GEOMORPHIC EVOLUTION AND NEOTECTONISM ALONG KACHCHH MAINLAND FAULT, NORTHERN HILL RANGE, KACHCHH, GUJARAT

A
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By

PRAMOD KUMAR SINGH

Department of Geology
Faculty of Science
The Maharaja Sayajirao University of Baroda
Vadodara-390002
Gujarat, India

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DECLARATION

This is to certify that the contents of this thesis comprise original research work of the candidate and have at no time been submitted for any other degree or diploma.

(Pramod Kumar Singh) **Candidate**	**(L.S.Chamyal)** **Guide**	**(L.S.Chamyal)** **Head** **Department of Geology**

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CHAPTER 1

INTRODUCTION

An inventory of field evidences supported by critical analysis of morphometric parameters is required to understand neotectonism and geomorphic evolution of an area. This in turn calls for multidisciplinary approach by combining structural, morphological and neotectonic data to study the setting of the area in relation to geological structures (Potter, 1978; Lanzhou and Scheidegger, 1981; Diamant et al., 1983; Centamore et al., 1996; Scheidegger, 2004). Tectonic movement, contemporaneous with the formation of the morphology of the modern river is referred to as 'active tectonic movement' (Ouchi, 1985).

Geomorphological parameters developed for the study of alluvial system have been used extensively and tested as a valuable tool to explore various aspects of the tectonic influences on the tectonically active areas. Fluvial landforms and deposits provide one of the most extensively studied continental Quaternary records. Moreover, studies related to long-term dynamics of fluvial systems and their responses to external controls provide important clues to geomorphic evolution of an area. These studies gained momentum in the last decades of the twentieth century. Sedimentary basins which are under the influence of tectonic disturbances show variable rates of sedimentation and changes in the spatial organization of alluvial facies (Mather, 1993). The geomorphic evolution of a reactivated sedimentary basin is mainly due to complex interplay between sedimentation process and tectonics (Jones et al., 1999). Tectonics is the dominant factor responsible for the development of the present day landscape of an area (Seeber and Gornitz, 1983; Sloss, 1991; Burbank, 1992) but existing climate of the area and the sea level changes also play important role in the process of sedimentation (Blum et al., 1994).

The neotectonic studies, which are based solely on the geomorphological studies are used to document the nature and type of movement along the faults (Schubert, 1982; Dumont, 1996) but they are not found to be useful in deciphering the timing and amount of movement along the fault. Therefore, an integrated approach involving geomorphic studies, geological and stratigraphic information, structural and tectonic evidences supplemented with palaeoseismic and coseismic features of the recent past, along with the geophysical data of sub-surface were assimilated to develop more precise investigation of the complexity of the process of geomorphic evolution and neotectonism in the Northern Hill Range of the Kachchh in Gujarat.

The Kachchh basin is an E-W trending rift graben located on the western Indian continental margin. The pre-Quaternary tectonic and sedimentary evolution of the Mainland Kachchh has been discussed at length by Biswas (1974, 1982, 1987). The region is one of the most seismically active regions in the subcontinent and experienced number of large magnitude earthquakes in the recent historic past. It falls within the seismotectonic zone-V in the seismic zonation map of India. Some of the large magnitude earthquakes (≥6) in Kachchh are Allah Bund (1819), Khavda (1940), Anjar (1956) and Bhuj (2001). The Kachchh region has been undergoing high compressive stress due to northward movement of the Indian plate and it’s locking with the Eurasian plate in the north (Subramanya, 1996; Biswas, 1982, 1987).

Kachchh Mainland Fault (KMF), one of the major E-W trending faults in the Kachchh rift basin, has been accommodating the compressive stress resulting into moderate to high intensity seismic activity in the area. For the better understanding and evaluation of the seismic risks and to suggest mitigation measures more data on the nature of neotectonic activities along the Kachchh Mainland Fault is required. Fluvial processes and landscape evolution are normally controlled by the Quaternary sedimentation processes, tectonism and environmental changes. The role of tectonism is crucial in the development of fluvial systems in an area like Kachchh. The features developed due to the recent seismic activities provide explicit data for the approval of the derived evidences from various procedures.

Aim and Scope

The main objectives of the present work are to assess the Late Quaternary movement along the Kachchh Mainland Fault, to understand the tectonic elements involved in the seismic activities in the area and to correlate the coseismic data of the 2001 Bhuj earthquake with the conclusions drawn from the study of the morphometric processes. Therefore, in the present study emphasis has been given to the application of the detailed morphometric analysis of the river basins, study of the coseismic data of the 2001 Bhuj earthquake, study of the alluvial fans of the rivers flowing across the Kachchh Mainland Fault and assimilation of the subsurface geophysical data. Five river basins, which fall in the zone of Kachchh Mainland Fault, have been selected for detailed morphometric analysis with the help of GIS and high resolution remote sensing data to produce linear and aerial parameters of morphometric analysis precisely and to analyze these data to infer the effects of the neotectonism on the fluvial systems. The study provides insight into the nature of neotectonic movements along the Kachchh Mainland Fault and the associated transverse faults. 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 basin. The study also aims to explain the nature of transverse faults to the KMF, their role in the recent seismic activities in the area and how they are responsible for the geomorphic evolution of the Mainland Kachchh. During the course of study new transverse faults were discovered and bearing of these faults on the KMF has been attempted. The coseismic features developed due to 2001 Bhuj earthquake were recorded during the course of study, trenching was done at some places to see the nature of movement of faults and other coseismic features and the information was correlated with the published data. The pre- and post- 2001 Bhuj earthquake LISS-III images were studied to see the changes due to the earthquake which resulted into documentation of various changes like emergence of buried channels and liquefaction features. The significant historic earthquakes like Allah Bund (1819) and Anjar (1856) earthquake, and geomorphic features developed due to these were also studied.

The spatial and temporal distribution of the epicenters of the earthquakes and their relationship with the tectonic elements of the area throws light on the relative activeness of the segments of KMF and nature of their movement. Various transverse faults were developed in the process of northward journey of the subcontinent and reactivated while accommodating the stress exerted on the sub-plate after the locking of the Indian plate with the Eurasian plate. These transverse faults have segmented the Mainland block and strike slip component of the movement along these faults has shaped the arcuate boundary of the northern fringe of the Mainland, in contact with Rann.

Preface to the Study area

Location and Accessibility

The Kachchh Peninsula, which comprises the Kachchh district of Gujarat, is located between latitudes 22.72°-24.68° N and longitudes 68.10°-71.80° E, in the western most part of India (Fig. 1.1). The district occupies an area of 45,612 sq km, it has length and width of about 320 and 170 km respectively, and the Tropic of Cancer passes through the district. The delta land of Sindh (Pakistan), borders it in the west. Its long southern margin is shared by the Gulf of Kachchh, which separates the peninsula from Saurashtra. Its northern margin makes the International border with Pakistan and the eastern margin abuts against the Gujarat Mainland. The district has a population of 20.9 lakhs (Census, 2011) inhabiting about 949 villages in ten Talukas (Census of Housing 2001).

The study area is confined to the region of the Kachchh Mainland Fault, popularly known as KMF. KMF runs from near Vondh in the east and passes through Bhachau - Dudhai - Khirsara - Jawaharnagar - Lodai - Loriya - Nirona -Chari up to Lakhpat in the west (Fig.1.1 & 1.2). The study area falls in Survey of India toposheet nos. 41 I/7, 3, 41 E/15, 11, 6, 7, 2 and 41 A/13, A/9 from east to west respectively. The nearest town is Bhuj, the district headquarter, which is about 415 km west of Ahmedabad. Bhuj is well connected by railways, National Highway and Airport. The area of investigation is well connected with Bhuj by Bhachau-Bhuj, Bhuj-Gandhidham, Bhuj-Nakhatrana-Lakhpat and Bhuj-Bibar state highways. Besides, there are several fair-weather roads giving reasonable accessibility to the study area.

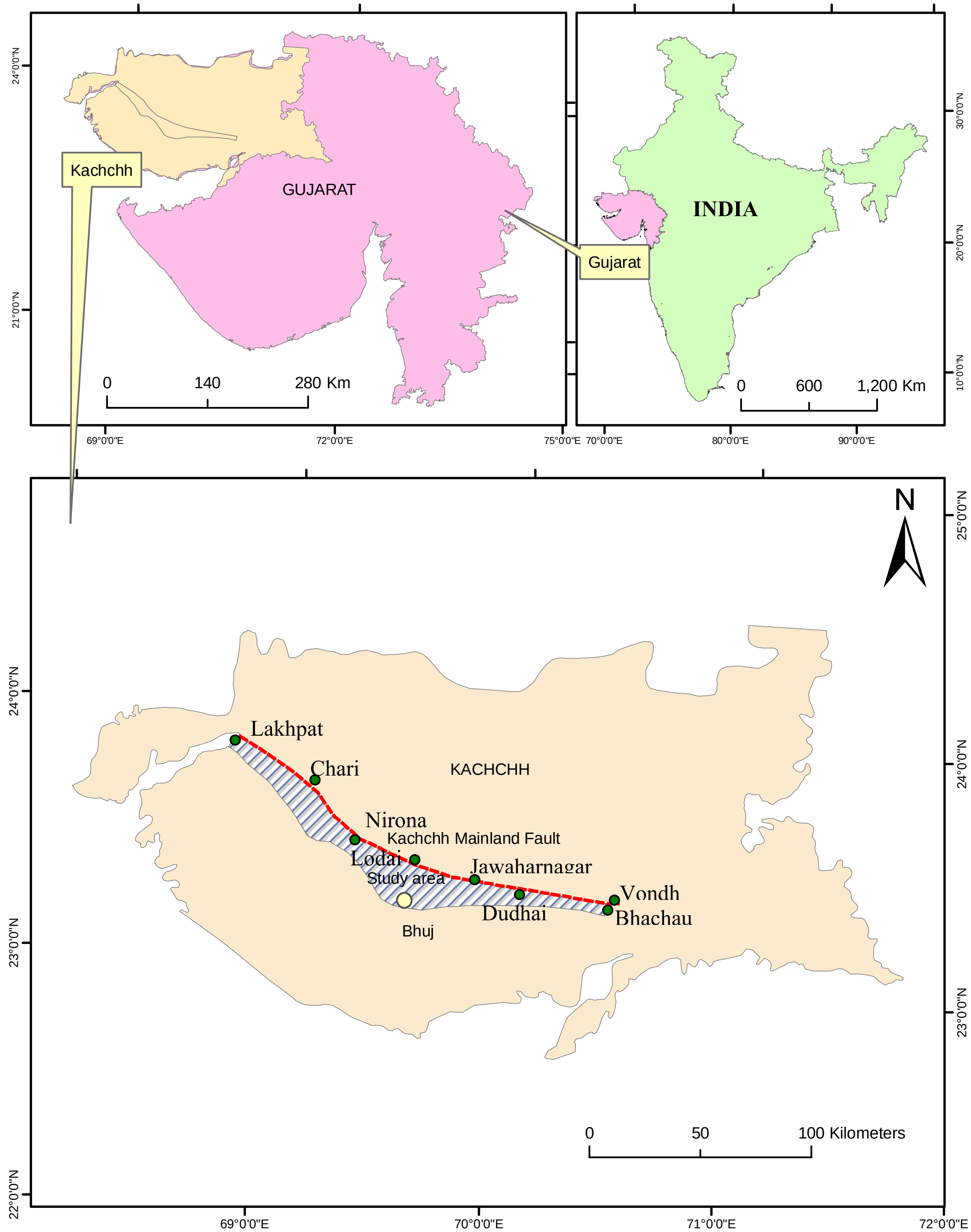


Fig.1.1: Location map of the Study area.

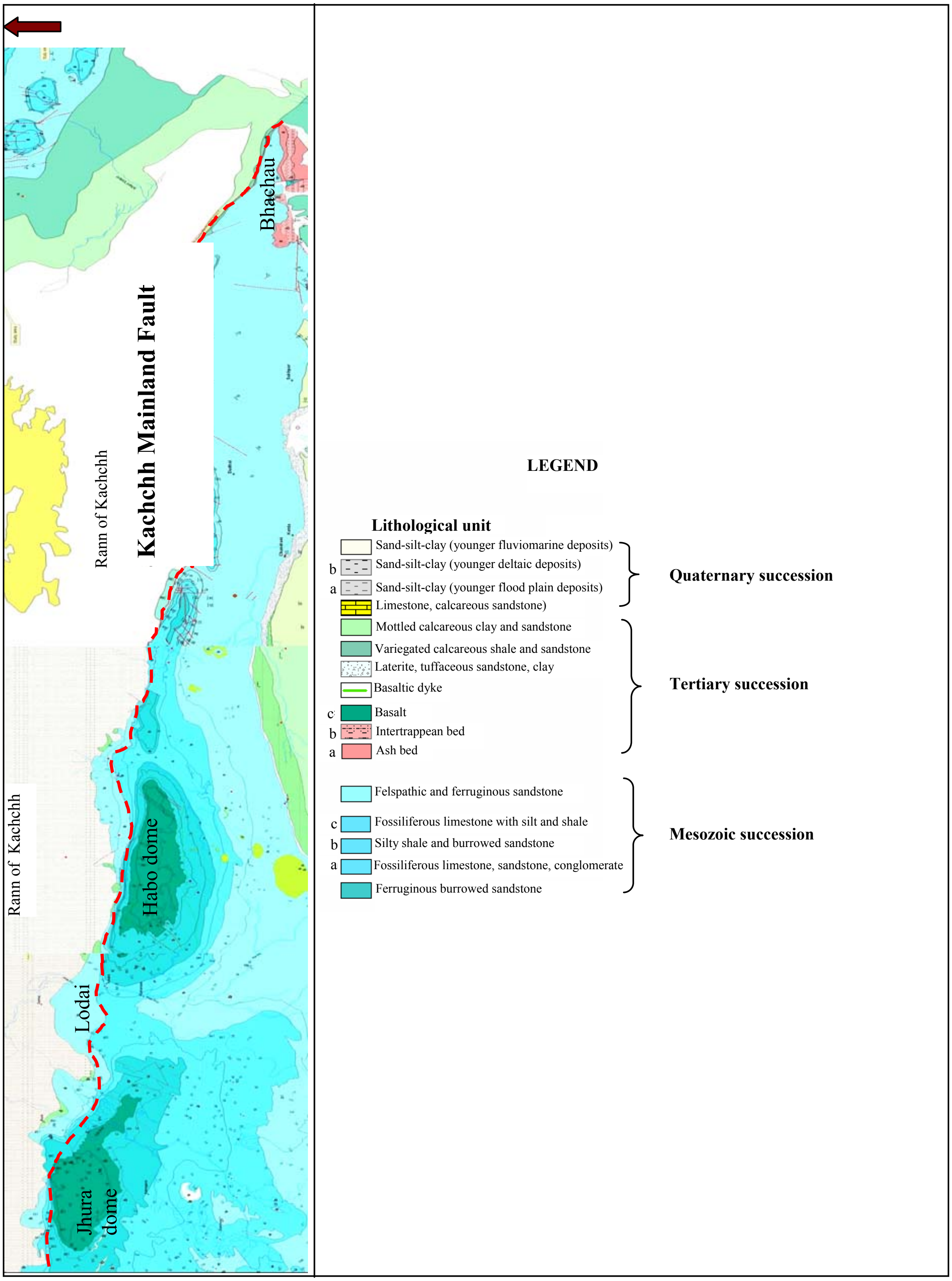


Fig. 1.2: Geological map of the area around Kachchh Mainland Fault (Generalized after Singh et al., 2008).

Climate

Gujarat lies in the tropical region however its proximity to the Arabian Sea reduces the climatic extremes and makes the climate more pleasant, comfortable and healthy. Kachchh region is characterized by arid climate (Fig. 1.3). The tropic of cancer passes through Kachchh. The area is far from the rain bringing influence of the monsoon. The monsoon prevails for a very short period (June-August) with a meager rainfall, which too is erratic (Fig. 1.4). Summers are scorching hot (Fig. 1.5). Hot gusty wind with finer sand makes the sky pale brown in summer storms. Sandstorms are common and obscure visibility beyond a few meters at times. Winter, especially during the months of December and January, is severe with mercury often dipping to 8°C or less (Fig. 1.3). Diurnal variation in temperature can be as large as 20°C. Humidity is less than 25%.

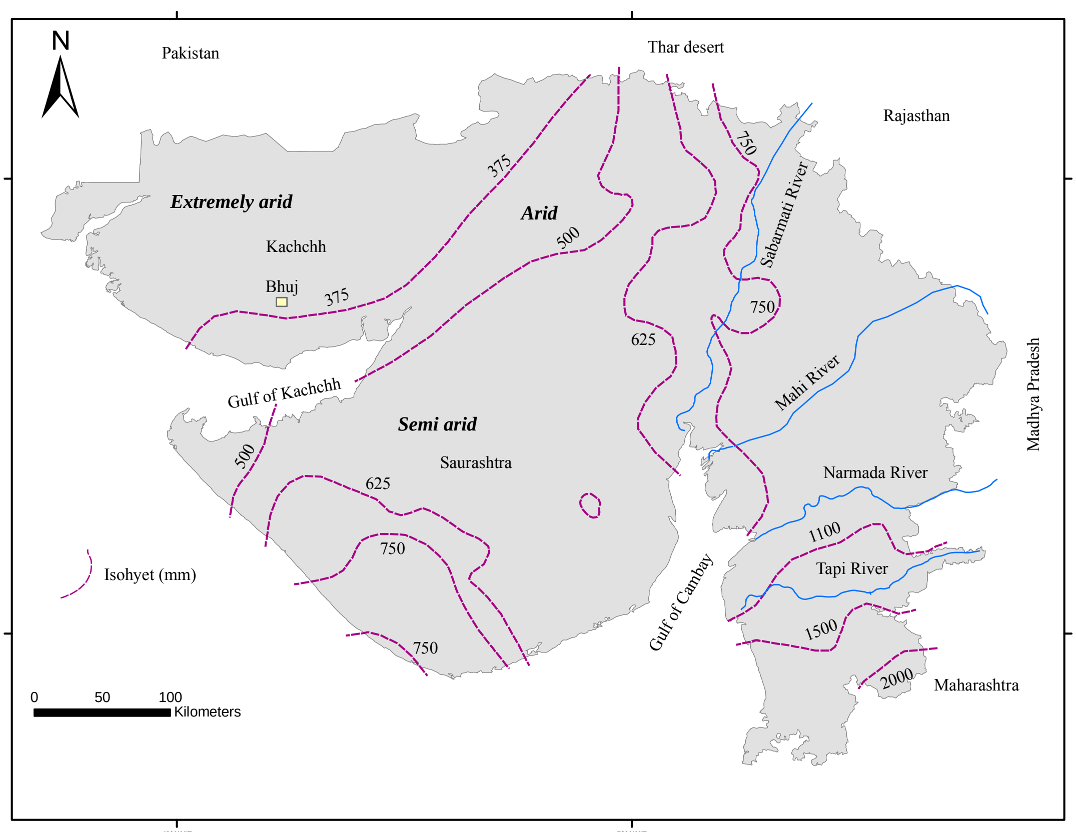


Fig.1.3: Map showing major physiographic divisions, isohyets and climatic zones of Gujarat (after Singh et al., 1991 and Department of Agriculture, Government of Gujarat).

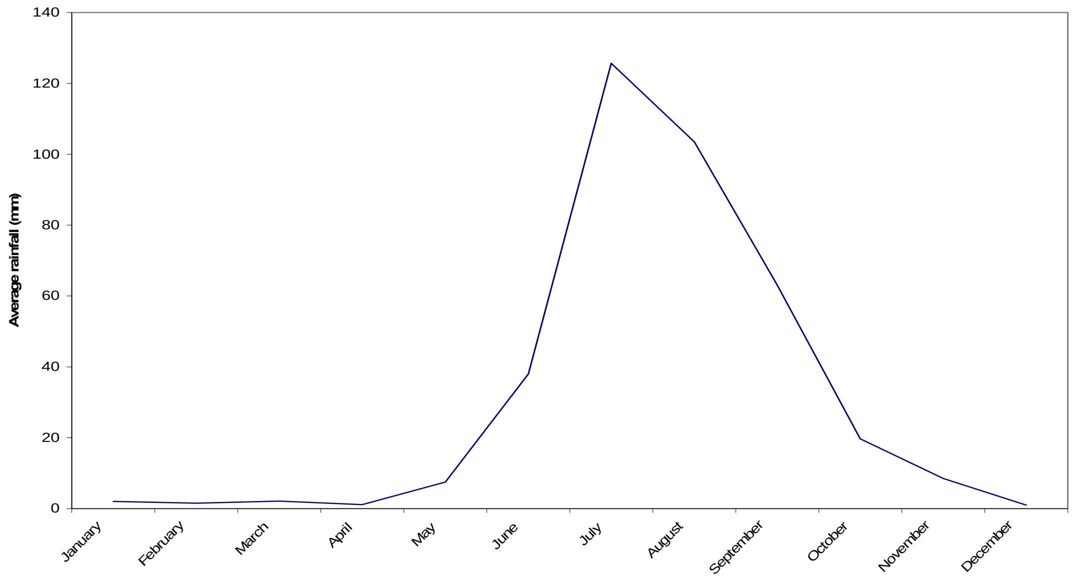


Fig.1.4: Graph showing average month wise rainfall in Kachchh district.

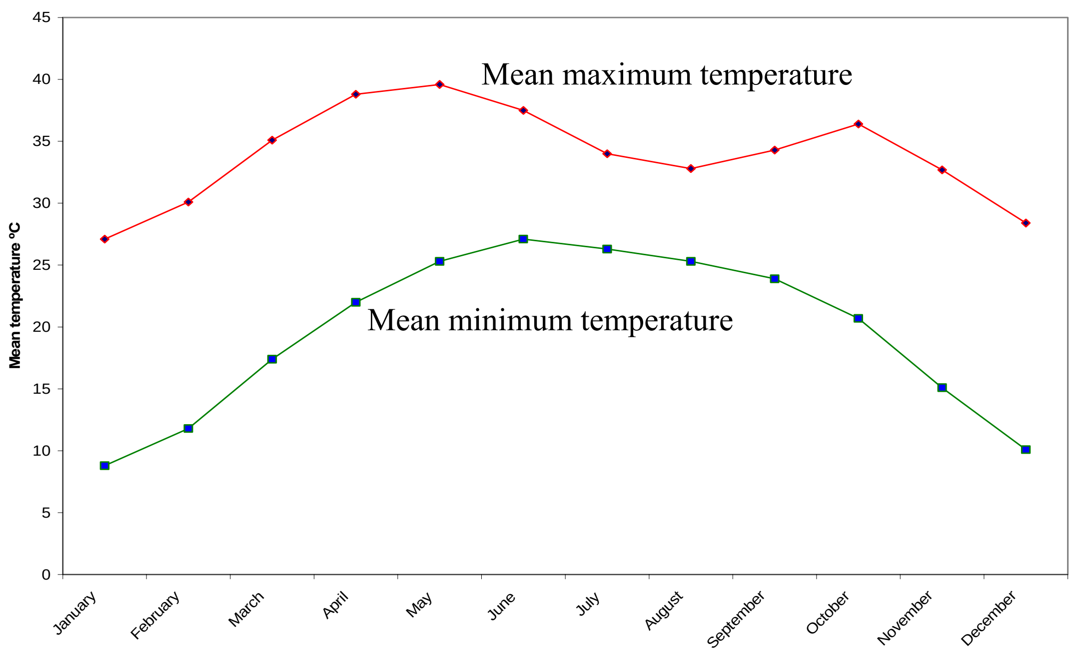


Fig.1.5: Graph showing average month wise temperature in Kachchh district.

Flora and Fauna

The most conspicuous vegetation in the area is cactus. Wild grass, bushes as well as wild maize are also found. There is a luxuriant growth of Acacia in the vicinity of check dams and local water bodies. In general, the area is devoid of trees. Local inhabitants cultivate jowar, maize, wheat, vegetables and pulses in the plains.

Jackals, rabbits, scorpions and snakes are very common. Antelopes are also seen at some places. Little Rann is famous for its wild ass sanctuary. Wild ass and peacocks are seen in other area as well. Siberian crane and flamingos are reported to be the migratory birds, which visit the marshy lands of Rann during the December to March. Gujarat state has less than 10% forest area of its total land cover. Gir forest in Gujarat is the only abode of Asiatic lions in the world.

Physiography and drainage

Gujarat State with an area of 1,96,077 sq. km lies in the western part of India with a coastline stretching over 1600 km along the Arabian Sea. The engulfing Sea has physiographically divided the state into three units the Kachchh, Saurashtra and Mainland Gujarat. The Kachchh region is a very good example of a landscape, controlled by tectonics and whose physiographic features are the demonstration of the earth movements along the tectonic planes of the Pre-Mesozoic basinal arrangement that was produced by the primordial faults in the Precambrian basement (Biswas, 1971; 1974). Topographically, the Kachchh region is made up of east-west trending hill ranges i.e. the Island belt, the Kachchh Mainland and the Wagad. The hill ranges in each of these areas are separated by large tracts of low ground. 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. Taking into consideration the factors like general slope, elevation and ruggedness of surface, Kachchh has been divided into four physiographic units from north to south direction, namely, the Rann, the Banni Plain (low lying areas), the Hilly tracts, and the Coastal Plains in the South (Fig. 1.6 to 1.8). These four units demonstrate significant diversity within each of them, on the basis of the lithology, their pattern of occurrences and orientation of faults. The highest peak in Kachchh is that of Kaladongar (Δ 465 m) in the Pachchham Island (Fig.1.9). Among various peaks in the Kachchh Mainland the Nanadongar showing the maximum altitude of 430 m. The Rann of Kachchh gets submerged during rainy season which is otherwise completely dry.

The main rivers of the Mainland Kachchh are Kankawati, Kharod, Rukmawati, Phot, Lerakh and Song, which originate from the central Mainland, flow towards south and debouch into the Arabian Sea; whereas the Kaswali, Pur (Khari), Kaila, Nirona (Trambo) and Charee Rivers originate from the northern part of the central Mainland, flow towards north across the KMF and debouch into the Rann making conspicuous alluvial fans. The Kankawati, Kaswali, Kharod, Rukmawati, Pur and Nirona Rivers have broad channels in general and show vertical cliffs on banks in lower reaches. The Pur (Khari) River is showing meandering between east of Bhuj to Rudramata whereas the Kaila River shows entrenched meandering in the south of Jhura dome. The Dhrung and Kaswali Rivers show high vertical cliffs (10-15 m) with boulder beds above the current base level.

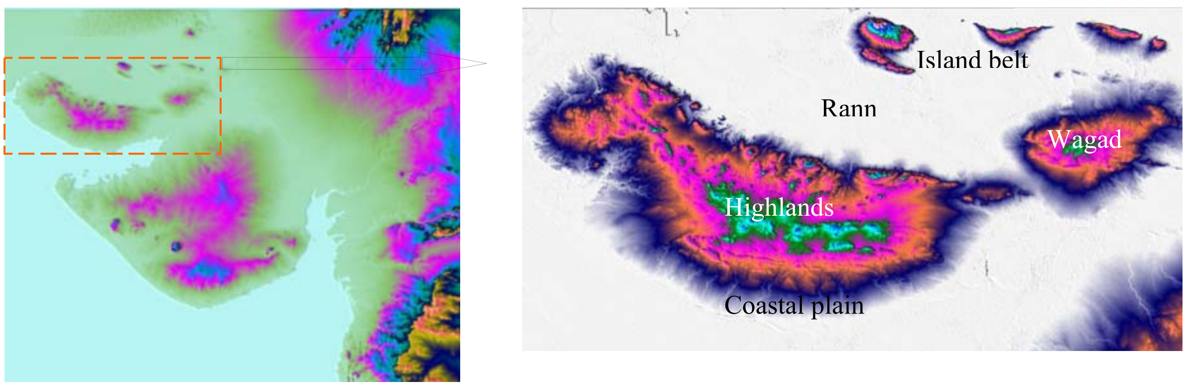


Fig.1.6: DEM of Gujarat showing general physiography of Gujarat and Kachchh region.

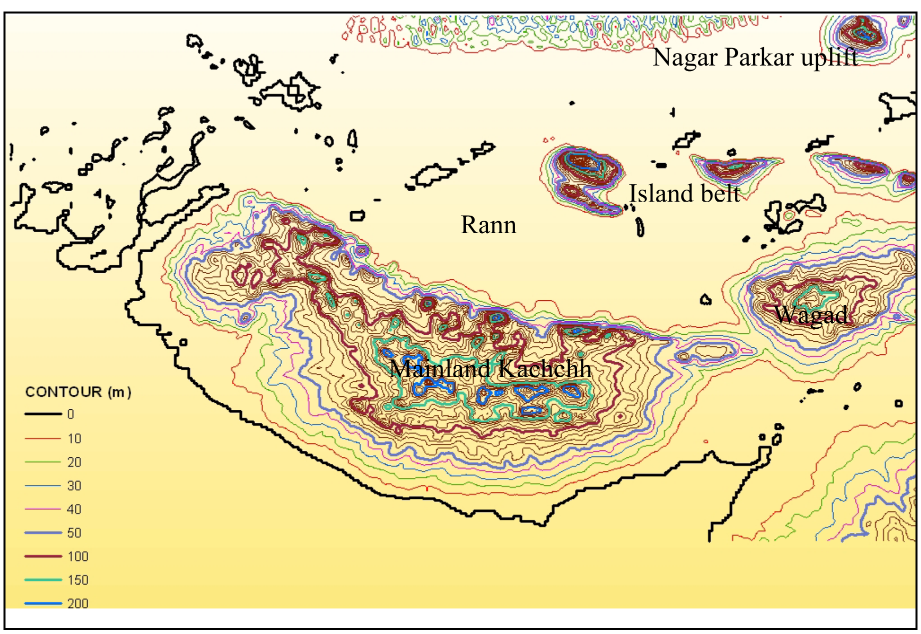
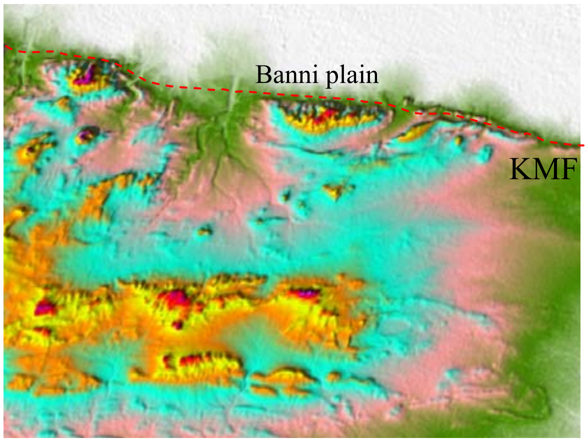


Fig. 1.7: SRTM generated contour map of the area showing topography.



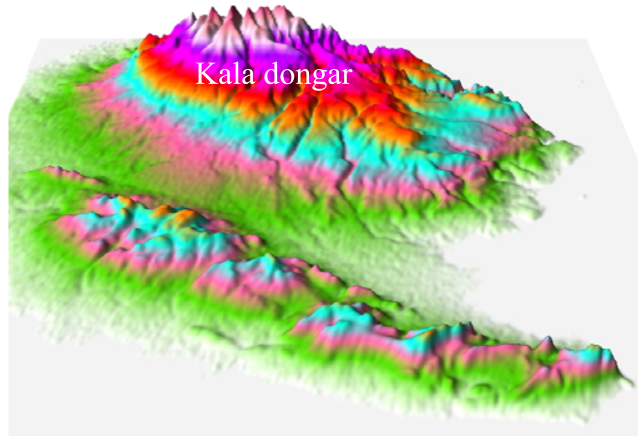


Fig.1.8: DEM of the area around the eastern part of Kachchh Mainland Fault.

Fig.1.9: DEM of Khadir Island (height exaggerated).

Previous work

The Kachchh region has attracted the attention of geo-scientists since long due to its unique exposures of Mesozoic rocks and their rich fossil records. The first comprehensive geological report on Kachchh was prepared by Grant (1840) in which he gave a complete description of the area and collected invertebrate fossils, which were studied by Sowerby (1840). Wynne (1872) is another pioneer worker who gave a detailed account of geology of Kachchh with a quarter-inch map. He classified the Mesozoic sediments of Kachchh into two major units i.e. marine and non-marine. Waagen (1875) studied the ammonites and correlated them with known European Zones to fix their age and gave four fold classification of the Mesozoic rocks into Patcham, Chari, Katrol and Umia in ascending order. Since then this four fold classification has been adopted widely with modifications from time to time. Subsequently Gregory (1893), Spath (1933), Cox (1940) added information about the area especially on invertebrate fossils.

Rajnath (1932) modified the classification by distinguishing Bhuj stage and later on established it separate as Bhuj Series. He subdivided Katrol Group into Lower, Middle and Upper Stages. Agrawal (1957) proposed Habo Series to replace the Chari Series from the four fold classification of Waagen (1875). He also suggested Mebha oolites for Dhosa oolite beds but these suggestions were not accepted by subsequent workers. Mitra & Ghosh (1964) carried out biostratigraphic work in Jhura dome area and gave more importance to brachiopods. He suggested that the brachiopod assemblage zone should be used for correlation and classification instead of ammonite zones.

Biswas (1971, 74) proposed a comprehensive lithostratigraphic classification of Mesozoic and Tertiary rocks of Kachchh in accordance with the code of stratigraphic nomenclature of India. He subdivided the Mesozoic rocks in to Jhurio, Jhumara, Jhuran and Bhuj Formations in ascending order. Biswas (1987) has discussed the sequential development of the Kachchh basin and its regional tectonic framework. The Jhurio, Jhumara and Jhuran Formations in Biswas' classification approximately correspond to Patcham, Chari and Katrol Formations of Waagen respectively. Lower part of Umia series of Waagen is included with Jhuran Formation of Biswas. He included the non-marine sequence with Bhuj Formation and the boundary between Jhuran and Bhuj Formation is based on first appearance of Iron Formation or last appearance of calcareous sandstone. Biswas (1982) has brought into play a unique feature in the Kachchh, a meridian high across the basin. The sediment thickness along with the facies present indicates that this high was developed in late Oxfordian time. Biswas (1987, 2005) has described the regional tectonic framework, structure, tectonics and the evolution of the Kutch basin, with special reference to earthquakes in detail. Biswas and Khatri (2002) have worked out a geological model to explain the cause of earthquake rupture nucleation.

Ghevariya et al. (1982, 1984), Ghevariya (1985) and Ghevariya and Srikarni (1987, 1991) have extensively carried out mapping in the area and added valuable information about the stratigraphy and paleontology of the area.

The various workers like Srivastava, (1964); Biswas, (1980, 1982); Biswas and Deshpande, (1970) and Sharma, (1990) recorded many structural elements which played major role in the post-Mesozoic geomorphological and geological evolution of the Kachchh Mainland.

Rajendran et al. (2001) described the coseismic surface features resulted due to 2001, Bhuj earthquake and their significance. They describe that the main rupture generated due to the Bhuj earthquake did not reach the surface but several secondary features were developed on the surface, like folds and flexures, which helped them to characterize the epicentral area in the Banni Plain.

Chamyal, et al. (2003) described fluvial systems and landscape of the dry lands of western India. They synthesized data on the fluvial systems of Mainland Gujarat, Saurashtra and Kachchh to evaluate the roles of geological factors in the evolution of these dry lands. They have recorded marine sediments of the interglacial (~125 ka) and post-glacial maximum (6 ka) above sea level, marking transgressed phases of the sea. Maurya, et al. (2002) have investigated the Quaternary Geology of the arid zone of Kachchh in detail and suggested that Late Quaternary sedimentation and geomorphic evolution of Kachchh have followed regional pattern of palaeoenvironmental and tectonic changes. Maurya et al. (2006) investigated two large closely spaced sand blow craters of different morphologies using Ground Penetrating Radar (GPR) with a view to understand the subsurface deformation, identify the vents and source of the vented sediments. The study comprises velocity surveys, GPR surveys along selected transect that is supplemented by data from trenches excavated. Study of seismic aspects of the region has been attempted by number of workers like Johnston, 1989, 1996; Chung and Gao, 1995; Rajendran et al., 1998; Sohoni and Malik, 1998 which are based on palaeoseismological studies.

Sedgeley et al. (1997) reported that a seismic survey reveals an asymmetrical graben with its axis near the Kachchh Mainland Fault and named it as the Banni Graben. General trend of this bathymetric low is ENE-WSW, which corresponds with the proposed Banni Graben. This graben was supposed to provide a channel for supply of sediments from the Indus River. Historical accounts say that the Great Rann was under water as recently as till 712 A.D. On the account of Alexander’s historian, Periplus, during the Alexander’s military raid to India (325 B.C.), it is clear that the Rann was navigable at those times (Sivewright, 1907). Periplus describes that Alexander sailed south to Arabian Sea through Nara, which is a branch of Indus but dry now, between 22°45N' to 24°00’N and 68°30'E to 71°00’E. He describes some islands in the area which may be the Island belt of the present times. Many important aspects of the Rann have been described by many workers from time to time (Frere, 1870; Glennie et al. 1976; Roy and Merh, 1977, Gupta, 1975; Ghosh, 1981 and Merh, 2005).

The Geological Survey of India (GSI) has been carrying out macroseismic survey (post-earthquake damage surveys for assessment of intensity) of earthquakes. An intensity map of 2001 Bhuj earthquake was prepared by GSI (Pande et al., 2003). Kayal et al. (2002)

conducted an aftershock investigation of 2001, Bhuj earthquake. A micro earthquake network with 12 stations was set in operation in the main shock epicentral area which consequently recorded more than 3000 aftershocks of magnitude 1 and above during the period from 28th January to 15th April 2001. The epicenter map of the 450 events showed a cluster area between latitudes 23.3°-23.6°N and longitudes 70.0°-70.6°E. It reflected the rupture area of the main shock at depth. Waveform modeling of the main shock, however, revealed a rupture dimension of 90 km × 30 km. The estimated focal depth of the Bhuj earthquake was at 25 km. The main shock could not be correlated with the KMF, which is dipping to the north. The main shock was generated by a south dipping hidden fault, and it is inferred that it propagated along a major rupture trending NE-SW direction and a conjugate rupture along the NW-SE direction. Both the ruptures occurred simultaneously. Based on the fault plane solutions, there were many interesting observations. The NW trending inferred fault showed reverse faulting with a right lateral slip at shallower depths of 2 to 8 km. At depths of 15 to 25 km, the solution showed pure reverse faulting, with no strike-slip component (Kayal et al., 2002b).

Based on their studies Thakkar et al. (1999, 2006) and Maurya et al. (2002, 2003) constructed a Quaternary stratigraphy and tectonic evolution of Mainland Kachchh, respectively and emphasized that the Quaternary tectonic uplift took place in two major phases. The Early Quaternary tectonic activity took place along the E-W trending faults while the Late Pleistocene phase took place along the NNE-SSW to NNW-SSE trending transverse faults. The E-W trending faults were more active during Early Quaternary, as evidenced by miliolites overlapping the colluvial deposits along the Katrol Hill Fault (Thakkar et al., 1999). This geometry suggests that the present configuration of the landscape came into being during the Early Quaternary due to differential uplift along E-W faults, *viz.* the Kachchh Mainland Fault and Katrol Hill Fault. The Early Quaternary physiographic setting has been modified by the Late Pleistocene-Holocene tectonic activity along transverse faults (Thakkar et al., 2001).

CHAPTER 2

GEOLOGY AND STRUCTURE

Regional Geology

The geology of Kachchh Peninsula is very intriguing as it comprises rocks ranging in age from Jurassic to Recent and the basement rocks are not exposed (Fig.2.1). However the basement rocks occur to the north of Kachchh in Nagar Parkar area which lies in Pakistan (Biswas, 2005). The Mesozoic rocks of Kachchh have attracted the attention of geologists from world over mainly because of exceptionally rich fossil records of Jurassic Period. The Mesozoic rocks range in age from Middle Jurassic to Late Cretaceous (GSI, 2001) and are bordered by the Deccan Traps to the south and by saline marsh of the Rann of Kachchh to the north. Based on the fossil assemblage and petrographic characters, these rocks have been identified as representing a near-shore, shallow marine deposits fluctuating from neritic, lagoonal to littoral environments (Biswas, 1971; GSI, 2001). The Tertiary rocks of the Kachchh basin are known for their economic importance. They have yielded good quality limestone, clay, lignite and bauxite deposits. Rann of Kachchh is also getting importance due to its salt and brine producing capabilities.

Waagen et al. (1875) subdivided the Mesozoic rocks of Kachchh into Patcham, Charee, Katrol and Oomia Groups and correlated them with the European equivalents. However, a much more comprehensive account of the Mesozoic stratigraphy of Kachchh was proposed by Rajnath (1932) and Krishnan (1982). Krishnan (1982) classified the Mesozoic succession of Kachchh as presented in Table 2.1.

Table-2.1: Jurassic Succession of Kachchh (after Krishnan, 1982)

Unit	Age	Sub-division	Lithology
UMIA (1000 m)	Post-Aptian	Bhuj beds (Umia Plant beds)	Sandstone and shale
	Aptian	Ukra beds	Marine calcareous shale
	Upper Neocomial	Umia beds	Barren sandstone and shale
	Valanginian	Trigonia beds	Barren sandstone
	Upper Tithonian	Umia ammonite beds	Shale and sandstone
KATROL (300 m)	Middle Tithonian	Upper Katrol Shales	Shale
	Middle Tithonian	Gajansar beds	Shale
	Lower Tithonian	Upper Katrol (Barren)	Sandstone
	Middle Kimmeridgian	Middle Katrol	Red sandstone
	Upper Oxfordian	Lower Katrol	Sandstone, shale, marl
CHARI (360 m)	Oxfordian	Dhosa Oolite	Green and brown oolitic limestone
	U. Callovian	Athleta beds	Marl and gypseous shale
	Middle Callovian	Anceps beds	Limestone and marl
	Middle Callovian	Rehmani beds	Yellow limestone
PATCHAM (300 m)	Lower Callovian	Macrocephalus beds	Shales with calcareous bands and golden oolites
	Lower Callovian	Coral bed	Shale and limestone
	Lower Callovian to Bathonian	Patcham shell limestone Patcham basal beds (Kuar Bet beds)	Limestone, shale and marl

Biswas (1971) while revising the stratigraphy of Kachchh proposed new nomenclature and classified the Mesozoic rocks of Kachchh into Jhurio, Jumara, Jhuran and Bhuj Formations corresponding to Patcham, Chari, Katrol and Umia Groups / Series of Waagen (1872, 1875), Rajnath (1932) and Krishnan (1982). The revised Mesozoic stratigraphy of Kachchh as given by Biswas (1971) is presented in Table-2.2.

