CHAPTER - 1
INTRODUCTION
Introduction:

1.1 General introduction:

Dynamic coupling between climate driven erosion and tectonics has been the focus of several researches worldwide and a number of theories and numerical simulations have been put forward (Koons, 1989; Beaumont et al., 1992; Willett, 1999; Whipple, 2004). Towards this, fluvial sequences and landforms have been used to reconstruct the history of Quaternary climate oscillations and tectonic uplift (Klimaszewski, 1967; Starkel, 2003; Bridgland and Westaway, 2008; Vandenberghe, 2008). For example, fluvial valleys could be defined in terms of their evolution-cycles which encompass well-marked phases of erosion, accumulation and lateral erosion (Hancock and Anderson, 2002). These phases bear climatic imprints due to their association with extreme changes in the climate, interspersed with transitional climatic conditions (Dziewanski and Starkel, 1962; Bridgland, 2000; Huisink, 2000; Bogaart and van Balen, 2000; Maddy et al., 2001; Bridgland and Westaway, 2008a; Gibbard and Lewin, 2009). Studies pertaining to fluvial dynamics, supplemented with geochronology help in quantification of the landscape evolution through time. Likelihood of a river to incise or aggrade would depend on the proportional relationship between fluvial discharge and sediment supply (Bogaart and van Balen, 2000). While the discharge and sediment supply are in equilibrium, the probability of incision or aggradation is reduced. In such conditions, discharge remains high enough to remove all slope materials supplied from the valley bottom (Blum and Törnqvist, 2000). However, due to time lag between fluvial discharge and sediment supply or by predominance of one of these factors the situations leads to disequilibrium, thereby resulting into incision or aggradation of the river valleys (Bogaart and van Balen, 2000).

Contrary to this, an actively uplifting terrain provides different scenario where the rivers have been observed to incise into the underlying resistant bedrock due to change in the gradient (Whipple, 2004), forming strath and fill terraces. The key factors in these terrains which govern the balancing act of the river and the landscape are change in the gradient and erosivity. Since the factors responsible for such readjustment of gradient are global in nature (viz. Climate change, uplift or change in sea-level), episodes of river terraces development could be used as best surrogates to correlate recent earth history over large areas and even from continent to continent.
Keller and Pinter (1996) and Willemin and Knuepfer (1994) proposed two approaches for investigations pertaining to the active tectonics and their implication in landforms viz. the forward and the inverse approaches. The former relates to the effects of known tectonic activities on landforms while the later involves interpretation of the nature and location of active tectonics from anomalous landforms. However, applications of these approaches are unique in specific cases of bedrock and alluvial rivers and corresponding landforms (Keller and Pinter, 1996; Willemin and Knuepfer, 1994).

Bedrock rivers are likely to form in actively incising parts of a tectonic setting and are distinctly different from their alluvial counterparts as these are characterized by hard, resistant substrates (Whipple, 2004) (Fig. 1.1A). Bedrock rivers could also be termed as mixed bedrock-alluvial rivers due to lack of continuous cover of alluvial sediments along their valleys (Howard, 1980; Howard et al., 1994; Benda and Dunne, 1997; Densmore et al., 1998) (Fig 1.1B). Discharge, sediment flux, substrate properties, and base-level conditions dictate self-adjusted combinations of channel gradient, width, and bed morphology in bedrock channels (Wohl and Ikeda, 1998; Wohl et al., 1999; Wohl and Merritt, 2001). In terms of sediment budget, the long-term dynamics of these river systems has been suggested as the transport capacity (Qc) exceeding bedload sediment flux (Qs) which is related by: Qs/Qc< 1 (Howard, 1980, Howard et al., 1994, Montgomery et al., 1996). These rivers act as key elements
in quantitative understanding of coupling of climate-driven denudation and structure-driven incision.

In areas of rapid erosion and tectonic uplift, the longitudinal profile of bedrock channels respond sensitively to the bedrock uplift rate rather than other morphological properties (Strahler, 1950, Schmidt and Montgomery, 1995, Burbank et al., 1996, Densmore et al., 1998). Though the changes in base level are transmitted through landscapes along the entire channel; the rate at which these signals are conveyed is governed by the timescale of landscape response to perturbations (Whipple and Tucker, 1999; Whipple, 2004). Further, a bedrock river may be subjected to aggradation or degradation/incision depending on threshold of critical power (i.e., specific stream power), which governs genesis of river terraces because it indicates the potential linkages among different variables and suggests how climate or tectonics could cause the river to switch from aggradation to degradation, or vice versa (Bull, 1991; Burbank and Anderson, 2001). Another important parameter that defines the active tectonics is the beveling of the bedrock surface which is considered to be a typical feature in down cutting rivers and occurs due to the change in the ratio of vertical incision to lateral planation (Hancock and Anderson, 2002). For example, if there is an intensive mobilization of slope materials to the channel, it will restrict channel deepening as a result the valley would be widened (Lave and Avouac, 2001) creating space for valley-fill aggradation. On the contrary, valley deepening would occur during events of low sediment supply and high stream power.

Compared to the bedrock rivers, alluvial rivers are characterized by a temporally and spatially continuous blanket of transportable sediment and well developed flood plains (Schumm, 1963). Based on the channel morphology Schumm (1963) classified alluvial rivers into five categories. These are the (i) straight channels with migrating sand waves, (ii) migrating channels with alternate bars forming a sinuous thalweg, (iii) meandering channels, (iv)meandering-braided transitional channel and (v) typical braided channels. Further, based on the channel stability/sediment load/transportability, the alluvial channels can be classified as stable, eroding, and depositing (Schumm, 1963). In fact, sediment supply and discharge are the major factors that govern the pattern of an alluvial river (Allen, 1985; Bridge, 2003). River discharge determines the size of stream channels (Leopold and Maddock, 1953) and the amplitude and wave length of meanders (Leopold and
Wolman, 1957). In addition to this, discharge also influences width/depth ratio of the channels which in turn influence sediment budget and subsidiary modifications (Schumm, 1963). In terms of stability, an alluvial river could be expected to attain equilibrium (graded stream) only if it attains its base level (Schumm et al., 2002). In an area which is undergoing slow deformation/uplift the alluvial river may tend to accommodate the deformation by small continuous incision which lead to small progressive changes (persistent imbalance) in river morphology leading to development of terrace (Fig. 1.2A).

