CHAPTER - 5
NORTH GUJARAT ALLUVIAL PLAIN
5.1. Introduction:

Inland alluvial–valley fills are the artefact of climatic, tectonic and localized-intrinsic events of varying magnitude and duration (Gibling et al., 2011). Evolution of valley-fills have been associated with different climatic parameters that include aridity (Molnar, 2001), changes in sediment loads due to glacial–interglacial cycles (Hancock and Anderson, 2002), variations in precipitation intensity (Tucker, 2004), changes in spatial distribution of discharge (Zaprowski et al., 2005) and changes in vegetation dynamics (Istanbulluoglu and Bras, 2005). Under monsoonal forcing, the alluvial systems show rapid alternation between incision and aggradation (Gibling et al., 2011). Climate preferentially advocates incision or aggradation by directly influencing the ratio of sediment to discharge (Bull, 1991; Bridgland, 1994; Maddy et al., 2001). Aggradation being promoted during high sediment supply while incision is favoured during higher discharge combined with low sediment supply. Incision is likely to initiate upstream in case of discharge outpacing sediment availability that may migrate downstream, a process referred to as ‘kinetic incision’, providing the transmission of upstream initiated incision throughout the whole basin (Maddy et al., 2001). However, climate induced incision due to eustatic sea-level lowering might not be considered to occur beyond 80 km up valley from the coastline (Leeigh and Fenney, 1995). Incision may migrate upstream due to knickpoint- migration which is a dominant mode of channel adjustment in response to either regional or local tectonic perturbation (Holland, 1976; Wolman, 1967; Wohl et al., 1999; Seidl et al., 1994; Stock and Montgomery, 1999; Zaprowski et al., 2001). Tectonic signatures are subdued in alluvial rivers and might manifest in the form of 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 (Peakall, 1995). A coupling between the climate and tectonic mechanisms could be observed by integrating aggradation and incision mechanisms in tectonically active and monsoon dominated terrain.

Gujarat alluvial plain of western India is one such terrain which lies in the monsoon dominated region and has been experiencing infrequent earthquakes.
Gujarat alluvial plain has been investigated with a view to establish the role of south-west Indian summer monsoon and structural discontinuities in designing river valley dynamics (Zeuner, 1950; Wasson et al., 1983; Pant and Chamyal, 1990; Kar, 1993; Merh and Chamyal, 1993; Sareen et al., 1993; Khadkikar et al., 1996; Juyal et al., 2000; 2006; Srivastava et al., 2001; Thiagarajan et al., 2001; Jain et al., 2004; Raj et al., 2004; Sridhar et al., 2013). The investigation of the sediment record on land with a view to record monsoonal influxes is the recent advancement (Juyal et al., 2006). Since the sediment record on the land provides a surrogate for precipitation (P)-evaporation (E) or (P-E) and the winds in contrast to the oceanic records which provide record of winds instead of precipitation on the land. Since sedimentation took place throughout the Cenozoic in the Gujarat alluvial plain, inter-valley monsoonal record have been established by the earlier workers along most of the river basins viz., Narmada, Orsang, Mahi, Sabarmati, Rupen and Luni rivers, however, such studies are lacking along the Banas and Saraswati river basins to the north of the Gujarat alluvial plain. Studies along these two major rivers lying in the middle of the Cambay graben would provide near complete monsoonal scenario along the Gujarat alluvial plain. In addition to this, the present study would highlight the climate-tectonic coupling in the Cambay graben.