Table-2.2: Mesozoic Stratigraphy of Kachchh (after Biswas, 1971)

Age	Litho-Unit	Lithology	Environment
I. Kachchh Mainland			
Cretaceous (Neocomian to Santonian)	Bhuj Formation (400 – 900 m +)	**Upper Part:** Coarse grained, felspathic sandstone **Lower part**: Brown and reddish felspathic sandstone, ironstone and kaolinitic shale	Fluviatile to deltaic
Argovian to Neocomian	Jhuran Formation (375 – 850 m)	**Upper Member**: Pink and yellow sandstone with minor shale **Middle Member**: Grey shale with thin sandstone **Lower Member:** Shale and sandstone with calcareous bands	Infra-littoral
Callovian to Oxfordian	Jumara Formation (300 m)	Grey gypseous shale with thin oolitic marl bands (Dhosa Oolite bands)	Sub-littoral
Upper Bathonian to Callovian	Jhurio Formation (325 m +)	**Upper part:** Bedded white limestone with Golden Oolite in the lower part. **Middle part**: Golden Oolite limestone with shale **Lower part**: Thinly bedded limestone, shale and Golden Oolite limestone	Sub-littoral
II. Pachchham Island:			
Callovian	Goradongar Formation (150 m +)	**Upper part:** Sandstone with minor shale **Lower part**: Sandstone, conglomerate, shale	Sub-littoral
Bathonian	Kaladongar Formation	**Upper Part:** Yellow-massive sandstone with calcareous beds **Lower part:** Sandstone, shale and conglomerate	Littoral
III. Eastern Kachchh:			
Argovian to Albian	Wagad Sandstone	Brown, current bedded felspathic sandstone with ferruginous bands and shale	Sub-littoral
Bathonian to Oxfordian	Khadir Formation	Shale and sandstone with wedges of granite cobble-conglomerate	Littoral to infra-littoral

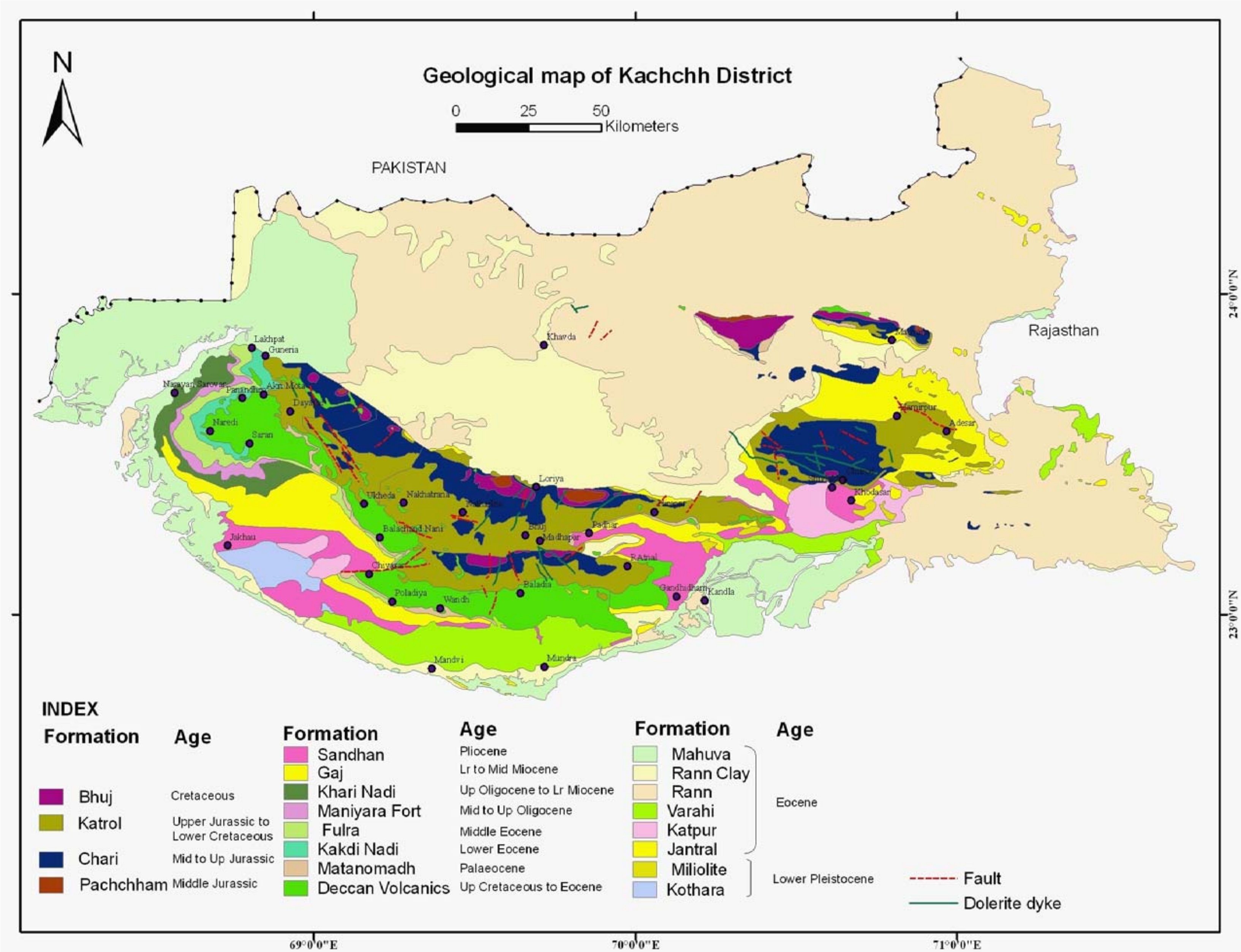


Fig. 2.1: Geological map of Kachchh (modified after GSI, 2001).

Later, Ghevariya (1987), Ghevariya and Srikarni (1991) and Ghevariya et al. (1984), provided details on these rocks retaining nomenclature of Waagen (1872), Rajnath (1932) and Krishnan (1982). The description of each of the four different formations representing the Mesozoic rocks of Kachchh along with their broad equivalents based on the classification of Biswas (1971) is given in the following pages:

Pachchham Formation

Pachchham (also spelt as Patcham) Formation is named after the Pachchham Island in the Rann of Kachchh. This is roughly equivalent to the Jhurio Formation of Biswas (1971). It is about 400 m in thickness and is exposed in parts of Pachchham (Kuar Bet, Kaladongar and Goradongar), Khadir, Bela and Chorar Islands. Pachchham Formation comprises intercalated sequence of siltstone, shale, marlite, claystone, coralline limestone, calcareous sandstone and grey to pink limestone. Small outcrops of these rocks are also seen at Jara, Kira, Jumara and Habo domes in the northern edge of Mainland Kachchh and south of Kachchh Mainland Fault. It extends from Lakhpat in the west to the north of Bhachau in the southeast. The formation is divisible into three litho-stratigraphic units (Krishnan, 1982). The basal unit, comprising calcareous sandstone, siltstone, and coralline limestone, is exposed in Kuar bet and Chhapri bet areas. These rocks have yielded rich assemblage of bivalves, brachiopods, cephalopods, corals (mainly solitary and sedentary forms) and dinosaurian bone fossils (Ghevariya, 1987; Jaitly, 1986). The basal unit is overlain by a sequence of shale with intercalations of limestone, thickly-bedded calcareous sandstone and conglomerate. These rocks also contain bivalves and a rich assemblage of corals and brachiopods (GSI, 2001). The uppermost unit comprises shale and limestone. Siltstone is exposed in southern part of Kaladongar and northern part of Goradongar. These rocks contain corals, cephalopods and bivalves (GSI, 2001).

Chari Formation

Chari, spelt earlier as Charee, derives its name from village Chari and unconformably overlies the rocks of the Pachchham Formation. This formation is roughly equivalent to the Jumara Formation of Biswas (1971). Rocks of the Chari Formation are exposed in the southern parts of Kaladongar and Goradongar ranges in Pachchham Island, southern part of Khadir in the Rann of Kachchh and in the northern part of Wagad highland. The rocks of the Chari Formation are exposed as inliers and lenses along the axis of East-West trending domal anticlinal ridges (south of Kachchh Mainland Fault) at Jara, Jumara, Jhura, Habo and other domes (GSI, 2001, Biswas, 1974). The other lensoid outcrops occur in Charwar and in other ridges located immediately south of the Katrol Hill Fault. KHF brings the rocks of the Chari Formation in juxtaposition with the rocks of the Bhuj Formation, near Sukhpar and Madhapar. It comprises about 350 m thick sequence of fossiliferous shale, golden oolite, fossiliferous limestone and calcareous sandstone containing ferruginous and calcareous nodules with ammonite fossils (Waagen, 1875). The Chari Formation is subdivided into four units based on lithology. The basal unit comprises a sequence of shale, siltstone and thinly-bedded sandstone alternating with golden oolite bands around Jara, Jhura, Jumara, Khirsara and Habo domes (Krishnan, 1982). These rocks contain bivalves, brachiopods, cephalopods, gastropods, corals and plant fossils (GSI, 2001; Jaitly, 1986). This unit is partly developed in Pachchham Island on the southern slopes of Kaladongar and Goradongar ranges and is about 25 m thick. The overlying second unit, about 100 m thick, dominantly comprises thickly-bedded, argillaceous sandstone with ocherous nodules bearing ammonites in lower section and forming minor cuesta with steeper slopes in northwestern part of Lakhpat, Jumara and Nara areas (GSI, 2001). The third unit, which is about 80 m thick, forms depressions and low-lying areas and comprises shales with calcareous nodules encasing fossils within gypseous layers. It forms relatively low ground with scattered low mounds. This unit laterally passes into the rocks of arenaceous character in central Kachchh. The youngest unit has variable thickness. Thickest exposed section (about 40 m) is seen around Sukhpar. It comprises alternate sequence of olive green oolites, gypseous shale, siltstone and greenish sandstone.

Katrol Formation

The rocks of the Chari Formation are unconformably overlain by about 400 m thick intercalated sequence of gypseous shale with cyclically repeated sequence of calcareous sandstone and shale, constituting the Katrol Formation, which roughly corresponds to the Jhuran Formation of Biswas (1971). Rocks of this formation are exposed in the form of two sub-parallel continuous exposures in the Mainland Kachchh. The first one forms a vast northwest-southeast trending outcrop from Guneri to Jhura which extends eastward up to Khirsara. The other one extends from Deshalpar to Malingara and south of Katrol Hill Fault in central part of Kachchh Mainland. These rocks are also exposed in the Wagad Mainland and in the Island belt. The Katrol Formation is divisible into four lithostratigraphic units (Krishnan, 1982). The basal unit comprises intercalated sequence of grey, gypseous shale and siltstone with ocherous nodules. The second unit is dominantly calcareous sandstone with intercalations of shale in the western Kachchh, which passes into dominantly argillaceous facies in east central Kachchh. These units contain rich assemblage of pelecypods, gastropods, ammonites and fossil wood (Ghevariya, 1987; Pandey and Westermann, 1988). The third unit comprises a dominantly gypseous shale horizon with minor silty and sandy intercalations and ocherous bands. The black shale horizon of this unit contains Upper Gondwana plant fossils, fossil fruits, cones and fronds along with shells of Trigonia and other bivalves (GSI, 2001). The uppermost unit forms conspicuous ridges at the periphery of domes at Guneri, Jara, Jumara, Jhura and Habo and in the southern vicinity of Katrol Hill Fault. It comprises an 80 m thick sequence of hard, compact, calcareous, quartzitic-sandstone and conglomerate intercalated with lenses of shale and burrowed siltstone. The intercalated sequence, at times, becomes very thick and forms transitional zone between the rocks of the Katrol and the overlying Bhuj Formation. This transition zone has been included as a part of Katrol Formation. The calcareous sandstone contains dinosaurian bone fossils, footprints and foot tracks of dinosaurs near Tharauda (Ghevariya, 1987).

Bhuj Formation

The rocks of the Bhuj Formation include the Umia Group of Waagen (1872) and are named after Bhuj Township. It unconformably overlies the rocks of the Katrol Formation in the western Mainland Kachchh and forms a thick sequence of friable, felspathic and ferruginous sandstone showing graded-bedding, ironstone, clays and trap-pebble conglomerates with many fossiliferous horizons (Ghevariya, 1985; Singh et al., 2008). These rocks are exposed in the form of continuous outcrop in the Mainland Kachchh with a maximum width between Lakhmipur and Roha. This outcrop extends from Guneri in the northwest to Deshalpar in the southeast, where it takes a turn and extends further up to Khirsara (GSI, 2001). A continuous and broadly elliptical exposure, bordering the Katrol Formation, extends from Andhon in the west to Fatehgarh and Deshalpar in the north. Besides this, small isolated outcrops occur in Pachchham Island, Goradongar and Kaladongar, Bela and Mardek Islands as inliers within younger volcanics and Tertiary rocks (GSI, 2001). In the east, a thick intervening transitional zone has developed in central Kachchh. The rocks of the Bhuj Formation contain a rich assemblage of Upper Gondwana plant fossils and many intervening fossiliferous marine bands, in the western and central parts (Rajnath, 1932). The Bhuj Formation is sub-divided into three members (i) lower- Guneri Member, (ii) middle- Ukra Member (limited to Guneri-Ukra area) and (iii) Upper Member (Krishnan, 1982). The Guneri Member comprises cyclically repeated intercalated sequence of burrowed ferruginous gritty sandstone, grey and black, carbonaceous shale and siltstone with coal partings. The ironstones and shales show rhythmic alternations. The ferruginous sandstone and shale contain tracks and trails of various invertebrates. Dinosaurian footprints are recorded from ferruginous sandstone near Pakhera. The Ukra Member occurs as a lensoid marine intervention between the Guneri Member and the Upper Member of the Bhuj Formation in the Ukra area and comprises a sequence of about 30 m thick hard, lateritic ferruginous sandstone, conglomerate, green glauconitic clay, shale, siltstone green friable sandstone and bands of fossiliferous limestone (GSI, 2001). The Upper Member comprises a sequence of coarse, gritty, variegated sandstone, siltstone, fossiliferous shale and clay with ferruginous and ocherous bands. Most part of Bhuj sandstone includes sandstone of the Upper Member overlain by intercalations of trap-pebble conglomerate and sandstone forming part of volcano-sedimentary sequence. The rocks of Bhuj Formation are overlain by Deccan lava flows.

The Mesozoic sediments of north-western Kachchh show interstratified volcano-sedimentary sequence. Several intertrappean beds are recorded interstratified with the Deccan lava flows in Anjar area (Ghevariya, 1985; Ghevariya and Srikarni, 1987, 1991). Some of these intertrappeans contain skeletal remains of dinosaurian fossils (Khosla and Sahni, 2003).

Deccan Traps

The Deccan Traps are exposed mainly in the southern part of Kachchh along a 10-20 km wide belt trending NW-SE. They overlie the Bhuj Formation. Normally the flows are plateau-type tholeiitic basalts in the west at Dayapar and Matanomadh and are alkaline at Baladia, Anjar and Bhachau. However, occurrence of highly alkaline intrusive rocks like nephelinite, essexite, olivine analcite basalt within the Mesozoic is also reported from a few places (Melluso et al., 2006; Mukherjee et al., 1988). Nine flows have been reported from southern part, where the total thickness of the trap section amounts to 140 -150 m (GSI, 2001). At most of the places, the lava is of pahoehoe type. Numerous alkali-type and tholeiitic-type intrusives occur in the Mesozoic sediments and Deccan Trap flows. Gabbroic rocks and pyroxenite constitute the main alkali body at Nirwandh and Kuran with metallic sulphide disseminations. Dykes and apophyses of hornblendite, ankaramite, granophyre, trachyte, andesite and syenite are found at the outer margin of the main body. In Kachchh Mainland, mantle-derived peridotite nodules are also reported from the alkaline plugs at Bhuj, Vithoniya and Dinodhar (Mukherjee et al., 1988). These xenolithic peridotite nodules occur as oblate, ellipsoidal fragments with long axis up to 2.5 cm. These xenoliths are distinct with coarser grain size and characterized by deep bottle-green colour in comparison to host basalt (Guha, 1998). Crustal xenoliths are also present. Compositionally all plugs are similar, but on the basis of presence or absence of mantle xenoliths, two groups can be distinguished. The absence of mantle xenoliths in the plugs may be indicative of slow rate of emplacement. Tholeiitic-type of plugs and dykes are confined to the Kachchh Mainland and they comprise olivine basalt and dolerite (Mukherjee et al., 1988; Paul et al., 2007).

Tertiary Rocks

Almost all the Mesozoic outcrops are accompanied by Tertiary patches on their flanks in Kachchh region. Tertiary rocks of Kachchh are well known for their rich marine fossil assemblage. After the eruption of lava flows of the Deccan volcanic activity there was a period marked by a phase of extensive lateratization under tropical conditions. Subsequently, the Tertiary sediments were deposited over the Mesozoic sedimentary rocks and Deccan Traps along the coastal strip of the Kachchh Mainland (GSI, 2001). The first detailed study of this region was made by Wynne (1869, 1872). Wynne (1872) classified the Tertiary rocks of Kachchh mostly on the basis of abundant nummulitic fossils and lithology. The Tertiary formations of Kachchh consist of three distinct facies; the lower one is volcanic and is represented by the lavas of the Deccan Traps. The middle and main part is typical marine transgressional facies and represents stratigraphic unit equivalent to the Laki, Kirthar, Nari and Gaj Series of Sind-Baluchistan (Krishnan, 1982). The upper part is fluviatile and represents the stratigraphic unit equivalent to Manchhar Series of Sind-Baluchistan (Krishnan, 1982). The Tertiary rocks are exposed all along the western, southern and southeastern parts of Kachchh, extending from Lakhpat in the west to as far as Vondh in the east. Some isolated outcrops of these rocks occur in the northern and eastern parts of Kachchh Peninsula. The Tertiary rocks overlie the denuded laterites and traps, and at places these directly rest on the Mesozoic formations (Chatterjee and Mathur, 1966). The succession of Tertiary rocks as exposed in Kachchh is given in Table-2.3.

Table-2.3: Stratigraphic succession of Tertiary rocks of Kachchh (after GSI, 2001)

Age	**Formation**	**Lithology**
Pliocene	Sandhan Formation	Friable sandstone, siltstone, calcareous clay and conglomerate
Lower to Middle Miocene	Gaj Formation	Olive green shale with gypsum and marlite
Oligocene to Lower Miocene	Kharinadi Formation	Mottled siltstone and variegated clay with marlite
Oligocene	Maniyara Fort Formation	Sandy limestone, glauconitic clay, siltstone and coralline limestone
Middle to Upper Eocene	Fulra Formation	Cream coloured foraminiferal limestone
Lower Eocene	Kakdinadi Formation	Greyish to variegated clay, carbonaceous and lignite bearing shale with fossiliferous marlite and limestone
Palaeocene	Matanomadh Formation	Lithomarge clay, laterite and lateritic conglomerate
Cretaceous to Eocene		Basalt

The oldest Tertiary rocks directly overlying the Deccan Traps belong to the Matanomadh Formation of Palaeocene age. This formation comprises laterite, lateritic conglomerate and lithomargic- and bentonitic clay, followed by gypseous and pyritous sandstone. The overlying Kakdinadi Formation (Lower Eocene) consists of greyish to variegated clay and shale with limestone bands rich in Nummulites (Biswas, 1992). The Fulra Formation (Middle to Upper Eocene) which overlies the Kakdinadi Formation comprises cream coloured limestone with abundant foraminifers. The Oligocene is represented by the overlying Maniyara Fort Formation, which consists of sandy limestone, coralline limestone, glauconitic clay, marl and siltstone (Ghevariya et al., 1991). The Kharinadi Formation (Oligocene to Lower Miocene) overlies the Maniyara Fort Formation and consists of mottled siltstone, variegated clay and fossiliferous marlite. The overlying Gaj Formation (Lower to Middle Miocene) comprises green siltstone and fossiliferous and gypseous marlites (Biswas and Raju, 1973). The Gaj Formation is overlain by the Sandhan Formation (Pliocene) which consists of micaceous sandstone, laminated siltstone, calcareous clay, marlite and conglomerate. Avian egg-shells have been reported from this formation (Jain, 1990).

STRUCTURE AND TECTONICS

Tectonics of the Kachchh Peninsula owes back to the rifting of the Aravalli -Delhi fold belt of the Gondwanaland in the Late Triassic – Early Jurassic Period (Biswas, 1987). Due to reactivation of the pre-existing faults along the trend of Delhi Fold Belt which is NE-SW but changes to EW in Kachchh region, several major faults resulted in the Kachchh Peninsula forming the Kachchh rift. The rift is bounded by Nagar Parkar Fault (NPF) to the north and the North Kathiawar Fault (NKF) to the south (Fig.2.2, 2.3). These faults are separated by grabens which are asymmetric and show tilting towards south along North Kathiawar Fault accommodating thick sediments deposited near Kathiawar block. There are several sub parallel intrabasinal strike faults responsible for the formation of a series of tilted half grabens (Biswas, 2005). These half grabens are sites for Quaternary sediment deposition forming extensive plains bounded by hill ranges (Fig.2.4). The E-W faults, related uplifts and drape folds form the structural elements of the Kachchh Peninsula.

The uplifts are bounded by five parallel faults from north to south (Fig.2.5, 2.6 & 2.7). The northern most faults is known as Nagar Parkar Fault (NPF) followed by Island Belt Fault (IBF), Kachchh Mainland Fault and the Katrol Hill Fault (KHF) in the south bounded by North Kathiawar Fault (NKF) in the southern most part. Four linear ridges called Nagar Parkar Uplift (NPU) in the north, followed by Island Belt Uplift, Kachchh Mainland Uplift (KMU) and Wagad Uplift (WU) in the south, resulted due to block tilting at the time of rift in the extensional regime. Probably unexposed transverse wrench faults have fragmented the Island Belt Uplift in to four individual islands as shown in Figures 2.2 and 2.3 (Biswas, 1987). These broken uplifts are standing as *islands* in the vast plains of the Rann hence called as Island Belt (Biswas, 1987).

The lineaments formed by these ridges are followed by positive Bouguer anomalies which indicate that these ridges are basement highs (Chandrasekhar, 2005). The trend of these positive anomalies changes from East-West in the Kachchh region to NE-SW across the Cambay graben and follows the general trend of the Delhi Fold Belt (Biswas, 1987). This indicates that there is control of pre-existing trends of Precambrian times in the rifting (Fig. 2.4).

Maximum sediment thickness recorded close to the KMF is 2.2 km, thinning gradually towards Pachchham Uplift. About 350 m thick Tertiary sequence overlies the Mesozoic rocks in the north of Kachchh Mainland Fault, below the Quaternary sequence in the Banni Plains (Biswas, 1992). This thick sedimentation of Tertiary sediments over a subsiding Mesozoic block indicates post-Tertiary activities in the vicinity of the KMF. Tilting of the Tertiary sequences near the KMF indicates post-Tertiary movements along the Kachchh Mainland Fault (Biswas, 1987; Singh, 2008). The master faults have characteristics of strike slip movements (Biswas, 2002). The uplifts are highly affected by the faults of later generations which are normal and strike as well as reverse faults at places. These secondary faults are cogenetic to the primary faults and developed during the different episodes of movements. Some of the transverse faults of the secondary origin are extensive wrench faults and have dislocated the primary faults considerably (Biswas, 1987; Maurya, et al., 2003). Kachchh Mainland Fault steps to the north as South Wagad Fault (Biswas, 1987). A transverse fault sympathetic to the Manfara Fault truncates the KMF in the east (Maurya, et al., 2003). These two faults overlap north of Dudhai-Bhachau segment

(Fig.2.2). The relative spatial position of Kachchh Mainland Uplift and Wagad Uplift suggest that they may be detached blocks of the same unit, as they show same lithological and structural set up. The South Wagad Fault seems to be the eastward continuation of the KMF, which has been cut off by a transverse fault. The tips of both the faults, the Kachchh Mainland fault and South Wagad Fault, dip steeply (about 80º-85º) towards each other. The KMF terminates near the transverse fault and the SWF continues east ward. So, it seems that at depth the KMF is either antithetic or may be down dip stepping over to SWF (Biswas and Deshpande, 1970; Biswas, 1987).

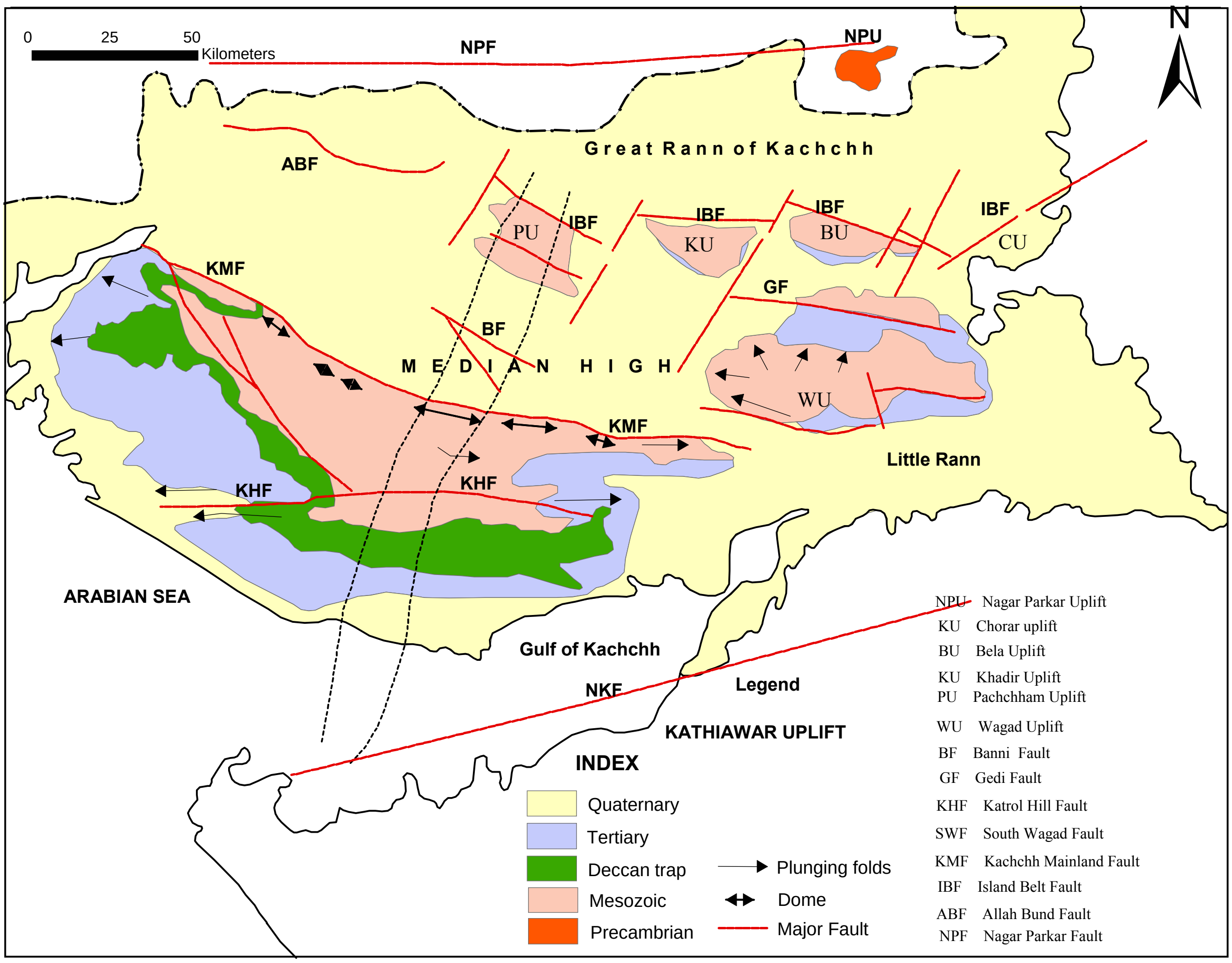


Fig. 2.2: Tectonic map of Kachchh region (modified after Biswas and Deshpande, 1970).

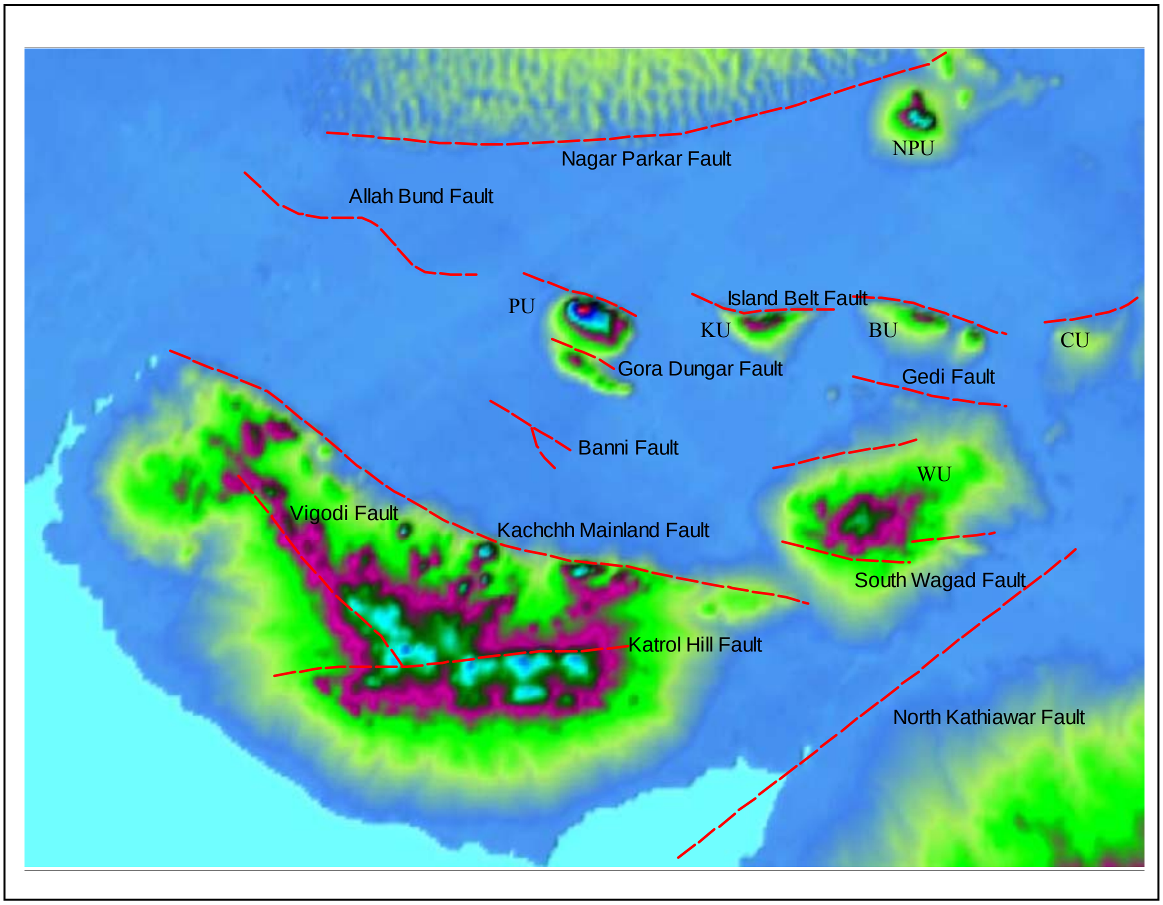


Fig. 2.3: Major Faults of the Kachchh draped over the DEM of the area.

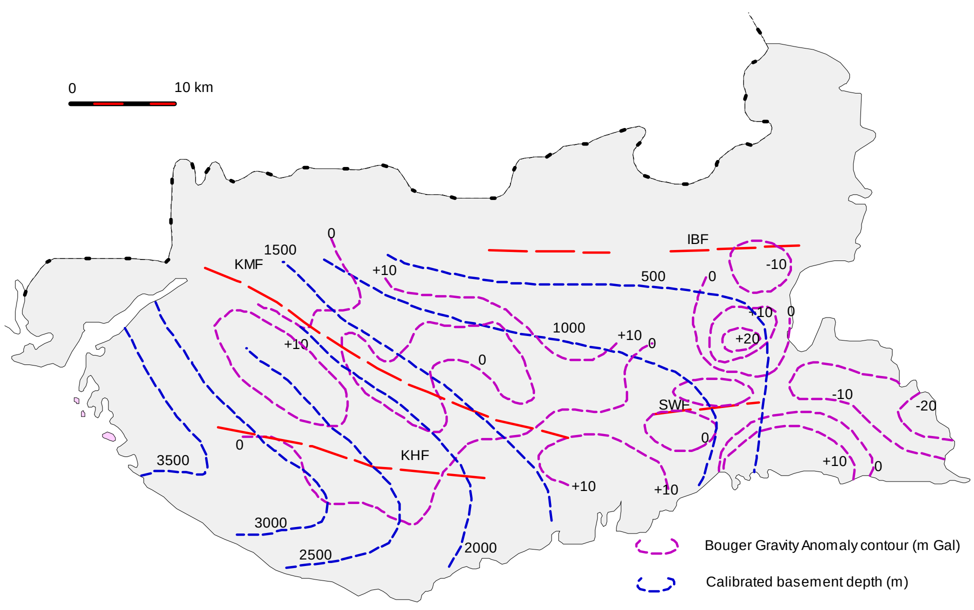


Fig. 2.4: Bouguer Anomaly map of Kachchh region (after GSI, 2001).

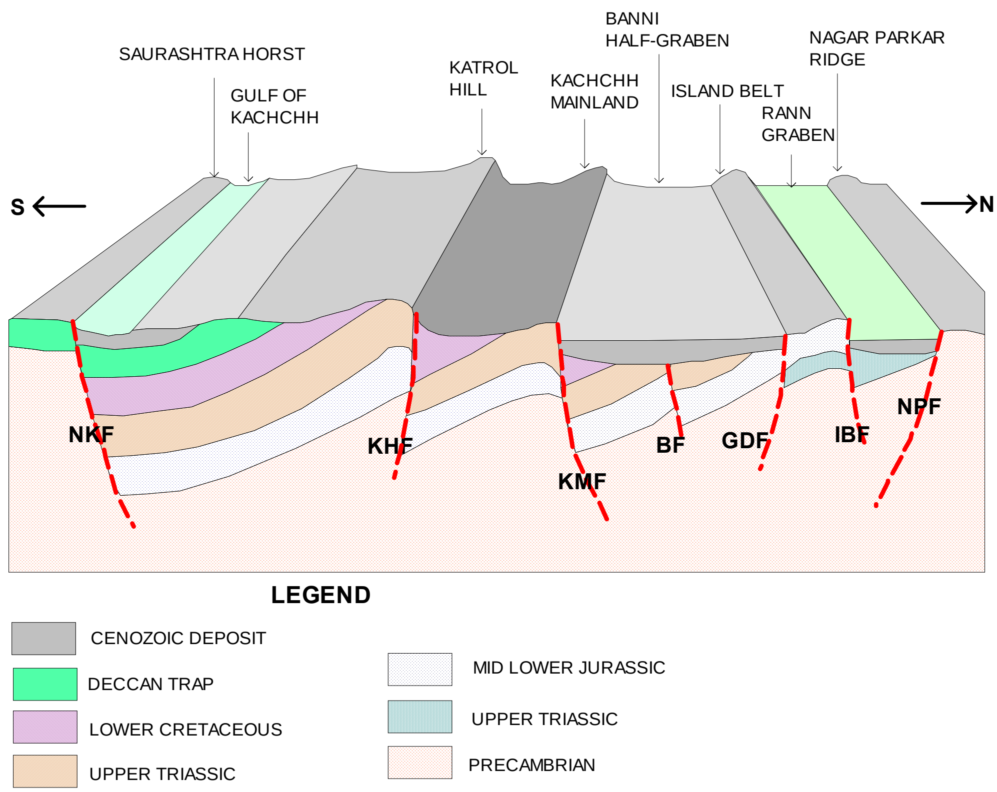


Fig.2.5: Geological Cross section across Kachchh basin along the median high (after Pande, 2007).

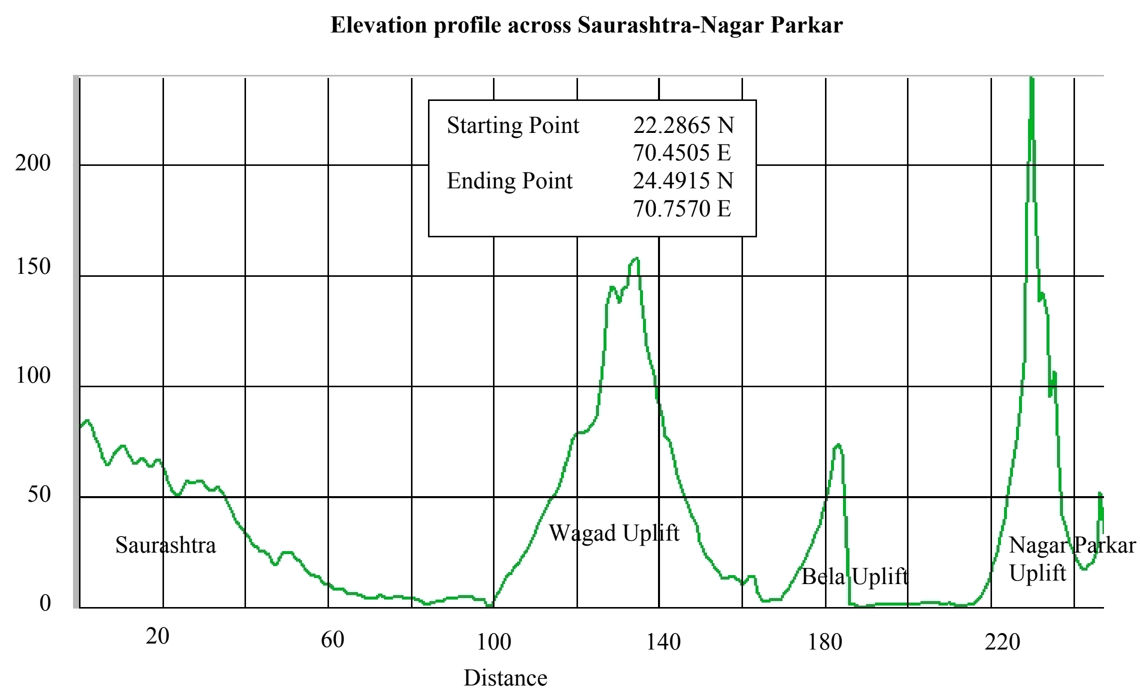


Fig.2.6: Elevation profile across Saurashtra-Nagar Parkar (generated from SRTM data).

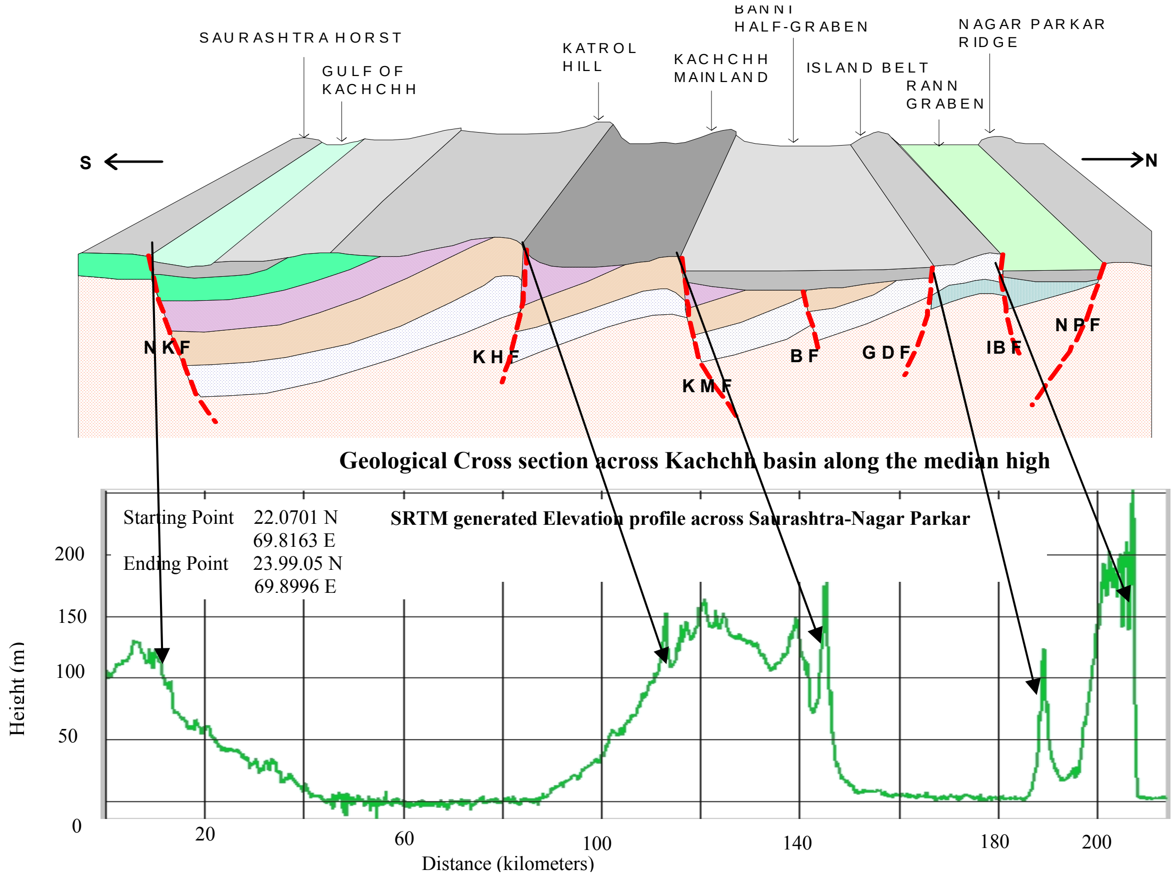


Fig.2.7: Correlation of major faults of Kachchh with the elevation profile of the area.

Igneous activity in the Kachchh region and its relationship with tectonics:

Igneous activities are always associated with deep rifts in any area. The igneous intrusions are very well known and common in the Kachchh uplifts from Nagar Parkar to the Katrol Hill Uplift. Most of the igneous intrusive forms are reported from the area. These intrusives are mainly concentrated in a zone of high deformation along the master faults (Biswas, 1980, 1993). The maximum number of intrusives is reported from the western part of KMF, in the western vicinity of the median high and from the Kaladongar hill of Island Belt Uplift. A series of igneous plugs occupy the central region of Kachchh Mainland (Karmalkar et al., 2008). These plugs are the main feeders of the volcanic flows in the Kachchh region which have been exposed due to erosion of the overlying basaltic flows. The chemical affinity of these plugs indicate that they are derived from the upper sub crustal mantle as indicated by the presence of lherzolite xenoliths (Karmalkar, et al., 2003) and olivine crystals (De, 1964). The intrusive bodies associated with the deformation zone of western part of Kachchh Mainland Uplift are of ultramafic composition (Ray, et al., 2006). The basic as well as ultramafic suite of rocks represents separate phases of igneous activities in the area. The various intrusive bodies occurring in the area manifest the rift related magmatism. The intrusive bodies represent only a fraction of large lava mass generated due to magnetism as result of rifting (Biswas, 2005).