Figure 1.2: Schematic diagram showing two possible types of river response to active upwarping. (A) Continuous adjustment leading to dynamic equilibrium and (B) Adjustment which occurs when deformation exceeds a threshold leading to dynamic metastable equilibrium. Kinks represent changes in river morphology (aggradation and incision). Please note that both the areas are tectonically active. Sporadic response as in (B) may lead to formation of gorges or knickpoints along the river profile.

However, in some cases, large scale incision and terrace formation occurs only when the deformation becomes large enough for the river to exceed a threshold. In such cases, the response is abrupt (Fig. 1.2B). Therefore, changes in river morphology and behavior play an important role to identify crustal movements. This small change along the river valley leading to tilting may possibly migrate downstream or upstream (Fischer, 1994; Boyd and Schumm, 1995).

Alluvial rivers are infrequently investigated in the context of active tectonics, however, in some of the cases striking evidences of lateral offsets of streams have been identified (Wallace, 1968; Sieh and Jahns, 1984). Some of the fluvial anomalies associated with the active tectonics could be the local development of meanders or a braided pattern, local widening or narrowing of channels, anomalous ponds, marshes
or alluvial fills, lateral tilting, variation of levee widths or discontinuous levees or any anomalous curve or turn along the river (DeBlieux, 1949; Tator, 1958; Peakall, 1995). Rivers respond to vertical displacement along faults by either aggrading or degrading the base level leading to steepness variation with respect to the original course of the river (Schumm et al., 2002). Displacement producing steeper channel segment give way to erosion/incision while lower-elevation segment induces aggradation. It has been suggested that meandering channel respond to active tectonics by way of downstream increase in sinuosity and upstream straightening or ponding of the river segment (Ouchi, 1985).

In the western India, spectacular examples of incised bedrock and alluvial rivers can be found in Kachchh, and in the alluvial plain of North Gujarat respectively (Fig. 1.3A and B). These are the dryland rivers which were not affected directly by the Quaternary glaciations as a result, sedimentary successions have remained unaffected by post depositional reworking (Merifield, 1987; Reid and Frostick, 1997). Climate and tectonics are the two major external or allogenic factors which influence the aggradation and incision in bedrock and alluvial rivers. Integrating qualitative and quantitative interpretation of aggradation and incision along bedrock and alluvial river valleys, it is possible to determine respective contribution of climate and tectonics in developing the present day landscape.

In the foregoing discussion, an attempt has been made to demonstrate that how the bedrock and alluvial rivers respond to a combination of climate and tectonic perturbations. With this background, the present study therefore, is an attempt to understand the nature and magnitude of bedrock and alluvial river response in a monsoon dominated and tectonically active western India (viz. Kachchh and North Gujarat Alluvial Plains).

Figure 1.3(A): Incised bedrock rivers exposing strath terraces at Pachcham Island, Kachchh. Patchy alluvium can be observed overlying the beveled bedrocks along Bandi river of Kachchh (B) Alluvial river of the North Gujarat.
1.2 Review of the previous work and motivation of the present study:

Considering the myriad of geomorphic processes that influence the genesis and subsequent preservation of fluvial stratigraphy, a few tangible explanations have been obtained towards climate and tectonic coupling following the decade-long researches in this aspect (Schumm, 1969; Schumm et al., 1987; Bull, 1990, 1991; Sugai, 1993; Tucker and Slingerland, 1997; Hancock and Anderson, 2002). Gujarat in the Western India encompassing the Kachchh peninsula which is tectonically active since its origin and the alluvial plain in the east along the Cambay graben consisting of ~300 m thick Quaternary sediments serve as prospective study area of such investigations. The Kachchh peninsula by virtue of its unique location in a monsoon-dominated tectonically- active terrain demonstrates climate and tectonics coupling towards its landform evolution. Fluvial terraces preserved along its bedrock river valleys could be considered as useful proxies to de-convolute respective contributions of climate and tectonics. In the active tectonic setting, the history of fluvial processes is suggested to be of direct consequence of the prevailing tectonics and hence the association could be considered to exhibit dynamic interaction (Bull and Kneupfer, 1987; Merritts et al., 1994; Personius, 1995; Gardner et al., 1992; Pazzaglia et al., 1998; Hancock et al., 1999). Though there have been some works corresponding to geomorphic and stratigraphic observations along the bedrock rivers of Kachchh, particularly along the Katrol Hill Range (Thakkar et al., 1999; Maurya et al., 2003a; 2003b; 2008; Patidar et al., 2007; 2008). However, the studies pertaining to the climate and tectonics coupling remains uninvestigated.

Some attempts were made in the past to identify Quaternary stratigraphic succession along the KHF. Thakkar et al. (1999) investigated Quaternary deposits along the river valleys of Katrol Hill Range which occur in the form of alluvial and colluvial fans, alluvial deposits and fluvio-aolian miliolites. Patidar et al. (2007; 2008) carried out detail investigations of the patchy occurrence of Quaternary deposits. In absence of chronology, these deposits have been assigned relative chronology based on the stratigraphic position. The miliolites were suggested to have been deposited during the Late-Pleistocene, the boulder colluviums deposits and valley-fill miliolites were assigned middle Pleistocene age. Sporadic occurrences of fine-grained channelized alluvium overlying the valley-fill miliolites were assigned a post-miliolite phase of fluvial deposition during the upper Late-Pleistocene to Middle
Holocene. Scarp derived colluviums, at the base of range front scarp and overlying the alluvium and valley-fill miliolites were assigned an age of Late-Holocene. These earlier studies were useful in delineating major aggradational facies, however in absence of chronology, the associated ages were mere speculative based on stratigraphic positions.