5.2. Location and setting:
5.2.1. Gujarat Alluvial Plain

Gujarat Alluvial Plain extends from the Narmada river basin in the south to the Luni river basin in the north. Major part of the Mainland is included within the Cambay and the Narmada grabens (Merh and Chamyal, 1997) (Fig.5.1). Precambrian rocks of Delhi and Aravalli super group marks the tectonic boundary along the East and the north-east. The Eastern Cambay Basin Bounding Fault extending almost N-S broadly delineates the Quaternary alluvium deposits of the Gujarat alluvial plain from the Precambrian rocks of Delhi and Aravalli super group. Mesozoic and Cenozoic tectonism related to the break-up of the Western continental margin and the subsequent drift of the Indian plate was responsible for controlling the geological evolution of Gujarat (Biswas, 1987). The present structural set-up of the Mainland Gujarat is an outcome of the reactivated movements along the Delhi and Aravalli
Precambrian orogenies. Mesozoic and Cenozoic tectonic events are exhibited in the form of uplifts and subsidence along the Cambay and Narmada rift systems. Cretaceous sedimentation is controlled by the E-W trending faults whereas Tertiary rocks bear the imprints of N-S as well as E-W trending faults (Merh and Chamyal, 1997).

Figure-5.1: Map showing the Gujarat Alluvial Plain and the rivers originating from the Aravalli hills traversing across the alluvial plain. Precambrian rocks of the Aravalli hills mark the tectonic boundary along the east and the north-east. Note the locations of Banas and Saraswati rivers approaching Little Rann, the Saraswati river is observed to disappear before it reaches the Little Rann.

5.2.2. Cambay basin:

Cambay Basin consists of mainly Tertiary and Quaternary rocks resting unconformably over Deccan trap basalts. Details of the Gujarat alluvial plain can be found in chapter-1. Here we discuss the Banas and Saraswati basins.
5.2.3. Banas basin

The river Banas originates from the Aravallis (Fig. 5.2) and flows about ~120 km across the Gujarat alluvial plains before draining into the Little Rann. It traverses through the Cambay rift basin, preferentially across the Patan basin. Two branches of the Banas river originating at the upstream, from Erinpura granitic terrain and Sirohi group adjoin near Dantiwada (Fig. 5.2). From Dantiwada to Goliya, it traverses through the piedmont, manifesting several geomorphic expressions such as point bars, modern flood plains and ravines. The Jabalpur-Barwani Lineament (JBL) and East Cambay Boundary Fault (ECBF) mark the boundary of the piedmont. Ravines are mainly present at the upstream and middle part of the Banas basin. The significance of their existence lies in the fact that these are located mainly towards the northwest part of the river implying preferential tilting of the basin. Innumerable braided bars representing typical dryland river characteristics are present throughout the basin, essentially at the downstream segments. These are the segments where sediments are choked into the main channel due to lesser gradient. Figure 5.3 indicates the sediment sequences at different locations along the Banas river basin.
5.2.4. Saraswati basin

The branch of the river Saraswati which is observed in the northern part of Gujarat alluvial plain originates from the Aravalli hills and flows south-westwards, towards the Little Rann (Fig. 5.4). It flows parallel to the Banas basin, approx. 25 km SE of the Banas river at the upstream. However the rivers have been observed to have converged downstream towards the Rann. The Saraswati river dies out at Punasan more than100 km north-eastwards inland from the Little Rann, proximal to Eastern Cambay Fault Boundary. Unlike the wide Banas basin, the Saraswati river basin is narrower which indicates that the river have been subjected to lesser discharge. Most
of the landscapes and geomorphic imprints of this river is obliterated due to huge sand cover or dunal activities in this region. Presently the river is characterized by its extremely weak hydrological regime. A near complete stratigraphic sequence has been investigated near Siddhpur along the Saraswati river basin in order to infer depositional environment.

Figure-5.4 (A): Major rivers of the Gujarat Alluvial Plain. Cambay rift segmented into ridges and basins are also marked (NSB=North Sanchor Basin, TR= Tharad Ridge, SSB=South Sanchor Basin, PB=Patan Basin, UR= Unhawa Ridge, GB=Gandhinagar Basin, EMCF =East Margin Cambay Fault, WMCF =West Margin Cambay Fault). (B) DEM of parts of Gujarat Alluvial Plain and the drainage basin of the Saraswati river. Note the location of Siddhpur from where fluvial sediment succession has been investigated and samples for optical dating have been collected for reconstructing paleoenvironment.