The orientation of the dykes and the faults recorded from the Kachchh may indicate the palaeostress conditions as the dykes show some relationship with rift and ruptures resulting into faults in the area.

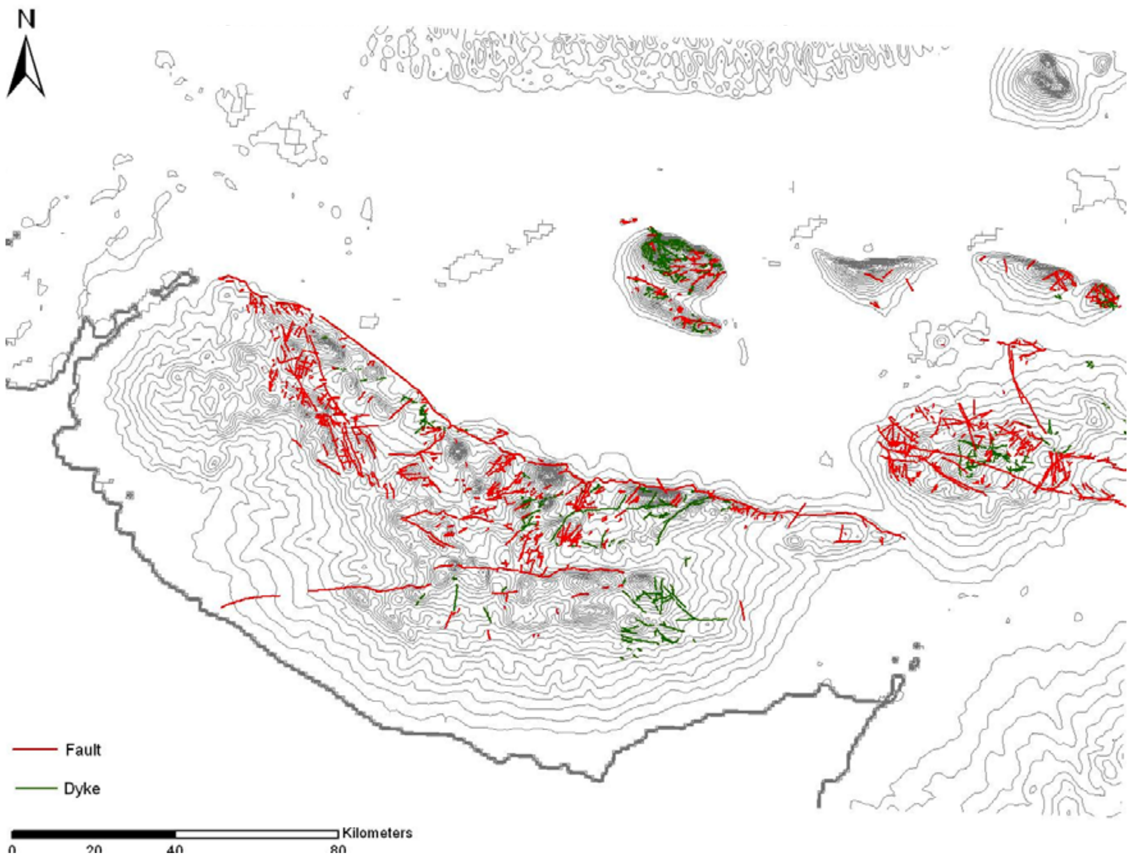


Fig.2.8: Spatial distribution of the dykes and faults in the Kachchh region.

Dykes of the Kachchh Peninsula

There are about 517 dykes recorded in the Kachchh Peninsula with cumulative length of about 783 km (Singh et al., 2010). They have intruded the Mesozoic rocks exposed in the various islands in the Rann as well as in the Kachchh Mainland areas

(Fig.2.8). The spatial orientation of these dykes has been shown and compared using rose diagram (Fig.2.9).

The dykes of the Kachchh Mainland are mineralogically similar to the tholeiitic basalts. Foid bearing doleritic dykes (theralite), fine grained mafic dykes and lamprophyre dykes, all of which fall in alkaline clan, are also reported from the Kaladongar area (Paul et al., 2007). Density of the dyke occurrence is more in the northern part of Kachchh Mainland while they are scarce in the southern part. A few sills are also reported from Kachchh Mainland and Pachchham Island. Major class of the dykes falls along NE-SW trend (25% of the dykes) while second largest group (19.5%) along E-W trend, followed by WNW-ESE trending pattern (17.5%).

The dykes at various places in the Kachchh Peninsula have been found in the vicinity of faults or along the faults, suggesting syntectonic nature of the intrusive rocks (Maurya et al., 2003). These activities took place after the deposition of Bhuj Formation (Late Cretaceous), but before the onset of Deccan Trap volcanic activity. This was followed by a major diastrophic cycle, which accompanied the main volcanic activity of Deccan trap, peaked around 65 Ma (Guha et al., 2005).

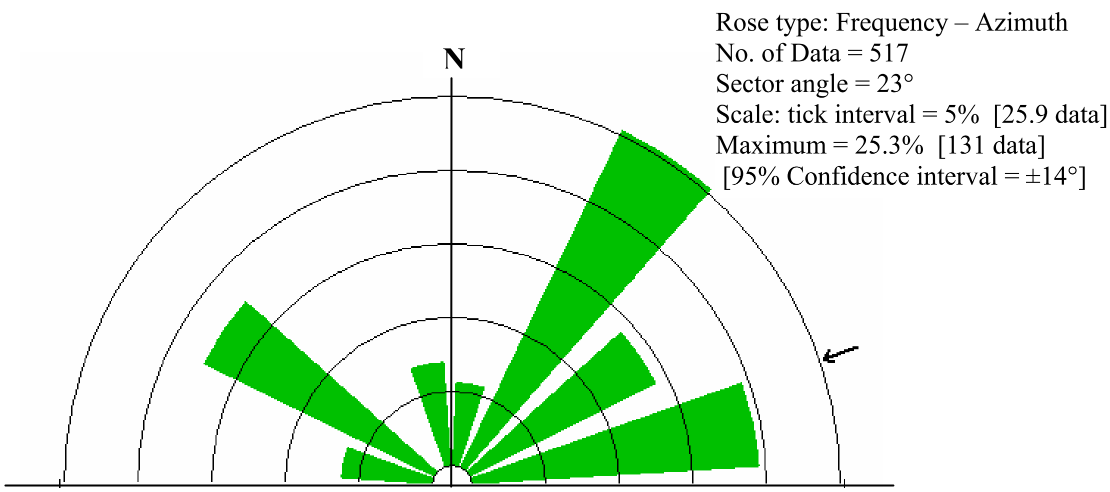


Fig.2.9: Rose diagram showing the orientation of the dykes in Kachchh.

Faults and folds showing change in the stress regime in the Kachchh Peninsula

Apart from the NPF, ABF, IBF, SWF, KMF and KHF, the major faults controlling the tectonic framework of Kachchh, there are several faults in the area recorded from the rocks of the age from Mesozoic to Holocene. During the extensional regime of stress condition in the Mesozoic Period normal faults were developed which have been recorded in abundance from the Mesozoic sequences of the area. All the major faults along with several sympathetic faults are of this nature. After the collision of the Indian plate with the Eurasian plate in the early Tertiary Period, the stress condition changed into compressional regime (Biswas, 1987).

Low-angle thrust faults are seen, abutting with asymmetric folds at one end. Examples of fault-bend folds are frequently seen in the interior parts of the highland (Karanth and Gadvi, 2007). Shearing is evident at the base of bedding parallel thrust sheets. Several structures developed on account of compressive stresses such as arching of beds of hanging wall and formation of contractional wedges is seen a few kilometres inside the margins of highlands (Karanth and Gadvi, 2007).

A number of transverse faults have been reported across the master faults which are very active and play an important role in the recent seismic activities in the Kachchh region. The total number of observed and inferred faults recorded from the Kachchh Peninsula is about 1100 with cumulative length of about 2400 km (Singh et al., 2010). The orientation of these faults has been plotted in the form of rose diagram (Fig.2.10).

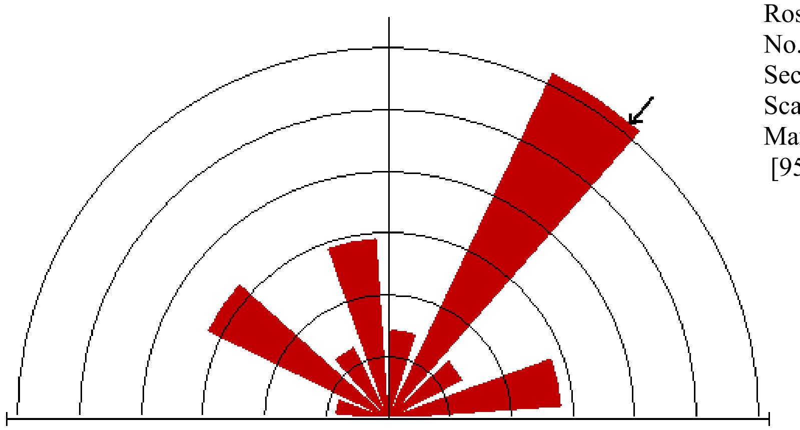


Fig.2.10: Rose diagram showing orientation of faults of Kachchh region.

The orientation of these transverse faults coincides with the trends of the dykes of the area. Major class of the faults (31%) shows NE-SW trend, while the second largest class (16.4%) fall in the WNW-ESE trend followed by N-S trending class (14.6%). Thus it is evident 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 the sub-plate. The vicinity and coincidence of faults and dykes at several places suggest syntectonic origin of these dykes in the region.

Thickness of Quaternary deposits to the north of KMF

A gravity survey was conducted in the Rudramata-Loriya-Bherandiyara section to understand the subsurface geology of the area across the Kachchh Mainland Fault. The geophysical results along this traverse corroborate the existence of KMF; demarcated in the geological mapping between Nokhania and Loriya village where the evaluated throw is 310 m. High fluctuation in the gravity values with steep gradient suggest shallow subsurface structural features as shown in the inferred geological model (Fig.2.11).

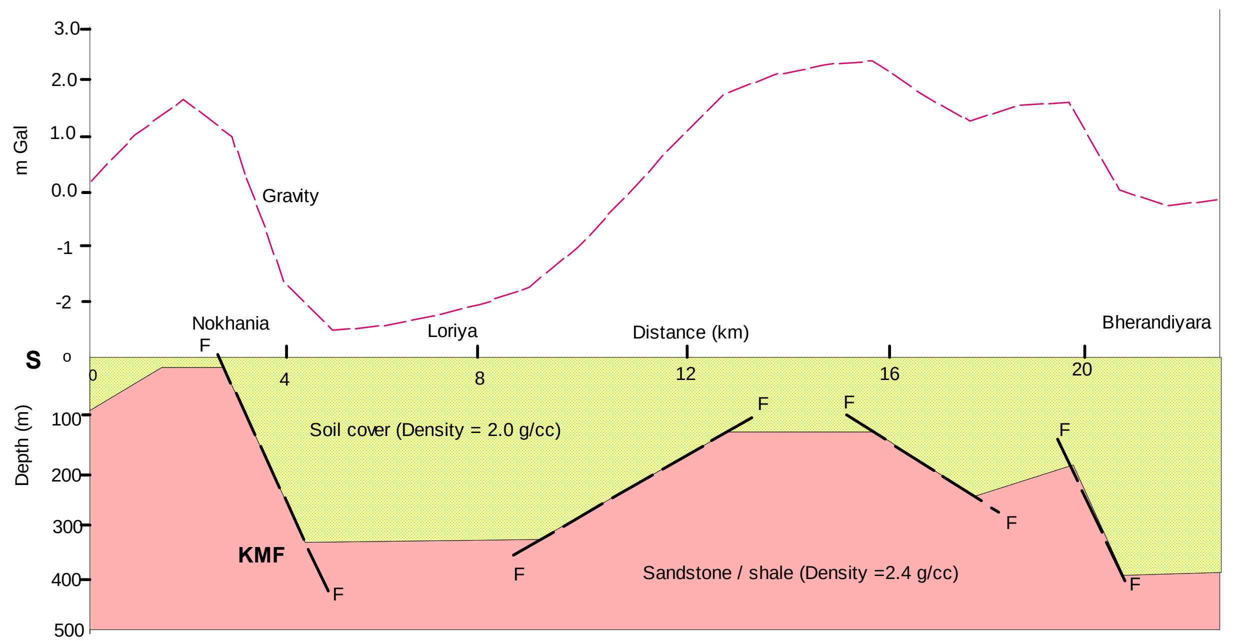


Fig.2.11: Gravity section across KMF (between Nokhania-Bherandiyara) and inferred geological model (after Singh and Lal, 2008).

The thickness of inferred soil cover is about 350 m in the north of KMF. Three more faults have been interpreted in the north of KMF making two grabens separated by a horst structure at shallow depth. The magnetic response along this section has brought out a broad magnetic high near Loriya. The source of this magnetic high may either be denser intrusive basic rock or the variation in concentration of magnetite content in the underlying layer of rocks.

CHAPTER 3

GEOMORPHOLOGY

The Kachchh Peninsula has been identified as the western margin of pericratonic rift basin of India (Biswas, 2005), exhibiting longest record of the Mesozoic succession in western India ranging in age from Late Triassic- Early Jurassic to Cretaceous (Biswas, 1987). This rift basin at present is under the influence of compressional stresses resulting due to the collision of the Indian plate with Eurasian plate. The landscape of Kachchh is therefore tectonically controlled and is studded with uplifts and subsidences. The Katrol Hill Range, the northern Hill Range in the Kachchh Mainland and Pachchham, Khadir, Bela islands represent uplifts while the Banni plain and Great Rann represent low lying depressions. The uplifts are confined to the major sub-parallel East-West trending faults viz. the Katrol Hill Fault (KHF), Kachchh Mainland Fault, Island Belt Fault (IBF) and Nagar Parkar Fault (NPF) (Biswas and Deshpande, 1970; Biswas, 1980, 1987).

Geomorphologically, Kachchh Peninsula can be grouped into following geomorphic units:

1. Dissected hills (Deccan traps and Mesozoics)
2. Piedmont zones
3. Pediplains
4. Banni Plains (fluvio-marine)
5. Alluvial plains and alluvial fans
6. Salt flats and encrustations
7. Mud flats

These geomorphic units have been described in different sectors like Kachchh Mainland, Wagad Highlands, Island Belt, Banni plains, alluvial plains, the Great Rann and Mud flats as follows:

1. Geomorphology of the Kachchh Mainland

The Kachchh Mainland has a rocky terrain with two major hill ranges viz. the Northern Hill Range and the Katrol Hill Range (Fig.3.1). These ranges are flanked in the north by major east-west trending faults, the Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF) respectively. The northern faces of the Katrol Hill Range and Northern Hill Range are the ideal examples of fault generated mountain fronts (Maurya et al., 2002), and are characterized by monoclinal flexures, anticlines and cuestas aligned along the southern flanks of East-West trending faults (Malik et al., 2001).

The E-W and WNW-ENE striking KMF marks the northern margin of Kachchh Mainland, where the northern hill range with average altitudes between 130 to 388 m abut against the low lying Great Rann-Banni plains with an average height of 2 to 5 m above MSL. This hill range is characterized by elongated domal structures producing steeply north facing escarpments with northerly dipping beds while in the south the beds are gently dipping towards south. According to Biswas (1980) the KMF is a vertical to steeply inclined normal fault at depth and changes to a high angle reverse fault near the surface. As described by Suppe (1983) this geomorphic expression suggests a phenomenon of fault propagated folding. It is also suggested that the movement is taking place along a south dipping low angle reverse fault (Biswas, 2002).

There are several streams flowing towards north across the Kachchh Mainland debouching into the Great Rann-Banni plain making semi conical alluvial fans in the piedmont zone of this range. The alluvial debris is seen resting unconformably on the Mesozoic rocks with thickness up to 3-15 m and is probably of Late Quaternary age.

The Katrol Hill Range is separated with the Northern Hill Range by a major East-West trending Katrol Hill Fault which marks the major drainage divide in the Kachchh Mainland. Uplift and deformation of this range along the KHF has controlled the development of numerous north and south flowing rivers (Malik et al., 2001). Deformation of this fault zone is similar to that of KMF zone. Intense asymmetric folding of Mesozoic and Tertiary rocks has given rise to north facing steep forelimbs with gentle back limbs due south (Malik et al., 2001). Folding in the Middle Pleistocene miliolitic rocks (Sohoni et al., 1999) suggest that similar deformation has continued during Upper Pleistocene to Holocene.

In the north of the Katrol Hill Range lies the Bhuj basin, a longitudinal tectonic depression between KMF in the north and KHF in the south. This basin comprises thin veneer of Quaternary fluvial terrace deposits overlying the Bhuj Formation of Cretaceous Period. The pediment zone along the Katrol Hill Range front exhibits occurrence of several colluvial cones consisting of angular fragments of Mesozoic-Tertiary rocks along with some clasts of miliolitic rocks.

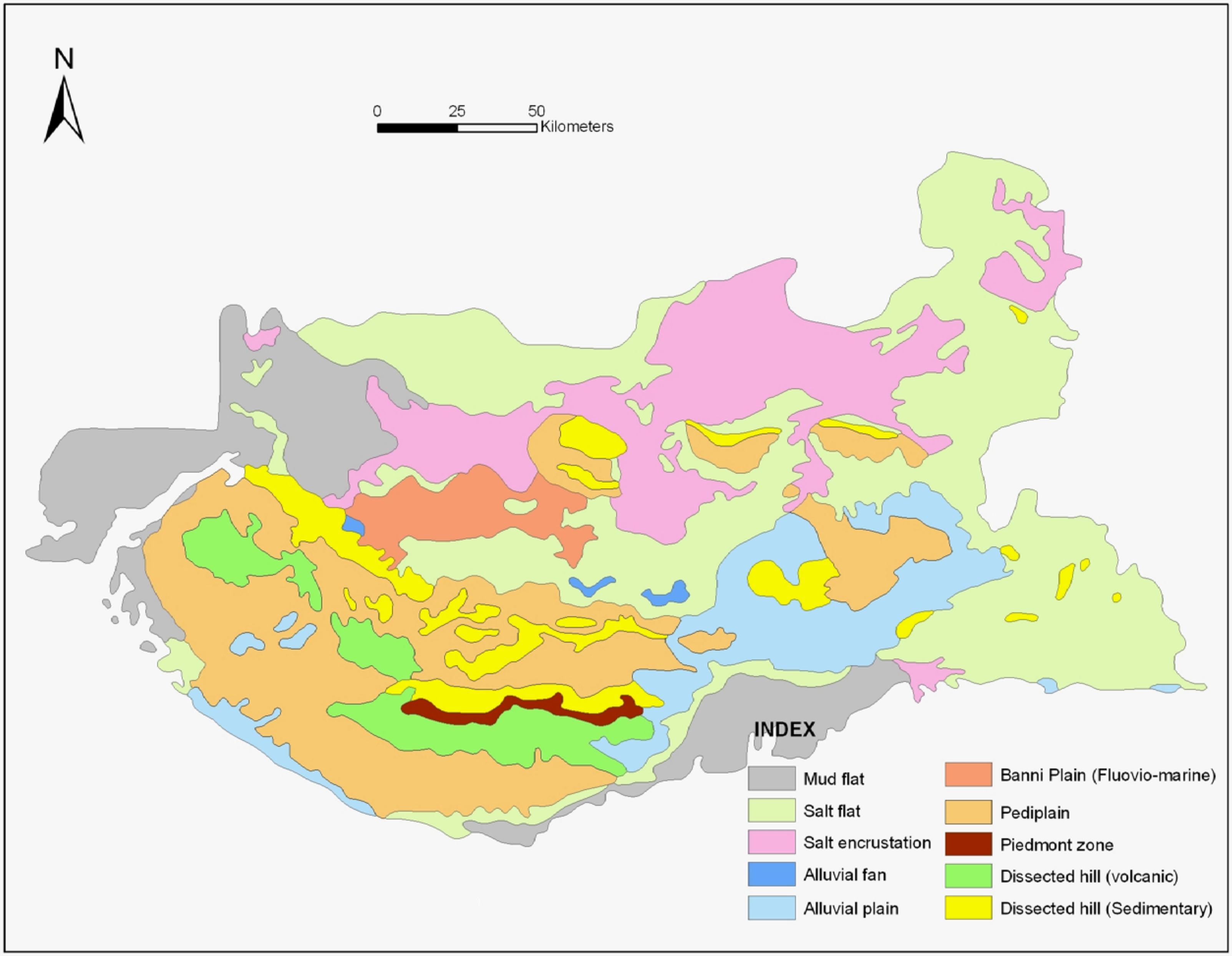


Fig.3.1: Geomorphological map of the Kachchh Peninsula (after ISRO, 1990 and GSI, 2001).

2. Island Belt

The Island belt comprises four isolated highlands in the Great Rann of Kachchh. These highlands viz. Pachchham, Khadir, Bela and Chorar are commonly described as 'Islands' as they stand out isolated in the submerged plains during the monsoon. They lie in the east-west line and are bounded by Island Belt Fault to the north making the northern side very steep while the southern slope is gentler.

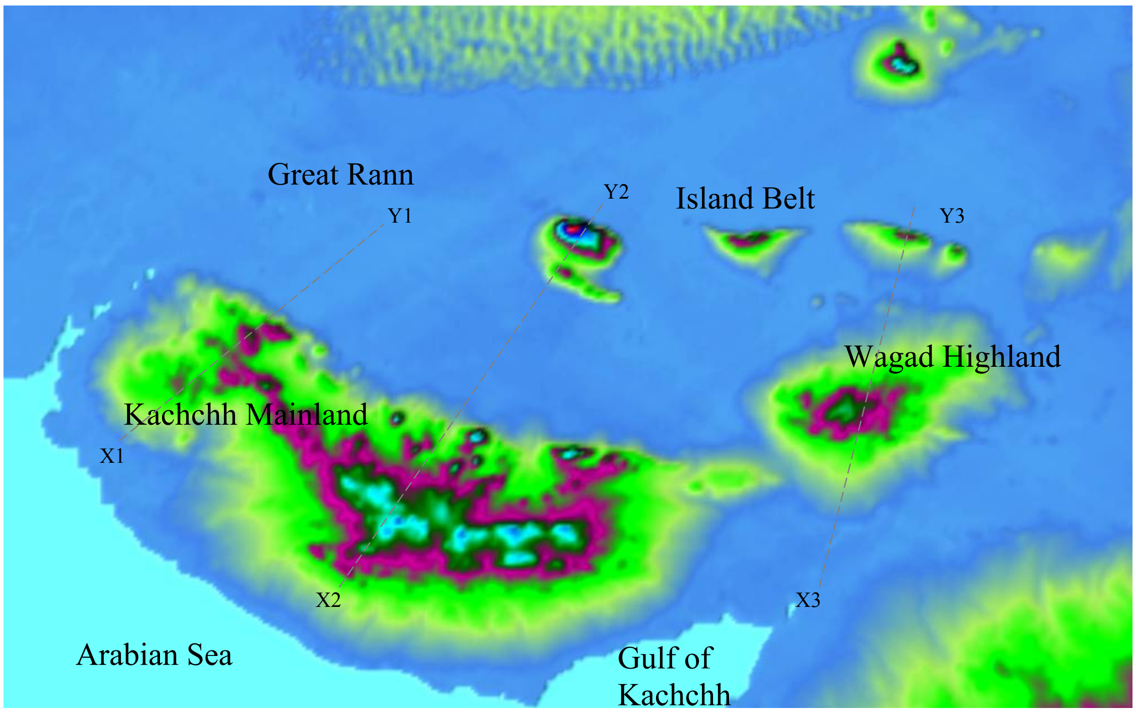


Fig.3.2: DEM of the Kachchh Peninsula depicting the geomorphic units.

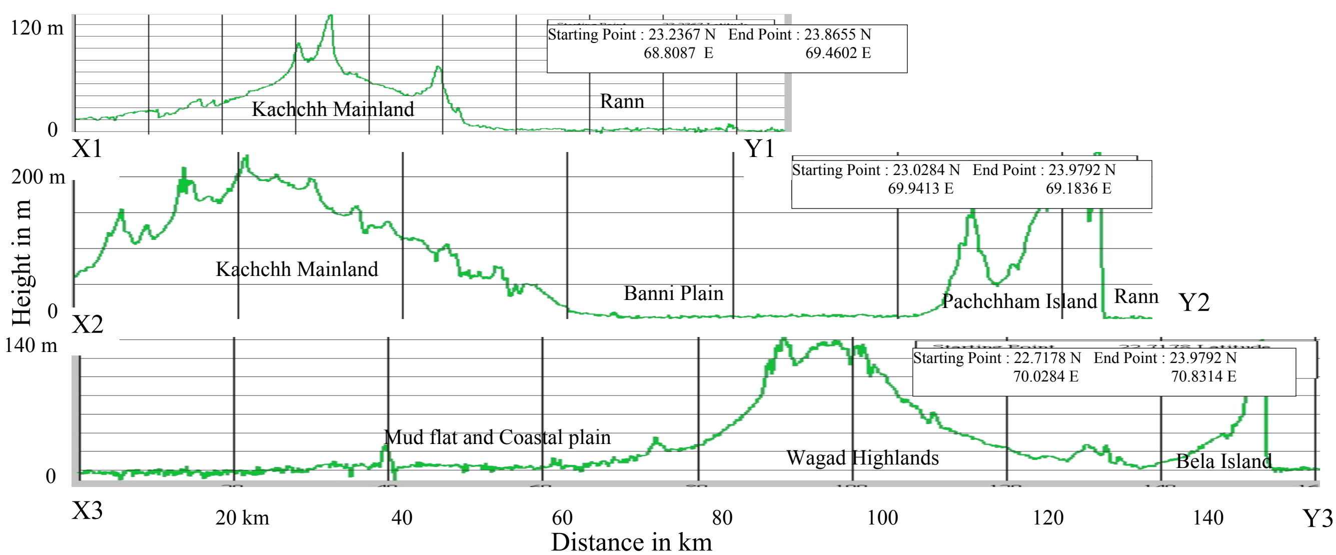


Fig.3.3: Topographic profile showing the general Physiography of the Kachchh Peninsula (Section lines are shown in Fig 3.2).

3. Wagad Highland

The upland region to the south of Khadir-Bela islands and towards the NE of Kachchh Mainland is known as Wagad Highland (Fig. 3.2 and 3.3). The Wagad Highland is separated from the Kachchh Mainland by South Wagad Fault (SWF) while a shallow graben separates it from Khadir and Bela islands in the north.

4. Banni Plain

The raised mud flats lying between the Kachchh Mainland in the south and the Great Rann in the north is known as the Banni Plain (Fig.3.1 and 3.4). It occurs 2 to 5 m above the mean sea level and is almost gradient less saline grassland with acacia and other bushy vegetation spread over it and covers around 3000 sq km of area. It is comprised mainly of silty and sandy sediments of varying thickness which overlie the Mesozoic-Tertiary sequence of rocks.

The Banni plain has been subdivided into three sub-units by Kar (1995) viz. a) high level mud flats, b) undifferentiated sloping and low level mud flat and, c) residual saline depression. The highest elevation occurs in NNW-SSE alignment which coincides with median high, a basement structural high that cuts across the Mainland Kachchh as well. Thus, on the basis of median high, the Banni plain can be divided in the western and eastern Banni Plains. The general slope of the western Banni plain is towards west while it is towards north in the eastern Banni plain. Alluvial fans are deposited along the northern margin of the Kachchh Mainland. Parts of Banni, therefore, could be representing a transitional zone formed by interaction between the marine processes operating in the north and a fluvial deposition by the rivers draining the Kachchh Mainland in the south (Kar, 1995). Presence of gullies, incised channels on the elevated parts of the Banni plains are indicative of the latest phase of uplift (Maurya et al., 2002).

5. Alluvial Plains

A narrow belt of fluvial deposits, up to 20-30 km width, is present along the southern coast of the Kachchh Peninsula fringing the pre-Quaternary rocks. These alluvial deposits are found to extend right up to the coast. These deposits comprise Late Quaternary fluvial deposits which are well exposed along the 10-25 m incised cliffs of the Nagwanti, Rukmawati (of Mandvi), Phot, Khari, Nira and Rukmawati (west) Rivers (Maurya et al., 2003). These deposits form a distinct geomorphic surface which shows extensive gullies/ ravines around river valleys. In general the sediment succession starts with a cross stratified gravel, with clasts of basalt (cobble to pebble size) and Tertiary rocks. This is overlain by a thick buried soil, which comprises mainly of fluvial sand and silt and abundant pedogenic calcrete (Maurya et al., 2003). Radio carbon dating of pedogenic calcrete nodules from this soil in Nagwanti basin have yielded a calibrated age range of 18980 – 18210 ya B.P. while those from Naira basin and Rukmawati (west) River provided a calibrated age range of 22,210 – 21,320 ya B.P. and a ^{14}C age of 24,300 ±640 ya B.P. (Maurya et al., 2003).

Further north in the Kachchh Mainland the alluvial deposits occur in patches within the various stream channels incised through pre-Quaternary rocks. They occupy the valleys bounded by cliffs of Miliolitic limestone in the Katrol Hill Range and represent deposits of post-miliolite depositional phase. Patches of Quaternary deposits are also found in rugged terrain of pre-Quaternary rocks. These deposits occur in the form of alluvial and colluvial fans and valley fill sheets of miliolitic limestone of fluvio-aeolian origin.

Alluvial fans develop under a distinct set of geological conditions. An abrupt physiographic break marked by a fault leading to the unconfinement of the channel is essential requirement for the development of an alluvial fan. The mountain front scarps of the Katrol Hill Fault and Kachchh Mainland Fault provide the absolute geomorphic conditions for the development of alluvial fans as a result alluvial fans are associated with the KHF and KMF and these are related to neotectonic activities. In general, the alluvial fans formed in the vicinity of the Kachchh Mainland Fault have rounded fragments and flat to gentle conical morphology while those associated with Katrol Hill Fault have less rounded shape (Thakkar et al., 1999).

6. The Great Rann

The gulf filled with accumulation of estuarine sediments during Late Holocene to the north of Kachchh Mainland is referred to as Great Rann. The Great Rann is a unique feature which occupies more than half of the aerial coverage of the Kachchh Peninsula. The Great Rann of Kachchh is a flat terrain which is about 2 to 3 m above MSL and can be divided into two main parts, the Great Rann, which occupies mostly the northern part, and the Little Rann which occupies mostly the eastern and the south eastern part of the Kachchh Peninsula. The Rann area remains dry for most of the time except in the rainy season when it is filled with saline water. During the summer and winter periods the lower parts of the Rann surface are salt encrusted while in rainy season salt playas are formed (Merh, 1995). The deeper portion of the playa lakes are made up of bluish grey and yellowish brown oxidized silty gypseous clay.

7. Mud Flats

The tidal waters, during the monsoon season, carry with them a lot of sediments brought from the Indus delta region. The coarse sediments are deposited in the inlet channels at their heads while the finer sediments are carried further and spread over the flooded areas and get deposited as mud flats (Merh, 1995).

The distribution of land and sea around the Kachchh Peninsula with the rise of the sea level illustrates the subtle physiography of the area. An exercise was carried out with the GLCF 90m, radar data with the help of 3dDEM with 1 m interval to depict the configuration of the sea and land. Historical records indicate that during the invasion of Alexander the Great Rann area was navigable with boats. This exercise indicates relative regression of the sea from the area. The configuration pattern at the 2 m and 3 m rise of the sea demarcate the Banni Plain very effectively.

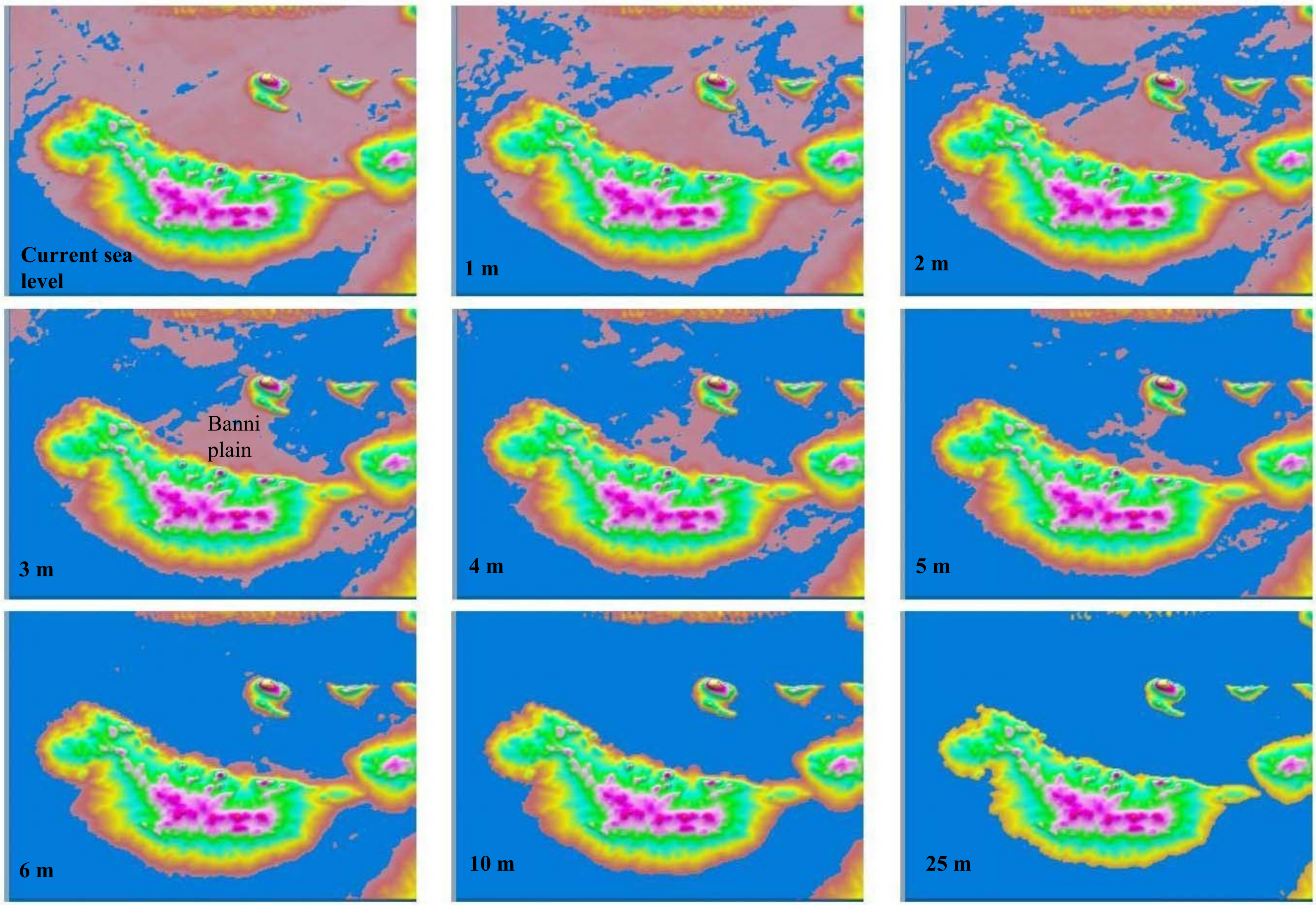


Fig. 3.4: Distribution of land and water with increase in the sea level, showing general topographic model of the Kachchh Peninsula. The rise in sea level is indicated in the each figure in m.

Drainage

The drainage of Kachchh is largely governed by the combination of lithology and tectonics however the affect of sea level changes also affect the drainage in such type of areas. The central high parts of Kachchh Mainland forms a water divide and streams originating from the Mainland flow in northern, southern and western directions debouching into the Rann / Banni Plains, Gulf of Kachchh and the Arabian Sea respectively (Fig. 3.5). The major rivers flowing towards south are the Barwali, Naira, Kharod, the Rukmawati, Khari, Phot, the Nagwanti, Sakra and Song rivers. They debouch into the Gulf of Kachchh or in the Arabian Sea. The streams originating from the northern slopes of the central and northern part of the Mainland Kachchh join together and flow towards north and ultimately debouch into the Rann through Banni Plains. The major rivers flowing towards north are the Kaswali, the Pur (Khari), the Kaila, the Nirona and the Chaari. These streams debouch into the Rann making conspicuous alluvial fans. The streams of the Kachchh region are ephemeral and carry water only during rainy seasons. Many of the above streams like Kankawati, Kaswali, Pur and Bhukhi make high cliffs in the lower reaches. The rivers of Kachchh Mainland are characterized by well carved valleys but they do not have much amount of flows now which indicates that the area has experienced very wet seasons when they carried more water and rich sediment load which help them to dissect the valleys effectively.

In general, the drainage pattern of the area is dendritic in nature which typically develops in areas with homogenous lithologies in terms of weathering that provide no preferred direction to the development of stream channels. At several places, which are marked by the domes and plug like features, radial pattern has also developed.

The drainage systems developed in the area around KMF and passing through the fault zone have been chosen for detailed analysis to evaluate the effect of tectonism in the area during the recent past.

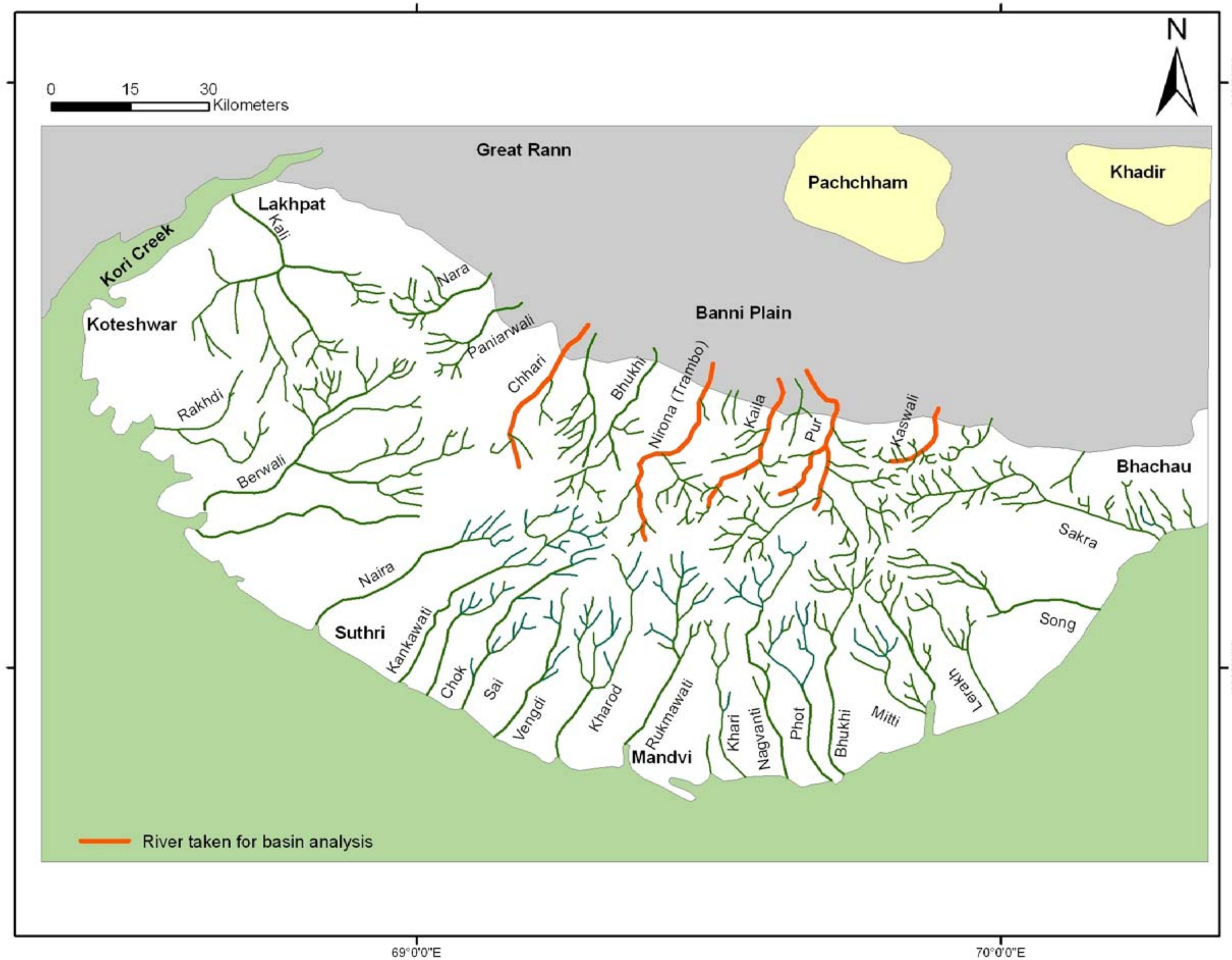


Fig. 3.5: Drainage map of the Mainland Kachchh.

Geomorphology, drainage pattern and nature of streams in the area along KMF:

The variety of geomorphic units of the Kachchh Peninsula indicates that number of factors have played roles in their carving. These factors are lithology, tectonics, climate, sea level changes and natural processes responsible for erosition and deposition. It is interesting to note that in Kachchh Peninsula conspicuous hills as well as vast table flat plains occur together. The hills comprise rugged terrain with Mesozoic and Tertiary sequences where as the Plains comprise Quaternary sequences. The hills are result of uplifts where as the plains are the part of grabens filled with alluvium, mud and the Rann clays.

The landform of the Kachchh Peninsula comprises the highlands amont the vast plains of Kachchh (Fig.3.6). The Rann and Banni Plains are depostional features whereas the hills have undergone many cycles of erosion (Biswas, 1987).

The study area exhibits an array of elongated domes / anticlines with roughly East-West trending axes, forming the uplands in the central part of the area, bounded by pediplain to the south. This hill range along the KMF forms a series of domes of rocks from Jurassic to Cretaceous age and its northern flank is marked by E-W trending Kachchh Mainland Fault. From east to west, it is marked by a chain of domes like Devisar dome, Khirsara dome, Habo dome, Jhura dome, Jumara dome, Nara dome and Kira dome. Kachchh Mainland Fault has played a significant role in carving the physiography of the area. The beds near the KMF are steeply dipping whereas the same sequences, as we move away from the Kachchh Mainland Fault, are gentler.

Fig.3.6: ETM FCC image of the Mainland Kachchh showing major geomorphic units and drainage around Kachchh Mainland Fault.

The highlands have been turned into denuded hills in the eastern part, especially near Vondh, Bhachau, Dudhai, and Devisar; giving rise to a few inselbergs standing in the pediplains. Typical cuestas are developed in the area between Jawaharnagar and Lodai (Fig.3.6). This is because of the elongated anticlinal structure with older softer lithounits. The beds dip northerly in the north and southerly in the south of these elongated domes. High plateau like structures are observed at places where harder rocks occur as capping over the thick softer units.