In addition to this, there have been some studies corresponding to the incised river valleys along KHF and Quaternary uplifts. The terrain along the Katrol Hill Range encompasses conspicuous presence of deep-incised gorges and prominent knick-points along the rivers originating from the back-valleys of KHF. The development of these gorges and knick points were attributed to tectonic activities of the KHF during the Holocene (Thakkar et al., 1999; Patidar et al., 2007). Based on their geomorphological studies, Patidar et al. (2007) suggested that the KHF exerts a major influence on the drainage network of the area. They investigated the incised valley and gorge walls along the Gunawari river which expose Mesozoic rocks, Quaternary miliolites and fine-grained alluvial deposits. Similarly, they investigated along the Khari river which incises through the Quaternary miliolite deposits and Mesozoic rocks. On the basis of morphological investigations, Thakkar et al. (1999) identified two major phases of Quaternary uplift: pre-miliolite (Early-Pleistocene) and post-miliolite (Late-Pleistocene to Recent) phases could be inferred. Former phase of uplift was attributed to the activities of the E-W trending major faults whereas later uplift was associated to NNE-SSW and NNW-SSE transverse faults. Maurya et al. (2003b) suggested that stresses accumulated at the E-W trending faults could possibly have been partially transmitted to NW-SE to NE-SW transverse faults which account for present seismicity. Based on the geomorphology and stratigraphy, Patidar et al. (2007) invoked three major phases of Quaternary tectonic uplift in the Katrol Hill Range. According to them, the oldest pre-miliolite phase (middle Pleistocene) was followed by a prominent phase of fluvial incision with formation of gorges during early Holocene which continues till present. The boulder colluvium was associated with pre-miliolite phase of neotectonic activity (reactivation of KHF) by virtue of their stratigraphic position of being uniformly overlain by the fluvial miliolites. A middle-Pleistocene age was speculated for this pre-miliolite phase of neotectonic activity. Similarly, the valley-fill miliolites were assigned a pre-miliolite phase of neotectonic uplift. The development of gorges in the Katrol Hill Range was
attributed to the Early-Holocene humid climate and southward tilting of KHF leading to a phase of prominent incision (Maurya et al., 2003b; Patidar et al., 2007). Patidar et al. (2007) associated scarp derived alluvium to the youngest phase of neotectonic activity that possibly occurred during the Late-Holocene and continues till present. Patidar et al. (2008) investigated Quaternary reactivation of KHF exhibited by the offsetting and deformation of Quaternary deposits observed in the Khari river basin. Based on the stratigraphy of the horizons, they invoked three phases of neotectonic events, Event-1 during the Late-Pleistocene, Event-2 during the Early Holocene and Event-3 younger than 2 ka. These events were tentatively bracketed in geologic time based on the correlation of the affected sediments and stratigraphic set-up. Morino et al. (2008) excavated trench along the Khari river at Wandhay dam to carry out active fault investigation of KHF. Their study revealed occurrence of at least three large magnitude seismic events along three major fault strands. On the basis of pattern of deformation on loose unconsolidated sediments and fault scarps developed on the alluvial-colluvial fan surfaces, they deduced late Holocene age for these events. Summing up the earlier works, it can be suggested that the past researches were of the opinion that the major rivers in the Kachchh peninsula are actively incising the Quaternary sediments along with the Mesozoic and Tertiary bedrocks and there were phases of aggradational event in the geological past (Thakkar et al., 1999; Maurya et al., 2003a; 2003b; Mathew et al., 2006; Patidar et al., 2007; 2008; Morino et al., 2008). However, these earlier studies along KHF lack chronological evidence and therefore could be considered as speculative.

Similarly, in Island Belt and Wagad Highland of Kachchh, chronological studies pertaining to aggradation and incision of sediments are completely lacking. Chowksey et al. (2010) attempted to decipher tectono-geomorphic characteristics of the Bela, Khadir and Bhanjada islands. On the basis of field based geomorphic evidences, they suggested that the presence of raised marine depositional and erosional features at the base of the escarpments could be attributed to Mid-Late Holocene uplift/tilting of IBF.

The Sabarmati and Mahi are the two most important river basins of the Gujarat Alluvial Plain in Western India. Modern Sabarmati river is suggested to have emerged later than 300 ka (Sareen et al., 1993; Tandon et al., 1997) and fluvial sedimentation continued till 39 ka which is also known to be the timing of adjustment
of its course (Tandon et al., 1997). Aeolian sedimentation in the Sabarmati river basin is suggested to have commenced around 26 ka and continued till 5 ka (Singhvi et al., 1982; Wasson et al., 1983; Tandon et al., 1997; Srivastava et al., 2001; Juyal et al., 2003). Sediments exposed in the lower Mahi basin indicates distinct marine, aeolian and fluvial depositional environment, with two major fluvial aggradation phases in the region corresponding to Oxygen Isotope Stages 5 and 3 (Juyal et al., 2000). It was envisaged that the fluvial sedimentation in the lower Mahi basin began after 125 ka and the upper one was deposited between 50 and 30 ka.

Inter-valley chrono-stratigraphic investigations along Luni, Mahi and Sabarmati basins highlighted two distinct succession types: Laterally extensive Pliocene Type-I succession is separated by a hiatus from the Late-Pleistocene Type-II succession which show patchy occurrence (Jain et al., 2004). It was suggested that these basins responded differently to climate changes during the Late-Pleistocene which resulted in different facies association. However, chrono-stratigraphic correlation was adequately addressed later on for fluvial and aeolian sequences along Mahi, Sabarmati and Orsang river basins which signify the southwest monsoon variability during the last 130 ka (Juyal et al., 2006).

A broad consensus on the slope deviatory nature of the major rivers of the Gujarat alluvial plain suggests fluvial adjustment due to neotectonic reactivation in the region (Sareen et al., 1993; Merh and Chamyal, 1997; Maurya et al., 1997; Tandon et al., 1997; Srivastava et al., 2001). Rivers have preferentially migrated south-east ward and the incision followed thereafter. The Banas and Saraswati are the only two major rivers which are non slope-deviatory rivers of Gujarat Alluvial Plain (Sareen et al., 1993). However, Quaternary as well as chrono-stratigraphic studies are completely lacking for these two rivers. More so these rivers are located in the northern extremity of the Gujarat alluvial plain which lies under the semi-arid to arid climatic condition. Therefore, it would be interesting to compare fluvial and aeolian process from the Saraswati and Banas rivers with that of the Sabarmati and Mahi rivers in order to understand the geomorphic response to rainfall gradient in the dryland.

