a more wet climatic phase in the past.

The rocks exposed in the Kachchh basin belong to Mesozoic, Tertiary and Quaternary Period. The Mesozoic sequence comprises the oldest rocks belonging to the Pachchham Formation followed by the rocks of Chari, the Katrol and the Bhuj Formations. The oldest exposed rocks in the area belong to Pachchham Formation of Middle Jurassic age, consisting mainly of shale, sandstone, limestone and golden oolite bands with gypseous shale. Rocks of the Chari and the Katrol Formations are restricted to western part

of the area whereas the Bhuj Formation covers the larger part of the area, especially in the eastern part.

Rifting of the Gondwanaland in the Late Triassic-Early Jurassic Period resulted ultimately into the Kachchh rift basin (Biswas, 1985). The major faults along the NE-SW trend of Delhi Fold Belt that swings to EW in Kachchh region resulted into the Kachchh rift. The rift is bounded by Nagar Parkar Fault to the north and the North Kathiawar Fault to the south. Tilting along several intrabasinal, sub-parallel strike faults resulted into a series of half grabens (Biswas, 2005). There are five major parallel faults from north to south in the Kachchh Peninsula. These faults are Nagar Parkar Fault, Island Belt Fault, Kachchh Mainland Fault, Katrol Hill Fault and North Kathiawar Faults. Block tilting along these faults during rift phase extension gave rise to four sub-parallel linear ridges; Nagar Parkar Uplift, Island Belt Uplift, Wagad Uplift and Kachchh Mainland Uplift.

The orientation of the transverse faults of the Kachchh region coincides with the trends of the dykes of the area. It indicates that the dyke emplacement in the area is influenced by the transverse fault system developed due to the stress release mechanism in the course of north ward movement of Kachchh basin. The vicinity and coincidence of faults and dykes at several places suggest syntectonic origin of these dykes in the region.

Basins of the five major rivers which are flowing towards north and crossing the KMF, thus in the most vicinity of the KMF, were analyzed to decipher the nature of neotectonism in the area. Different morphometric parameters of the basins along with sinuosity, long profile, valley floor to valley width ratio and the mountain front sinuosity indices have been found useful in characterizing the degree and nature of tectonic activity while the drainage orientation studies helped in reconstructing the sequence of recent tectonic activities in the area (Centamore et al., 1996).

Period of neotectonic activities vary from area to area. In the 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 events as neotectonic activities. The northward movement of the Indian plate and it's locking with the Eurasian plate in the north changed the stress regime of the Kachchh region into compressive nature (Subramanya, 1996, Biswas, 1982, 1987).

Various evidences have been collected and compiled indicating the neotectonic activities in the Kachchh basin. The coseismic features have given explicit evidences of the nature of movements supported by the direct as well as derived geomorphic evidences.

The present study has led to the following main conclusions:

1. Topography of Kachchh basin comprises East-West trending hill ranges i.e. Nagar Parkar range, the Island belt, the Kachchh Mainland and the Wagad Highlands. The hill ranges in each of these areas are separated by large tracts of low ground, which are sites for Quaternary sedimentation. These geomorphic units are very well visible on the topographic 3D maps and have been correlated with tectonic features of the area in the topographic profiles. The tectonic features have very effectively carved the topography of the area.
2. Morphometric analysis of the river basins combined with fluvial depositional history, geological, tectonic and coseismic features have helped in understanding the landscape evolution of the fluvial systems. The present drainage of the northern hill range of the Kachchh basin is incisive as evidenced by 15-20 m high alluvial cliffs and knick points observed in the long profiles of the rivers.
3. The bifurcation ratios of the various basins indicate that they arise from hilly terrains and have high gradient. This ratio is generally higher for lower orders and higher bifurcation ratios may be attributed to the high degree of tectonic activity in the area during Quaternary. The circularity ratio values range from 0.307 for the Chhari basin to 0.437 for the Kaila basin. Highest elongation ratio is for the Kaila basin while for all other basins it is near 0.6 indicating that the basins are elongated and are tectonically controlled.
4. Drainage density of the river basins of the area comes under high density class. Since the area falls in the arid climatic zone, the high density is attributed to neotectonic activity. Texture ratios of basins vary from 6.01 in Kaswali basin to as high as 23.087 in the Nirona basin which is extremely high. This high texture ratio is indicative of recent uplift. The ruggedness for the Kaila and Nirona basins is more than 1 while it is about 0.5 to 0.7 for the Kaswali, Pur and Chhari

basins. These values suggest high drainage density and comparatively low relief, indicating neotectonic activity in the area.

5. Kachchh Peninsula has a long history of earthquakes of varying magnitudes ranging between M_L 3.5 to 8. The number of seismic events seems to have increased in the last decade after 2000. The better instrumentation facilities definitely increased the number by recording 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 yrs to 20 in 10 yrs.

6. The Asymmetry Factors calculated for the Kaswali, Pur, Kaila, Nirona and Chhari basins are 53.11, 78.3, 48.94, 66.26 and 66.76 respectively. This is interesting to know that four river basins out of five show broader right sides whereas for the Kaila River basin right and left sides are roughly equal with RF 48.94. It indicates that the river basins are tilted towards west in the area. Since all the river basins are showing westward tilting, it is concluded that the Mainland block has undergone westward tilting during the Quaternary. West ward tilting of the Kachchh Mainland is also manifested in the form of general bending of the streams towards west after crossing the Kachchh Mainland Fault.

7. The Pseudo Hypsometric Integral of the rivers, in general, is high, especially for the Kaswali, Kaila and Chhari basins which indicate that the area has undergone rejuvenation in the recent past. The long profiles of the rivers show prominent breaks in their longitudinal profiles. These breaks are indicative of rejuvenations forming knick points which are strong evidence of neotectonic activity in the area. The convex-up curves with high integrals are typical for youth and disequilibrium stage of the landscape which is characteristic of the Kaswali stream and indicate the influence of the neotectonism in the area.