The general elevation of the area varies from 20 m to 80 m above mean sea level. The Dhinodhar Dongar is 388 m high while the Jhura dome touches 324 m height. The Rann, popularly known as Great Rann of Kachchh lying north of Kachchh Mainland Fault, is roughly 2 to 5 m above MSL.

The axial zone of domal anticline roughly forms the water divide, which extends in East-West direction. The streams south of the hill range drain southerly while streams in north make alluvial fans and ultimately pour in the Great Rann of Kachchh. Most of the streams flowing towards north in the mainland are fault controlled. The transverse faults have been followed by streams which show strike slip movement in the area.

Fig. 3.7: Detailed drainage map of the area along Kachchh Mainland Fault.

The drainage pattern is mainly dendritic which is controlled by homogeneity in lithology and structure but in the alluvial fans radial drainage pattern has been observed. Around the Jhura dome, the drainage is radial. The streams show meandering and braided nature at places. Sharp turns in the streams, flowing towards north, are observed at number of places, which may be correlated with the reactivation of the pre existing faults / weak zones. Rejuvenation of streams flowing north is also recorded with formation of knick points characterized by head-ward erosion to the northwest of Devisar village. There is a significant down cutting (≥10m) in the channels of the Kaila and Pur Rivers.

The Kaswali River, Lotia nala and Nihwara nala, Dhrung River, the Khari / Pur River, the Kaila River, Nirona River, Jabri Nadi, Gumar Nadi, Bukhi Nadi and Chhari River are the main streams flowing northward (Fig.3.5, 3.7). The Kaswali River near Lodai village makes a typical alluvial fan with a semi circular plan which indicates that stream gradient is not very steep. The converging streams in the pediplain region now diverge into radially distributing pattern, which is typical of an alluvial fan. The Lotia and Nihwara nalas together make a bigger alluvial fan to the north of Jawaharnagar. The Pur River to the north of Rudramata makes another important alluvial fan which is cut by an active fault in its northwestern part. The long profile of the Kaswali, Pur, Kaila and Nirona are prepared to show the nature of gradient of the streams which have been studied in detail (Fig. 3.8, 3.15, 3.16 and 3.17). Fluvial terraces of the river sections and their lithologs are shown in Fig. 3.9, 3.10, 3.11, 3.12 and 3.13. The foot hills along the northern side of the elongated range form a narrow pediment zone covered with thin alluvium. At places bare rocks denuded up to ground level can be seen. This pediment is broader in southern side because of gentle dip of the lithounits and presence of comparatively softer felspathic sandstone of the upper Bhuj Formation. The Upper Bhuj sandstone makes a good aquifer in the area and provides potable fresh water for domestic and agricultural use. All the rivers flowing in the area are rain fed and remain dry almost throughout the year but in rainy seasons.

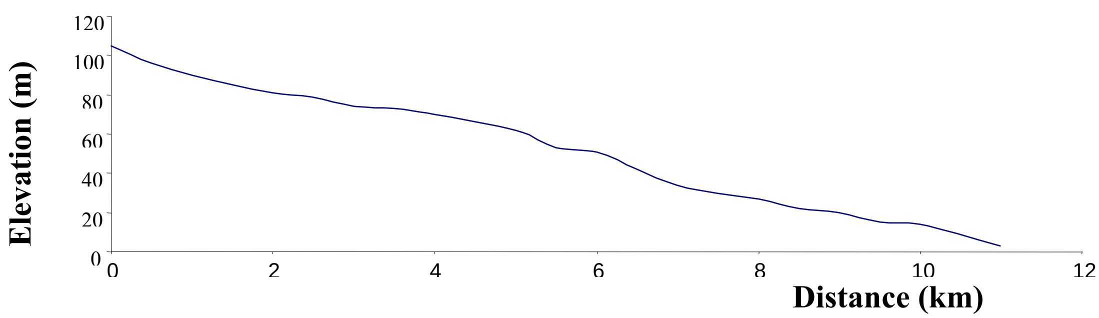


Fig.3.8: Longitudinal profile of the Kaswali River

Fig.3.9: Fluvial terrace sequence exposed along the Dhrung River.

Fig.3.10: Fluvial terrace sequence exposed along the Kaswali River, near Lodai village.

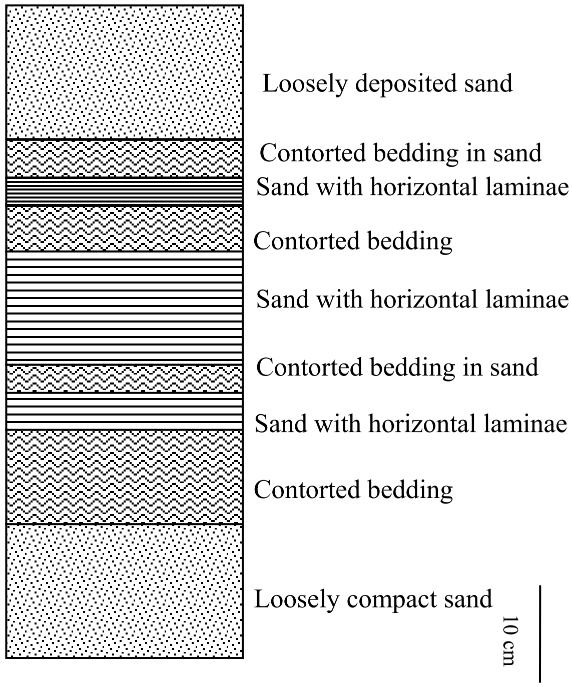


Fig.3.11: Litholog of a trench in the Recent alluvial deposit north of Khirsara village.

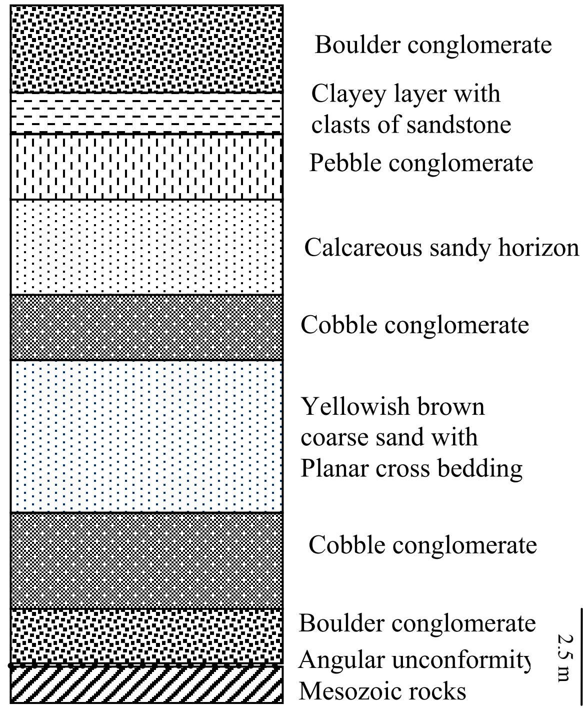


Fig.3.12: Litholog of the Dhrung River Section, Near Dhrung Dam.

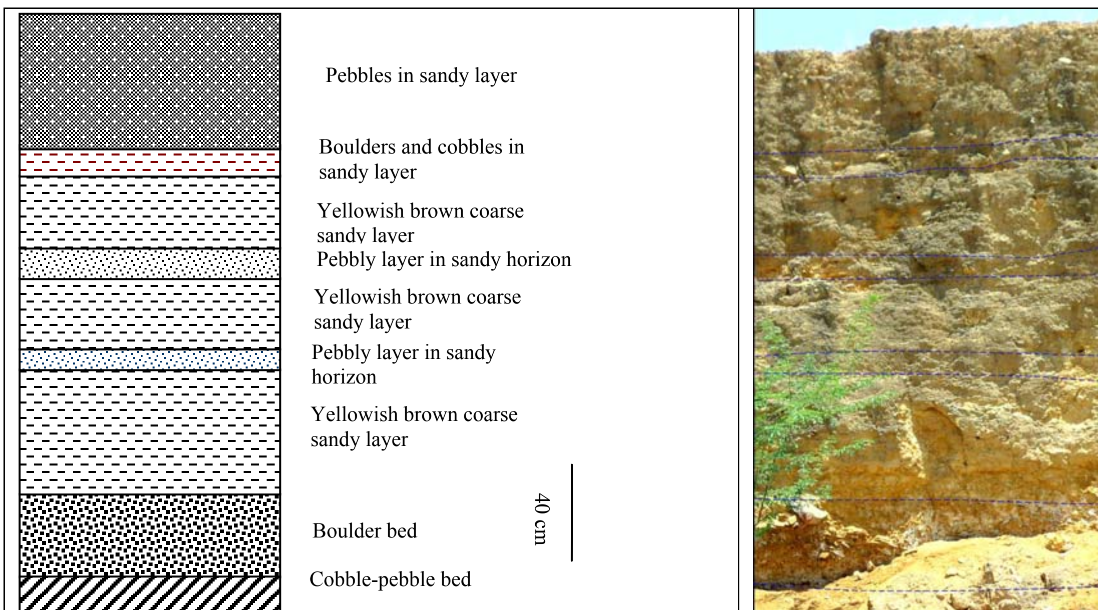


Fig.3.13: Litholog of the Dhrung River Section, Near Dhrung Dam with corresponding section in photograph.

Fig.3.14: Upstream view of the Dhrung River, near Dhrung Dam.

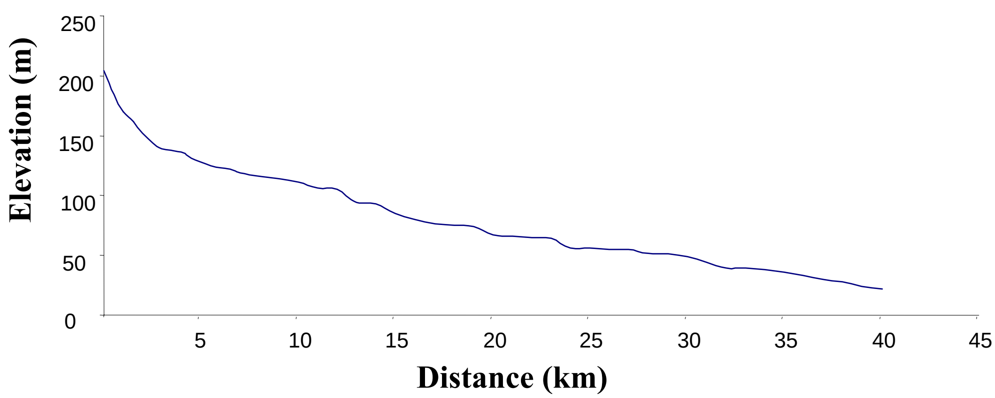


Fig.3.15 Longitudinal profile of the Pur River

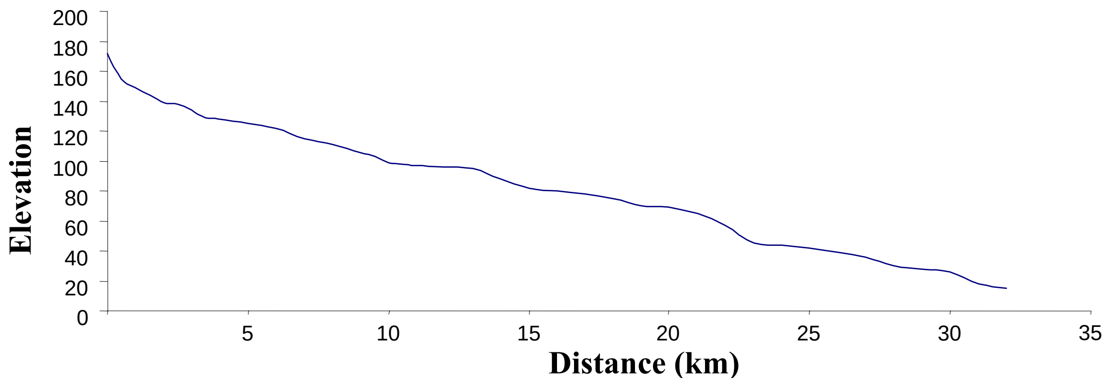


Fig.3.16: Longitudinal profile of the Kaila River

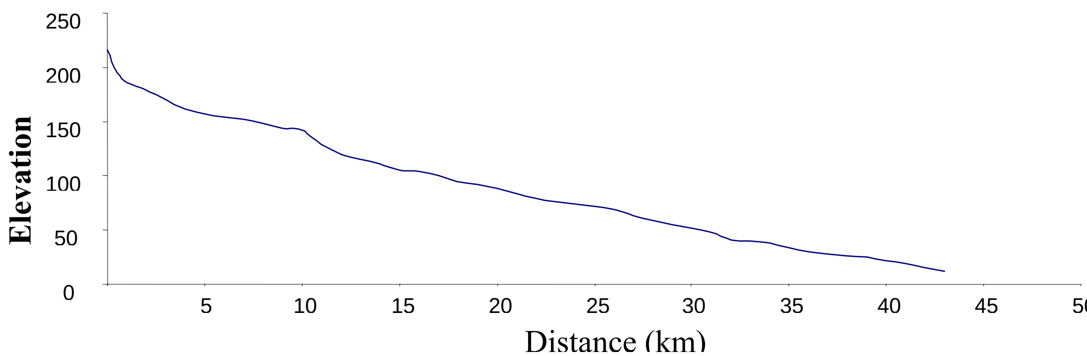


Fig.3.17: Longitudinal profile of the Nirona River

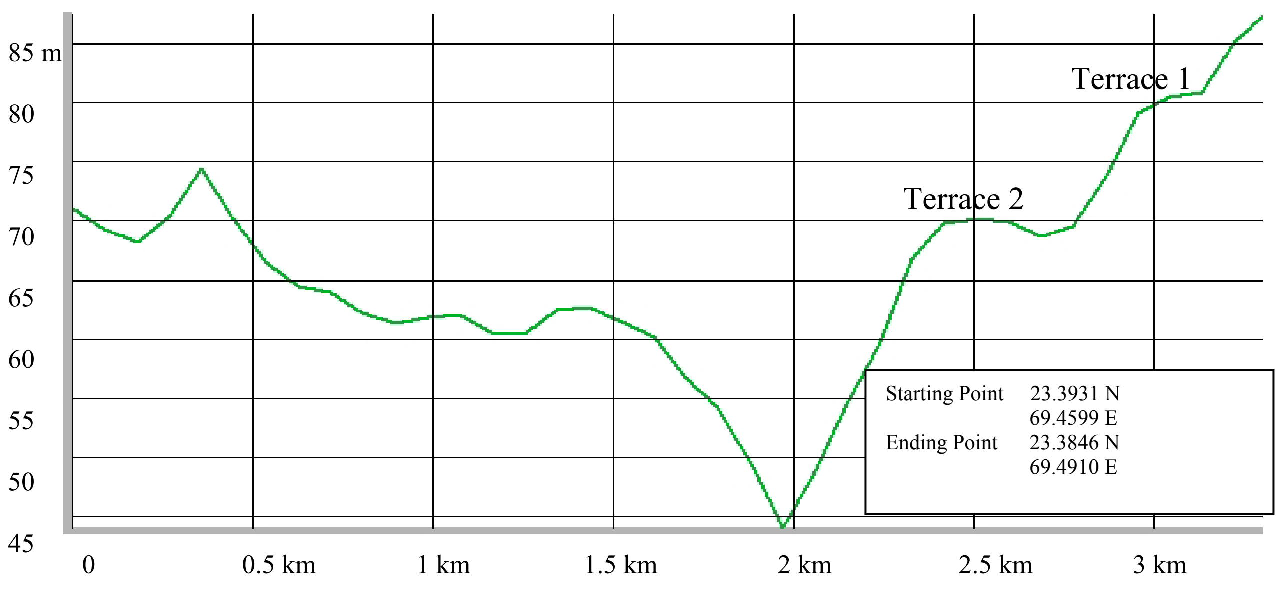


Fig. 3.18: Valley cross section of the Nirona River, away from mouth showing terraces.

The terraces formed by the rivers indicate the tectonic influence in their course of development. These aspects have been described in the next chapter in detail. Typical V-shaped cross section of a stream of the Nirona River, away from the mouth of the river (Fig.3.18) indicates rejuvenation of the stream.

CHAPTER 4

MORPHOMETRIC ANALYSIS

Tectonics induces permanent deformations on the earth surface and controls the drainage pattern and associated geomorphic/ sedimentary processes. The uplifted area goes under process of erosion, while the subsiding area is subjected to focusing of drainage and deposition. Primarily, tectonics manifests itself by either steepening or reducing the local valley gradient, which changes the existing slope of the channels. This introduces disturbance in the natural equilibrium of a river. In the process of restoring the equilibrium, the river tries to adjust to the new conditions by changing its slope, roughness, bed material size, cross-sectional shape and meandering pattern (Twidale, 1966; Schumm, 1986; Chang, 1988). Thus, the secondary changes as a consequence of tectonics are reflected in aggradation / degradation and variations in channel morphology. This variation in morphology of a river basin is studied in detail applying morphometric techniques. The various measurements related with the shapes and distribution of the drainage in a particular river basin is known as morphometric analysis. The morphometric studies of river basins were first initiated by Horton (1945) followed by Strahler (1964). The main purpose of morphometric analyses is to discover holistic stream properties from the measurement of various stream attributes. Thus, the science of morphometry is concerned with the quantitative measurement and generalization of the land surface geometry.

Different morphometric parameters such as sinuosity, long profile, valley floor to valley width ratio and the mountain front sinuosity characterize the degree and nature of tectonic activity while the drainage orientation studies help in reconstructing the sequence of recent tectonic activities in the area (Centamore et al., 1996). The orientation related to lower order streams are indicative of the most recent active tectonic phase because these streams are the youngest component of the drainage network (Centamore et al., 1996).

Basins of the five major rivers which are flowing towards north and crossing the KMF, thus in the most vicinity to the KMF, are taken for detailed morphometric analysis to decipher the nature of neotectonism in the area. These basins are as follows:

1. Kaswali River Basin
2. Pur River Basin
3. Kaila River Basin
4. Nirona River Basin
5. Chhari River Basin

Materials and Methods

As reference and base map preparation, six Survey of India topographic sheets on 1:50,000 scale were used. The digital data format from Indian Remote Sensing Satellite (IRS1D), LISS III (resolution 23.5 m) with four spectral bands i.e. B1 (blue) B2 (green), B3 (red) and B4 (near infrared) and ETM data of Landsat (resolution 30m merged with 15 m panchromatic band) were used to meet the requirement of remote sensing study of the area. Digitization work has been carried out for entire analysis of basin morphometry.

The drainage network of the Kaswali and Kaila River basins were derived from tracing them from 50,000 scale topographic sheets manually, digitizing them in the Arc GIS software and there after deriving the linear and aerial aspects using respective tools and calculating the other factors using the appropriate formulae.

The SRTM data of 90 m resolution and ASTER GDEM data of 30 m resolution have been used to generate the drainage of the Pur, Nirona and Chhari River basins. The radar data was processed using the ILWIS 3.3 software. The DEM hydro processing tools of the ILWIS were used to generate the slope, flow accumulation, drainage network ordering and catchment extraction. The drainage networks were extracted on 9 pixel thresholds (for SRTM data) on which the drainage matches most with the topographic sheet of 1:50,000 scale.

The drainage order was given to each stream following Strahler (1964) stream ordering rule. The attributes were assigned to create the digital data base for drainage layer of the river basins. Various morphometric parameters such as linear aspects of the drainage network: stream order (Nu), bifurcation ratio (Rb), stream length (Lu) and aerial aspects of the drainage basin: drainage density (D), stream frequency (Fs), texture ratio (T), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf) of the basins were computed.

Parameters of Morphometric Analysis:

The parameters of morphometric analysis of a river basin can be grouped into linear and aerial elements on the basis of the aspect utilized for its calculation. The important linear aspects of drainage network are stream order (Nu), bifurcation ratio (Rb), stream length (Lu) and basin length while area of the basin, basin perimeter, drainage density, stream frequency, texture ratio, elongation ratio, circularity ratio and form-factor ratio are calculated under aerial aspects of analysis.

Stream Order (u)

Stream ordering is the first step in the morphometric analysis of a drainage basin. It is the linear property of fluvial system. The stream network is subdivided in various fluvial segments of increasing hierarchical order (Horton, 1945; Strahler, 1964). Horton emphasized topographic characteristics of the drainage area and gave hierarchical order to every channel in the drainage basin using a 'top-down' approach in which the smaller streams have lower order number and the central channel has the highest order number. In the present study, the channel segments of the drainage basin have been ranked according to Strahler's stream ordering system. According to Strahler (1964), the smallest fingertip tributaries are designated as order 1. Where two first order channels join, a channel segment of order 2 is formed, where two of order 2 streams join, a segment of order 3 is formed, and so forth. The trunk stream through which all discharge of water and sediment passes is therefore the stream segment of highest order.

Stream Number (N_u)

The total number of stream segments computed order wise is known as the stream number. Horton's (1945) laws of stream numbers states that the number of stream segments of each order forms an inverse geometric sequence, when plotted against order, most drainage networks show a linear relationship, with small deviation from a straight line. According to the Horton's law the plotting of logarithm of number of streams against stream order gives a straight line.

Bifurcation Ratio (Rb)

In a drainage basin the term bifurcation ratio (Rb) is used to express the ratio of the number of streams of any given order to the number of streams in next higher order (Schumm, 1956). The hydrographical network is subdivided in fluvial segments of increasing hierarchical order. Calculation of parameters of hierarchy allows defining the influence of tectonics on the hydrographic network evolution (Guarnieri and Pirrotta, 2008). The bifurcation ratio is the measure of the degree of branching within the hydrographic network (Horton, 1945; Strahler, 1952). It depends on the presence of hierarchical anomalies in the network and can give useful information on typology of the erosive processes and on the degree of evolution of the basin (Guarnieri and Pirrotta, 2008). Bifurcation ratios characteristically range between 3.0 and 5.0 for basins in which the geologic structures do not distort the drainage pattern (Strahler, 1964).

Stream Length (L_u)

Stream length is one of the most significant hydrological features of the basin as it reveals surface runoff characteristics of area. Longer lengths of streams are generally indicative of flatter gradients. Generally, the total length of stream segments is highest in first order streams and decreases as the stream order increases.

Area of a basin (A) and perimeter (P)

Area of the basin and its perimeter are the important parameters in quantitative morphology. The area of the basin is defined as the total area projected upon a horizontal plane feeding the streams of all orders of the basin. Perimeter is the length of the boundary of the basin which can be drawn from topographical maps or can be derived by digital data using GIS softwares.

Drainage Density (R_D)

Drainage density is the ratio of total channel segment lengths cumulated for all orders within a basin to the basin area, which is expressed in terms of km / sq km.

$$R_D = \sum L / A$$

Horton (1932) introduced the drainage density (**R_D**) as an important indicator of the linear scale of landform elements in stream eroded topography. The drainage density indicates the closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin. It has been observed from drainage density measurements made over a wide range of geologic and climatic types that a low drainage density is more likely to occur in regions of highly permeable subsoil material under dense vegetation cover, and where relief is low. High drainage density is the resultant of weak or impermeable subsurface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine drainage texture (Strahler, 1964).

Stream Frequency (Fs)

Stream frequency or channel frequency (Fs) is the total number of stream segments of all orders per unit area (Horton, 1932).

$$Fs = \Sigma\ Nu / A$$

Texture Ratio (T)

Texture ratio (T) is an important factor in the drainage morphometric analysis and depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. It is the ratio of number of all the 1st order streams (N1) to the perimeter of the basin.

Elongation Ratio (Re)

Schumm (1956) defined elongation ratio (Re) as the ratio of diameter of a circle of the same area as the basin to the maximum basin length. It is a very significant index in the analysis of basin shape which helps to give an idea about the hydrological character of a drainage basin. Values near to 1.0 are typical of regions of very low relief (Strahler, 1964).

$$Re = Dc / Lb$$

where, Dc is diameter of a circle of the same area of the basin and Lb is the maximum basin length.

Circularity Ratio (Rc)

The ratio between total basin area and the area of a circle having the same perimeter as the basin is known as Circularity ratio of the basin (Miller, 1953). He described that the basins of the circularity ratios 0.4 to 0.5 indicate strongly elongated and highly permeable homogenous geologic materials. The elongated basins may be due to neotectonic activities in the area.

The elongation and circularity ratios are recently used effectively as a very important tool for indirectly providing information about the degree of maturity of the basin by quantitatively describing the planimetric shape of the basin. The basins draining tectonically active areas are more elongated and tend to become more circular with the cessation of uplift (Bull and McFadden, 1977).

Relief Ratio (Rr)

Relief ratio is defined as the ratio between the basin relief and the longest dimension of the basin parallel to the principal drainage line i.e. basin length. Schumm (1956) gives a simple expression for describing relief ratio (Rr) as:

$$Rr = h / L$$

Where L is the maximum length of the basin parallel to the principal drainage line, and h is the difference in elevation between the mouth of the basin and the highest point on the drainage divide.

Form Factor Ratio (Rf)

Quantitative expression of drainage basin outline form was made by Horton (1932) through a form factor ratio (Rf), which is the dimensionless ratio of basin area to the square of basin length. Basin shape may be indexed by simple dimensionless ratio of the basic measurements of area, perimeter and length (Singh, 1998).

PATTERN OF DRAINAGE NETWORK

Drainage network development of an area is a result of combination of factors such as climate, lithology and the attitude of the strata, active tectonics, regional uplift and subsidence. Drainage patterns of stream network from the basin have been observed as dendritic type in some stretches/reaches which indicates the homogeneity in texture and lack of structural control. This pattern is characterized by a tree like pattern with branches that intersect primarily at acute angles. In some parts of the basins parallel and radial pattern are observed. A parallel drainage pattern is shown by tributaries of lower orders that flow nearly parallel to one another and all the tributaries join the main channel at approximately the same angle. Parallel drainage suggest that the area has a gentle, uniform slope and with less resistant bed rock. A radial drainage pattern forms when water flows outward from a dome like feature, flowing away from a central high point (Jensen, 2006). The properties of the stream networks are very important to study the landform making processes (Strahler and Strahler, 2002). The drainage network development provides clues which can be used to understand the history of development of the landscape of the area.

Various aerial and linear parameters calculated for the river basins are given in the tables from 4.1A to 4.5B.

The Kaswali River is identified as 5^{th} order stream whereas Kaila and Chhari are 6^{th} order and Pur and Nirona are 7^{th} order streams. Total channel length and stream frequencies are quite high in all the river basins (Table 4.1A to 4.5B, Fig. 4.1- 4.5). Length and number of lower order streams suggest moderate to high head-water relief in the head water area, however, lesser number and length of the higher order streams suggest small extent of the river basins.

1. KASWALI RIVER BASIN:

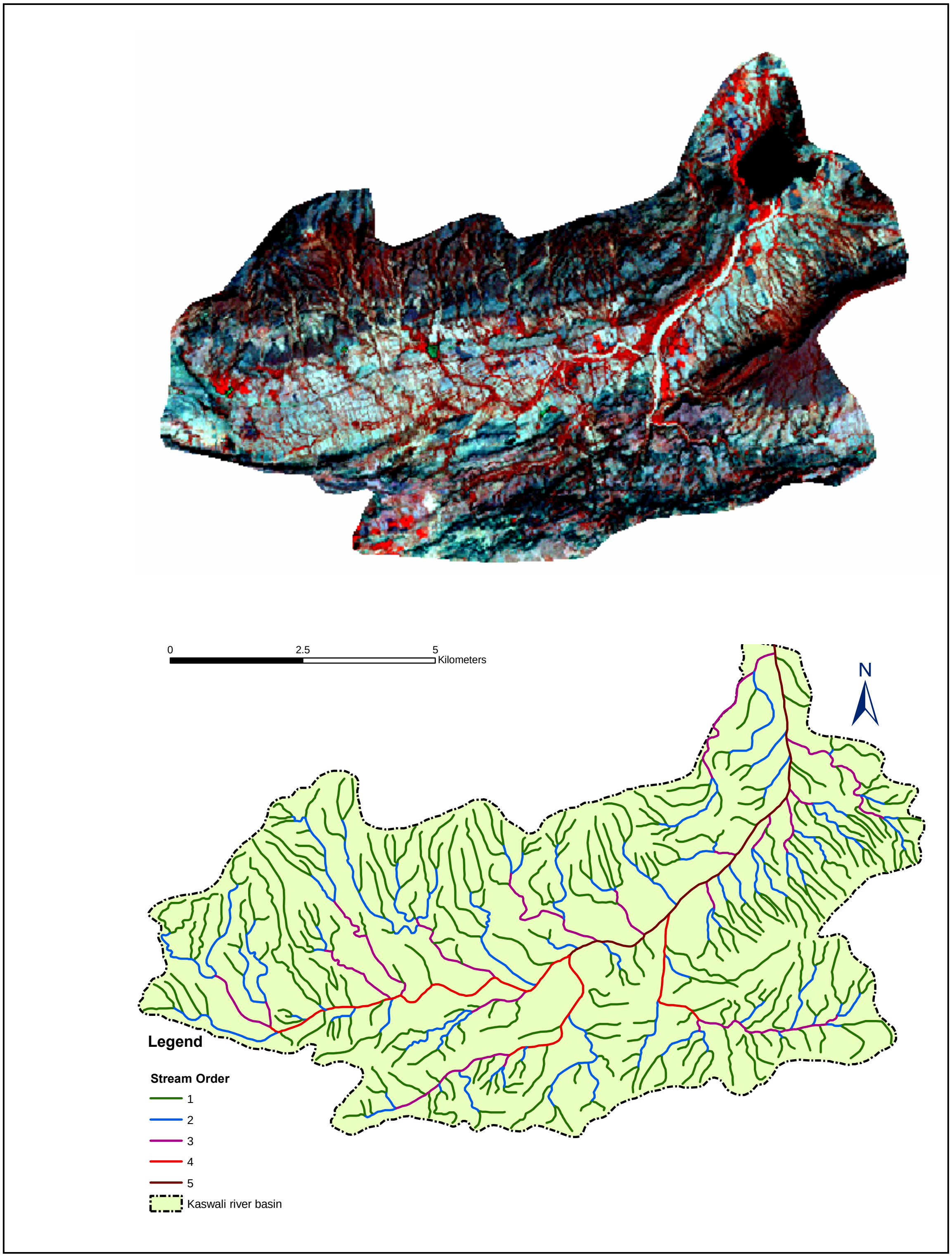


Fig.4.1: LISS-III FCC imagery of Kaswali River basin and detailed drainage map of the basin showing different order of streams.

Table 4.1A: Linear aspects of the drainage network of the Kaswali River basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1st	276 (N1)	177.86	0.644	2.441	2.250
Kaswali River Basin	2nd	70	61.05	0.872	1.845	1.786
	3rd	20	25.60	1.280	1.301	1.408
	4th	4	11.40	2.85	0.602	1.057
	5th	1	8.03	8.03	0.000	0.905
		ΣN_u = 371	ΣL_u = 283.94			

Bifurcation Ratio (R_b)				**Mean Bifurcation Ratio**
1st order/ 2nd order	**2nd order/ 3rd order**	**3rd order/ 4th order**	**4th order/ 5th order**	
3.942	3.50	5.0	4.0	3.369

Table 4.1B: Aerial aspects of the morphometric analysis of the Kaswali River Basin

Area of the River basin	**A**	70.98 sq km
Perimeter	**P**	45.89 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	4.00
Stream Frequency	$F_s = \Sigma N_u / A$	5.23 streams / sq km
Texture Ratio	$T = N_1/P$	6.01
Basin Length	L_b	14.1 km
Basin Relief	H_b	225 m
Relief Ratio	$R_R = H_b / L_b$	15.96 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.674
Ruggedness Number	$R_N = (D \times H_b) / 1000$	0.564
Circularity ratio	$R_C = 4 \pi A / P^2$	0.424
Form factor ratio	$R_F = A / L_b^2$	0.357

2. PUR RIVER BASIN:

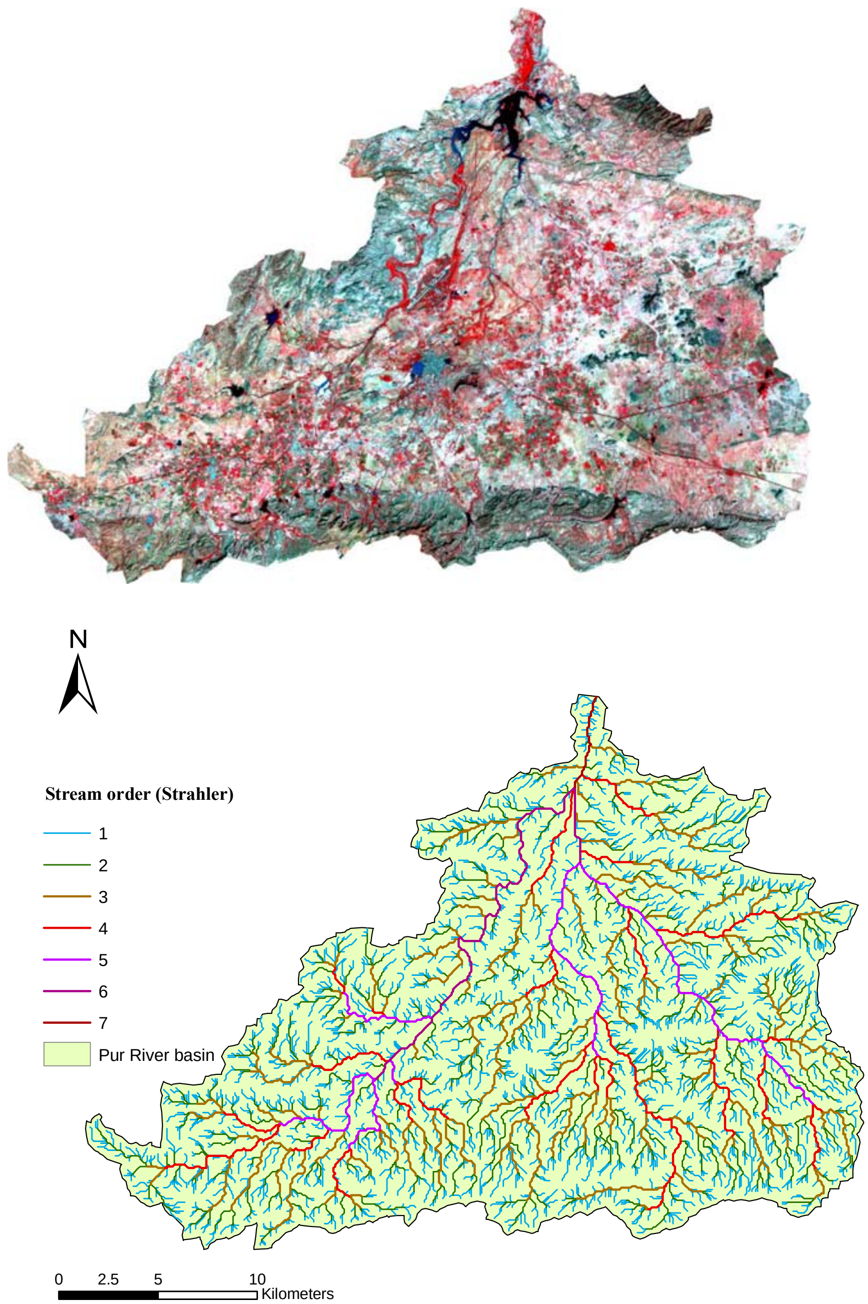


Fig.4.2: ETM Landsat FCC imagery (234) of the Pur River basin and detailed drainage map of the basin showing different order of streams.

Table 4.2A: Linear aspects of the drainage network of the Pur River basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1^{st}	2413 (N1)	1051.98	0.436	3.383	3.022
	2^{nd}	456	402.96	0.8885	2.659	2.605
	3^{rd}	108	247.81	2.295	2.033	2.394
PUR RIVER BASIN	4^{th}	24	102.71	4.280	1.380	2.012
	5^{th}	6	53.1	8.850	0.778	1.725
	6^{nd}	2	27.52	13.760	0.301	1.440
	7^{th}	1	5.19	5.190	0.000	0.715
		ΣN_u = 3010	ΣL_u = 1891.27	0.628		
Bifurcation Ratio (R_b)						**Mean R_b**
1^{st} order/ 2^{nd} order	**2^{nd} order/ 3^{rd} order**	**3^{rd} order/ 4^{th} order**	**4^{th} order/ 5^{th} order**	**5^{th} order/ 6^{th} order**	**6^{th} order/ 7^{th} order**	
5.292	4.222	4.500	4.000	3.000	2.000	**3.835**

Table 4.2B: Aerial aspects of the morphometric analysis of the Pur River basin

Area of the River basin	**A**	601.70 sq km
Perimeter	**P**	149.97 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	3.143
Stream Frequency	$F_s = \Sigma N_u / A$	5.00 streams / sq km
Texture Ratio	$T = N_1/P$	16.1
Basin Length	L_b	42.8 km
Basin Relief	H_b	212 m
Relief Ratio	$R_R = H_b / L_b$	6.18 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.647
Ruggedness Number	$R_N = (D \times H_b) / 1000$	0.666
Circularity ratio	$R_C = 4 \pi A / P^2$	0.336
Form factor ratio	$R_F = A / L_b^2$	0.511

3. KAILA RIVER BASIN:

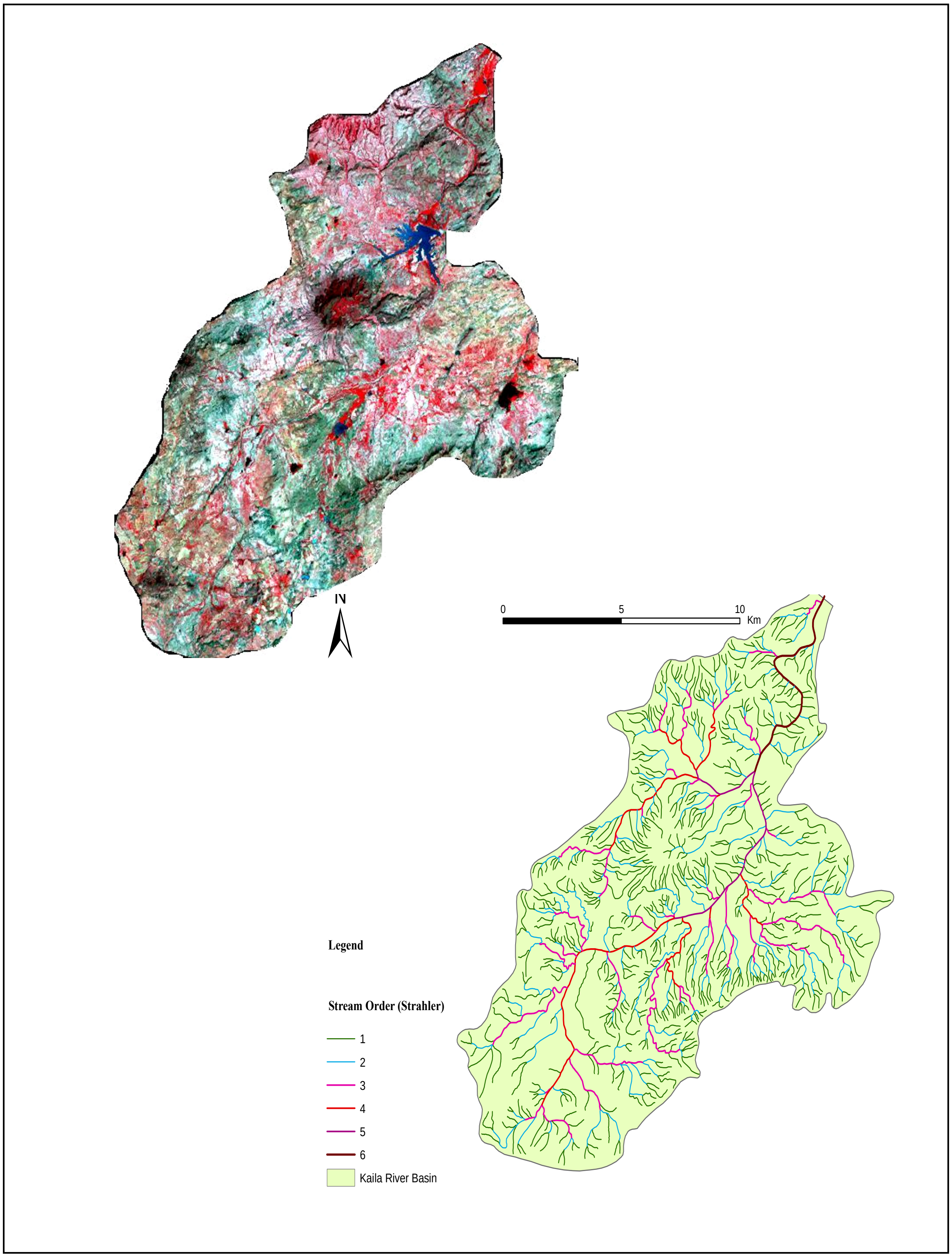


Fig.4.3: LISS-III FCC imagery of Kaila River basin and detailed drainage map of the basin showing different order of streams.