Earlier studies corresponding to Kachchh and Gujarat Alluvial Plain suggest that the terrain has the potential for reconstructing the late Quaternary deformations/uplift and climate variability. However, due to lack of detailed
sedimentological observations and limited chronometric data, the inferences drawn are non-definitive or non-quantified.

1.3 Objective:

Therefore, the present study would be an attempt to integrate the chronologically constrained fragmentary sedimentary records from the bed rock rivers (Kachchh) with that of a laterally persistent and relatively continuous sedimentary records from the northern alluvial plain of Gujarat. This will help in developing a regional and integrated picture of the late Quaternary tectonics and climate from the arid-semi arid western part of India. The specific objectives of the present studies are:

(i) Reconstruction of climate variability (monsoon) using the valley fill sequences from the bed rock and alluvial plain rivers.
(ii) Quantifying the rate of incision/uplift and ascertaining the role of tectonics and climate in the evolution of fluvial landforms.
(iii) Develop a model of fluvial landform evolution with emphasis on the climate and tectonic interaction during the late Quaternary.

1.4 Area of study

1.4.1 Kachchh:

Kachchh is located at the westernmost part of Indian peninsula between latitude 22°30’-24°30’N and longitude 68°-72°E (Fig. 1.4). It is flanked by the Great Rann in the north and east, Little Rann in the southeast and Gulf of Kutch in the southwest. Based on the landform characteristics and altitudinal variability, the Kachchh is divided into three broad geomorphic units. From south to north, these are (i) Katrol Hill Range and Northern Hill Range, forming the Rocky Highlands (with an elevation of 150–445 m, (ii) Banni (100–150 m) and (iii) the Rann (<100 m) (Fig. 1.5). The Rann which is the most important geomorphic entity in the Kachchh peninsula, is one of the richest repositories of Quaternary climate and tectonics (Biswas, 1972).
Kachchh is a part of intraplate region of the Indian peninsula. Conventionally, such areas are considered to be tectonically stable (Stein et al., 2002). However, there are evidences contrary to this indicating intraplate earthquake of varying magnitude in the past (Fig. 1.6) (Gupta et al. 1972; Chandra, 1977; Quittmeyer and Jacob, 1979; Chung and Gao, 1995; Bilham and Gaur, 2000; Rajenderan and Rajenderan 2001). For example, Allah Bund (1819), Anjar (1957) and Bhuj (2001) are the major earthquakes indicating the tectonic instability of the Kachchh peninsula (Rastogi et al., 2001; Rajendran and Rajendran, 2001; Gupta et al., 2001; Kayal et al., 2002; Mandal et al., 2004; Morino et al., 2008; Kundu et al., 2010).

Figure 1.4: Map showing location of Kachchh and the three major rift zones (viz. the Kachchh, Cambay and Narmada).

Figure 1.5: Broad geomorphic zones of Kachchh (modified after Kar et al., 2011).
(I) **Major Structures of Kachchh:**

According to Biswas (1987), the Kachchh rift evolved during the break-up of Gondwana land, in the Mesozoic (245-66 Ma), followed by the northward drift of the Indian plate. The break-up was controlled by movements along a series of normal faults, resulting in multiple horsts and graben structures. The Rann of Kachchh and the Cambay basin are the grabens formed during the rifting phase (Biswas, 1987). Following this, a reversal in the stress regime (extension to compression) was probably initiated ~40 million years ago. This is ascribed to the collision of the Indian plate with that of the Eurasian plate (Biswas, 1987; Talwani and Gangopadhyay, 2001; Biswas and Khattri, 2002) which also led to the folding superimposed on an originally extensional tectonic regime and considered to be the most spectacular manifestations of stress reversal.

Kachchh peninsula is traversed by a number of E–W trending major tectonic faults, which are (i) Island Belt Fault (IBF), (ii) Kachchh Mainland Fault (KMF), (iii) Katrol Hill Fault (KHF), (iv) South-Wagad Fault (SWF) and (v) Gedi Fault (GF) (Biswas, 1987; Biswas and Deshpande, 1973) (Fig.1.6). Kachchh rift basin is delimited by the NPF in the north.

![Figure 1.6: Map showing geology, major structures and recent major earthquake epicenters of Kachchh (after Biswas and Deshpande, 1970). Beachball indicates the fault plane solution of 2001 Bhuj earthquake.](image-url)
(a) Island Belt Fault (IBF): exhibits in the form of steeply dipping beds and escarpments facing due north. The fault is dislocated by left lateral NE-SW trending strike-slip faults and separated into Pachcham uplift, Bela uplift, Khadir uplift and Chorar uplift (Fig. 1.6). Kaladongar and Goradongar are the two important fault systems of the Pachcham Island.

(b) Kachchh Mainland Fault (KMF): This is the largest fault in the Kachchh mainland extending about 200 km along east-west and is geomorphologically expressed as a prominent escarpment also known as the Northern Hill Range. The escarpment rises abruptly from the Banni plain which is the downthrown side of the KMF. Additional, there are domal structures in the vicinity of the KMF zone and are delimited by transverse faults. The transverse faults (NE-SW and NW-SE) are occupied by the major drainage system (Fig.1.6).

(c) Katrol Hill Fault (KHF): KHF which strikes parallel to KMF and dips towards the south splies out to the west as Vigodi fault (Fig. 1.6). The fault zone consists of several domes and anticlinal structures and associated transverse faults (trending NE-SW and NW-SE). Some of these domes in their central portion consist of basic rocks, N-S dykes and plugs with occasional sills (Biswas and Deshpande, 1970). KHF acts as a drainage divide between north and south-flowing rivers.

(d) South Wagad Fault (SWF): SWF is located in the south of the Wagad uplift (upland) and is broken into several blocks bounded by faults. Some of the important fault blocks are Adhoi, Kanthkot, Khanpur, Dedarwa, Kharol, Kanmer and Vekra. Eastern tip of KMF and western tip of SWF overlap and dip steeply towards each other (Biswas, 2005).

(e) Gedi Fault (GF): The east-west trending GF running from Deshalpar-Gedi-Fatehgarh area, lies between the Bela horst and Rapar half-graben to the north of the Wagad highland.