8. 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 the rocky plains. The high values of Topographic Sinuosity Index 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 for Nirona River is indicative of uplift in the basin. The ruggedness of the basins suggests high drainage density over comparatively low relief indicating towards active tectonism in the area.

9. The Mountain Front Sinuosity indices of the East-West trending fronts, near the KMF, fall within the tectonic activity class I of Bull and McFadden (1977) indicating recent activity along these faults.

10. 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 north of Khirsara village. Thus, they indicate a compressive stress regime in the KMF zone after Neogene times.

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

12. Deflection in stream courses recorded to 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 m the streams flow in the regional slope direction towards north. Further at Devisar a stream has abandoned the old course and taken a new course developed parallel to the KMF. New ground fissures are recorded along the present course developed due to Bhuj earthquake. This indicates that the deflection was induced by the development of fissures during earlier earthquakes.

13. Four horizons of contorted beddings / laminations bounded by undisturbed horizons are recorded from a nala terrace sequence to the north of Khirsara

village indicate that the beds have experienced some disturbance / seismic-shaking during the period of their deposition / lithification may be Holocene.

14. 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 observed near the KMF and to the north of KMF. Plotting of these fissures and cracks on the geological map provides the spatial information about the location of the faults in the area which got activated due to Bhuj 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. The transverse fault at Kharoi village shows both dip as well as strike slip movements.

15. Dating of sediments from trenches across the Manfara Fault indicate different ages of sandy horizons. 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 4,424 ± 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 Bhuj earthquake.

16. The Loriya Transverse Fault was mapped in this study as an old fault which got reactivated during Bhuj (2001) earthquake. The fault has incised the recent alluvial fan deposit, pointing towards recent activity along the fault. The ground fissures developed due to Bhuj earthquake are found in clusters running parallel to the fault. They make an en-echelon pattern with right lateral fashion. 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. Ground fissures, due to 2001 Bhuj earthquake, are recorded from the east of the Loriya village, which also follow the trend of the Loriya fault. The geophysical survey in the area across the Loriya fault also indicates the signature of faulting in the form of gravity and magnetic variations.

17. 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-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 area near Lodai, Khengarpar, Wanthra and north of Jawaharnagar. The linear array of some of the liquefaction centers indicates existence of some buried sand channels having water holding capacity.

18. A reverse fault of mesoscopic size is recorded to the left side of the Dhrung River just near the Dhrung dam. The fault plane dips about 30° due north. This fault passes through the Mesozoic rocks to the Quaternary miliolitic limestone upward. A splay of the main fault plane is also seen.

19. A ~350 m long east-west trending upwarp was formed about 1 km north of Budharmora village due to Bhuj (2001) earthquake. 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 indicating reactivation along KMF.

20. Various new streams have developed 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.

21. The study of pre- and post- earthquake imagery of the area reveals emergence of various stream channels due to the Bhuj earthquake. These channels are noticed mostly in the Rann areas which are distinctly seen in the post earthquake LISS III imagery of the area. Many other features noticed are mud volcanoes, sand blows and fissures from which salty ground water erupted over a large area.

22. Though the eastern termination point of the KMF is not known exactly but it is supposed to truncate along a NNW-SSE trending transverse fault. Though this transverse fault does not have a spectacular geomorphic expression but the straight western margin of the Wagad highland, abrupt termination of the west

flowing streams along the fault indicates the existence of a transverse fault. The most evident feature to corroborate the existence of the transverse fault is the Manfara Fault in the close vicinity of the supposed major fault.

23. The first order topography and the seismic activities provide ample evidences of tectonic instability in the area during Quaternary. Neotectonic uplifts along various faults have been responsible for the present landscape of the Kachchh Mainland. Recent studies have indicated that the Quaternary uplift took place in two major phases. These two phases are separated by a phase of miliolitic deposition. The pre-miliolite uplift phase took place during the Early Quaternary and the post-miliolite uplift phase took place during the Late Pleistocene and Holocene, which is still continuing. The Early Quaternary tectonic activity took place along the E-W trending master faults i.e. KHF and KMF whereas the Late Pleistocene -Holocene phase of tectonic activity took place along the transverse faults. Tectonic activities along the transverse faults have been modifying the physiography of the Early Quaternary times. The Loriya transverse fault has cut the alluvial fan of the Pur River. Tilting of miliolitic limestone sheets near the transverse faults also indicates that the recent activity is more concentrated along the transverse faults.

24. The transverse faults are playing important role in recent seismic activities as well as in the landscape evolution of the Kachchh Peninsula. The most recent among these faults are the Manfara and the Loriya faults. The fault planes of these transverse faults are either vertical or steeply dipping. In general these faults dip towards the domes. Significant shifting of the East-West trending KMF has been recorded due to the lateral movement along these transverse faults, which has given the current slightly curved shape to the KMF and thus the configuration to the Kachchh Mainland.

25. The gravity survey across the KMF along Nokhania-Bherandiyara section shows about 350 m of throw for the Kachchh Mainland Fault. It also reveals other subsurface faults making horst and graben structure below the Quaternary cover in the Rann.

26. On the basis of evidences in the field and published data, a tectonic map of Kachchh showing the KMF and its transverse faults has been prepared. The coseismic features recorded from the Bhuj (2001) earthquake indicate that a segment of the KMF bounded by the Manfara Fault to the east and the Loriya Fault to the west was affected the most. Thus, it seems pertinent to mention that the transverse faults should be of prime concern for understanding the recurrent seismic activities in the Kachchh region and for their mitigation measures.