Table 4.3A: Linear aspects of the drainage network of the Kaila River Basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1st	662 (N1)	380.4	0.575	2.821	2.580
	2nd	168	134.84	0.798	2.225	2.130
KAILA RIVER BASIN	3rd	44	67.00	1.523	1.643	1.826
	4th	9	27.24	3.027	0.954	1.435
	5th	2	10.44	5.220	0.301	1.019
	6th	1	8.98	8.98	0.000	0.953
		Σ N_u = 886	**Σ L_u =** 628.9			

Bifurcation Ratio (R_b)					**Mean R_b**
1st order/ 2nd order	**2nd order/ 3rd order**	**3rd order/ 4th order**	**4th order/ 5th order**	**5th order/ 6th order**	
3.940	3.818	4.889	4.500	2.000	3.829

Table 4.3B: Aerial aspects of the morphometric analysis of the Kaila River Basin

Area of the River basin	**A**	180.93 sq km
Perimeter	**P**	72.14 km
Drainage Density (km/sq km)	**$D = \Sigma L_u / A$**	3.476
Stream Frequency	**$F_s = \Sigma N_u / A$**	4.897 streams / sq km
Texture Ratio	**$T = N_1/P$**	9.177
Basin Length	**L_b**	23.5 km
Basin Relief	**H_b**	299 m
Relief Ratio	**$R_R = H_b / L_b$**	12.723 m/ km
Elongation Ratio	**$R_E = (2 \sqrt{A/\pi}) / L_b$**	0.646
Ruggedness Number	**$R_N = (D \times H_b) / 1000$**	1.039
Circularity ratio	**$R_C = 4 \pi A / P^2$**	0.437
Form factor ratio	**$R_F = A / L_b^2$**	0.328

4. NIRONA RIVER BASIN:

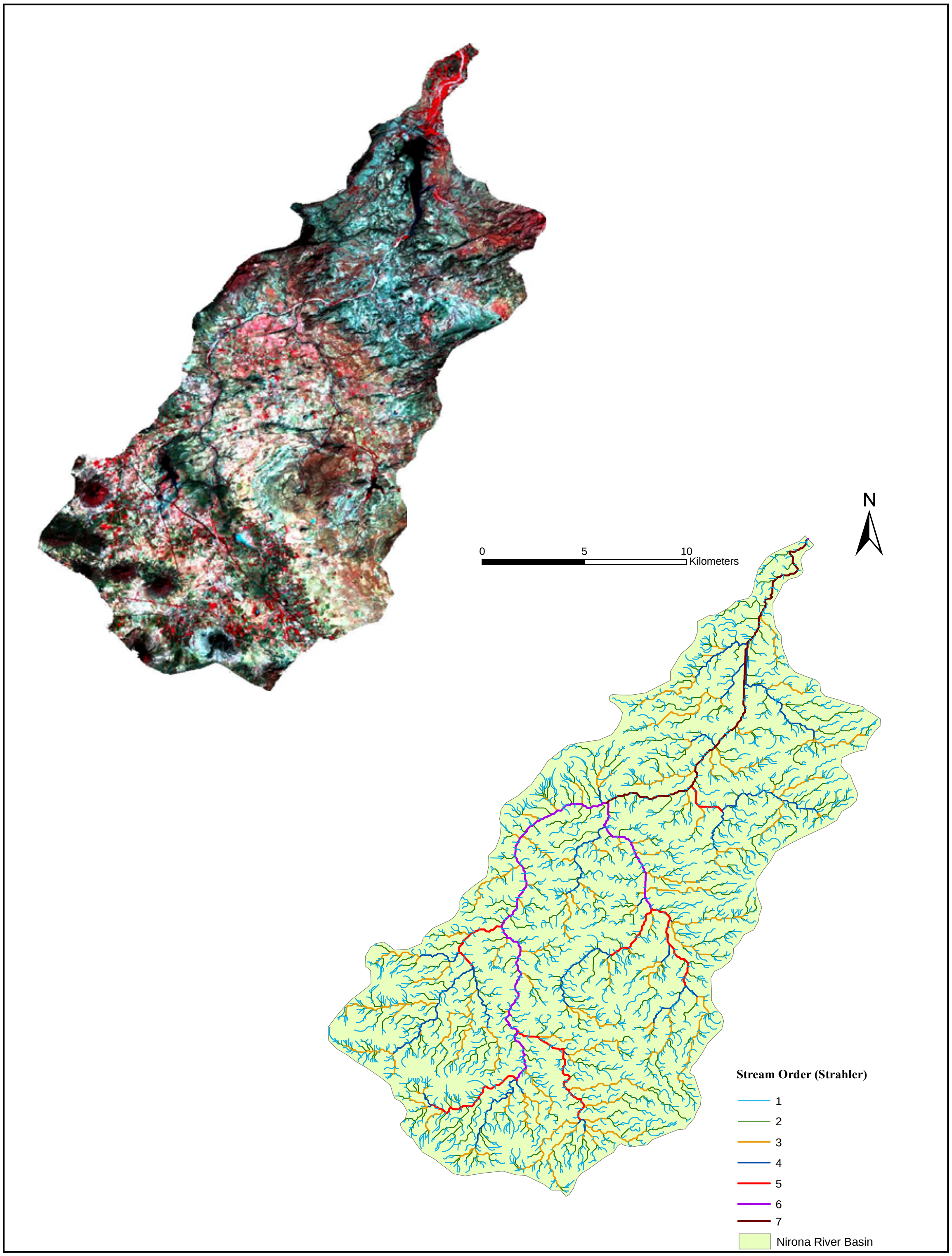


Fig.4.4: LISS-III FCC imagery of Nirona River basin and detailed drainage map of the basin showing different order of streams.

Table 4.4A: Linear aspects of the drainage network of the Nirona River basin

River Basin	**Stream Order u**	**Stream Numbers N_u**	**Total length of the streams in km L_u**	**Average stream length (km)**	**Log N_u**	**Log L_u**
	1st	2378 (N1)	680.057	0.286	3.376	2.833
	2nd	482	323.325	0.671	2.683	2.510
	3rd	101	176.788	1.750	2.004	2.247
NIRONA RIVER BASIN	4th	22	61.729	2.806	1.342	1.790
	5th	6	28.213	4.702	0.778	1.450
	6nd	2	27.130	13.565	0.301	1.433
	7th	1	19.8	19.80	0.000	1.297
		ΣN_u = 2992	**ΣL_u =** 1317.042			
Bifurcation Ratio (R_b)						**Mean R_b**
1st order/ 2nd order	**2nd order/ 3rd order**	**3rd order/ 4th order**	**4th order/ 5th order**	**5th order/ 6th order**	**6th order/ 7th order**	
4.933	4.772	4.591	3.667	3.000	2.000	**3.827**

Table 4.4B: Aerial aspects of the morphometric analysis of the Nirona River Basin

Area of the River basin	**A**	389.00 sq km
Perimeter	**P**	103.00 km
Drainage Density (km/sq km)	**$D = \Sigma L_u / A$**	3.386
Stream Frequency	**$F_s = \Sigma N_u / A$**	7.69 streams / sq km
Texture Ratio	**$T = N_1/P$**	23.087
Basin Length	**L_b**	35.9 km
Basin Relief	**H_b**	298 m
Relief Ratio	**$R_R = H_b / L_b$**	8.031 m/ km
Elongation Ratio	**$R_E = (2 \sqrt{A/\pi}) / L_b$**	0.620
Ruggedness Number	**$R_N = (D \times H_b) / 1000$**	1.009
Circularity ratio	**$R_C = 4 \pi A / P^2$**	0.461
Form factor ratio	**$R_F = A / L_b^2$**	0.302

5. CHHARI RIVER BASIN:

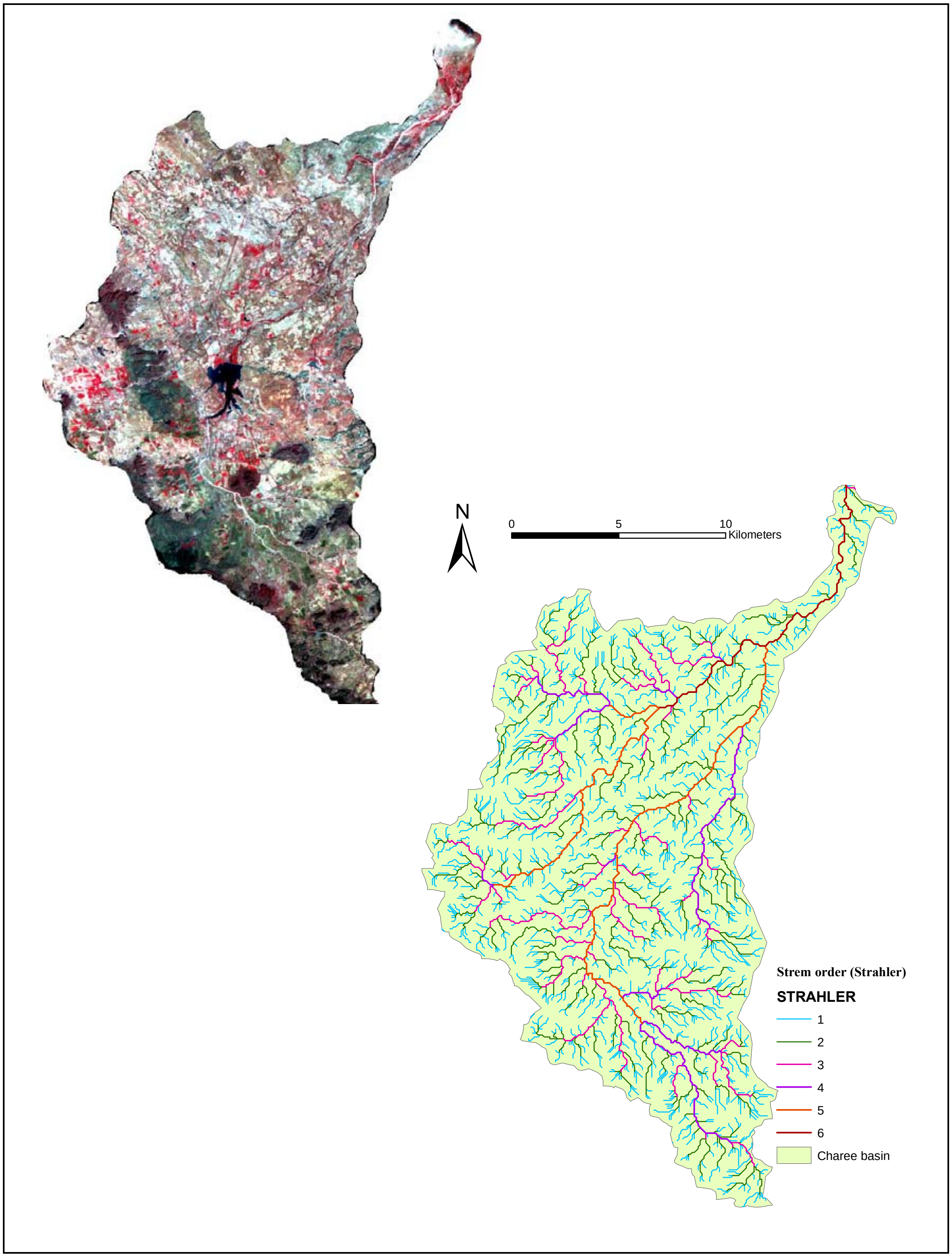


Fig.4.5: ETM Landsat FCC imagery (234) of Chhari River basin and detailed drainage map of the basin showing different order of streams.

Table 4.5A: Linear aspects of the drainage network of the Chhari River Basin

River Basin	Stream Order u	Stream Numbers N_u	Total length of the streams in km L_u	Average stream length (km)	Log N_u	Log L_u
	1st	1261 (N1)	551.369	0.437	3.101	2.741
	2nd	226	235.630	1.043	2.354	2.372
Chhari River Basin	3rd	54	102.385	1.896	1.732	2.010
	4th	11	42.057	3.823	1.041	1.624
	5th	3	42.630	14.210	0.477	1.630
	6th	1	18.600	18.600	0.000	1.270
		ΣN_u = 1556	ΣL_u = 992.671			

Bifurcation Ratio (R_b)					Mean R_b
1st order/ 2nd order	2nd order/ 3rd order	3rd order/ 4th order	4th order/ 5th order	5th order/ 6th order	
5.579	4.185	4.909	3.667	3.000	4.268

Table 4.5B: Aerial aspects of the morphometric analysis of the Chhari River Basin

Area of the River basin	A	311.042 sq km
Perimeter	P	112.870 km
Drainage Density (km/sq km)	$D = \Sigma L_u / A$	3.191
Stream Frequency	$F_s = \Sigma N_u / A$	5.003 streams / sq km
Texture Ratio	$T = N_1/P$	11.172 streams/ km
Basin Length	L_b	32.5 km
Basin Relief	H_b	245 m
Relief Ratio	$R_R = H_b / L_b$	7.538 m/ km
Elongation Ratio	$R_E = (2 \sqrt{A/\pi}) / L_b$	0.612
Ruggedness Number	$R_N = (D \times H_b) / 1000$	0.782
Circularity ratio	$R_C = 4 \pi A / P^2$	0.307
Form factor ratio	$R_F = A / L_b^2$	0.294

The stream frequency values range from lowest of 4.897 for Kaila basin to highest of 7.69 for Nirona basin. The value of stream frequency (Fs) for the basin exhibit positive correlation with the drainage density value of the area indicating the increase in stream population with respect to increase in drainage density. Melton (1958) related the frequency and drainage density by the equation F = 0.694 D2. The dimension less number F/D2 tends to approach a constant value of 0.694 even under diverse physiographic situations and size of drainage basin. Here this constant is ranging from 0.654 to 0.795 indicating that the basins originated from under diverse physiographic conditions.

Horton's (1945) law of stream numbers states that the number of stream segments of each order form an inverse geometric sequence plotted against order. The plotting of logarithm of number of streams against stream order is given in Fig. 4.6. The plots are straight as per the Horton's law.

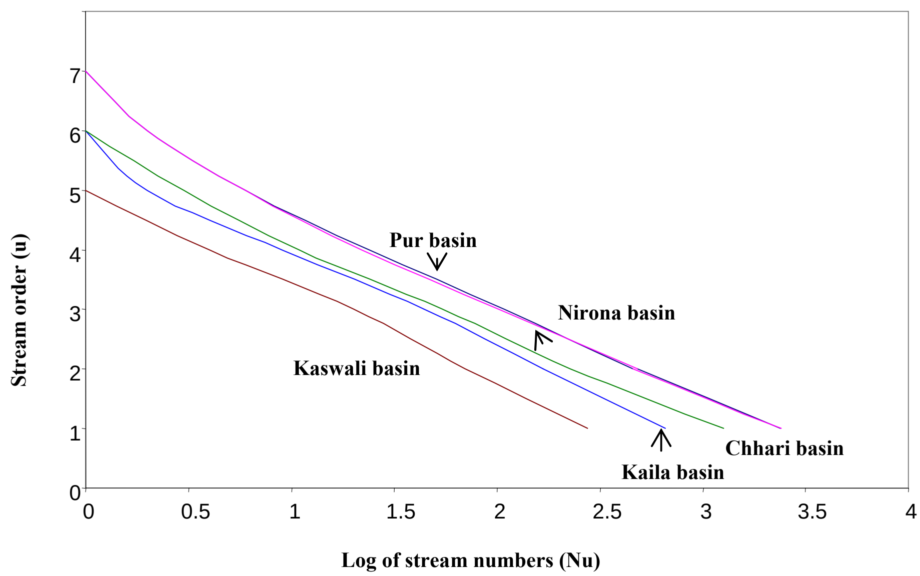


Fig. 4.6: Regression log of Stream numbers versus Stream order.

The circularity ratio values range from 0.307 for Chhari basin to 0.437 for Kaila basin. Highest elongation ratio is for the Kaila basin while for all the basin it is near 0.6 which indicate that all the basin are elongated in shape. The basins draining tectonically active areas are more elongated and tend to become more circular with the cessation of uplift (Bull and McFadden, 1977), so it is interpreted that the elongated shape of Kaila Chhari and Nirona basins points towards the area undergoing active tectonism.

The bifurcation ratio tends to be constant for a drainage basin having a uniform climate, lithology and stages of development. The bifurcation ratios of the various basins, especially Pur, Nirona and Chhari 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.

Drainage density varies from 3 to 4 km / sq km. Increase in the drainage density decreases the size of the individual units. Factors affecting drainage density are erodibility of rock and climate. Drainage density is generally lower in arid climates but comparatively high in humid terrain (Gardiner et al., 1987). In case of the river basins of the area it is ranging from 3-4 km/ sq km which come under high density class (Horton, 1945). Since area falls in the arid climate, 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 for Nirona basin which is extremely high. This high texture ratio is indicative of recent upliftment.

The ruggedness for the Kaila and Nirona basins is more than 1 while it is about 0.5 to 0.7 for Kaswali, Pur and Chhari basins. These values suggest high drainage density and comparatively low relief, indicating neotectonic activity in the area.

Trend analysis of the 1stand 2nd 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 directions. This analysis reveals that the lower order streams are governed by the tilting of the basins.

BASIN ASYMMETRY

The shape of a river basin is attained by the slope of the area. The slope is the function of tilting hence the basin asymmetry can be used to decipher the tilting of the area, thus neotectonic activities (Hare and Gardner, 1985; Cox, 1994). The basin asymmetry is defined in the form of Asymmetry Factor. Asymmetry Factor (AF) has been developed to detect the tilting transverse to flow of the channels.

$$\mathbf{AF = 100 \times (Ar / At)}$$

Where, Ar is the area of basin to the right side (facing downstream) of the trunk stream whereas At represents the total area of the basin. AF values are sensitive to the tectonic tilting transverse to the trend of the trunk stream. Value of AF will be either less or more than 50 in case of tectonic tilting and tributaries present in the tilted side of the trunk stream will grow longer compared to the other side (Keller and Pinter, 1996). If the migration of streams is independent of the bed rock dip and the streams prefer to migrate in a particular direction, it indicates a period of ground tilting in that direction (Keller and Pinter, 1996).

The asymmetry factor has been calculated for the five river basins of the area around KMF. The AF values are given in the table-4.6.

Table 4.6: Asymmetry factor of the river basins

River basin	Total area (sq km)	Area in the right of the trunk stream (Ar)	AF	Deviation from 50
Kaswali River basin	70.98	37.7	53.11	3.11
Pur River basin	601.70	470.78	78.3	28.3
Kaila River basin	180.93	88.55	48.94	1.06
Nirona River basin	388.68	257.53	66.26	16.66
Chhari River basin	311.042	207.66	66.76	16.76

The general trend of the beds in all the river basins studied is east-west dipping moderately to steeply near the KMF while the amount of dip decreases away from the KMF (Ghevariya, 1984, 87; Singh et al., 2008). All the river basins studied are extending roughly across the KMF. The general strike of the beds is East-West in the area. Thus the streams are transverse to the general trend of the beds of litho-units and the little influence of the beds on the drainage is nullified on either side of the river basins.

The AF 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. (Fig.4.8). 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 in the Quaternary Period.

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, where they are not obstructed by the hard rocks of valley sides and show deflection following the direction of gradient changes (Fig.4.7).

Fig. 4.7: Drainage map of the area along Kachchh Mainland Fault showing the deflection of the streams towards west.

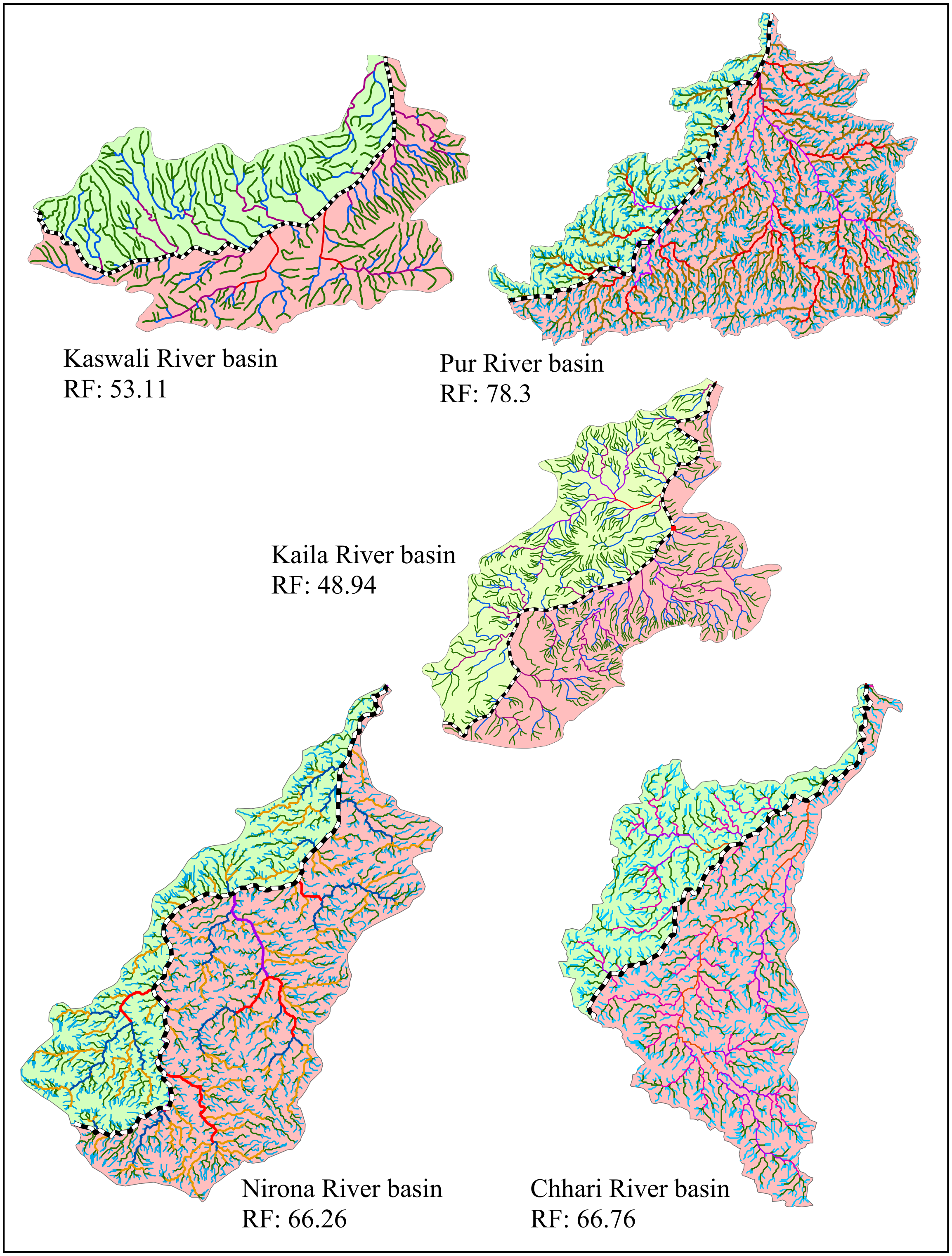


Fig. 4.8: River basins with their main trunks and left and right tributaries showing basin asymmetry.

VALLEY CROSS SECTION

Study of the cross section of the river valley may give clues of the tectonic insinuations the area has suffered. Valley incision is a measure that can be used to define relative uplift (Bull and McFadden, 1977; Ouchi, 1985). It basically describes the maturity of the valley. The Valley floor width to the Valley height ratio (Vf) is an index developed by Bull and McFadden (1977) to study the relative rate of uplift an area is undergoing. Rockwell et al. (1984) also tested this index for mountain fronts and found the trends to be similar to those established by Bull and McFadden.

The formula for this parameter (Valley floor width-Valley height ratio) is as follows:

$$Vf = 2\ Vfw / [(Eld - Esc) + (Erd - Esc)]$$

where, Vf = Valley floor width-Valley height ratio, Vfw = width of the valley floor, Eld = elevation of the left divide, Erd = elevation of the right divide and Esc = altitude of the stream channel.

The valley floor width is measured between the abrupt slope increases adjacent to the river and valley height is estimated from the elevation between the stream channel and the water divides on either sides of the river. A high value of the Vf, as seen in the broader valleys, is indicative of a tectonic quiescence because of availability of enough time for lateral erosion. Conversely, a low Vf, as seen in the steep narrow valleys, is associated with the recent tectonic movements (Mayer, 1986).

The cross-valley profiles are generated taking the data from various sources like topographic maps, SRTM 90 radar data, Aster data (30 m), google map and geo-referenced imagery of the area. Vf has been calculated for the Kaswali, Pur, Kaila, Nirona and Chhari Rivers and their tributaries at several distances from the source. The streams near the source show very low Vf (from 0.24 to 1.4) whereas it increases as we move away from source due to increase in the valley floor width. At places it becomes very low, as valley incision is quite high for a particular part of the area, indicating periodic tectonic activity. The higher values near the mountain fronts indicate the broad valley floors and lateral cutting of the streams. It is important to mention that the lithology, climatic factors and hydraulic conditions of the rivers also play important role in shaping the valley cross section but for the most part of the stream channels of the area these factors appeared to be constant.

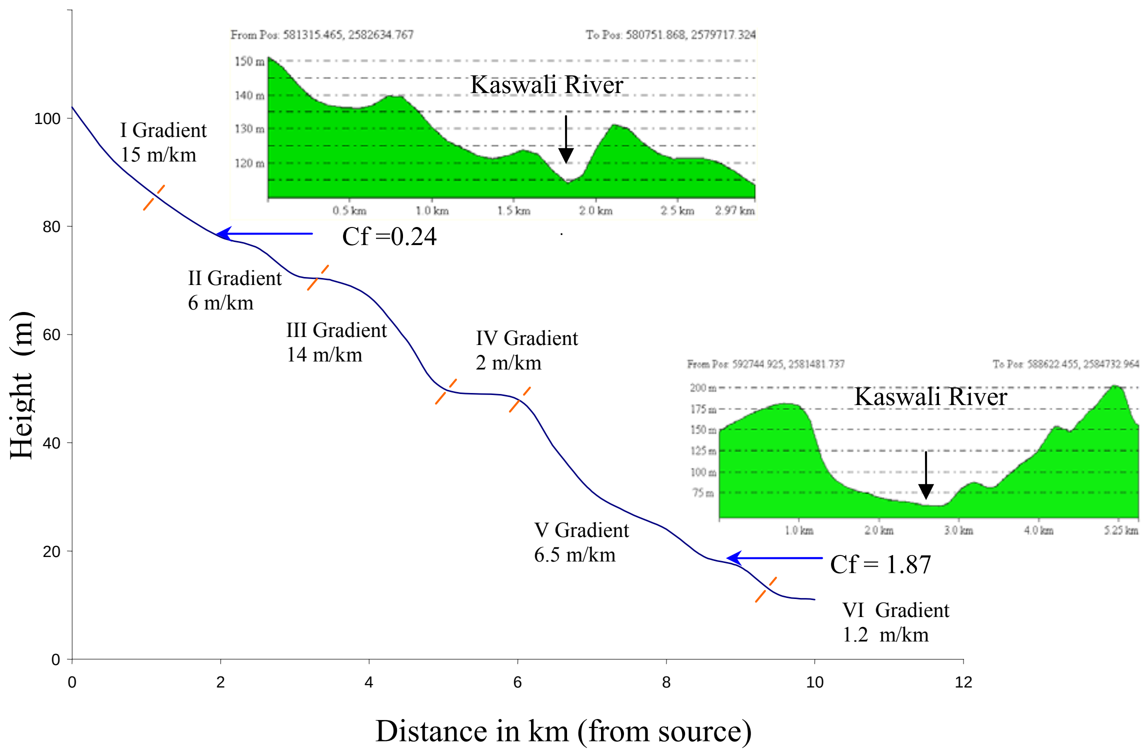


Fig. 4.9: Longitudinal profile of the Kaswali River with Vf values and valley cross section; near source cross section is V-shaped whereas away from source it is U-shaped.

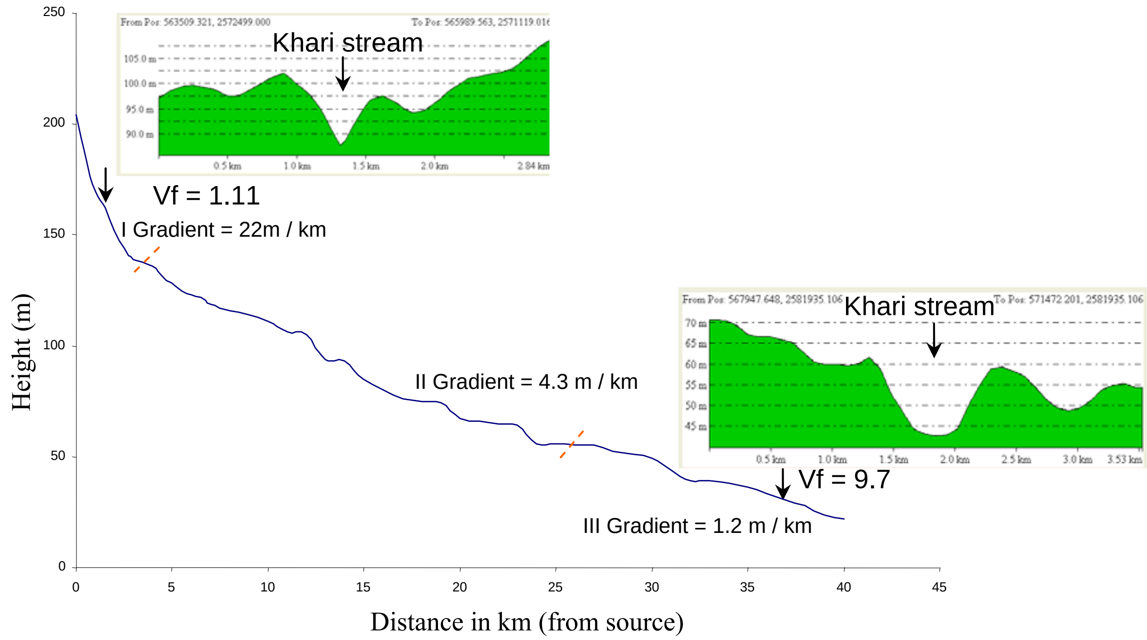


Fig. 4.10: Longitudinal profile of the Khari stream of the Pur River with Vf values and valley cross section.

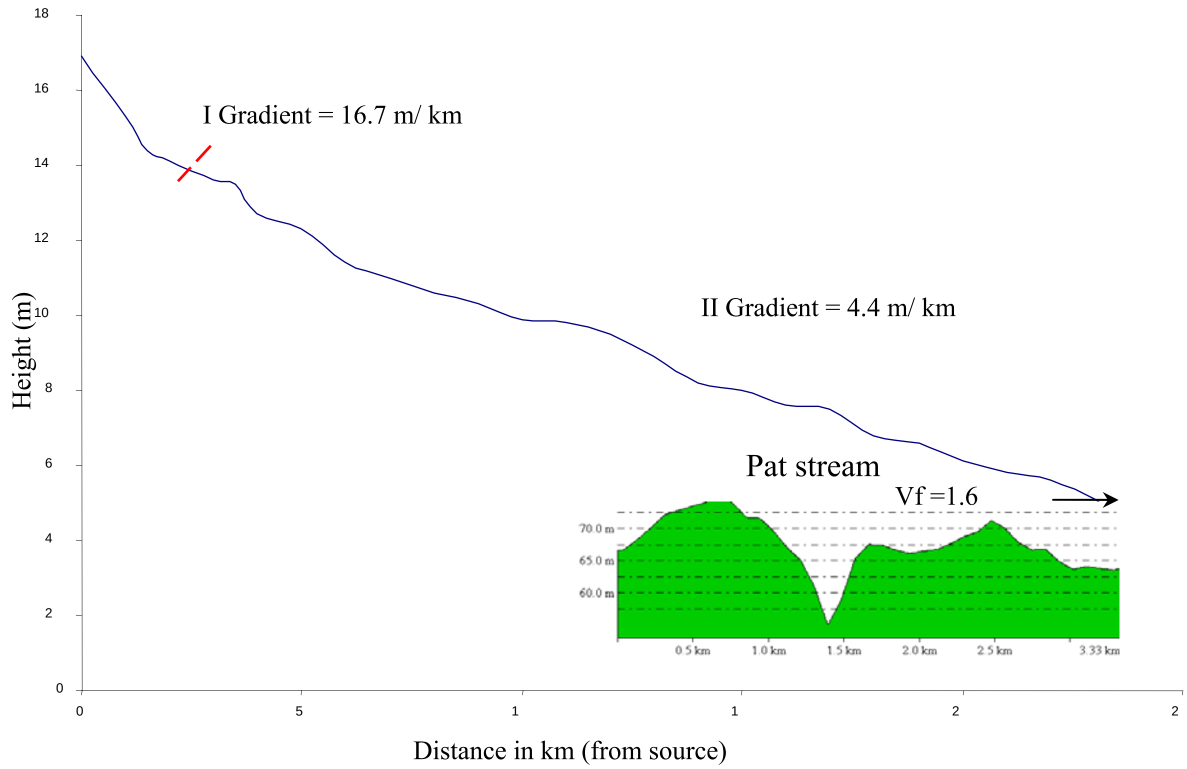


Fig. 4.11: Longitudinal profile of the Pat stream of the Pur River with Vf values and valley cross section.

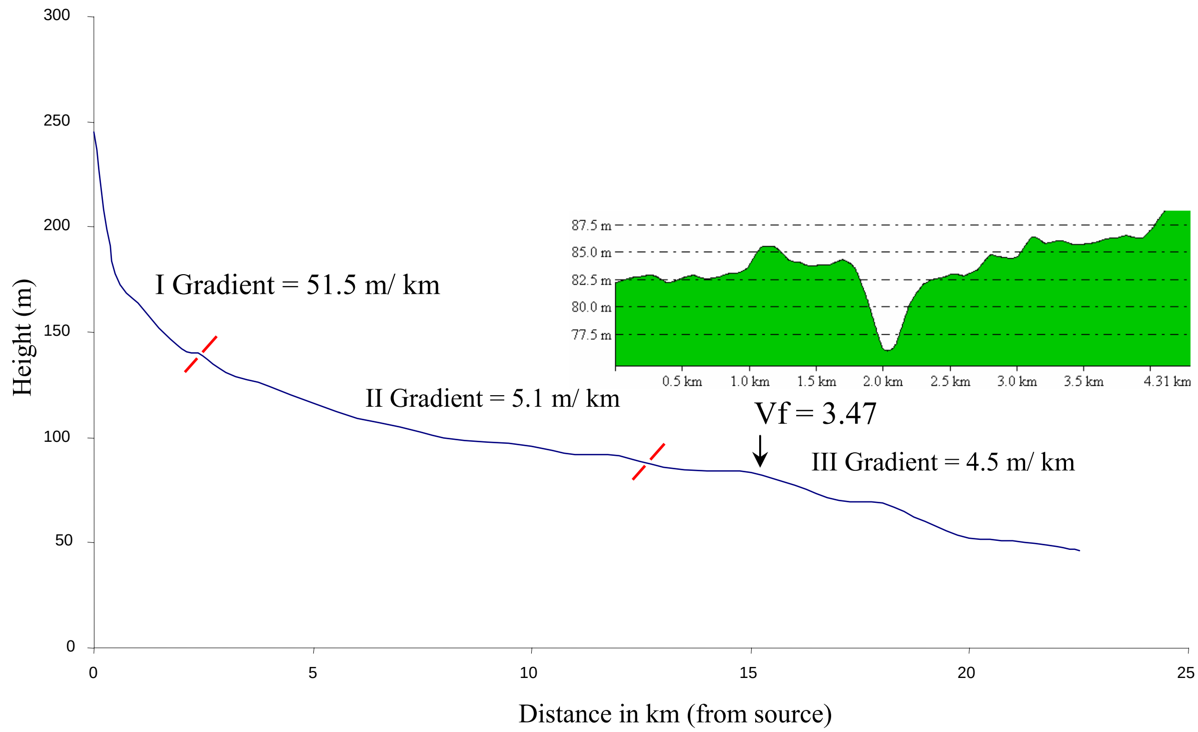


Fig. 4.12: Longitudinal profile of the Pur River with Vf value and valley cross section.

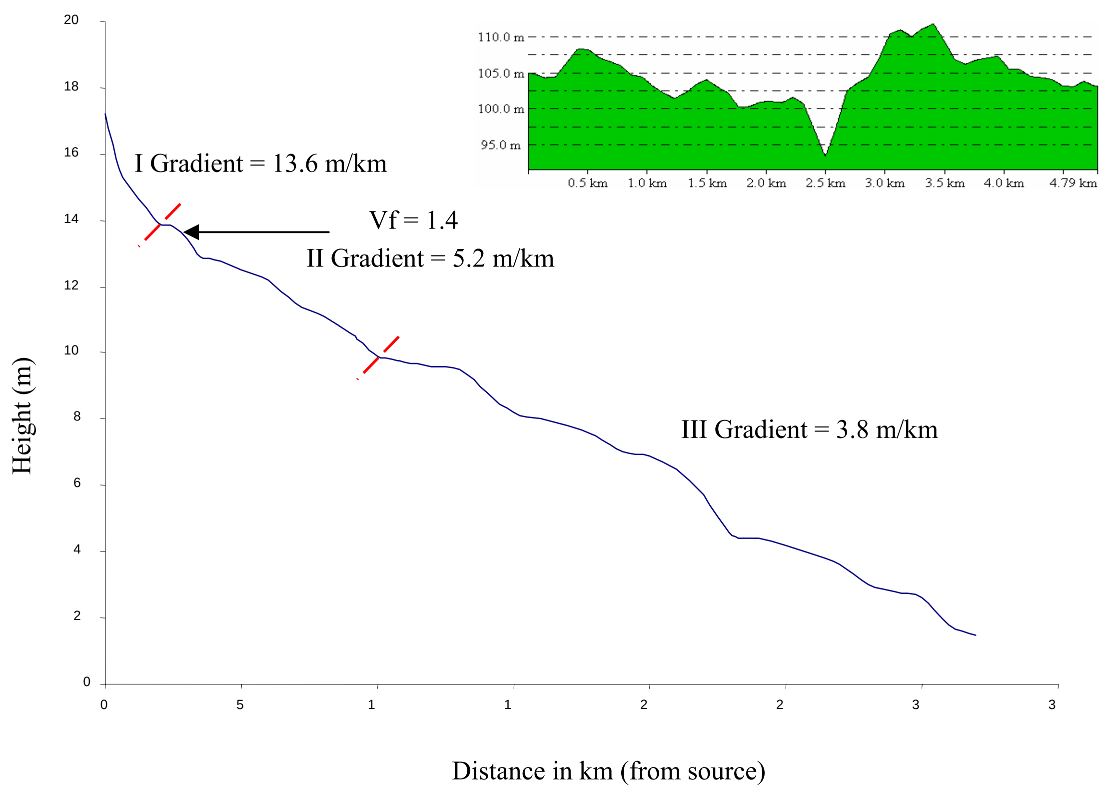


Fig. 4.13: Longitudinal profile of the Kaila River with Vf value and valley cross section.

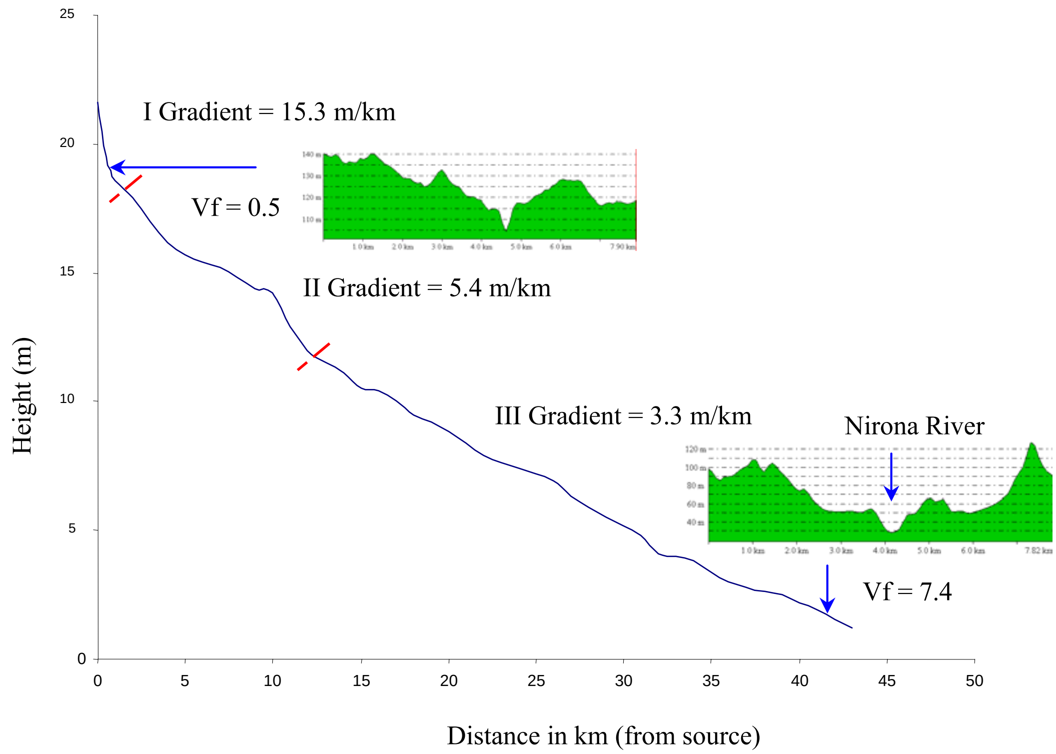


Fig. 4.14: Longitudinal profile of the Nirona River with Vf value and valley cross section.

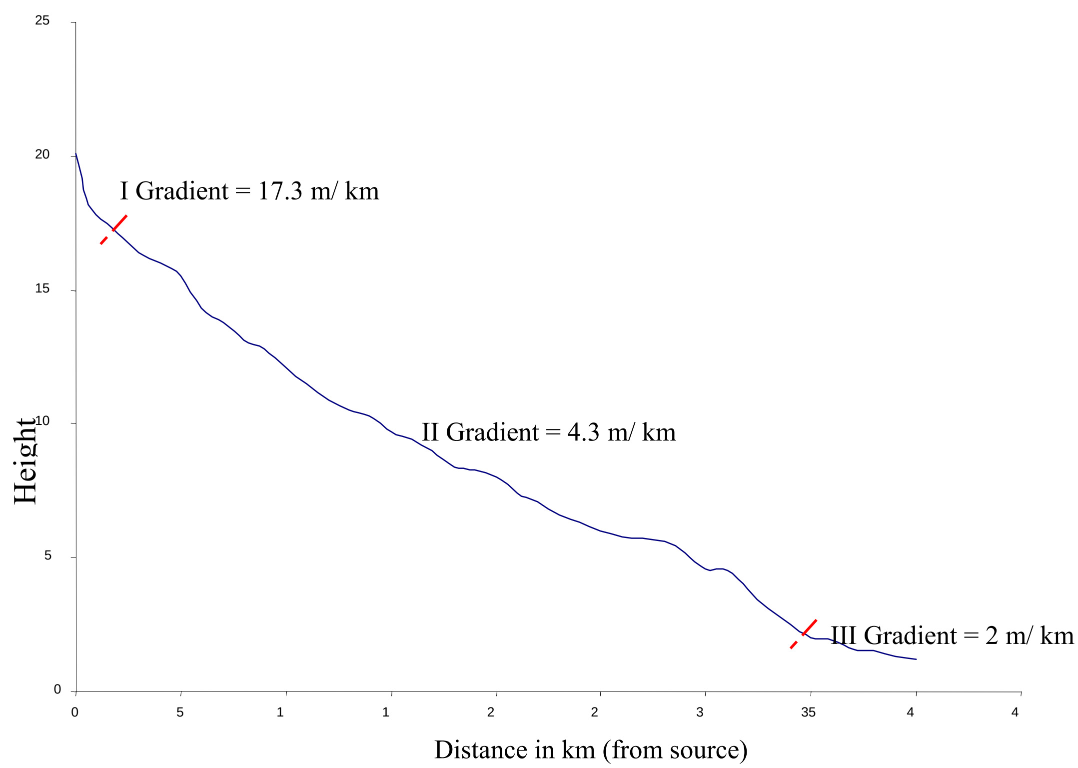


Fig. 4.15: Longitudinal profile of the Chhari River showing gradient in sectors.