(II) Geology of Kachchh:

(a) Mesozoic and Tertiary:

The Kachchh basin preserves longest Mesozoic sedimentation record in Western India (Biswas, 1987). The Mesozoic rocks are ~2400 m thick and cover the major part of the basin. These rocks are separated from the upper Tertiary rocks by the Deccan Trap basalt of late Cretaceous to early Paleocene age. Around 300 m thick
Tertiary rocks are present towards the outer parts of the basin bordering the uplifted Mesozoic rocks (Biswas, 1982; Fig.1.6).

According to Biswas (1999), the sub-littoral and deltaic Mesozoic sediments were deposited on the Precambrian granitic basement. The initial depositional cycle constitutes the Late Triassic and Early Jurassic transgressive facies which resulted due to the opening-up of the rift along the northern faults (viz., Nagar Parkar and Island Belt Faults) forming half-grabens which were then deposited with piedmont conglomerates and coarse clastic debris flows and fan deltas. Subsequently, the southern half-grabens opened-up leading to Middle Jurassic marine transgression. This resulted in the deposition of fine detritus along with the carbonate sedimentation. The second cycle commenced towards the end of Jurassic and in the Early-Cretaceous when most of the intra-cratonic Gondwana basins were filled-up and uplifted. The marginal Kachchh basin experienced regression during which deposition of coarse clastic conglomerates, sandstones, thin shale interbeds and ironstone bands occurred. This phase of deposition was followed by an uplift, during which the sediments were folded and intruded by Late Cretaceous-Early Palaeocene Deccan Trap basaltic flows (Biswas and Deshpande, 1970). The Tertiary sedimentation occurred during the Early Eocene transgression in peripheral lows bordering the Mesozoic highs. In addition to this, lesser degree, cyclic tectonic movements in the Tertiary led to the development of extensive unconformities which are discernable in the stratigraphic columns (Biswas, 1982; 1987; 1999).

(b) Quaternary Deposits:

Quaternary deposits, especially fluvio-aolian miliolites of Kachchh form the major component of Quaternary sediment. The sediment which constitute miliolites are dominantly biogenic carbonate of marine origin which were transported from the Gulf of Kachchh by aeolian processes and deposited in Kachchh as obstacle dunes, sheet deposits, basal hill deposits, on the hill ranges or ridges (Biswas, 1974; Mathur, 2005). Though aeolian transport was invoked for the miliolitic deposits of Kachchh, sheet miliolites, especially those containing pebbles and cobbles indicate a fluvio-aolian deposition (Biswas, 1974; Thakkar et al., 1999). Baskaran et al. (1989) characterised the Kachchh miliolites by lower carbonate contents than their Saurashtra counterparts and have been extensively studied for their modes of accumulations, petrography, faunal aspects, depositional pattern, consolidation phenomenon and
chronology (Baskaran, 1985; 1986, Baskaran and Somyajulu, 1986; Allahabadi and Patel, 1986). On the basis of uranium series dating, these deposits are assigned three age brackets viz., >140, 75-115 and 50-70 ka respectively (Baskaran and Somyajulu, 1986). Besides the miliolites, the other Quaternary deposits of Kachchh are the sediments accumulated in the Rann, Banni plain, along the Gulf of Kachchh and fluvial valley-fill deposits and aeolian sand sheet. Based on the sediment characteristics and their mode of occurrence, Mehr (2005) proposed three main divisions of Quaternary sedimentation in Kachchh:

Table-1.1: Quaternary sedimentation in Kachchh

<table>
<thead>
<tr>
<th>Table-1.1: Quaternary sedimentation in Kachchh</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Holocene (Sub-Recent to Recent)</strong></td>
<td><strong>Sediments of the Little and Great Ranns; Raised mud-flats along the Kachchh coast</strong></td>
</tr>
<tr>
<td><strong>Upper to Middle Pleistocene</strong></td>
<td><strong>Dunal accumulations of Miliolite</strong></td>
</tr>
<tr>
<td><strong>Lower Pleistocene</strong></td>
<td><strong>Conglomerate and grit of the upper part of Kankawati Series.</strong></td>
</tr>
</tbody>
</table>

The present study encompasses investigations of fluvial sediments which is (i) transverse to the main Khari and Gunawari river in the Kachchh Mainland (Katrol Hill Range, Kachchh; 23.18° to 23.19° N, 69.71° to 69.75° E), (ii) Wagad highland, Kachchh (23.40°-23°50N and 70.5°-70.7° E) (iii) Island Belt, Kachchh (Pachcham island; 24° N-70° E and Bela; 23.8°N-70.7°E) (Fig. 1.7 and
(III) Katrol Hill Ranges:

The Kachchh Mainland consists of two major hill ranges trending east-west, viz., Northern Hill Range (NHR) and Katrol Hill Range (KHR or Charwar Range). Several domes and valleys characterize these hill ranges (Fig. 1.8). The eastern and western limits of the domes are marked by N−S transverse faults (Thakkar et al., 1999; Maurya et al., 2003b). The N−S and NW−SE to NE−SW trending faults and fractures are associated with the trend of basic igneous dykes. The dykes mostly occur in the vicinity of faults or along the faults which suggest syn-tectonic nature of intrusive rocks (Biswas, 1972). The palaeontological and stratigraphic studies indicate lateral displacement of lithological units along the transverse faults (Agarwal et al., 1957; Kanjilal, 1978; Bardhan et al., 1987; Prasad, 1998). Katrol Hill Fault (KHF) is the major tectonic structure in the study area, which is geomorphologically expressed as a linear scarp of KHR.