5.3. Stratigraphy:

5.3.1. Banas basin
a) Iqbalgarh (24°21’50.6”N,72°32’23.5”E):

Iqbalgarh is located at the upstream part of the Banas river where it originates from Sirohi group of the Aravalli hills and preserves 6.8 m thick fluvio-aeolian sedimentary sequence (Figs. 5.2 and 5.5). The sequence commences with the deposition of unit-I which is 150 cm thick cross stratified gravels embedded in gritty
matrix. The dip of the cross stratified bed is towards SW. This horizon consists of angular to sub-rounded clasts of quartzite, quartz and calcretes. This is overlain by unit-II which is 110 cm thick pedogenised clayey-silt containing diffused CO$_3$. Above this, unit-III consists of 120cm thick assorted gravels which show crude laminations supported by clasts which are angular to sub-rounded and are dominated by quartzites and basic rocks. Clasts are embedded in sandy matrix. Finally at the top unit-IV consists of 3m thick buff-colored massive aeolian micaceous sands.

![sediment succession diagram](image)

**Figure-5.5:** Sediment succession at Iqbalgarh (Upper catchment of the Banas river). OSL age is marked by black rectangle (unit-III). SS=Silty sand, FS=Fine sand, MS=Medium sand, CS=Coarse sand, Gr = Gravel.

**b) Dantiwada (24°20°'47.5°'N, 72°19°'33.2°'E):**

Downstream section at Dantiwada (~25 km downstream of Iqbalgarh; Fig.5.3) consists of ~3 m sedimentary successions of which unit-I at the bottommost consists of 15 cm crudely laminated pale yellow, mottled, medium to fine sand containing friable calcretes. Overlying this unit-II consists of 20 cm thick medium to coarse crudely laminated sand with disperse calcretes which is followed above by unit-III which is 10-20 cm angular assorted gravel horizon, dominated by granite angular clasts. This is overlain by unit-IV which is 30 cm light-grey massive sand with disperse nodular calcretes. Above this is unit-V which is 20 cm pale yellow medium to fine crudely laminated sand, upper part contains bedded calcretes. Following this is unit-VI which is a 40 cm thick pale yellow crudely laminated mottled sands. Upper
10cm of this unit contains bedded calcretes. At the top is unit-VII which is 170 cm coarse to medium sands with evenly distributed nodular calcretes. Bottom part of this horizon is pale yellow in colour which grades into ash grey color towards the upper part. Some lithoclasts can also be found.

c) **Moti Akhol (24°16’36.9”N, 72°10’08.7”E):**

Further downstream from Dantiwada (Figs. 5.2 and 5.6.), at Moti Akhol which is located at the piedmont of the Aravalli hills comprises two sections which have preserved incomplete sedimentary successions: The sequence commences from the bottom with 3 m thick highly calcretised, bedded calcrete dominated fine sand (unit-I) which is overlain by a 4 m thick highly weathered, mottled silty-sand (unit-II). Both rhizolithic and nodular calcretes are present. Rhizolithic calcretes dominates the lower part of this horizon. Overlying unit-III consists of 3m thick pedogenised horizon dominated by high concentration of nodular calcretes. This horizon is brownish red in color. Overlying this is a meter thick aeolian sand (unit-IV).