LONG PROFILE ANALYSIS

The long profile is the plot of river channel length with respect to channel elevation above sea level. Long profiles of stream channels result from the interactions between fluvial incision, lithology, tectonics and base level change (Larue, 2008). The shape of the long profile is the result of the influence of each of these factors and of the evolution time. The longitudinal profile of a river reflects the tectonic activity the area has experienced (Rhea, 1993). To quantify the general shape of stream long profile, the pseudo-hypsometric integral (PHI) has been measured. It reflects the relative amount of deformation and degradation that has occurred on each river (Rhea, 1993). In some earlier studies hypsometric analysis (or area-altitude analysis), which is the study of the distribution of horizontal cross-sectional area of a landmass with respect to elevation (Strahler, 1952), was used to classify and differentiate between erosional landforms at different stages during their evolution (Strahler, 1952, Schumm, 1956). It provides a measure of the distribution of landmass volume remaining beneath or above a basal reference plane. But recently pseudo-hypsometric integral is used more effectively to numerically compare the long profiles of various rivers. Pseudo Hypsometric Index parameter is calculated as follows:

$$PHI = Ap / Ar$$

where, PHI is the Pseudo Hypsometric Integral, Ap is the area under long profile and Ar is the area of the rectangle formed by the height and length of the river basin.

PHI of the streams were calculated using the longitudinal profile of the rivers derived using topographic maps, high resolution google earth images and SRTM height data (Fig.4.16).

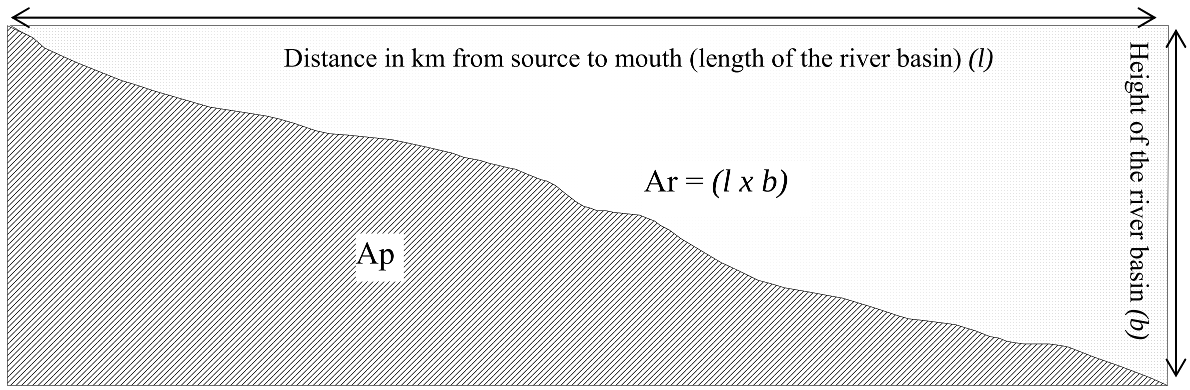


Fig. 4.16: Longitudinal profile of the Kaswali River showing Ap and Ar for PHI calculation.

Table 4.7: Pseudo Hypsometric Integral values of the rivers

River (stream)	PHI (in%)
Kaswali River	48.49 %
Khari stream of Pur River	31.29 %
Pat stream of Pur River	39.94 %
Pur River	25.85 %
Kaila River	42.14 %
Nirona River	38.13 %
Chhari River	39.25 %

The long profiles of the rivers show prominent breaks in their longitudinal profiles (Fig.4.9 to 4.15). These breaks are indicative of rejuvenations forming knick point which is 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 thus indicate the influence of the neotectonism in the area. The PHI of the river are in agreement with the long profile as they are in general high, specially for the Kaswali, Kaila and Chhari Rivers which indicate that the area has under gone rejuvenation in the recent past.

MOUNTAIN FRONT SINUOSITY

Geomorphic indices for mountain-front sinuosity was developed by Bull and McFadden (1977) which is useful in the general assessment of the degree of tectonic activity experienced by an area.

The Mountain Front Sinuosity (S) is defined as the ratio of length of a mountain front, as measured from an aerial photograph or topographic map or other method, to the straight-line length along the mountain front. It therefore, reflects a balance between the tendency of erosional processes to produce an irregular or sinuous mountain front and the effect of vertical active tectonic movement on steeply dipping, range-bounding faults, which tend to produce a relatively straight front. Broadly speaking, a straight mountain front is indicative of an active fault or fold while the irregular fronts indicate tectonic pause when erosion has got enough time to act upon and make the front irregular (Bull and McFadden, 1977). The Mountain front sinuosity index is calculated as follows:

$$\textbf{Mountain Front Sinuosity (S)} = \mathbf{Lmf / Ls}$$

Where, Lmf is the length along the edge of the mountain-piedmont junction and Ls is the straight length of mountain front.

Low values of the S correlate with relatively high rates of uplift along faults which bound mountain ranges. Mountain front sinuosity of the fronts calculated along the Kachchh Mainland Fault is calculated using more accurate data of Google Earth, zooming the image enough to get all the details available, keeping the 3D view on. The fronts were selected for analysis along the KMF which were continuous for more than 2 km in length (Fig.4.17). The detail of the analysis is given in Table 4.8.

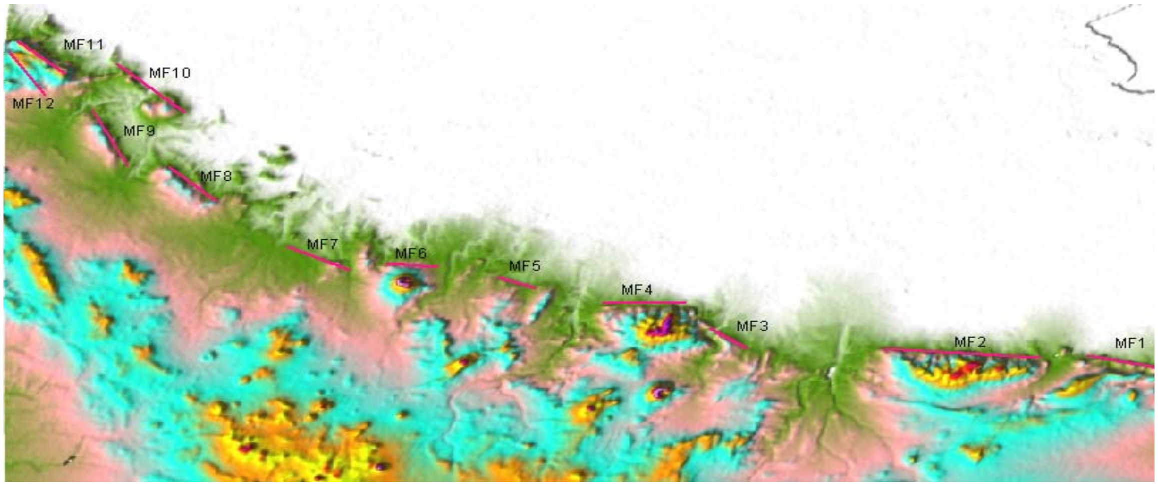


Fig. 4.17: Location of mountain fronts selected for sinuosity index calculation.

Table 4.8: Mountain front sinuosity of the selected fronts along the KMF

Mountain Front	**Lmf (km)**	**Ls (km)**	**Sinuosity Index (S)**	**Tectonic Activity Class**
1	13.92	13.69	**1.02**	**I**
2	14.81	14.60	**1.01**	**I**
3	3.51	3.23	**1.09**	**I**
4	8.83	8.64	**1.02**	**I**
5	2.45	2.32	**1.05**	**I**
6	4.08	3.70	**1.10**	**I**
7	2.10	2.02	**1.04**	**I**
8	7.04	6.37	**1.10**	**I**
9	12.92	12.25	**1.01**	**I**
10	17.84	17.22	**1.04**	**I**
11	6.30	6.23	**1.01**	**I**
12	10.66	9.98	**1.07**	**I**

The analysis of the Mountain front sinuosity index of the East-West trending mountain fronts associated with the KMF fall within the tectonic activity class I of Bull and McFadden (1977) indicating that the area is experiencing active tectonism.

RIVER SINUOSITY

Sinuosity of a river is its tendency to deviate from a straight line. The river sinuosity parameters have been used to understand the role of tectonism (Rhea, 1993). The sinuosity of a meandering stream is the result of topographic and hydraulic factors which can be expressed by a ratio called the index of sinuosity (Mueller, 1968). Friend and Sinha (1993) suggested a simpler method of measuring sinuosity by dividing the river into segments and determining the sinuosity parameter for each segment. Leopold and Langbein (1966) described Topographic Sinuosity Index (TSI) and the Hydraulic Sinuosity Index (HSI) as additional variables for defining the sinuosity of the channels. A higher value of the TSI over HSI is indication of rejuvenation, i.e. tectonic factors domination over hydraulic factors.

The indices of sinuosity are calculated as follows:

Channel Index (CI)	**= CL / AL** where, CL is Channel Length and AL is air Length (Straight Length)
Valley Index (VI)	**= VL / AL,** where VL is Valley length
Standard Sinuosity Index (SSI)	**= CI / VI**
Hydraulic Sinuosity Index (HSI)	**= (CI - VI / CI - 1) x 100**
Topographic Sinuosity Index (TSI)	**= (VI-1 / CI – 1) x 100**

The Sinuosity indices of the two rivers, the Kaswali and the Nirona, have been calculated in the present course of study. The Google earth images have been used to calculate the channel length, valley length and their aerial lengths zooming the images up to about 1:2000 to 1:5000 scale.

Sinuosity Indices of Kaswali River

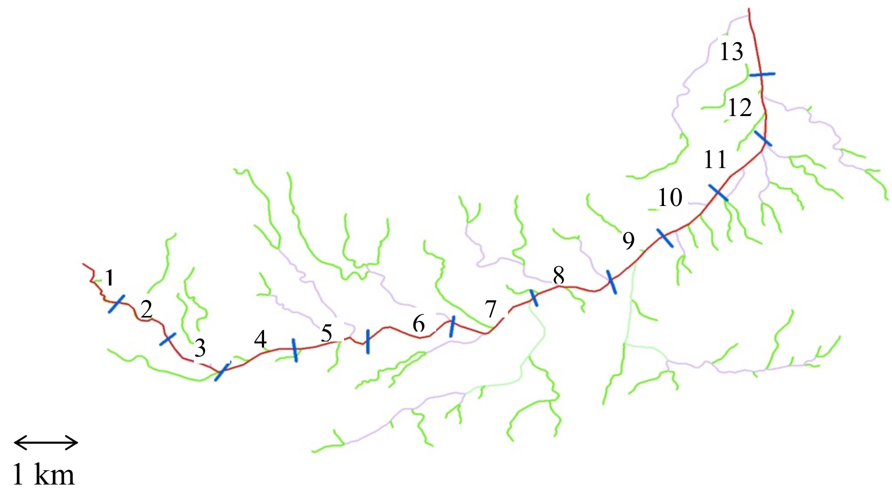


Fig.4.18: Segments of the Kaswali River used for calculation of river sinuosity.

Table 4.9: Table showing values of Channel Index (CI), Valley Index (VI), Standard Sinuosity Index (SSI), Hydraulic Sinuosity Index (HSI) and Topographic Sinuosity Index (TSI) computed for the various segments of Kaswali main channel

Segment Number	Channel Index (CI)	Valley Index (VI)	S.S.I.	H.S.I. (in %)	T.S.I. (in %)
1	1.02	1.02	1.00	0.00	100.00
2	1.06	1.06	1.00	0.00	100.00
3	1.09	1.09	1.00	0.00	100.00
4	1.03	1.03	1.00	0.00	100.00
5	1.22	1.18	1.03	16.67	83.33
6	1.27	1.22	1.04	19.05	80.95
7	1.19	1.13	1.05	31.25	68.75
8	1.06	1.06	1.00	0.00	100.00
9	1.14	1.09	1.04	33.33	66.67
10	1.39	1.33	1.04	14.29	85.71
11	1.01	0.98	1.03	50.00	50.00
12	1.02	1.01	1.01	50.00	50.00
13	1.09	1.07	1.02	25.00	75.00

Table 4.10: Table showing values of Channel Index (CI), Valley Index (VI), Standard Sinuosity Index (SSI), Hydraulic Sinuosity Index (HSI) and Topographic Sinuosity Index (TSI) computed for the various segments of Nirona main channel

Segment Number	Channel Index (CI)	Valley Index (VI)	S.S.I.	H.S.I. (in %)	T.S.I. (in %)
1	1.04	1.04	1.00	0.00	100.00
2	1.11	1.11	1.00	0.00	100.00
3	1.16	1.16	1.00	0.00	100.00
4	1.10	1.10	1.00	0.00	100.00
5	1.06	1.06	1.00	0.00	100.00
6	1.14	1.14	1.00	0.00	100.00
7	1.18	1.18	1.00	0.00	100.00
8	1.15	1.15	1.00	0.00	100.00
9	1.03	1.01	1.03	83.33	16.67
10	1.03	1.01	1.02	66.67	33.33
11	1.03	1.02	1.02	50.00	50.00
12	1.04	1.02	1.02	57.14	42.86
13	1.06	1.04	1.02	33.33	66.67
14	1.16	1.13	1.03	18.52	81.48
15	1.03	1.01	1.02	80.00	20.00
16	1.15	1.05	1.10	69.23	30.77
17	1.04	1.01	1.03	71.43	28.57
18	1.11	1.09	1.02	20.00	80.00
19	1.02	1.01	1.01	50.00	50.00
20	1.01	1.01	1.00	0.00	100.00
21	1.01	1.00	1.01	49.75	50.25
22	1.16	1.13	1.03	21.43	78.57

Sinuosity Indices of Nirona River

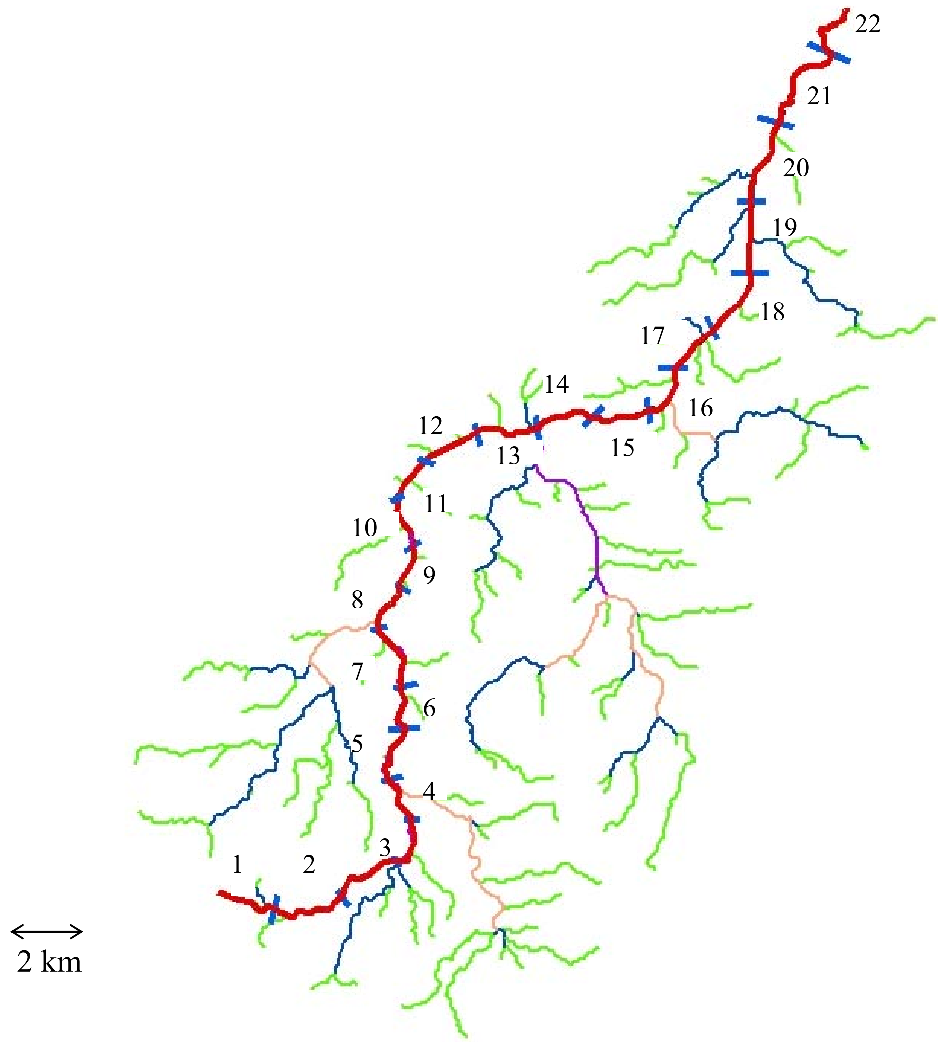


Fig. 4.19: Segments of the Nirona River used for calculation of river sinuosity.

The sinuosity indices for Kaswali River (Fig.4.18, Table 4.9)) and Nirona River (Fig.4.19, Table 4.10) show that the topographic sinuosity index is 100% in higher reaches while it starts decreasing in the middle reaches of rocky plains. Both the basins show high values of TSI as compared to HSI which indicate that the tectonic factors are dominating over hydraulic factors in shaping the course of the rivers.

CHAPTER 5

NEOTECTONICS

The term 'neotectonics' was introduced by Obruchev (1948) who defined it as the 'recent tectonic movements which occurred in the upper Tertiary (Neogene) and Quaternary times, and played an essential role in shaping the contemporary topography'. There has been debate since them on the time period which can be defined as to mark the distinct neotectonic activity. Some people consider the neotectonics as synonymous with 'active tectonics', whereas some consider neotectonic period beginging from the Middle Miocene. A general consensus has been rising that the actual time frame may vary in different geological environments. 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 are still occurring or which have occurred in a particular region after its orogeny or after the last significant tectonic set-up of the area." The neotectonic activities are recent enough so that they can permit a detailed analysis by definite methods, and their results are directly compatible with the observations of the seismological studies. Many researchers have accepted this approach of neotectonics. 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 the field data, 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 originated by rifting of the Eastern Gondwanaland during Late Triassic to Late Cretaceous Period, followed by its drift towards north along an anticlockwise path which resulted into collision with the Eurasian plate in late Middle-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 complicated folding or crinkling of the laminae of a sedimentation unit which can be well defined (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 one of the important factors in the origin 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).

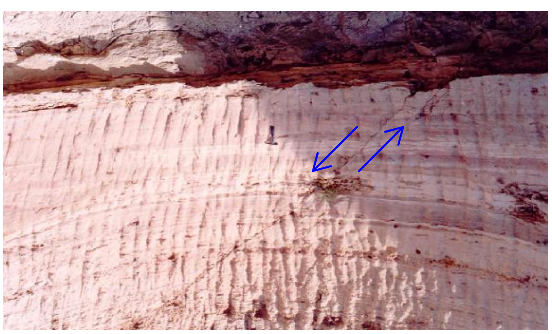


Fig.5.1: Normal fault in the Bhuj Formation.

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 1-2 centimeters upto 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 (≥6) in Kachchh over a period of 182 years are Allah Bund earthquake (1819), Khavda earthquake (1940), Anjar earthquake (1956) and Bhuj earthquake (2001).

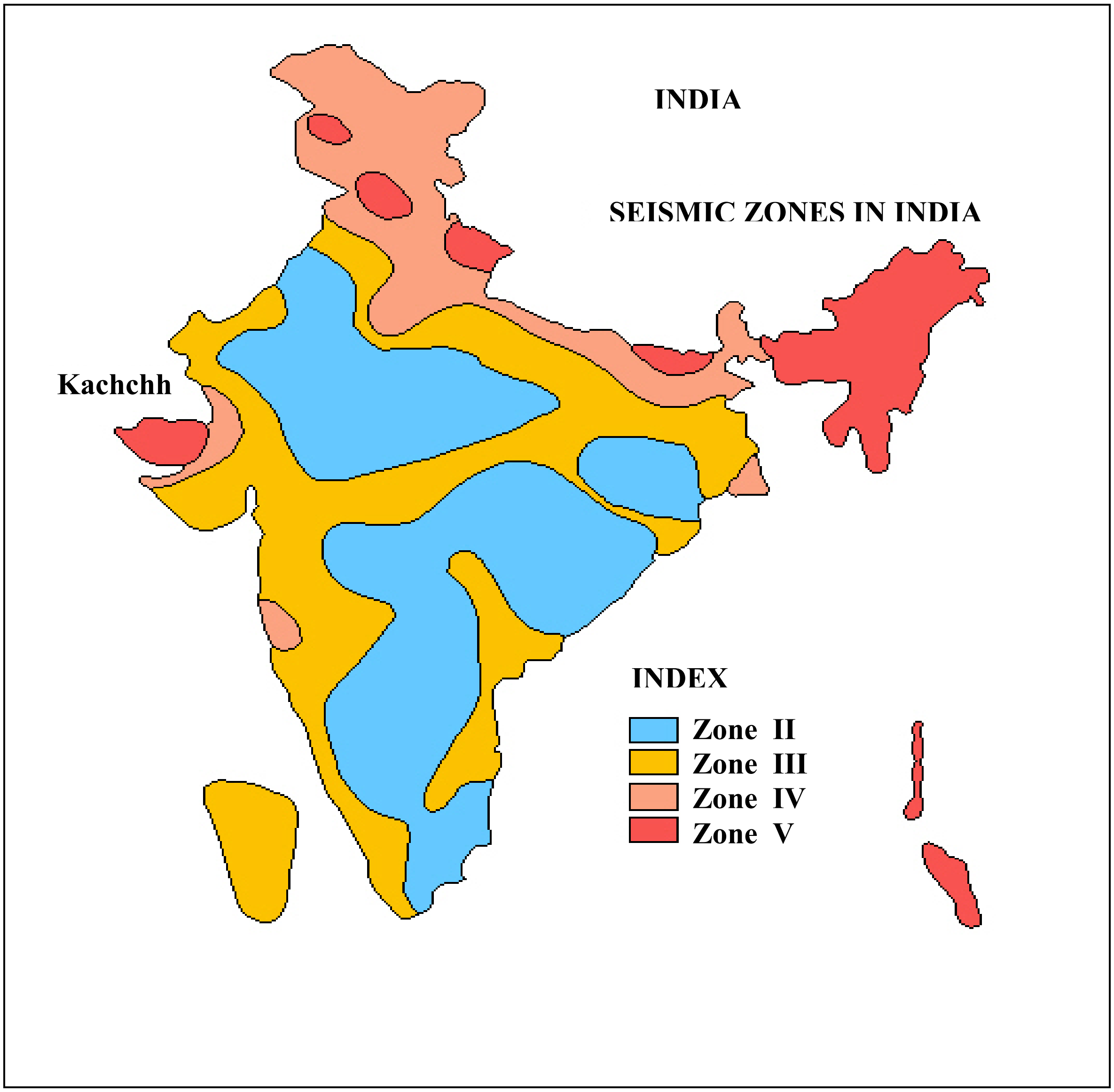


Fig 5.6: Seismic Zones in India (Source: Bureau of Indian Standard).

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)

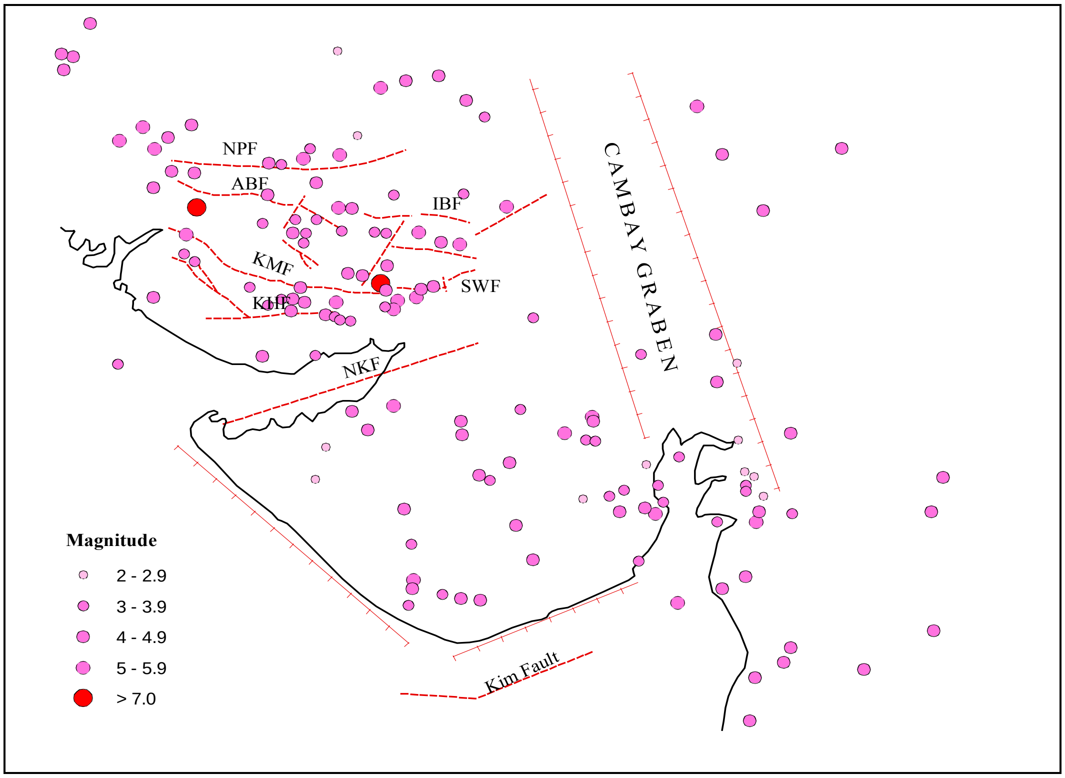


Fig.5.7: Earthquake records of Kachchh region from historic times through 2010 (Source: ISR, 2010).

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.

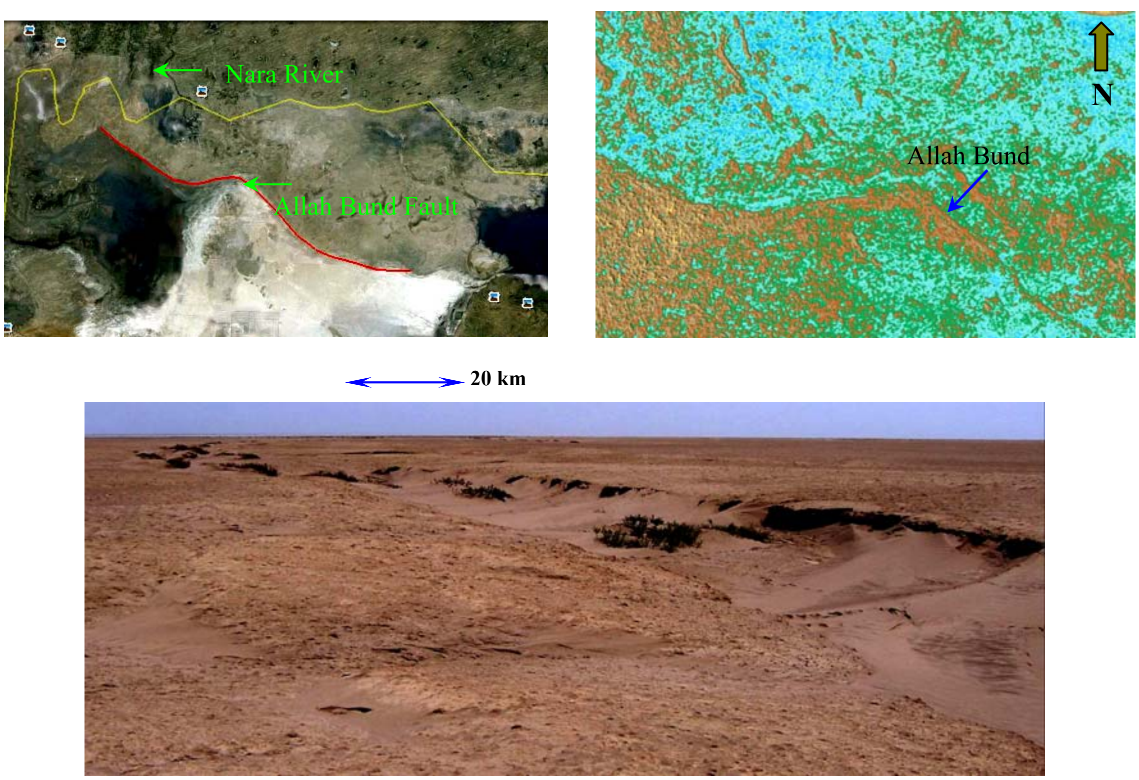


Fig. 5.8: Allah Bund Fault, over Google image (left), visible in the ASTER DEM (right) and field photograph (north of Dharmshala).

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 45º 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 (23.40º N, 70.28º 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).

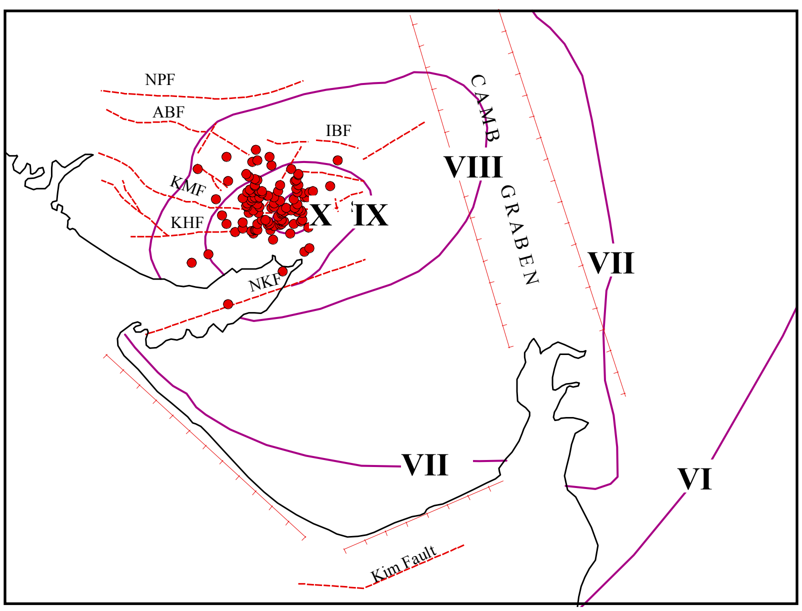


Fig.5.9: Map showing the Isoseismals of 2001 Bhuj Earthquake and the epicenters of the aftershocks in 2001 (after GSI, 2001).

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.

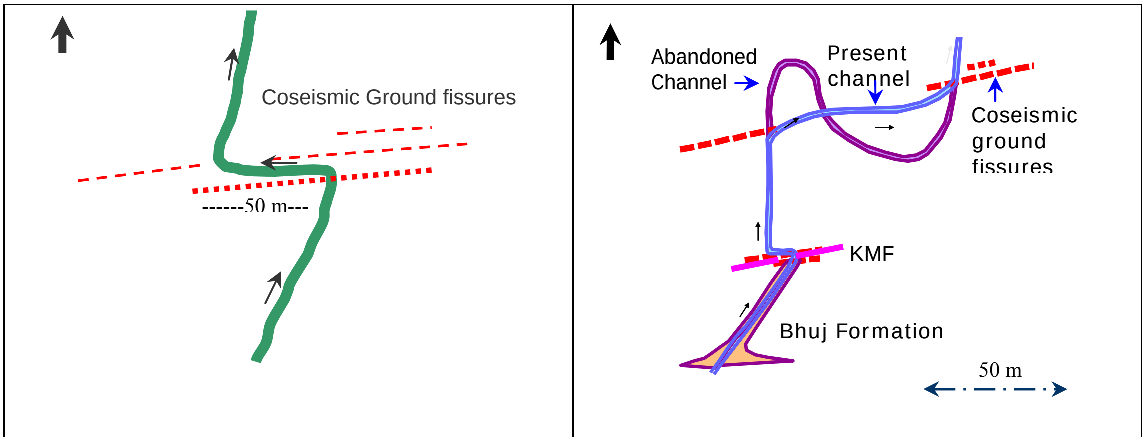


Fig.5.11: Schematic diagrams sowing stream deflection at KMF, north of Devisar.

(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.

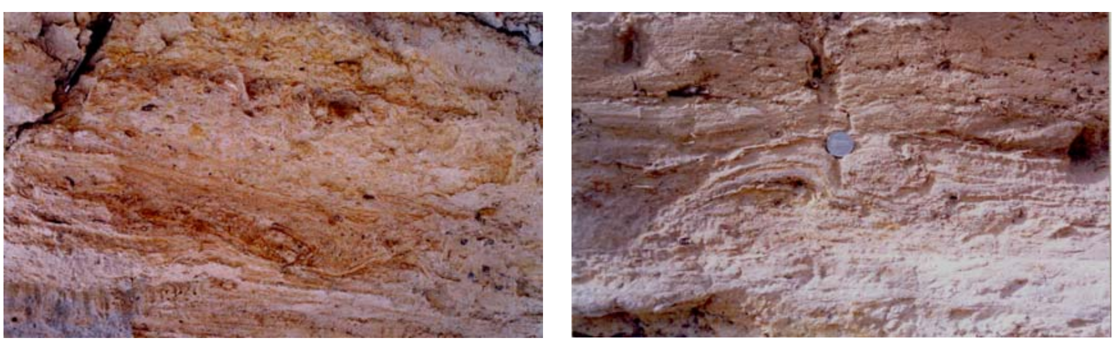


Fig.5.12: Contorted laminations in sandy horizons, north of Khirsara village.

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 (23º23.557'N / 69º48.628'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.

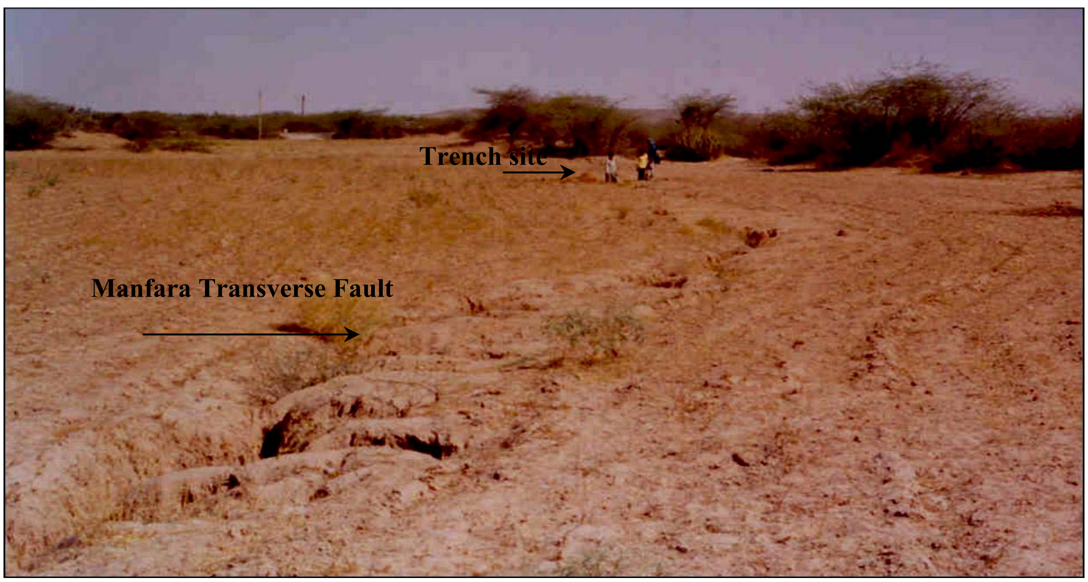


Fig.5.15: Manfara Transverse Fault visible as coseismic ground fissures due to Bhuj (2001) earthquake, near Kharoi village.

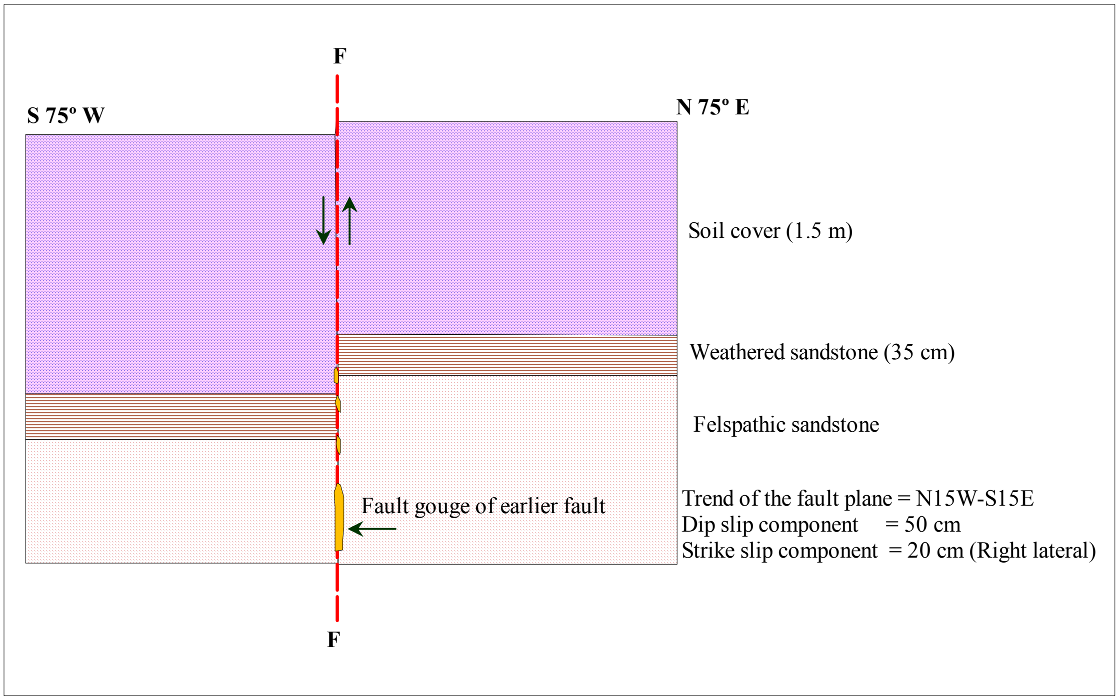


Fig.5.16: Litholog of the trench made across the Manfara Fault, near Kharoi.

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.

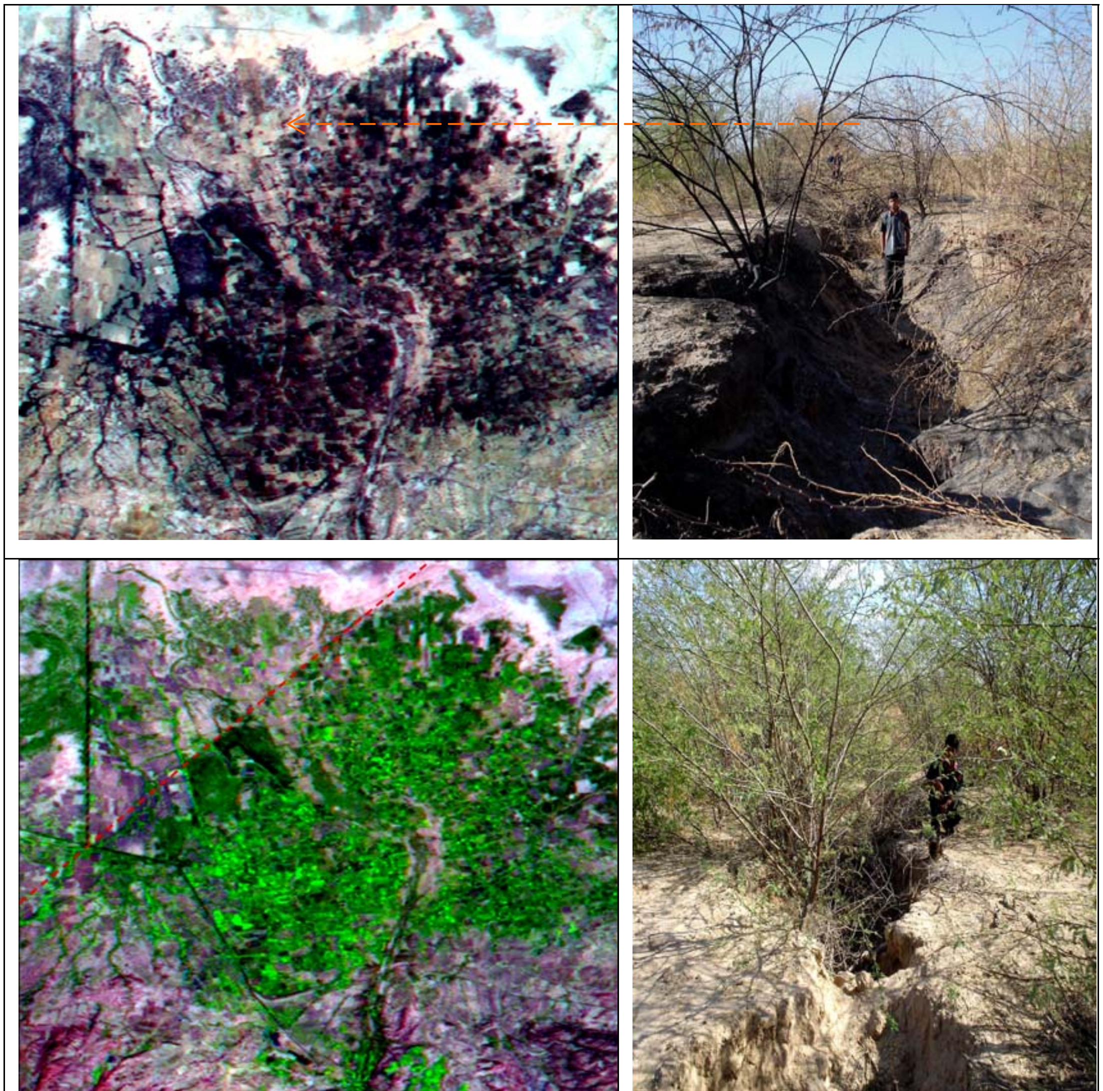


Fig.5.17: LISS-III imagery of alluvial fan of the Pur River showing lineament, which proved to be an active fault. The lower imagery is the enhanced one by PCA method and fault is better viewed in this imagery. Coseismic ground fissures (due to Bhuj (2001) earthquake), developed along the Loriya fault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

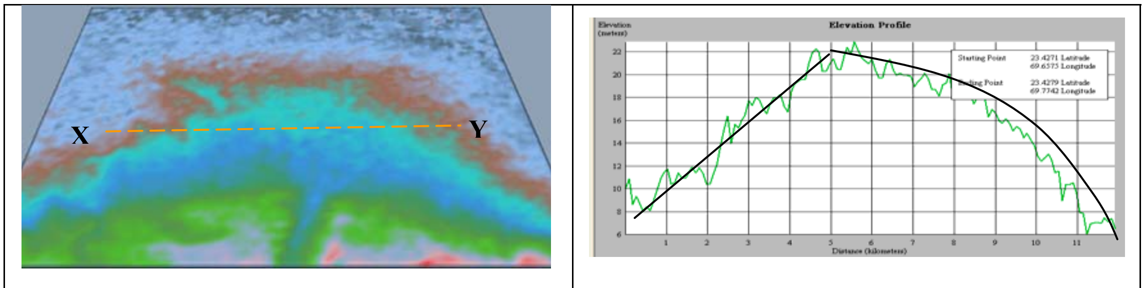


Fig. 5.18: DEM of alluvial fan of Pur River (left) and asymmetrical profile indicating the effect of Loriya fault (right). X-Y is the section line for profile.