Figure 1.8: Map of Kachchh showing two major hill ranges (Northern Hill Range; NHR and Katrol Hill Range; KHR along KMF and KHF respectively). Note that KHR acts as a major drainage divide. Khari and Gunawari rivers originating from KHR and flowing towards north into the Banni plain. Red box indicates locations of the studied section in Khari and Gunawari river valleys (modified after McCalpin and Thakkar, 2003).
Mesozoic sandstones and Tertiary shale and limestone are the major lithologies (Biswas, 2005). Based on the fault plane solutions, Chung and Gao (1995) suggested that the KHF is a reverse fault, which is further supported by the geomorphic and structural studies by Thakkar et al. (1999), Maurya et al., 2005 and Patidar et al. (2007, 2008). Uplift of the KHR range is suggested to occur during the Quaternary in response to differential uplift along the KHF (Patidar et al., 2007). The rivers are following through the structural discontinuities and bear imprints of activities related to NE–SW, NW–SE, NNE–SSW and NNW–SSE trending transverse faults (Thakkar et al., 1999; Maurya et al., 2003b). The two major hill ranges viz., NHR and KHR form the main watershed of the mainland with north flowing rivers traversing through the water-gaps between the high hills of KHR and NHR and flowing out into the Rann and Banni Plains. The south flowing rivers traverse across the KHR and drain into the Gulf of Kachchh.

Towards reconstructing the climate and tectonic coupling, present study involves the sedimentological and chronometric study of the Khari and Gunawari rivers in the KHR (Fig. 1.8). Earlier studies based on the presence of deep gorges along with prominent knick points were ascribed to the tectonic activity during the Holocene (Thakkar et al., 1999). The role of Quaternary climate oscillations and tectonic uplift in the terrace formation in the Kachchh fluvial systems has been discussed by many workers (e.g. Thakkar et al., 1999; Maurya et. al, 2003, Patidar et al., 2008). The faults and regional joint systems have modified the drainages forming water gaps, elbow-bends etc. Investigations of the fluvial aggradation also suggest that the region responded to the Indian Summer Monsoon (ISM) variability during the Late-Quaternary (Patidar et al., 2008; Bhattacharya et al., 2013, 2014).

(IV) Island Belt:

Towards the extreme northern part of the Kachchh, the four major islands viz. Pachham, Bela, Khadir and Chorar abruptly rises above the monotonous flat, salt encrusted Rann surface and are ascribed to the surficial manifestations of E-W trending Island Belt Fault (IBF) (Fig 1.9). The Mesozoic to Neogene rocks of the Island Belts show a preferential southward tilting (Oldham, 1926; Merh 2005, Maurya et al. 2008; Chowksey etal., 2010).
Chowksey et al. (2010) have noted some major geomorphic features of these islands, which are: the north facing escarpment at the northern margin of each islands, south tilting back slopes, raised intertidal flats, notches and marine erosional surfaces. They have also reported raised and tilted marine depositional and erosional features at the base of the escarpments which were attributed to the mid-late Holocene uplift of the islands along the *IBF*. Additional evidence in support of neotectonic movements along the *IBF* is provided by the development of back slopes in all the islands which is ascribed to the tilting of Mesozoic and Tertiary rocks (Biswas, 1993; Chowksey et al., 2010). In the Pachcham Island, the Kaladongar, Goradongar and Bela ranges constituting parts of Island Belt exhibit typical faulted topography (Biswas, 1993) (Fig 1.10).

Pachham Island forms the westernmost part of the *Island belt* (Fig.1.10). This island comprises of two hill ranges: Kaladongar and Goradongar hill ranges. These two hill ranges are separated by a Central Valley. The Kaladongar range trending east-west is located at the northern margin of the island with an escarpment facing the Rann to the north and a high plateau gently dipping down to the south towards the Central Valley. Goradongar range to the south of the island is structurally more complex than the Kaladongar range. Kaladongar range also comprises several igneous intrusions as compared to Goradongar range (Biswas, 2005). Bandi river flowing along west and Pipri and Kiska river (Semri Nala) flowing along east are the important rivers of this island (Fig. 1.10).
Similarly, the Bela island located to east of Pachham and Khadir island consists of an escarpment to the north (Fig. 1.11). This escarpment controls the drainage pattern of the Bela Island. The Island can be divided into three structural zones these are (i) Bela flexure: along the northern margin, (ii) Desalpar flexure: along south and (iii) Balasar lowland: between the two flexure zones (Biswas, 1974). Bela flexure is like an asymmetric anticline and can be divided into Lodrani Anticline (in the west) and Mouana Dome (in the east). Lodrani anticline located in the northern margin of the Bela Island is a long narrow asymmetric range plunging towards the east and the west (Fig.1.11). Two sets of faults trending NE–SW and NW–SE and along with basic dykes and sills characterize this flexure zone. The major streams originating from these ranges flow into the Balasar lowland to the south. Some of the rivers flow to the east and the west into the Rann. Small streams to the north flow down the steep scarp facing into the Rann. The Desalpar flexure zone consists of a number of secondary folds. The Gedi Fault at the southern margin of the Bela uplift is a high angle reverse fault striking along E–W (Biswas, 1974; Maurya et al., 2013).

Figure 1.10: Major structures around the Pachcham island. Note the conspicuous diversion of the Bandi and Kiska rivers as they approach the Goradungar fault.
The Wagad highland is the second highest hilly region in the Kachchh peninsula and is a combination of multiple hill ranges separated by the South and North Wagad Fault System (Biswa, 1974; Rastogi et al., 2001) (Fig.1.12A). The highland is delimited to the north by approximately E–W trending flexure zone known as the Desalpar Flexure Zone (Biswa, 1999; Merh, 2005). This flexure zone exhibiting a rugged topography borders the Balasar synclinal low to its north and the Rav basin to its south (Fig.1.12A and B). The Balasar syncline is a flat salt-encrusted surface of the Great Rann while the Rav basin exposes the marine rocks belonging to the Khari Series of the Miocene age (Biswa 1993). The Wagad highland featuring several concentric, mutually converging, peripheral faults presents a complex structural pattern. Its northern part is downthrown against the Gedi fault with northerly tilt against the Rav basin. This basin separates the Bela Island from the Wagad Uplift. In this part of the terrain, the Quaternary sediments consist of miliolites, Rann sediments and fluvial sands.