![Figure-5.6: Sediment succession at Moti-Akhol divided into four units. Sample for OSL dating is collected from unit-II](image)
d) Juna-Deesa (24°13′06.1″N, 72°09′03.6″E):

The sedimentary sequence at Juna-Deesa further downstream (Figs. 5.2 and 5.7) provides near complete record of sediment succession along the Banas river valley where ~11 m of sedimentary succession is preserved along the left bank (south-east) of the river. The bottommost unit-I of this succession consists of a 70 cm thick medium (27%) to fine (35%) friable sand with disperse calcretes. This is overlain by unit-II which is a 80 cm thick crudely laminated very coarse (61%) sand with discrete nodular calcretes which become bedded in nature towards the upper part of the horizon. Following this above is unit-III which is 70 cm thick dominated by medium sand (49%) containing friable calcretes and is overlain by 60 cm thick sand containing moderate concentration of friable calcretes. This horizon is followed above by unit-IV which is 3 m thick medium (46%) to fine massive sand (35%) and is pedogenised, degree of pedogenesis increases upward. At places disperse nodular calcretes and rhizoliths could be seen. Concentration of nodular calcretes increases upward (maximum concentration is at around upper 1.5 m).

Figure-5.7: Sediment succession at Juna Deesa. Sample locations for OSL dating is also indicated at corresponding units.
Notably, this horizon has a distinct brownish red color which makes it quite different from all other horizons. This is overlain by unit-V which is a 140 cm thick medium friable sand (58%) interspersed with nine fluvially reworked rolled calcrete gravels. Thickness of these gravels range from 2-10 cm. Overall the sequence is dominated by well sorted medium to fine aeolian sand. Following this above is unit-VI which is 300 cm thick fine light-grey aeolian dune sands (47%) containing dispersed nodular calcretes.

e) Historical flood-plain sequence near Juna-Deesa

A fining upward sedimentary sequence is exposed along the left bank of the Banas river near Juna-Deesa (Fig. 5.2). At this location around 100 cm thick alternating sand and silty-clay sequence is exposed (Fig. 5.8). The lowermost horizon is a 30 cm thick massive sand overlain by a 2 cm thick laminated silty-clay (unit-I). This is succeeded by 4 cm thick laminated fine sand capped by a 2 cm thick convoluted silty-clay (unit-II). Overlying this is 3 cm thick laminated fine sand overlain by 1 cm thick silty-clay (unit-III) which in turn is overlain by 2 cm thick laminated fine sand and capped by 2 cm thick laminated sandy-clay (unit-IV).

Figure-5.8 (A): Historical flood plain sequence at Juna-Deesa (B) Close-up of flood plain and location of OSL dating sample has been indicated. The flood plain is divided into fifteen laminae and is dated to ~ 1 ka.
This is overlain by 2 cm thick laminated fine sand which is capped by 1 cm thick silty-clay (unit-V). Above this is 2 cm thick laminated fine-sand overlain by 2 cm thick sandy-clay (unit-VI). Following this above is a 2 cm thick swelling and pinching fine sand which is followed above by 2 cm thick sandy clay (unit-VII). Finally the succession is terminated with the deposition of a 15 cm thick trough and cross stratified coarse to gritty sand.

*f) Goliya (24°12′25.4″N, 72°06′31.6″E):*

This location is around ~7 km downstream of Juna-Deesa (Fig. 5.2) and is exposed along the right flank of the Banas river (Fig 5.9). The sequence commences with deposition of 3 m thick crudely laminated, highly indurated pedogenised sandy horizon with well developed ped faces (unit-I). This is overlain by 5 m thick highly calcretised reddish brown sandy-silt with occasional mud-balls and bedded calcretes (unit-II). Overlying this is a 3 m thick massive, compact and pedogenised brownish aeolian sand, middle part of this horizon contains high concentration of nodular calcretes (unit-III).

Figure-5.9: Photograph of sediment succession at Goliya. The lithostratigraphic units along with the optical ages are shown along side.
(g) **Gotnath (24°45′52.5″N, 71°37′29.0″E):**

Gotnath is located at ~20 km upstream of the Little Rann of Kachchh (Fig. 5.2). At this location, the Banas river virtually merges with the vast saline plain of the Little Rann of Kachchh. The lowermost horizon consists of 120 cm light grey, silty-clay with high concentration of dispersed nodular calcrites (unit-I; Fig 5.10). This is overlain by 100 cm thick massive, compact dark brown to light coloured silty-clay (unit-II). Following this above is 30 cm gritty to coarse sand and is punctuated by channel sand. At places parallely laminated graded sand layers show up-warping and convolutions (unit-III). Finally the succession ends with a 70 cm thick dark-brown pedogenised silty-clay mixed with brick fragments (unit-IV).