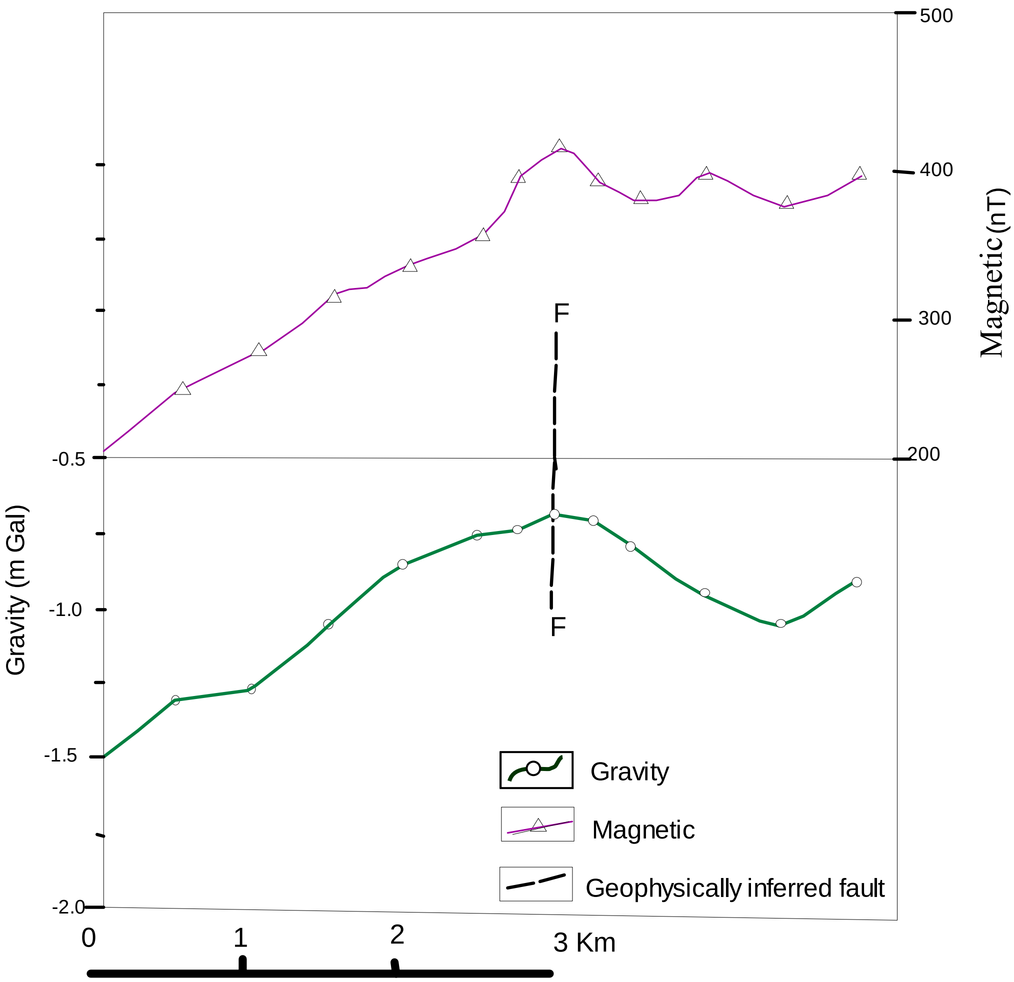


Fig.5.19: Geophysical profile across the Loriya Fault, signatures of gravity and magnetic anomaly is detected on the fault (after Singh and Lal, 2008).

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.

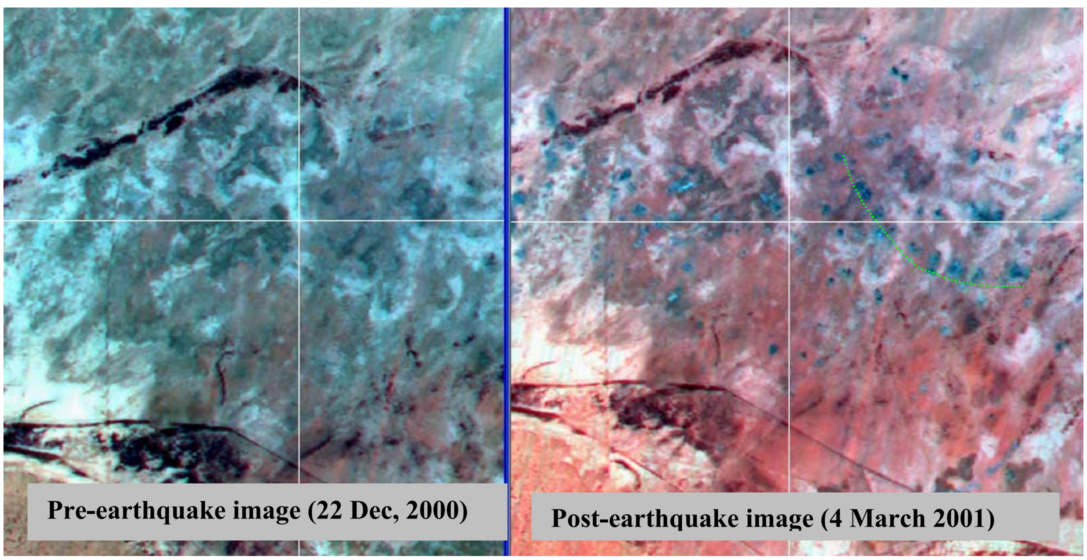


Fig. 5.20: Pre- and post- Bhuj (2001) earthquake images showing the liquefaction centers.

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 30º 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.

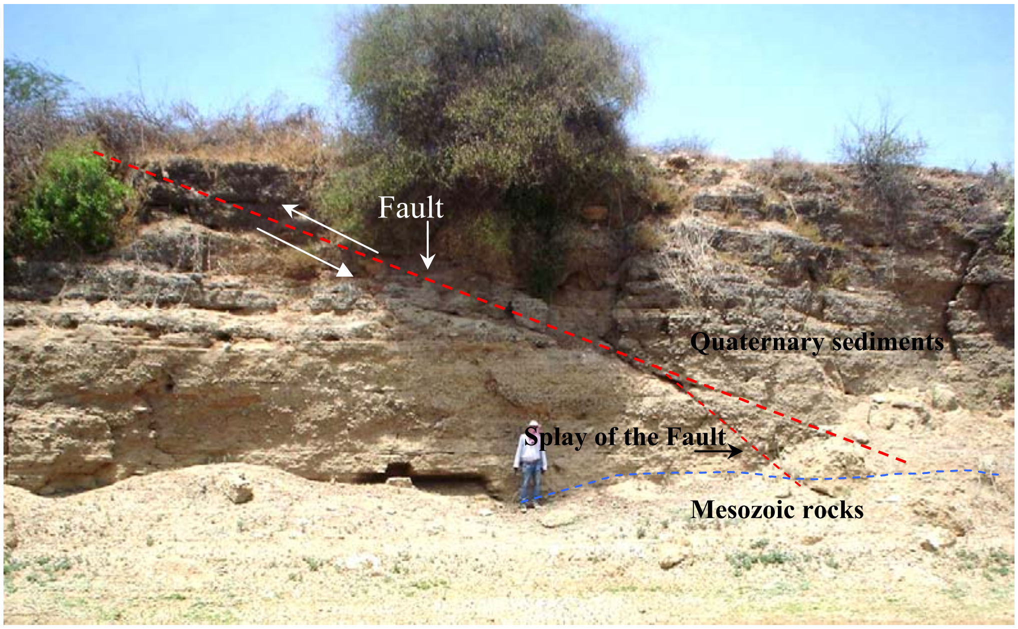


Fig. 5.21: View of the eastern terrace of the Dhrung River, near Dam, showing a Quaternary reverse fault.

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.

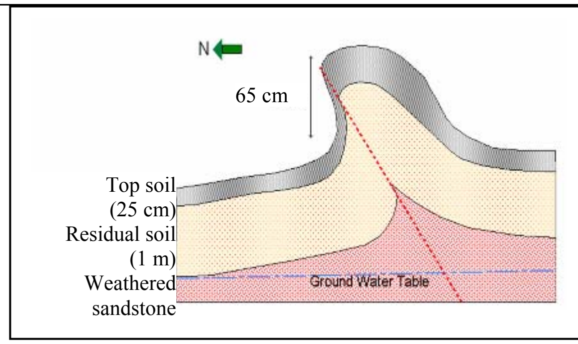


Fig.5.22: Budharmora upwarp developed due to Bhuj (2001) earthquake and the schematic diagram of a trench made across it.

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 (5^{th} 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 resulted into the settling and expeling their interstitial water to the surface. Field investigations have found number evidences of mud volcanoes, sand blows, and fissures from which salty ground water erupted over a large area.

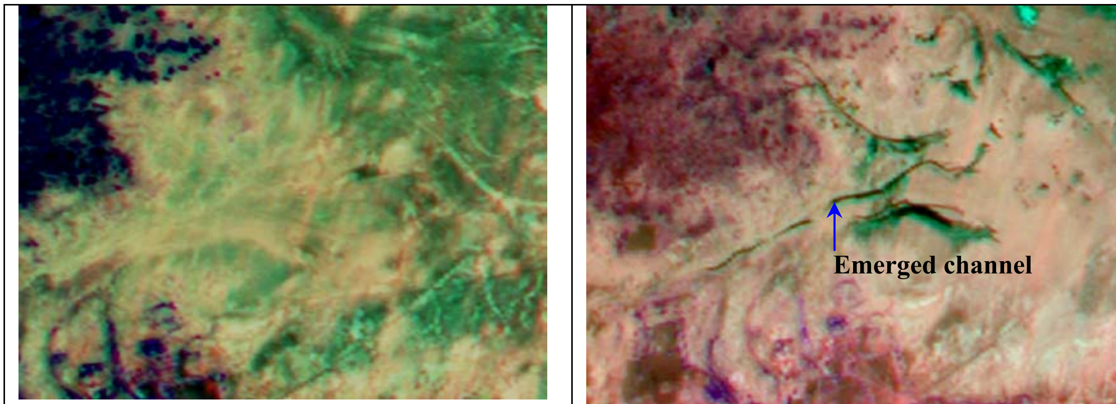


Fig.5.23: Emergence of buried channels, north of Amrapar. In Pre-Bhuj earthquake no channel is seen but in the post-Bhuj earthquake imagery emerged channels are visible.

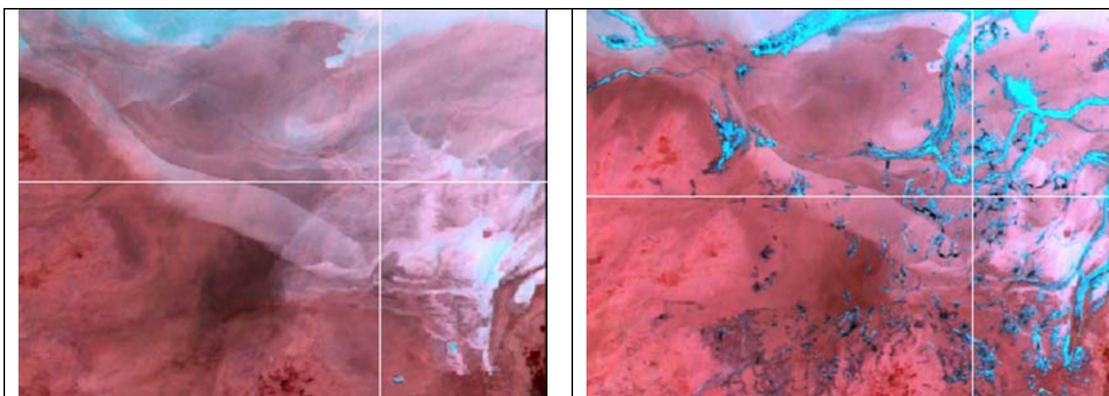


Fig. 5.24: Oozing of water in the channels in marshy region of Rann of Kachchh, (Pre-Bhuj earthquake imagery in the left and post earthquake imagery in the right).

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.

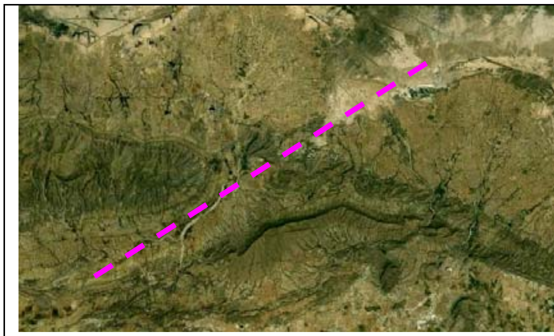


Fig.5.25: Lodai Transverse Fault.

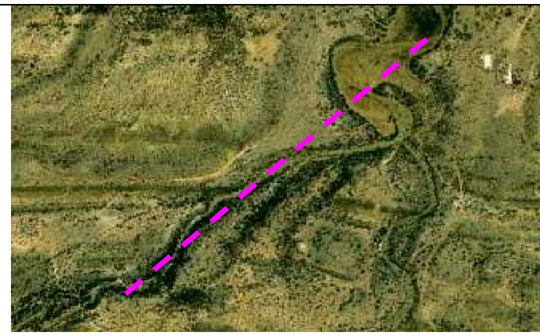


Fig.5.26 Dhrung Transverse Fault.

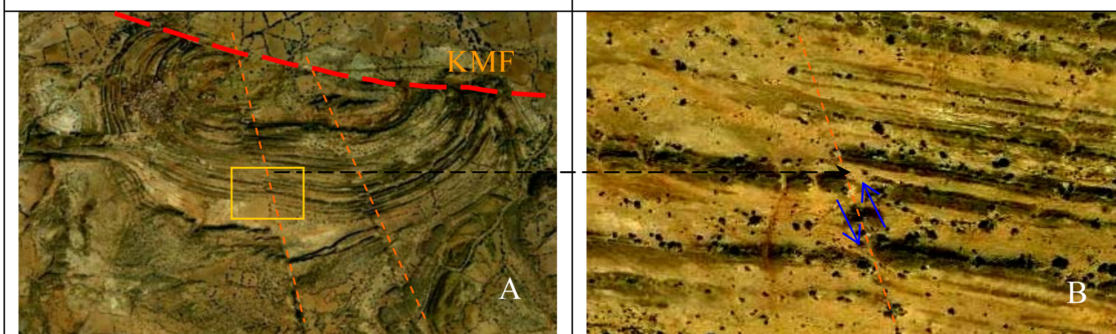


Fig.5.27 A: Distant view and, B: close view of transverse faults cutting the Jara dome to the SW of Lakhpat.

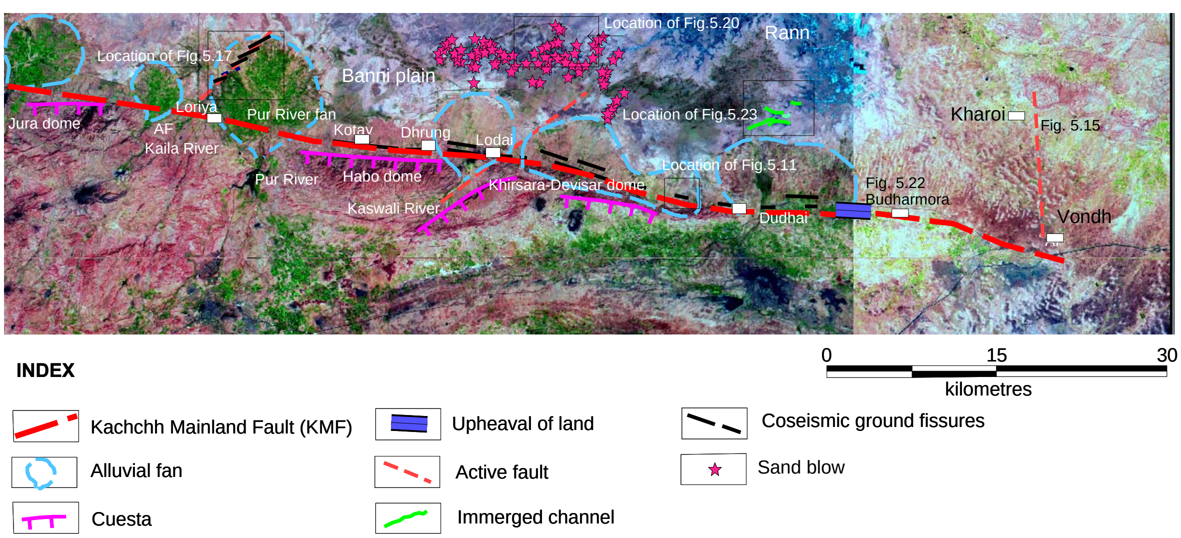


Fig. 5.28: Neotectonic map of the area along KMF between Loriya and Manfara Faults.

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.

CHAPTER 6

GEOMORPHIC EVOLUTION

Landscape evolution of a basin is the function of climate, tectonism and geologic parameters such as gross lithology and structure. Climatic parameters tend to degrade landscapes through the chemical and physical action of various agents. Tectonism, on the other hand, tends to construct landscapes through uplift and crustal warping.

Structural style of Kachchh Rift Basin is unique in India but the numerous Late Cretaceous uplifts associated with plutonic bodies and intervening Tertiary basins can be compared with the Laramide structures of the Colorado Plateau, Central Montana Rockies of North America (Eardly, 1962; Prucha, et al., 1965) and structures of Russian Platform (Beloussov, 1962).

The development of Kachchh basin has been dealt in detail by Biswas (1982, 1987) and Gombos et al. (2005). Biswas (1982) opines that the rifting of the Indian Plate occurred in different stages when it was migrating after break up from the Gondwanaland during Late Triassic to Early Jurassic times. Initial rifting of the Gondwanaland took place along the main trend of Precambrian Dharwars. During this rifting moderate rotation in the sinistral direction resulted into opening of the Kachchh rift which follows the Precambrian Delhi trend (Biswas, 1982). After breaking from its parent mass during the time of Late Triassic, the Indian subcontinent started moving in the northward direction with a faster pace of 16 cm / yr in Late Triassic (Biswas, 1982). The northward drift of the continent was checked during Eocene-Oligocene times, when the subduction of its oceanic crust started below the Tibetan plate. By the 45-50 Ma the collision of the Indian and Tibetan continental crust began and uplift of the Himalayan range started. In the course of its northward journey the Indian plate passed over four mantle plume heads centered at Crojet, Keruguelen, Marion and Reunion Islands. Then Reunion plume provoked Deccan volcanism in the subcontinent. Around 66 Ma (Maastrichtian age) the western part of Indian Plate crossed the equatorial region and passed over the Réunion/Deccan hot spot resulting into Deccan volcanic eruption (Courtillot et al., 1986; Biswas, 1982). Copious amount of lava was erupted in the form of sub aerial eruptions and several basalt flows covered about two million square km area in the next million years (Biswas, 1982). In the mantle plume area the lithosphere was weakened as a result the Seychelles were separated from the Mainland India about 63 Ma (Biswas, 1982). When the Indian Plate moved off the hot spot, it resulted into cooling of the lithosphere and subsidence occurred in the form of Son-Narmada-Tapti Graben and its offshore extension, the Surat Depression (Biswas, 1982 and Gombos et al., 2005).

Rifting in the subcontinent along certain Precambrian structural trends started since its detachment from the mainland. In the western margin of the Indian Shield, the faulting was controlled by NE-SW Aravalli-Delhi trend, ENE-WSW Son-Narmada-Tapti trend and NNW-SSE Dharwar trend (Biswas, 1987). Thus, during the northward migration of the Indian subcontinent, Kachchh, Cambay and Son-Narmada-Tapti basins developed. Thick sedimentation of different ages along with the volcanic activities marked the depositional history of these basins (Fig.6.1). These basins are separated by the Saurashtra horst, which is established to be the extension of the Aravalli range, which got uplifted in part during the Late Cretaceous times. The sea started receding from the Kachchh Rift Basin by the Early Cretaceous times and allowed deposition of continental facies.

The onset of the collision of Indian plate with the southern margin of Eurasian Plate occurred in Late Palaeocene-Eocene times. This date of collision has been estimated by different workers. Patriat and Achache (1984) and Besse et al. (1984) estimated this event to happen about 50 Ma whereas as per Jaeger et al. (1989) and Beck et al. (1995) this collision occurred about 66 Ma ago. After the collision the speed of the northward movement of Indian Plate slowed down to 4-6 cm per anum. On the basis of stratigraphic data, Beck et al. (1995) argue that the suturing of the two plates completed by 49 Ma. As per Biswas (1982) this welding of the two plates completed in Eocene-Oligocene times when the northward movement of India plate nearly halted. Very slow northward movement of the Indian Plate continued with a rotation of about 9º in the anticlockwise direction in Mio-Pliocene times. By stress orientation due to this collision of the two plates, Gombos et al. (1995) interpreted that Surat Depression underwent a subsidence with an increased rate in Early Miocene (about 20 Ma). The E-W trending Kachchh basin was formed by Late Miocene and underwent a N-S compressive stress due to collision with Eurasian Plate (Biswas, 1982). Gowd et al. (1992) observed that the maximum stresses responsible for the present day seismic activities are N-S to NNE-SSW oriented.

In the Kachchh basin the Mesozoic sediments were deposited in two cycles of Late Triassic- Late Jurassic marine transgression and Late Jurassic-Early Cretaceous post rift deltaic regression environment. After the deposition of the Mesozoic sediments, the Tertiary sedimentation took place in the terrestrial environment but by the Early Eocene times, there was marine transgression while the Eocene-Middle Miocene Period saw a varied environment of lagoonal, marine shelf to open marine platform type. In Plio-Pleistocene times the environment of deposition was littoral to fore shore. Most of the Quaternary Period experienced a terrestrial environment of deposition with dominance of marshy deposits in the latest part. Dry and hot spell of the environment in the early Holocene Period is responsible of the desertification of Kachchh (Biswas, 1981).

The complex interaction of the climate, geology and the tectonism, especially in the active areas like Kachchh, has resulted into the current configuration of the landscape of the peninsula. The differences in the lithology give rise to differential erosion of the different litho-units; resulting into a particular landscape whereas the climatic parameters degrade the landscapes through the chemical and physical erosive action of various agents like wind, water etc. These variables have direct influence on the evolution of fluvial systems and thus provide information on the manner in which they carve the landscape (Schumm, 1956, 1977; Keller, 1986; Bull and Knuepfer, 1987; Schumm et al., 1987). Temporal or spatial changes in one or more of these variables can therefore have influence on landscape evolution. In the foregoing chapters of ‘Morphometric Analysis’ and ‘Neotectonism’ the interaction of geology, structure and tectonism on the geomorphic processes of fluvial systems have been described in detail.

The five river basins, which have been described in detail, form a crucial and major area of the Kachchh, whose evolution is closely associated with evolutionary history of Mainland Kachchh. The evolutionary history of the area dates back to Mesozoic, as has been described earlier. Majority of the litho-units exposed in the area belong to Mesozoic with localized occurrences of Tertiary and Quaternary patches. In general the strata show a gentle southerly dip but near the KMF they are northerly dipping with steep to moderate dips. This is due to the effect of faulting and warping in the KMF zone.

Evolutionary history of Kachchh basin starts with the marine transgression during the Middle Jurassic Period subsequent to the formation of the basin. During this transgression the Pachchham and Chari Formation of the rocks were deposited. The Mainland was the main centre of deposition during this transgressive phase (Biswas, 1981). Subsequently, the sea started to regress while the Katrol and Bhuj Formation of rocks were deposited during the regressive phase. These two phases are separated by an unconformity (Biswas, 1977, 1981). The Bhuj Formation of rocks shows fluvial nature in the east with increasing marine influence in the west. This unit was deposited in the final phase of the marine regression resulting into delta complex (Biswas, 1981). During this period the basin subsided at a faster rate resulting into thick sedimentation and came into influence of the median high (Biswas, 1982), which is responsible for the poorly developed upper and middle parts of the Bhuj Formation in the area. This phase of Mesozoic sedimentation was truncated by a phase of orogenic movement.

Mesozoic rocks in Kachchh Peninsula are intruded by basic dykes at various places which have been found in the vicinity of faults or along the faults, suggesting syntectonic nature of the intrusive rocks (Biswas and Deshpande, 1973; Maurya et al., 2003). These activities took place after the deposition of Bhuj Formation (Late Cretaceous), but before the onset of Deccan Trap volcanic activity. This was followed by a major diastrophic cycle, which accompanied the main volcanic activity of Deccan trap, around 65 Ma (Guha et al., 2005). The Matanomadh Formation (Madh Series) of Paleocene age is exposed north of Kukma village extending further north-eastward up to Paddhhar and is of continental origin (Biswas et al., 1973). Upper Miocene units occur in the form of scattered patches deposited in tidal flat to littoral environment of a transgressive sea (Biswas et al., 1973).

The Quaternary sediments are confined along the fault lines and in the river valleys of the area, but the most extensive Quaternary deposits comprise the Banni plain in the north of the KMF, hosting the alluvial fans of all the channels debouching into the Rann. The Quaternary deposits of the area comprise alluvial and colluvial fans and valley fill miliolitic limestone of fluvio-aeolian environment. Numbers of conspicuous alluvial and colluvial fans are found associated with the Kachchh Mainland Fault which is suggestive of degradation of the fault scarps. The colluvial fans are incised by various streams and are overlain by miliolitic limestone suggesting that these deposits are of Pleistocene age. The miliolitic deposits occurring on the hill slopes are aeolian in origin whereas in valleys they seem to be fluvial or fluvio-aeolian as they contain cobbles, pebbles and some boulders in the fine grained calcareous sand.

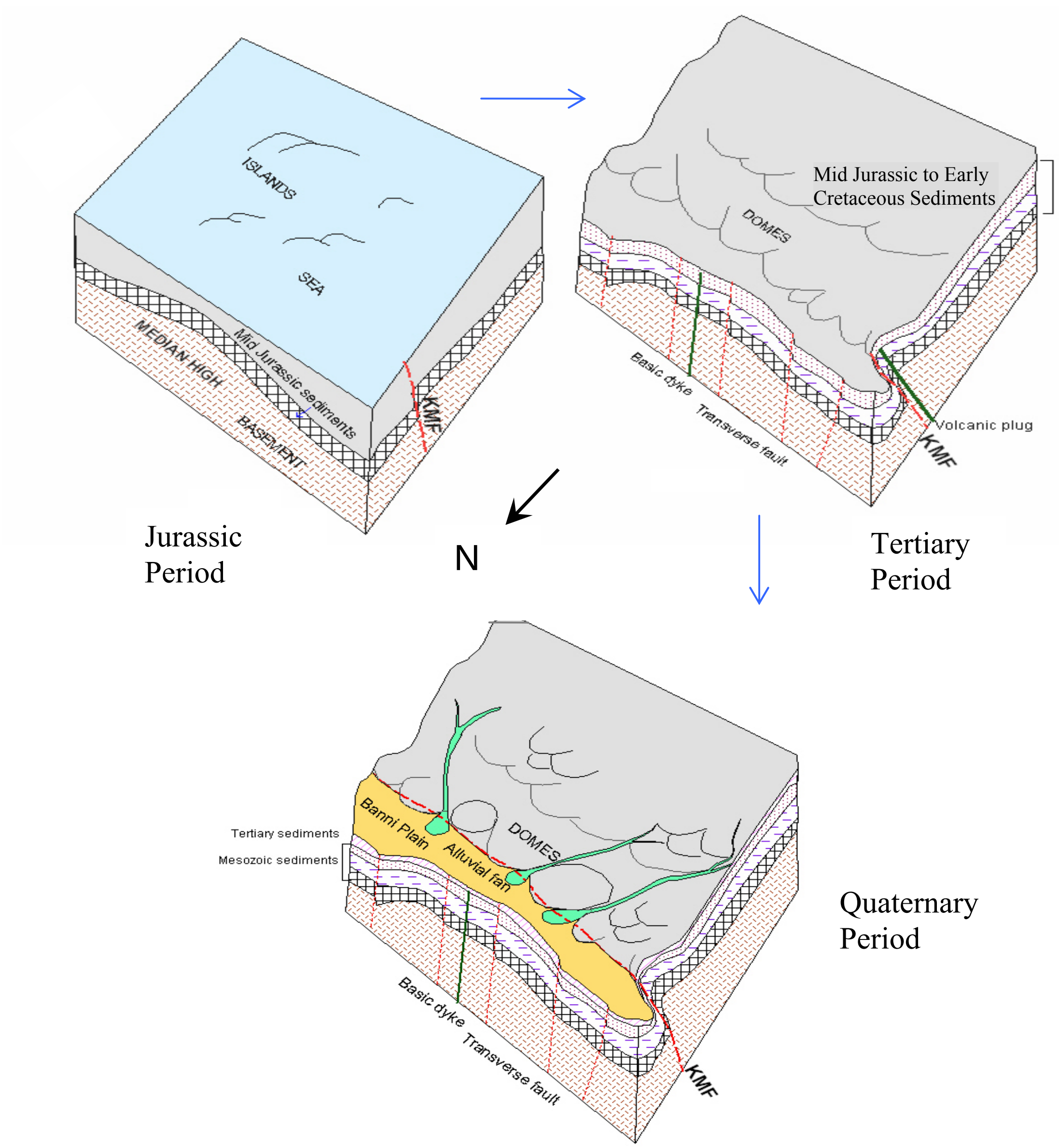


Fig.6.1: Evolution of Kachchh Mainland in relation to the KMF.

The Kachchh Mainland Fault is marked by the straight fault scarps which is typical of a fault generated mount front (Mayer, 1986; Bull and McFadden, 1977). The formation of domes along the KMF has influenced the geomorphology of the area in a large extent. The series of domes like Devisar, Khirsara, Habo, Jhura, Keera, Nara, Jumara and Jara domes, from east to west, flank the Kachchh Mainland Fault. The northern sides of these domes are steeply dipping, at places vertical, while they show gentle slopes (10-22º) in the south. Some of the domes show basic rocks in their core, several N-S trending dykes, plugs and sills. Many of these domes are cut through or bounded by transverse faults in the east and west sides. The tectonic upheaval after the termination of the Mesozoic sedimentation is responsible for the complication in the structural set up of the area which is manifested in the present landscape. Various transverse faults were developed during this period. The general trends of these transverse faults are NNW-SSE, NW-SE, NE-SW and N-S.

The phase of transverse faulting and intrusion of dykes was followed by a major diastrophic cycle which accompanied the main trappean volcanic activity. This phase of activity gave rise to several domes and flexures described earlier. The presences of volcanic plugs related to the eruption of trappean lavas (Biswas and Deshpande, 1973) in the central portions of the domes indicate syntectonic volcanic activity. According to Biswas and Deshpande (1973) the intrusives with the exception of plugs belong to a pre-Deccan trap phase. As discussed earlier, the Indian plate was passing over the Reunion hot spot during the Cretaceous Period which resulted into massive effusion of Deccan lava in India (Raval, 1995). The age of the traps is 65 Ma and the oldest sea floor spreading magnetic anomalies in the Arabian Sea is 59.0 to 63.3 Ma (Condie et al., 1989). This indicates that Deccan trap volcanism is synrift event. The trappean lavas are erupted from Hawaiian type shield volcanoes and most of the domes were evolved during that time (Biswas and Deshpande, 1973). This phase of tectonic upheaval ceased before the on set of Tertiary Period as evidenced by the very gently dipping Tertiary sequences overlying the Mesozoic rocks. But these Tertiary sequences are tilted near the KMF due to post Tertiary neotectonic activities in the area under compression. Near Amardi village the conglomerate beds overlying the Bhuj sequence are tilted northerly at about 30º (Fig.6.2).

Fig.6.2: Tertiary polymictic conglomerate overlying the Bhuj sandstone, Amardi village.

Role of Transverse faults in the evolution of the Kachchh Mainland:

The KMF and KHF are the major faults which control the present geomorphic configuration of Mainland Kachchh. These faults are not continuous but laterally displaced by various transverse faults. These transverse faults have great role in shaping the Kachchh Mainland. The possible implication of these transverse faults has been explained which seems to be intricately linked with the evolutionary history of Kachchh in the pre-Quaternary and Quaternary times. It has been pointed by Maurya et al. (2003) that some part of the stress being accumulated on the E-W trending faults is being possibly transmitted to the NW-SE to NE-SW transverse faults, which may account for the present seismic phenomenon in Kachchh.

Though the eastern termination point of the KMF is not known exactly but it is supposed that it truncates 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 indicate 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.

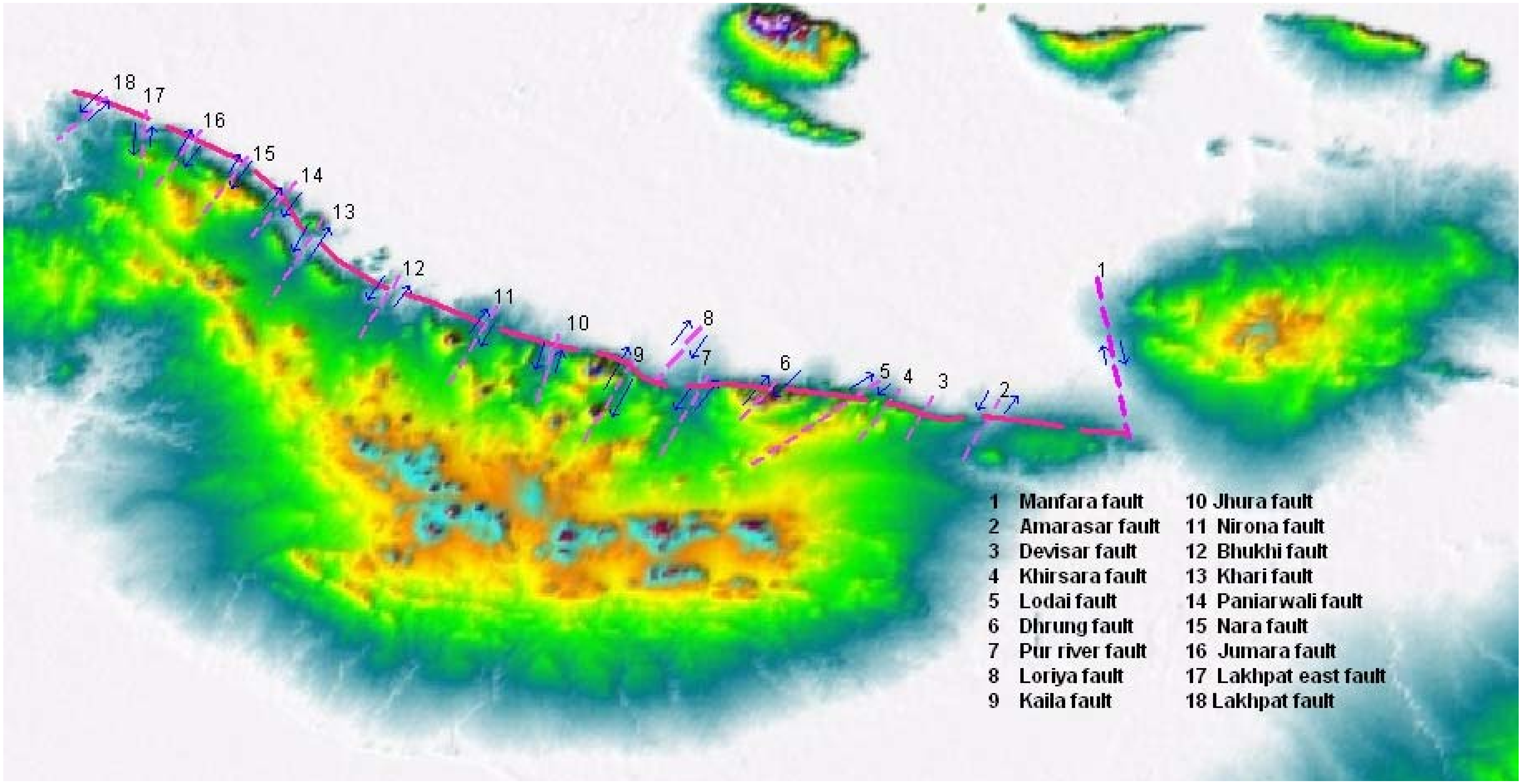


Fig. 6.3 Digital Elevation Model of the Kachchh s showing the transverse faults to the KMF and their inferred strike slip movement.

The Manfara fault shows right lateral strike slip. The various transverse faults to the KMF have been reported by various workers (Fig. 6.3). The most recent among them are the Manfara and the Loriya transverse faults (Singh et al., 2011). The fault planes of these transverse faults are either vertical or steeply dipping (Maurya et al., 2003). 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.

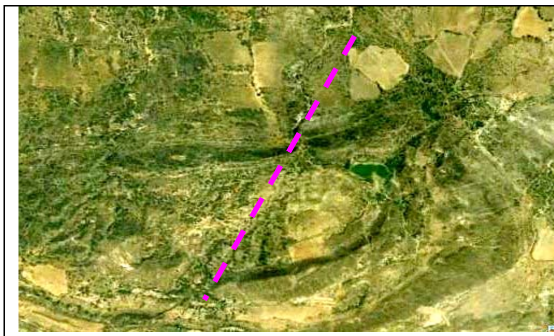


Fig. 6.4: Devisar Transverse Fault.

Fig.6.5: Amrapar (Dudhai) Transverse Fault.

Fig 6.6: Transverse fault in the east of Lakhpat.

Fig.6.7: Transverse fault across the Jara dome.

Various landforms are developed due to the effect of these transverse faults along the KMF which includes offset fault scarps of KMF, deflected or beheaded drainage, sags, shutter and pressure ridges (Maurya et al., 2003). A significant feature observed in the mainland is that all major transverse faults have been occupied by stream channels debouching into the Banni plain, making conspicuous alluvial fans. The faults have been named on the basis of the channels occupying them or nearest villages (Fig.6.3). These rivers are characterized by the deeply incised channels and other features like entrenched meanders, drainage offsets, small sags, knick points as seen in their long profiles, which all suggest lateral movement along the transverse faults. The faults show dextral as well as sinistral slips, as indicated by fault scarp offsets and by direct observation during coseismic activities. Exceptionally fresh nature of fault scarps has also been recorded in the KMF zone (Thakkar et al., 1999). Observed amount of offset of KMF segments, along the transverse faults, range from a few hundred meters to kilometres (Maurya, et al., 2003).

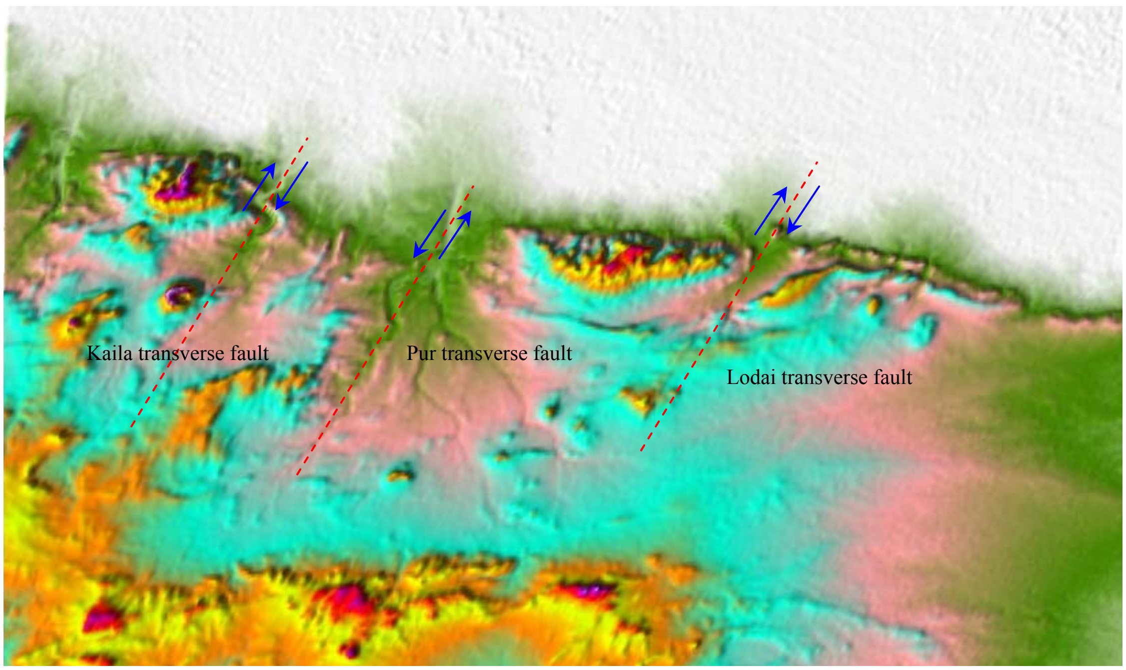


Fig.6.8: Strike-slip movement along the Lodai, Pur and Kaila transverse faults visible on the DEM of the area along KMF.

The lateral displacements of the strata in various domes along transverse faults (Fig. 6.4 to 6.8) suggest that the last phase is dominated by strike-slip movement, as evidenced by horizontally displaced fault scarps of the KMF. This event is related with the final drift history of the Indian plate which resulted into complete welding of Indian and Eurasian plate during Eocene-Oligocene Period (Biswas, 1974, 1982). These transverse faults have been accommodating part of the stress generated during the northward movement of the Indian plate.

Quaternary Tectonic Evolution

Quaternary tectonic activities have been affecting the present landscape of the area. The first order topography and the seismic activities provide ample evidences of tectonic instability in the area during Quaternary (Kar, 1993). 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 (Thakkar et al., 1999, 2001). 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 during the Late Pleistocene and Holocene which is still continuing. The Early Quaternary tectonic activity took place mainly along the E-W trending master faults i.e. KHF and KMF whereas the Late Pleistocene-Holocene phase of tectonic activity took along the transverse faults (Thakkar et al., 1999; Maurya et al., 2003). The miliolite deposits found overlapping the colluvial deposits along KHF indicate that E-W faults were more active during Early Quaternary (Thakkar et al., 1999) but the master-fault (KMF) can not remain isolated with any type of neotectonic activity in the area in recent times. The compressive stress accumulates along these faults and then is accommodated by movements along the transverse faults. During the Bhuj (2001) earthquake, ground fissures and upheaval of land was also associated with the KMF, though the causative fault was a hidden transverse fault. 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 in the Recent times (Singh et al., 2011). Tilting of miliolitic limestone sheets near the transverse faults also indicate that most recent activity is more concentrated along the transverse faults.