Rivers originating from the Wagad Hills and draining towards the Rann in the north follow the regional topography and structural pattern. These rivers exhibit parallel drainage pattern. There are five major streams of fifth order: Bhimguda River, Narelawali River, Phalku River, Karswali River and Malan River (Fig. 1.12B).
Gujarat Alluvial Plain

Gujarat Alluvial Plain is enclosed between 22°-25°N and 72°-73.5°E and falls under the desert margin zone at the southern fringe of the Thar desert, Rajasthan (Fig. 1.13). Desert margin are ideal location for paleo-environmental reconstruction by virtue of their sensitivity towards minor changes in the temperature and precipitation which is manifested as amplified response in the geomorphic processes (Juyal et al., 2006 and reference therein).

Regional stratigraphy based on sub-surface data shows nearly 300 m thick Quaternary sediments resting on Tertiary basement (Biswas, 1987; Maurya et al., 1995; Tandon et al., 1997). Zeuner (1950) recognized the palaeoclimatic significance of the exposed Quaternary deposits in the Gujarat alluvial plain, and postulated that the climate fluctuated between wet and dry during the Pleistocene.

1.4.2 Gujarat Alluvial Plain:

Gujarat Alluvial Plain is enclosed between 22°-25°N and 72°-73.5°E and falls under the desert margin zone at the southern fringe of the Thar desert, Rajasthan (Fig. 1.13). Desert margin are ideal location for paleo-environmental reconstruction by virtue of their sensitivity towards minor changes in the temperature and precipitation which is manifested as amplified response in the geomorphic processes (Juyal et al., 2006 and reference therein).

Regional stratigraphy based on sub-surface data shows nearly 300 m thick Quaternary sediments resting on Tertiary basement (Biswas, 1987; Maurya et al., 1995; Tandon et al., 1997). Zeuner (1950) recognized the palaeoclimatic significance of the exposed Quaternary deposits in the Gujarat alluvial plain, and postulated that the climate fluctuated between wet and dry during the Pleistocene.

(I) Geology of Gujarat Alluvial Plain:

Gujarat Alluvial Plain located in the Cambay graben is traversed by major rivers of Gujarat. The NNW–SSE trending Cambay graben (rift) has preserved ~11 km thick Cenozoic sediments which overlie the Deccan basalt basement. According to Kundu and Wani (1992), the 400 km long Cambay basin was evolved in three stages. The earliest stage-I was a phase of rifting during the Paleocene and Early Eocene. This is marked by crustal extension along NNW–SSE trending listric faults. The stage-2 occurred during the Early-Middle Miocene. During this phase post-rift thermal subsidence and development of ENE-WSW-trending orthogonal transfer
faults occurred. Finally, stage-3 occurred during the Middle Miocene. During this stage, compressional structures and anticlines developed which are caused due to the structural inversion. Although Cambay basin had not produced any major earthquakes in the historical past like that of Kachchh, however, the southern part of the basin near Bhavnagar and Broach is known for smaller magnitude earthquakes in the recent past (Rajenderan et al., 2008). Based on the seismic data, Biswas (1982) inferred ~1200 m thick Mesozoic sediments underlying the Deccan Trap basalt. The Deccan trap constitutes the basement for ~5000 m thick Tertiary (Palaeocene to Pliocene) marine and fluviatile sediments. Overlying the Tertiary rocks are the Quaternary sediments which were deposited on the rifted Tertiary basement (Maurya et al., 2003).

(II) Geomorphology

Geomorphologically the Gujarat Alluvial Plain can be divided into (i) the rocky upland (Aravalli hills), (ii) piedmont zone (between Jaisalmer-Barwani lineament and East Margin Cambay Fault) and (ii) the alluvial plains (between Eastern Margin Cambay Fault and Little Rann (Merh and Chamyal, 1993) (Fig. 1.14).

(i) The rocky upland: is located in the eastern fringe of the Gujarat alluvial plain. These are dominated by the Aravalli, Satpura and Sahyadri ranges. The Aravalli hills regionally conform to NE–SW trend which is in accordance with the Delhi-Aravalli supergroup.

(ii) Piedmont zone: This is a narrow sloping surface covered with think sediment veneer and is bounded by Jaisalmer-Barwani lineament and East Cambay Basement Fault. Rivers debouch into this zone upon originating from the rocky highland and flow towards the south-west which is the regional slope of this terrain.

(iii) Alluvial plain: The western alluvial plains comprising a thick pile of unconsolidated sediments are deposited by the combined effects of fluvial and aeolian processes during the Quaternary period. The eastern part of this alluvial plain gradually merges into highlands whereas the northern and central alluvial plain is the zone of thickest alluvium which at places is > 500 m (Mehr, 2005; Merh and Chamyal, 1997). The alluvial plain extending from the foothills of the eastern Aravalli corridor extends WSW up to the Gulf of Cambay and Rann of Kachchh (Fig. 1.13). The alluvial plain has a distinct slope towards west-southwest (Sareen et al., 1993). Except for the rivers like Banas, Saraswati and Rupen the other major rivers viz. the
Sabarmati, Mahi and Orsang are considered to be the slope deviatory rivers (deviate from the regional N–S slope to the SE) (Fig. 1.14).

In the alluvial plain, these rivers have deeply incised channels reaching a depth of ~40 m. Following this, the banks become less steep and the river channels progressively widen towards the lower estuarine zone.

Major rivers of the Gujarat which have contributed to the development of the alluvial plain can be categorized into two groups. The rivers in the northwestern part (Rupen, Saraswati and Banas) originate from the Aravalli hills to drain into the Rann of Kachchh. These are shallow rivers which consist of wide sandy channels in the lower reaches. The rivers in the central and southern parts flow into Gulf of Cambay (Arabian Sea). These are the Tapi, Narmada, Mahi and Sabarmati which traversing

Figure 1.13: Geomorphic zones and drainages of North Gujarat Alluvial Plain. Note three major ridges flanked by major alluvial basins. Banas and Sarswati rivers flows between the Unhawa ridge in the south and Diydar ridge in the north.

In the alluvial plain, these rivers have deeply incised channels reaching a depth of ~40 m. Following this, the banks become less steep and the river channels progressively widen towards the lower estuarine zone.

Major rivers of the Gujarat which have contributed to the development of the alluvial plain can be categorized into two groups. The rivers in the northwestern part (Rupen, Saraswati and Banas) originate from the Aravalli hills to drain into the Rann of Kachchh. These are shallow rivers which consist of wide sandy channels in the lower reaches. The rivers in the central and southern parts flow into Gulf of Cambay (Arabian Sea). These are the Tapi, Narmada, Mahi and Sabarmati which traversing
through Madhya Pradesh and Maharashtra enters Gujarat and eventually debouch into the Gulf of Cambay (Merh, 2005).

(III) Structural framework:

The alluvial plain of Gujarat lies within the Cambay basin and extends NNW–SSE with a northward swing SW–NE into the Rajasthan basin (Merh and Chamayal, 1993). The basin is bounded in the east and west by the East Margin Cambay Basement Fault (EMCBF) and West Margin Cambay Basement Fault (WMCBF) (Fig. 1.13). The basin is further divided into minor blocks by horsts and graben structures which have influenced the spatial and temporal changes in the Quaternary sedimentation (Juyal et al., 2000).

According to Merh and Chamyal (1997), tectonics seems to be the major driver of Quaternary sedimentation for the following reasons. (i) The basinal structure has provided a site for accumulation of sediments and (ii) presence of uplifted area in the north-east and south-west provided the required sediments for aggradation. During the Tertiary, marine sedimentation was dominating. With the withdrawal of Tertiary sea, the continental sedimentation took over which was dominated by fluvial and aeolian processes during the Quaternary period. Presence of thick (~100 to 500 m thick) Quaternary deposits may be attributed to subsidence of the Cambay basin along with the simultaneous uplift of Saurashtra horst in the west, rejuvenation of Aravalli in the NE and uplift of parts south of Narmada river (Ahmad, 1986). Differential movement along the various faults during the Tertiary and Quaternary was considered responsible for the variation in sediment thickness during the Quaternary period (syn-depositional tectonics). It has been argued that during the Quaternary period, E–W and ENE–WSW were the major fractural trends in the region: The rivers originating from the eastern rocky upland flow parallel to this major fractural trends and deposited their sediments in the structural depression which was eventually terminated with the onset of aridity during the late Pleistocene period (Merh and Chamyal, 1997 and references therein).
Numerous NNE–SSW trending fractures have developed consequent to the formation of Cambay graben, which are responsible for the present day N–S course of the Sabarmati River. Sareen et al. (1993) suggested an age of <300 ka for the emergence of the modern Sabarmati river that has captured the course of Vatrak river (Maurya et al., 2000) (Fig. 1.14). According to Sridhar et al. (1994) it is undoubtedly the most recent and active river, which had the power to incise the Quaternary sediments. Tandon et al. (1997) based on luminescence dating suggested that the fluvial sedimentation in the Sabarmati River basin continued at least up to 39 ka and the N-S adjustment of the Sabarmati River could have occurred around this time. According to Srivastava et al. (2001), the Gujarat alluvial plain seems to have undergone tectonic instability during the early and middle Holocene which was responsible for river adjustment and incision of the aeolian and fluvial sediments.
Table-1.2: Stratigraphy of the Quaternary sequences in the Gujarat alluvial plain:

<table>
<thead>
<tr>
<th>North Gujarat (Banas basin)</th>
<th>North Gujarat (Sabarmati basin)</th>
<th>North Gujarat (Sabarmati basin)</th>
<th>Geological Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rann Clay Fm (Marine)</td>
<td>Rann Clay Fm (Marine)</td>
<td>Late Holocene</td>
<td></td>
</tr>
<tr>
<td>Varahi Fm (Marine/Fluvial)</td>
<td>Mahudi Fm. (Aeolian)</td>
<td>Sabarmati Fm (Fluvial/Aeolian)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>?</td>
<td>Akhaj (Aeolian)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>?</td>
<td>Late Holocene to Middle Holocene</td>
<td></td>
</tr>
<tr>
<td>Radhanpur Fm (Fluvial/Aeolian)</td>
<td>Saroli Fm (Fluvial)</td>
<td>Mehsana Fm (Fluvial/aeolian)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vijapur Fm. (Fluvial)</td>
<td>Waghpur[Sand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hirapura Fm (Fluvial)</td>
<td>Mem.(Fluvial/Aeolian)]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Late Pleistocene to Early Holocene</td>
<td></td>
</tr>
<tr>
<td>Vend Fm (Marine/Aeolian)</td>
<td>Lakroda Fm. (Fluvial)</td>
<td>Congl. Mem, of Waghpur Fm. (Fluvial)</td>
<td></td>
</tr>
<tr>
<td>Miliolite Fm. (Marine)</td>
<td>Blue clay (Marine)</td>
<td>Blue clay (Marine)</td>
<td></td>
</tr>
</tbody>
</table>

Similarly in the structurally controlled Mahi River basin, the chronology of the exposed Quaternary sediment indicate that deposition commenced around the Last Interglacial (125 ka) and continued till 30 ka (Juyal et al., 2000). This was the period when the river was flowing due southwest from its present course as suggested by Agrawal et al. (1996). It is likely that the present course would have been occupied after at least 30 ka when it captured the course of Mini, Mesri and Goma rivers.
(Maurya et al., 2000). Several NNW-SSE trending fractures that developed parallel to the ECBMF have strongly influenced the drainage pattern of the river. It has been found that whenever the river approaches a lineament it deviates from its original NE-SW path and takes a NNE-SSW course (Merh and Chamyal, 1997).

The dryland fluvial systems by virtue of their amplified responses to small changes in climate conditions serve as suitable archives for paleoclimatic studies (Nanson and Tooth, 1999; Juyal et al., 2000; 2006). For example, a dryland river can show substantial changes in its form and function as it switches over between wet and dry phases (Williams et al., 1998). The Quaternary deposits of Gujarat Alluvial Plain, particularly in the river basins of Sabarmati and Mahi have been extensively studied for palaeoclimatic reconstruction (Zeuner, 1950; Tandon et al., 1999; Juyal et al. 2000; 2006; Srivastava et al., 2001; Jain and Tandon, 2003). These studies suggested that the fluvial sedimentation occurred during the phases of enhanced Indian Summer Monsoon (ISM), whereas events of weak ISM were periods of aeolian sedimentation in the region. It has been suggested that the fluvial system in western India responded to the global climate changes (Jain and Tandon 2003; Juyal et al. 2006).