The asymmetry factor clearly indicates that the river basins have experienced tilting during the Quaternary times. Since all the river basins are showing westward tilting, it is concluded that the Kachchh Mainland has undergone westward tilting, in general, during Quaternary Period. Biswas (1974) opined that there is differential uplift along various faults of the Mainland during Early Quaternary due to which the entire Kachchh region including Rann and Banni plains have been elevated. Sharma (1990) also postulated that middle block of the Kachchh Mainland is elevated in comparison to the other two blocks.

Late Pleistocene tectonic activity along transverse faults is evidenced in the Late Pleistocene alluvial deposits in the form of tilting of miliolite sheets near these faults and youthful fault scarps. The present tectonic instability of the Kachchh region is evidenced by the seismic activities in the area due to tectonic movements along these transverse faults (Johnston, 1996). In the Himalayan region the neotectonic movements along thrust planes are transmitted to various transverse faults which account for the present day seismicity (Valdiya, 1973). The tectonic rejuvenation of peninsular India during Quaternary (Radhakrishna, 1993) is also attributed to repeated tectonic movements along the various transcurrent faults (Valdiya, 1998). The compressive stresses accumulating on the E-W trending master faults like KMF and KHF due to locking up of the Indian plate with Eurasian plate is responsible for the movements along the transverse faults resulting into seismic activities in the area and shaping the basin.

As it is evident from the above discussion that transverse faults are playing crucial role in Quaternary evolution of the Kachchh Mainland and more importantly, the current tectonic activities are concentrated along these transverse faults. These transverse faults were originated during a phase of pre-Deccan trap dyke emplacement and the compressive stresses generated on the KMF, due to collision of the Indian plate with Eurasian plate during Eocene-Oligocene. 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 attempted, which gives the nature of movement along the transverse faults. Segmental effect of the seismic activities can be addressed demarcated by the transverse faults. The coseismic features recorded from the Bhuj earthquake indicate that a segment of the KMF bounded by the Manfara fault in the east and the Loriya fault in the west was affected most (Singh et al., 2011). Thus, it seems pertinent to mention that the transverse faults are of prime concern for understanding the recurrent seismic activities in the Kachchh region and for their mitigation measures.

The studies of the basin morphometric analysis suggest strong proof of episodic upliftment of the landmass. The parameters like longitudinal profile, valley height and width ratio and mountain front analysis of the five river basins corroborate the concept of Quaternary upliftment of the Mainland. The Pur and Nirona Rivers are 7th order channels while Chhari and Kaila Rivers are 6th order streams. The total channel lengths of all the stream orders indicate stream richness, especially in the Pur, Nirona and Chhari basins. The length and the number of the lower order streams in all the basins suggest moderate to high relief head water area in general. The circularity ratio values range from 0.307 for Chhari basin to 0.437 for Kaila basin. Highest elongation ratio is for the Kaila basin while for all other basins it is near 0.6 which indicates that all these basins are elongated in shape due to neotectonic activity. Texture ratios of basins vary from 6.01 in Kaswali basin to as high as 23.087 for Nirona basin which is extremely high. High texture ratio of the basins is indicative of recent upliftment. 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, definitely indicating neotectonic activity in the area.

All the streams have very low Vf ratio near their source in the hilly terrain while away from the source near KMF, it is quite high due to broad valley morphology. The results of the sinuosity parameters of the Pur and Nirona Rivers suggest that they are controlled dominantly by tectonism. The evolution of these river basins in the later phase of tectonism is indicated by the sinuosity indices. The analysis of the Mountain front sinuosity index of the east-west trending mountain fronts associated with the KMF are very near to 1, which falls in the tectonic activity class-I of Bull and McFadden (1977) indicating that the area has experienced active tectonism.

Many interesting features are formed due to latest tectonic episodes in Quaternary Period like boulder and gravel beds in the river valley terraces at levels higher than valley floor. Deep gorges are formed around Dhrung, Jawaharnagar and Lodai villages. The reactivation along the transverse faults during Bhuj earthquake, like Loriya and Manfara faults; development of the new streams as a result of tectonic tilting and coseismic features like ground fissures indicate that the area is tectonically very active.

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. The Kachchh Peninsula is characterized by E-W trending master faults namely Nagar Parkar Fault in the north to the Island Belt, Kachchh Mainland, Katrol Hill and North Kathiawar faults in the south. These faults are located at the flanks of geomorphic highs called as uplifts. These uplifts are separated by intervening flat low lands called grabens which are places of Quaternary deposition. These uplifts and grabens are roughly parallel. The Kaladongar hill (Δ 465 m) in the Pachchham Island is the highest peak of Kachchh whereas Nanadongar is highest among several peaks in the Kachchh Mainland.

Kachch, taking into account the geomorphic elements of the area like general altitude, slope and nature of relief, has been divided into four major physiographic units. These units are the table flat region of the Rann of Kachchh, the low lying Banni Plains in the north of Kachchh Mainland, the hilly tract of Mainland Kachchh and the Coastal Plains in the south. Though, there are considerable amount of diversity within each of these units, itself, due to local changes in lithology and effect of 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. Physiography of the Kachchh region has been significantly controlled by the KMF. The streams originating from the northern slopes of the Mainland flow together to join the major streams like 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. One of the characteristics of the valleys of the Kachchh is that they have relatively well carved valleys with less amount of water these days. It indicates that these valleys were carved when more amount of water with heavy sediment load was flowing through them and show a change in climatic condition from wet in past to dry at present.

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 direction of the Delhi Fold Belt that changes 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. Tilting of the blocks along these major faults during extensional regime gave rise to uplifts like Nagar Parkar, Island Belt, Wagad and Kachchh Mainland uplifts, alternated with grabens.

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. These ranges are the Nagar Parkar in the north to Island Belt Ridge, which has been broken as islands due to transverse faults, then the Kachchh Mainland ridge followed by Wagad highlands, separated by grabens; 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 sediment horizons. Age of 4,424 ± 0.656 Ka is of a sand fill in a preexisting 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. 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 30º 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.

REFERENCES

Agrawal, S. K. (1957). Kutch Mesozoic: A study of the Jurassic of Kutch with special reference to Jhura dome. J. Pal. Soc. Ind., v.2, pp.119-130.

Allen, C. R. (1975). Geological criteria for evaluating seismicity. Geol. Soc. Am. Bull., v.86, pp.1041-1057.

Antoliok, M. and Dreger, D. S. (2003). Rupture process of the 26 January 2001 Mw 7.6 Bhuj, India, earthquake from teleseismic broadband data. Bull. Seismol. Soc. Am., v.93, pp.1235-1248.

Baker, W. E. (1846). Remarks on Allah Bund and on the drainage of the eastern part of the Sind Basin. Transactions of the Bombay Geographical Society, v.7, pp.186-188.

Beck, R. A., Burbank. D. W., Sercombe. W. J., Riley, G. W., Barndt. J. K., Berry, J., Afzal, R. and Khan, J. (1995). Stratigraphic evidence for an early collision between northwest India and Asia. Nature, v.373, pp.55-58.

Beloussov, V. V. (1962). Basic problems of Geotectonics. McGraw-Hill, London, 816p.

Besse, J., Courtillot, V., Pozzi J. P., Westphl, M. and Zhou, Y. X. (1984). Palaeomagnetic estimates of crustal shortening in the Himalayan thrusts and Zangbo Suture, Nature, v.311, pp. 621-626.

Biswas, S. K. (1971). Note on the Geology of Kutch. Quart Jour. Geol. Min. Metal Soc. India. v. 43, pp. 223-235.

Biswas, S. K. (1974). Landscape of Kutch, A Morphotectonic Analysis. Indian Journal of Earth Science, pp.177-190.

Biswas S. K. (1977). Mesozoic rock stratigraphy of Kutch. Quarterly Journal of the Geological, Mining and Metallurgical Society of India, v.49, pp.1-52.

Biswas, S. K. (1980). Regional tectonic framework, structure and evolution of the Western marginal basins of India. Tectonophysics, v.135, pp.307-327.

Biswas, S. K. (1981). Basin framework, paleo-environment and depositional history of the Mesozoic sediments of Kutch basin, Western India, Q. J. Geol. Min. Metall. Soc. India, v. 53 (1-2), pp.56-85.

Biswas, S. K. (1982). Rift basins in western margin of India with special reference to hydrocarbon prospects. Bull. Am. Assoc. Petrol. Geol., v.66, pp.1497-1513.

Biswas, S. K. (1987). Regional tectonic framework, structure and evolution of the western marginal basins of India. Tectonophysics, v.135, pp.307-327.

Biswas, S. K. (1992). Tertiary stratigraphy of Kutch. J. Pal. Soc. India, v.37, pp.1-29.

Biswas, S. K. (1993). Geology of Kutch, KDM Institute of Petroleum Exploration, Dehradun, 450p.

Biswas, S. K. (2002). Structure and tectonics of the Kutch Basin, Western India, with special reference to Earthquakes. 8th Foundation Lecture, Indian Geological Congress, Roorkee.

Biswas, S. K. (2005). A review of structure and tectonics of Kutch basin, western India, with special reference to earthquakes. Curr. Sci., v.88, pp.1592-1600.

Biswas, S. K. and Deshpande, S. V. (1970). Geological and Tectonic maps of Kutch. Bull. O.N.G.C., v.7, pp.115-123.

Biswas, S. K. and Deshpande, S. V. (1973). A note on the mode of eruption of the Deccan Trap lavas with special reference to Kutch. J. Geol. Soc. Ind., v. 14, pp.134-141.

Biswas, S. K. and Khattri, K. N. (2002). A geological study of earthquakes in Kutch, Gujarat, India. Jour. Geol. Soc. India, v.60, pp.131-142.

Biswas, S. K. and Raju, D. S. N. (1973). The rock-stratigraphic classification on the Tertiary sediments of Kutch. Bulletin of Oil and Natural Gas Commission, v. 10 (1&2), pp.37-46.

Blum, M. D., Toomey, R. S. and Valastro Jr., S. (1994). Fluvial response to Late Quaternary climatic and environmental change, Edwards Plateau, Texas. Palaeogeography, Palaeoclimatology, Palaeoecology, v.108, pp.1-21.

Bodin, P. and Horton, S. (2004). Source parameters and tectonic implications of the aftershocks of the Mw7.6 Bhuj earthquake of January 26, 2001. Bull. Seismol. Soc. Am., v.94, pp.818-827.

Bull, W. B. and Knuepfer, P. L. K. (1987). Adjustment by the Charlwell River, New Zealand, to uplift and climatic changes. Geomorphology, v.1, pp.15-32.

Bull, W. B. and McFadden, L. M. (1977). Tectonic Geomorphology of north and south of the Garlock Fault, California. In: D.O.Doehring (ED.), Geomorphology in arid regions. Eighth Annual Geomorphology Symp. SUNY, Binghampton, pp.127-137.

Burbank, D. W. (1992). Causes of recent Himalayan uplift deduced from deposition patterns in the Ganges basin, Nature, v.357, pp.680-683.

Burnes, A. (1835). Memoir on the eastern Branch of the River Indus, giving an account of the alterations produced on it by an earthquake, also theory of the formation of the Rann and some conjectures on the route of the Alexander the Great; drawn up in the years 1827-1828, Royal Asiatic Society Transactions, v.3, pp.550-588.

Centamore E., Ciccacci S., Del Monte M., Fredi P., Lupia Pal-mieri E. (1996). Morphological and morphometric approach to the study of the structural arrangement of the North-Eastern Abruzzo (central Italy). Geomorphology, v.16, pp.127-137.

Chamyal, L. S., Maurya, D. M. and Raj, R. (2003). Fluvial systems of the drylands of western India: a synthesis of Late Quaternary environmental and tectonic changes, Quaternary International, v.104, p.69-86.

Chandrasekhar, D. V., Singh, B., Firozishah, M. and Mishra, D.C. (2005). Analysis of gravity and magnetic anomalies of Kachchh rift basin, India and its comparison with the New Madrid seismic zone, USA. Curr. sci., v. 88, (10), pp.1601-1608.

Chang, H. H. (1988). Fluvial Processes in River Engineering. Wiley- Interscience, New York, 429 p.

Chatterji, A. K. and Mathur, U. B. (1966). Note on the Nari Series of Kutch, Gujarat; Bull. Geol. Soc. India, v.3. pp.9-11.

Chung, W. P. and Gao, H. (1995). Source parameters of Anjar earthquake of July, 1956, India, and its seismotectonic implications for the Kutch rift basin. Tectonophysics, v. 242, pp.281-292.

Condie, K. C. (1989). Plate Tectonics and Crustal Evolution, third ed. Pergamon Press, Oxford, 476p.

Courtillot, V., Besse, J., Vandamme, D., Montigny, R., Jaeger, J. J., and Cappetta, H. (1986). Deccan flood basalts at the Cretaceous Tertiary boundary: Earth and Planetary Science Letters, v.80, pp.361-374.

Cox, L. R. (1940). The Jurassic lamellibranch of Kutch (Cutch). Paleontologica Indica, v.9 (3), 157 p.

Cox, R. T. (1994). Analysis of drainage-basin symmetry as a rapid technique to identify areas of possible Quaternary tilt-block tectonics: an example from the Mississippi Embayment, GSA Bull., v.106 (5), pp.571-581.

De, A. (1964). Iron–titanium oxides of the alkali olivine basalts, tholeiites, and acidic rocks of the Deccan Trap series and their significance. Int Geol Congr 24th sess., v.7, pp.126-138

Diamant, E., Polishook, B. and Hever, A. (1983). A positive correlation between joint trends and drainage pattern (under ground storage project Israel) Bull. Int. Assoc. Eng. Geol., v.28, pp.103-107.

Dumont, J. F. (1996). Neotectonics of the Sub-Andes– Brazilian craton boundary using geomorphological data: the Maranon and Beni basins. Tectonophysics, v.257, pp.137- 151.

Eardly, A. J. (1962). Structural Geology of North America. Harper and Row, New York, N.Y., 624p.

Frere, H. B. E. (1870). Notes on the Rann of Cutch and neighbouring region, Jour. Roy. Geogr. Soc. London, v.40, pp.181-207.

Friend, P. F. and Sinha, R. (1993). Braiding and meandering parameters. In: Best, J. L. and Bristow C. S. (eds), Braided Rivers. Geological Society Special Publication No. 75. Geological Society, London, UK, pp.105-111.

Gardiner, V. and Gregory, K. J. (1987). Drainage density in rainfall-runoff modeling. In Rainfall-Runoff Relationships, V. Singh. ed., Water Resources Publications, Fort Collins, Colorado, pp. 449-476.

Ghevariya, Z. G. (1985). Geological Mapping of Mesozoic Rocks around Anjar. Progress Report for the F.S.1984-85 of Geological Survey of India (Unpublished).

Ghevariya, Z. G., Sabale, A. B. and Rakshit P. (1984). Geological mapping of the Mesozoic Rocks, Kachchh district, Gujarat. (Unpublished report for the progress Report for the F.S.(1981-82).

Ghevariya, Z. G., Sable, A. B., Rakshit, P. and Shah, S. C (1982). Vertebrate fossils from non marine Lameta sequence from Kachchh, GSI, News Bull.

Ghevariya, Z. G. and Srikarni, C. (1987). Report on the systematic geological mapping of the area west of Anjar, Kachchh district. (Parts of toposheet nos. 41 E/16 and 41 I/4).

Ghevariya, Z. G. and Srikarni, C. (1991). Report on the systematic geological mapping of Mesozoic rocks in parts of Kachchh district, Gujarat (Toposheet nos. 41E/7, 13, 14; 41I/1, 6, 7). (Unpublished) Geol. Surv. Ind.

Ghosh, R. N. (1981). Quaternary events and environments in little Rann of Kutch. 4th regional conf. of Geology. Min. & Energy resources of SE Asia, Manila.

Glennie, K. W. and Evans, G. (1976). A reconnaissance of the Great Rann of Kutch, India. Sedimentology. v.23, pp.625-647.

Gombos Jr, A. M.., Powell, W. G., Norton, I. O. (2005). The tectonic evolution of western India and its impact on hydrocarbon occurrences: an overview, Sedimentary Geology, v.96, pp.119-129.

Gowd, T. N., Srirama Rao, S. V. and Gaur, V. K. (1992). Tectonic stress field in the Subcontinent, J. Geophys. Res., v.97, pp.11879-11888.

Grant. (1840). Memoir on Geology of Cutch.

Gregory (1893). Jurassic fauna of Kutch, Pal. Ind. Geol. Surv. of India, The Echinoids Sec. 9 2(1), The corals, v.2(2), pp.115.

GSI (2000). Seismotectonic Atlas of India and its Environs, Geol. Surv. India Sp. Pub. Calcutta.

GSI (Geological Survey of India). (2001). Geology and Mineral Resources of Gujarat, Daman and Diu, Miscellaneous Publication, v. 30, Part XIV, 102p.

GSI, (2003). The January 26, 2001 Bhuj Earthquake, Ed. P. Pande and J.R. Kayal, Geol. Survey of India Sp. Publication v.73, 300p.

Guarnieri, P., and Pirrotta, C. (2008). The response of drainage basins to the late Quaternary tectonic in the Sicilian side of the Messina Strait (NE Sicily). Geomorphology, v. 95(3-4), pp.260-273.

Guha D., Das, S., Srikarni, C. and Chakraborty, S. K. (2005). Alkali basalt of Kachchh: its implication in the tectonic framework of Mesozoic of western India. J. Geol. Soc. Ind., v.66, pp.599-608.

Guha, D. (1998). Petrological studies of alkaline plugs of Kachchh district and gabbro-pyroxinite-hornblendite and other differentiates around Kuran and Nirwandh areas in Pachchham Island, Kachchh district, Gujarat. Rep (Unpublished) Geol. Surv. Ind. (F.S. 1994-96).

Gupta, S. K. (1975): Silting of the Rann of the Kutch during the Holocene. Ind. J. of Earth Sci., v.2, pp.163-175.

Hancock, P. L. (1986). Neotectonics. Journal of the Geological Society, London, v.143, pp.325-326.

Hare, P. H. & Gardner, T. W. (1985). Geomorphic indicators of vertical neotectonism along the converging plate margins, Nicoya Peninsula, Costa Rica, in Tectonic Geomorphology, chap., v.4, pp.75-104, eds Morisawa, M. & Hack, J.T., Allen and Unwin, Boston.

Horton, R. E. (1932). Drainage basin characteristics, Trans. Amer. Geophys. Union., v.13, pp.350-361.

Horton, R. E. (1945). Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology, Bull. Geol. Soc. Amer., v.5, pp.275-370.

Horton, S., Bodin, P., Johnston, A., Patterson, G., Bollwerk, J., Rydelek, P., Raphael, A., Chiu, C. Chiu, J-m, Busdhbatti, K. and Gomberg, J. (2001). Bhuj aftershocks recorded by the MAE/ISTAR temporary seismic network, Int. Conf. Seismic Hazard with particular reference to Bhuj earthquake of January 26, 2001, IMD-DST, New Delhi, Abs. vol.103-104.

IMD, (2001).Bhuj earthquake of January 26, 2001. A consolidated preliminary report, Indian Meteorological Department, 44p.

IMD, (2002). Bhuj Earthquake of January 26, 2001, a consolidated document, Unpub. Report, Seismology No. 3/2002, 131P. IMD, New Delhi,120p.

ISR, (2010). Earthquake Monitoring Programme, Website: http://www.isr.gujarat.gov.in/maps.shtm

Jaeger, J. J., V. Courtillot, and Tapponnier P. (1989), Paleontological view of the ages of the Deccan Traps, the Cretaceous/Tertiary boundary, and the India-Asia collision, Geology, v.17, pp.316-319.

Jain, R. L. (1990). Avian Egg shells from the Lower Miocene rocks of Eastern Kachchh, Gujarat. Jour. Geol. Soc. Ind., v.35, pp.106-113.

Jain, S. K., C. V. R. Murty, U. Dayal, J. N. Arlekar, and S.K. Chaubey (2001). A field report on structural and geotechnical damages sustained during the 26 January 2001 M7.9 Bhuj Earthquake in Western India, Department of Civil Engineering, Indian Institute of Technology Kanpur, India http://www.nicee.org/NICEE/Gujarat/gujaratslides/gujarat_slides.htm.

Jaitly A K. (1986). Indomya, a new subgenus of Pholadomya from Middle Jurassic of Kachchh, W. India (Bivalvia: Pholadomyidae). Veliger, v.28(4), pp.457-459

Jensen, J. R. (2006). Remote Sensing of the Environment, Dorling Kindersley (India) Pvt. Ltd., New Delhi, 1st edition.

Johnston, A. C. (1996). Seismic moment assessment of earthquakes in stable continental regions I. Geophys. J. Int., v.124, pp.281-414.

Johnston, A. C. (1989). Seismicity of stable continental interiors. In: Gregersen, S., Basham, P.W. (Eds.), Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound, Kluwer, Dordrecht, pp.299-327.

Jones, S. J., Frostick, L. E., Tomothy, R. A. (1999). Climatic and tectonic controls on fluvial incision and aggradation in the Spanish Pyrenees. J. Geol. Soc. (London), v.56, pp.761-769.

Kar, A. (1993). Neotectonic influence on morphological variations along the coastline of Kachchh, India. Geomorphology Rishi Publ. Varanasi, Geomorphology, v.8, pp.199-219.

Kar, A. (1995). Geomorphology of the western India. Mem. Geol. Soc.India, v.32, pp.68-190.

Karanth, R. V., and Gadhavi, M. S. (2007). Structural intricacies: emergent thrusts and blind thrusts of central Kachchh, western India. Curr. Sci., v.93, pp.1271-80.

Karmalkar, N. R. and Sharma, P. K. (2003). Plume affected upper mantle beneath Kutch: Evidence from spinel lherzolite xenoliths and host alkali basalt. Deep continental studies in India, v.13, pp.2-3.

Karmalkar, N. R., Kale, M. G., Duriswami, R. A. and Jonalgadda, M. (2008). Magma underplating and storage in the crust-building process beneath the Kutch region, NW India. Curr. Sc., v.94, pp.1582-1588.

Kayal, J. R., De. Reena, Ram, S., Sriram, B.V. and Ganokar, S. G. (2002). Aftershocks of 26th January Bhuj Earthquake in western India and its seismotectonic implications. J. Geol.Soc. India, v.59, pp.395-418.

Kayal, J. R., Zhao, D., Mishra, O. P., De, R. and Singh, O. P. (2002 b). The 2001 Bhuj earthquake: Tomography evidence for fluids at hypocentre and its implications for rupture nucleation, Geophys. Res. Lett., v.29 (24), pp.51-54.

Keller, E. A. (1986). Investigation of active tectonics: use of surficial Earth processes in Wallace, R. E. (Ed.), *Active Tectonics*, Studies in Geophysics, National Academy Press, Washington, DC, pp.136-147.

Keller, E. A. and Pinter, N. (1996). Paleoseismology and earthquake prediction. In: Corey, P. (Ed.), Active Tectonics: Earthquakes, uplift, and Landscapes. Prentice-Hall, Inc., Upper Saddle River, New Jersey, pp. 245-286.

Khosla, A. and Sahni, A. (2003). Biodiversity during the Deccan volcanic eruptive episode. Jour. Asian Earth Sc., v.21, pp.895-908.

Krishnan, M. S. (1982). Geology of India and Burma (6th Edition): Delhi, CBS Publishers
.

Kuenen, Ph. H. (1953). Significant features of graded bedding. Bull. Am. Ass. Petrol. Geologists v.37, pp.1044-1066

Lanzhou, N. S., Scheidegger, A. E. (1981). Valley trends in Tibet. Zeitschrift fu¨ r Geomorphologie N.F., v.25, pp.203-212.

Larue, J. P. (2008), Effects of tectonics and lithology on long profiles of 16 rivers of the southern Central Massif border between the Aude and the Orb (France), Geomorphology, v. 93, pp.343-367.

Leopold, L. B. and Langbein, W. B. (1966). River meanders. Sci. Am., v.214, pp.60-70.

Lyell, C. (1857). Principles of Geology, 11th ed. Appleton and co.Newyork, 834 p.

MacMurdo, J. (1824). Papers relating to the earthquake which occurred in India in 1819, Philosophical. Magazine, v.63, pp.105-177.

Malik, J. N., T. Nakata, H. Sato, T. Imaizumi, T.Yoshioka, G. Philip, A.K. Mahajan, and R.V. Karanth (2001). January 26, 2001, the Republic Day (Bhuj) earthquake of Kachchh and active faults, Gujarat, western India, Active Fault Research, v.20, pp.112-116.

Malik, J. N., Sohoni, P. S., Merh, S. S., Karanth, R. V. (2001). Active tectonic control on alluvial fan architecture along the Kachchh Mainland Hill Range, Western India. Zeithschrift fu¨r Geomorphologie, v. 45 (1), pp.81-100.

Mandal, P., Rastogi, B. K., Satyanarayana, H. V. S., Kousalya, M, Vijayraghavan, R, Satyamurthy, C., Raju, I.. P., Sarma, A. N. S. and Kumar, N. (2004). Characterization of the causative fault system for 2001 Bhuj Earthquake of Mw 7.7. Tectonophysics, v.378, pp.105-121.

Mather, A. E. (1993). Basin inversion: some consequences for drainage evolution and alluvial architecture. Sedimentology, v. 40, pp.1069-1089.

Maurya, D. M., Goyal, B., Patidar, A. K., Mulchandani, N., Thakkar, M. G. and Chamyal, L. S. (2006). Ground Penetrating Radar imaging of two large sand blow craters related to the 2001 Bhuj earthquake, Kachchh, western India. J. Appl. Geophys., v.60, pp.142-152.

Maurya, D. M., Thakkar, M. G. and Chamyal, L. S. (2002). Quaternary Geology of the Arid Zone Kachchh: Terra Incognita, Proc. Indian Natn. Sci. Acad, v.69. A.No.2, pp.123-135.

Maurya, D. M., Thakkar, M. G. and Chamyal, L. S. (2003). Implication of transverse fault system on tectonic evolution of Mainland Kachchh, western India. Curr. Sci., v. 85, pp.661-667.

Mayer, L. (1986). Tectonic Geomorphology of escarpments and mountain fronts. In: R.E. Wallace(Ed.), Active Tectonic. Natl.Res.Counc. Washington DC, pp.125-135.

McCalpin, J. P. and Thakkar, M. G. (2003). 2001 Bhuj-Kachchh earthquake : surface faulting and its relation with neotectonics and regional structures, Gujarat, Western India, Annals of Geophysics, v. 46, pp.937-956.

Melluso, L., Mahoney, J. J.and Dallai, L. (2006). Mantle sources and crustal input as recorded in high-Mg Deccan Traps basalts of Gujarat (India), Lithos, v. 89, Issues 3-4, pp.259-274.

Melton, M. A. (1958). Geometric properties of mature drainage systems and their representation in E4 phase space. Journal of Geology, v.66, pp.1076-1084.

Merh, S.S. (1995). Geology of Gujarat, Geological Society of India, Bangalore, 222p.

Merh, S. S. (2005): The Great Rann of Kachchh: Perception of a field geologist. J. Geol. Soc.of India, v.65, pp.9-25.

Miller, V. C. (1953). A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Varginia and Tennessee. Project NR 389-042, Tech. Rept.3.,Columbia University, Department of Geology, ONR, Geography Branch, New York.

Mitra, K. C. and Ghosh, D. N. (1964). A note on the Chari Series around Jhura Dome, Kutch.

Mukherjee, A. B., Biswas, S. (1988). Mantle derived spinel lherzolite xenoliths from the Deccan Volcanic Province (India): implication for the thermal structure of the lithosphere underlying the Deccan Traps. J. Volcanol. Geotherm. Res., v.35, pp.269-276.

Mueller, J. E. (1968). An introduction to the hydraulic and topographic sinuosity indexes, Annals of the Association of American Geographers, v.58, pp.371-385.

Negishi, H., Mori, J., Sato, T., Singh, R., Kumar, S. and Hirata, N. (2002). Size and orientation of the fault plane for the 2001 Gujarat, India earthquake Mw 7.7 from aftershock observations : A high stress drop event, *Geophys. Res. Lett.,* v.29(20), pp.101-104.

Obruchev, V.A. (1948). Osnovnyje certy kinetiki i plastiki neotectoniki. Izvestiya Akademii Nauk UzSSR Sertiya Geologicheskaya, **5**

Oldham, R. D. (1926): The Cutch (Kachchh) earthquake of 16th June 1819 with a revision of the great earthquake of 12th June 1897. Mem. Geol. Soc. of India, v. 46, pp.1-77.

Ouchi, S. (1985). Response of alluvial rivers to slow active tectonics movement. Geological Society of American Bulletin. v.96, pp.504-515.

Pande, P. (2001). Source mechanism of Kutch (Bhuj) earthquake of 26 Jan, 2001. Abstract volume, International conference on seismic hazard with particular reference to Bhuj earthquake of Jan., 26, 2001.pp.196-198.

Pande, P. (2007). Evaluation of seismotectonics of Kachchh rift basin, Gujarat, India and assessment of seismic hazard potential of the region. PhD Thesis. p.144.

Pande, P., Kayal, J. R., Joshi, Y. C. and Ghevariya, Z. G. (2003). Lithotectonic frame work of Gujarat and adjoining regions; In Kutch (Bhuj) Earthquake 26 January, 2001. Ed. P. Pande and J.R. Kayal, Geol. Surv. Sp. Pub. v.76, pp.5-9.

Pandey, D. K., Westermann, G. E. G. (1988). First record of Bathonian Bullatimorphites (Jurassic Ammonitina) from Kachchh, India. J Paleont, v.62, pp.148–150.

Patriat, P. and Achache, J. (1984). Indian-Asia collision chronology its implications for crustal shortening and driving mechanism of plates, Nature, v. 311, pp. 615-621.

Paul, D. K., Ray, A., Das, B., Patil, S. K. and Biswas, S. K. (2007). Petrology, geochemistry and paleomagnetism of the earliest magmatic rocks of Deccan Volcanic Province, Kutch, Northwest India, LITHOS-01643; p. 23.

Pavlides, S. B. (1989). Looking for a definition of neotectonics. Terra New. v.1, n.3, pp.233-235.

Potter, P. E. and Pettijohn, F. J. (1963). Palaeocurrents and basin analysis: Berlin (Springer-Verlag), 296p.

Potter, P. E. (1978). Significance and origin of big rivers. Journal of Geology, v.86, pp.13-33.

Prucha, J. J., Graham, J. A. and Nickelsen, R. P. (1965). Basement controlled deformation in Rocky Mountains foreland. Am. Assoc. Pet. Geol. Bull., v.49(7), pp.966-992.

Radhakrishna, B. R. (1993) Neogene uplift and geomorphic rejuvenation of the Indian Peninsula. Curr. Sci., v. 64, pp. 787-793.

Rajendran, C. P. and Rajendran, K. (2001). The 1819 and 2001 Kutch earthquakes: A comparative perspective. Abstract volume. International conference on seismic hazard with particular reference to Bhuj earthquake of Jan. 26, 2001.pp.15-18.

Rajendran, C. P., Rajendran, K. and John, B. (1998). Surface deformation related to the 1819 Kachchh earthquake: Evidence for recurrent activity, Current Science, v.75, pp.623-626.

Rajendran, K., Rajendran, C. P., Thakkar, M. G., Tuttle, M. P. (2001). The 2001 Kutch (Bhuj) earthquake: coseismic features and their significance. Current Science, v.80, pp.1397-1405.

Rajendran, C. P., Rajendran, K., Duarah, B. P., Baruah, S. and Earnest, A. (2004). Interpreting the style of faulting and paleoseismicity associated with the 1897 Shillong, northeast India, earthquake: Implications for regional tectonism, Tectonics, v. 23, TC4009, doi:10.1029/2003TC001605.

Rajendran, C. P., Rajendran, K., Thakkar, M., Goyal, B. and Goyal. B. (2008). Assessing the previous activity at the source zone of the 2001 Bhuj earthquake based on the near-source and distant paleoseismological indicators, Jour. Geop. Res., v. 113, B05311, doi:10.1029/2006JB004845.

Rajnath, (1932). A contribution to the stratigraphy of Cutch. Quart. J. Geol. Mining. Met. Soc. Ind., v.14 (4), pp.161-174.

Rastogi, B. K., Mandal, P., Satyanarayana, H. V. S., Kousalya, M., Raghavan, R., Jain, R., Sharma, A. N. S., Kumar, N. and Satyamurty, C. (2001). Aftershock study of the 26 January Bhuj earthquake of Ms 8.0, www.ngri.org, National Geophysical Research Institute, Hyderabad.

Raval, U. (1995). Seismicity of the Koyna region and regional tectonomagmatism of the western margin (India), Pure Appl. Geophys., v.145, pp.175-192.

Ravishankar and Pande, P. (2001). Geoseismological studies of Kutch (Bhuj) earthquake of 26 January, 2001, J. Geol. Soc. India, v.58, pp.203-208.

Ray, A., Patil, S. K., Paul, D. K., Biswas, S. K., Das, B. and Pant, N. C. (2006). Petrology, geochemistry and magnetic properties of Sadara sill: evidence of rift related magmatism from Kutch basin, northwest India. J Asian Earth Sci., v.27, pp.907-921.

Reineck, H. E. and Singh, I. B. (1973). Depositional Sedimentary Environments. Berlin (Springer-Verlag), 439p.

Rhea, S. (1993). Geomorphic observations of rivers in the Oregon Coast Range from a regional reconnaissance perspective. Geomorphology, v.6(2), pp.135-150.

Rockwell, T. K., Keller, E. A., Clark, M. N. and Johnson, D. L. (1984). Chronology and rates of faulting of Ventura River terraces, California, Geol. Soc. Am. Bull., v.95, pp. 1466-1474.

Rossetti, D. F. and Goes, A. M. (2000). Deciphering the sedimentological imprint of paleoseismic events: an example from the Aptian Formation, northern Brazil. Sediment. Geol., v.135, pp.137-156.

Rossetti, D. F. (1999). Soft-sediment deformation structures in late Albian to Cenomanian deposits, Sao Luis Basin, northern Brazil: evidence for palaeoseismicity. Sedimentology, v. 46, pp.1065-1081.

Roy, B. and Merh, S. S. (1977). The Great Rann of Kutch : An intriguing Quaternary terrain. Rec. Res. Geol., v.9, pp.100-108.

Scheidegger A. E. (2004). Morphotectonics. Springer Verlag, Berlin, 197p.

Schubert, C. (1982). Neotectonics of Bocono Fault, Western Venezuela. Tectonophysics v.85, pp.205-220.

Schumm, S. A., Mosley, M. P. and Weaver, W. E. (1987). Experimental Fluvial Geomorphology. John Wiley and Sons, New York.

Schumm, S. A. (1956). Evolution of drainage system and slopes in badlands at Perth Amboy, New Jersy, Bull. Geol. Soc. Amer, v.67, pp.597-646.

Schumm, S. A. (1977). The Fluvial System, Wiley, New York.

Schumm, S. A. (1986). Alluvial rivers response to active tectonics. National Academy Press, Washington, D.C., pp.80-94.

Sedgeley, D., Yawanarajah, S. and Bastia, R. (1997). Petroleum potential of the Banni Graben, Kutch Basin, AAPG Bull. v.81, p.1411.

Seeber, L. and Gornitz, V. (1983). River profiles along the Himalayan arc as indicators of active tectonics, Tectonophysics, v.92, pp.335-367.

Sharma, V. (1990). Geomorphic evolution of Kutch coastline with special reference to erosional and depositional processes. Unpublished Ph.D Thesis, University of Delhi, Delhi.

Sieh, K. E. (1978). Prehistoric large earthquakes produced by slip on the San Andreas fault at Pallet Creek, California, J. Geophys. Res., v.83, pp.3907-3939.

Sim, J. D. (1973). Earthquake-induced structures in sediments of Van Norman Lake Fernando, California. Science, v.182, pp.161-163.

Sim, J. D. (1975). Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. Tectonophysics. v.29, pp.144-152.

Singh, G., Pant, G. B. and Mulye, S. S. (1991). Distribution and long term features of the spatial variations of the moisture regions over India. Int. J. Climatol., v.11, pp.413-427.

Singh, P. K., Das, S. and Dey, A. (2010). 6^{th} International Conference of Dykes (4^{th} -7^{th} Feb. 2010). Abstr. vol.

Singh, P. K., Das, S. and Mohapatra, S. R. (2011). Identification of Loriya Fault, Its Reactivation Due to 2001 Bhuj earthquake (Using Remote Sensing data) and Its Bearing on Kachchh Mainland Fault, Kachchh District, Gujarat, Ind.J. Rem.Sen, 10.1007/s12524-011-0127-x (pub online, under press).

Singh, P. K., Sahu, B. K. and Mohapatra, S. R. (2008). Geological mapping along the Kachchh Mainland Fault. Unpublished Report of GSI, FS. (2005-07).

Singh, S. L. and Lal, S. (2008). Report of the regional gravity, magnetic (VF) and deep vertical electrical sounding for structural study in Bhuj-Bhachau area, Kachchh district, Gujarat; Unpublished Report of GSI, F.S. (2005-06).

Singh, S. K., Pacheco, J. F., Bansal, B. K., Perez-campos, X., Dattatrayam and Suresh G. (2004). A source study of the Bhuj, India Earthquake of 26 January, 2001 (MW 7.6), Bull. Seism. Soc. Am., v.94(4), pp.1195-1206.

Singh, S. (1998). Physical Geography, Prayag Pustak Bhawan, Allahabad, India.

Sivewright, R. (1907). Cutch and the Ran: Geogr. Jour., v.29, pp.518-539.

Slemmons, D. B. (1991). Introduction. In: Slemmons, D. B., Engdahi, E. R., Zoback, M. D. & Blackwell, D. D. (eds), Neotectonics of North America. Geological Society of America, Boulder, Co., pp.1-20.

Sloss, L. L. (1991). The tectonic factor in sea level change: a countervailing view. J. Geophys. Res., v. 96, pp.6607-6617.

Sohoni, P. S., and Malik, J. N. (1998). Remnants of Large magnitude earthquakes: Evidences from the Great Rann sediments, Kachchh, Western India. Current Science, v. 74(11), pp.985-989

Sohoni, P. S., Malik, J. N., Merh, S. S. and Karanth, R. V. (1999). Active tectonics astride Katrol Hill Zone, Kachchh, W. India, Jour. Geol. Soc. of India, v. 53, pp.579-586.

Sowerby, J. C. (1840). Systematic list of organic remains. Appendix to Grant C.W.: Memoir to illustrate a geological map of Cutch : Transaction Geological Society, v. 5 (2), pp.327-329.

Spath, L. F. (1933), Revision of the Jurassic cephalopod fauna of Kachchh (Cutch). Pal. Ind. (n.s.), v. 9 (2), pp.19-45.

Srinivasan, R. and Reddy, G. K. (2001). Geological and soil-gas Helium Emanometric studies in the suspected surface rupture zones in the mezoseismal area of Jan 26, 2001-Bhuj earthquake. Abstract volume, International conference on seismic hazard with particular reference to Bhuj earthquake of Jan., 26, 2001. pp.159-161.

Srivastava, P. K., Koli, M. D. and Hardas, M. G. (1964). Geological report of Tertiary rocks of western and southern Kutch. Field season, 1963-64, ONGC report (unpublished).

Stewart, I. S. and Hancock, P. L. (1994). Neotectonics. In: Hancock, P.L. (ed), continental Deformation. Pergamon Press, London, pp. 341-399.

Strahler A. N. (1952). Dynamic basis of geomorphology. Bulletin of the Geological Society of America, v.63, pp. 923-938.

Strahler, A. N. (1964). Quantitative geomorphology of drainage basins and channel network in Handbook of Applied Hydrology, McGraw Hill Book Company, New york, Section 4-II.

Strahler, A. N. and Strahler, A. H. (2002). A Text Book of Physical Geography, John Wiley & Sons, New York.

Subramanya, K. R. (1996). Active intraplate deformation in south India. Tectonophysics, v.262, pp.231-241.

Suppe J. (1983). Geometry and kinematics of Fault-Bend Folding. American Journal of Science, v.283, pp.684-721.

Thakkar, M. G., Maurya, D. M., Raj, R. and Chamyal, L. S. (1999). Quaternary tectonic history and terrain evolution of the area around Bhuj, mainland Kachchh, western India. J. Geol. Soc. India, v.53, pp.601-610.

Thakkar, M. G., Maurya, D. M., Rachna Raj and Chamyal, L. S. (2001).Morphotectonic analysis of Khari drainage basin in Mainland Kachchh: Evidence for neotectonic activity along transverse faults. Bull. Indian Geol. Assoc., v.34, pp.205–220.

Thakkar, M. G., Goyal, B., Patidar, A. K., Maurya, D. M. and Chamyal, L. S. (2006). Bedrock gorges in the central mainland Kachchh: Implications for landscape evolution. Journal of Earth System Science, v.115(2), pp.249-256.

Twidale, C. R. (1966). Chronology of denudation in the southern Flinders Ranges, South Australia. Transactions of the Royal Society of South Australia, v.90, pp.3-28.

Valdiya, K. S. (1973). Tectonic framework of India: A review and interpretation of recent structural and tectonic studies. Geoph. Res.Bull., v.11, pp.79-114.

Valdiya, K. S. (1998). Late Quaternary movements and landscape rejuvenation in south-eastern Karnataka and adjoining Tamil Nadu, Jour. Geol.Soc. Ind, v. 51, pp.139-166.

Waagen, A. B. (1872). Memoir on the geology of Kutch, to accompany the map compiled by A.B. Wynne and F.Fedden during the seasons of 1867-68 and 1868-69. Mem. Geol. Surv.India. v.9 (Pt.1), 293p.

Waagen et al. (1875). Jurassic fauna of Cutch. The Cephalopoda. Mem. Geol. Surv. Ind., Pal. Ind., Ser. 9, pt. 1, pp.1-27.

Wesnousky, S. G., Seeber, L., Rockwell, T. K., Thakur, V., Briggs, R., Kumar, S. and Ragona, D. (2001). Eight days in Bhuj: Field report bearing on surface rupture and Genesis of the 26 January, 2001 earthquake in India, Seism. Res. Lett., v.72(5), pp.514-524.

Williams, E. (1960). Intra-stratal flow and convolute folding. Geol. Mag., v.97, pp.208-214.

Wynne, A. B. (1872), Memoir on the Geology of Kutch, to accompany a map compiled by A.B. Wynne and F. Fedden during the season 1867-68 and 1868-69. Mem. Geol. Surv. Ind. 9, pt. 1.

Wynne, W. B. (1869). Rec. Geol. Surv. India, 11, pt.1, pp.1-5.

Yeats R. S., Sieh, K. E. and Allen, C. R (1997). The Geology of Earthquakes, Oxford University Press, New York, 568p.

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