![Figure 5.10. Sediment succession at Gotnath. The sediments have been disturbed by up-warping laminae and convolutions.](image)

**5.3.2. Saraswati basin:**

Near Sidhpur, around 15 m thick sediment succession is exposed due to sand mining activity on the Sarswati river bed (Fig. 5.4B). The stratigraphy is reconstructed at two locations, the lower succession is shown in fig. 5.11, whereas the upper sequence which has incised through the uppermost aeolian sequence and is dominated by fluvial succession is exposed towards the downstream shown in fig. 5.12. The
lowermost sediment succession is dominated by a 1.6 m thick massive medium sand (46%) (Fig.5.11). Lower and upper part of the horizon contains bedded calcretes (unit-I). Thickness of bedded calcretes is ~5 cm. Overlying this is 20 cm thick, crudely laminated, friable, medium sand (68%) (unit-II) which is laterally persistent. The upper 10 cm of unit-II contain bedded calcretes.

Figure 5.11: Sediment succession at Siddhpur along Saraswati river basin indicating the four bottom units. Lower part is capped by aeolian sedimentation which is shown in detail in figure-5.12

Figure 5.12: The upper fluvial sequence showing cross-cutting relationship with the topmost aeolian sequence. Note the radiocarbon age obtained for unit-VII is shown in italic.
This is overlain by 4 m thick pale yellow, very fine weathered sand (46%) which shows no internal laminations (unit-III). However, discrete carbonate nodules can be observed. This is followed above by 4 m thick pebbly sand dominated by sub-rounded to rounded calcrites (unit-IV). Overlying this is the aeolian sand (unit-V) (Fig.5.12). Fig. 5.11 discusses the lower units of the stratigraphical succession of the Saraswati river basin while the upper units are being discussed in fig. 5.12. The upper dominantly fluvial sequence began with the clast dominated horizon at the contact immediately above the underlying aeolian horizon (unit-VI). Relatively larger calcrite litho-clasts show their occurrences. This horizon overlies a channeled base which has incised through unit-V of fig. 5.11. Overlying this is a 1.5 m thick medium to very fine (75%) aeolian sand which has undergone pedogenesis as indicated by the presence of upper 40 cm thick humus horizon (Unit-VII). Above this humus horizon is a 3 m thick cross stratified gravelly, sandy intercalation of trough cross stratified layers (Unit-VIII). Massive buff-colored fine aeolian sand (56%) caps the horizon (Unit-IX). The composite stratigraphy of the Saraswati river basin at Siddhpur is shown in fig. 5.13H.

5.4. Depositional environment:
5.4.1. Banas basin

a) Iqbalgarh:

Presence of cross-stratified gravels at the bottom indicates high energy episodic fluvial discharge suggesting deposition under braided river condition. Geomorphologically, the site is located in the piedmont zone, such areas are usually subjected to enhance stream power caused due to the over-steepening of the river gradient. The cross-stratified beds dipping towards SW conforms to the regional gradient of the Gujarat alluvial plain. Overlying this unit is the pedogenised clayey-silt unit which indicates periods of non-deposition and subaerial exposure of the sediment that led to the pedogenesis. The overlying crudely laminated sandy-matrix indicates improved hydrological regime. Finally presence of aeolian sand capping the succession points towards dwindling hydrological condition.
b) *Dantiwada:*

The lowermost pale-yellow mottled sandy unit implies deposition under low energy environment. Mottling of the sediment implies prolong saturation of the sediment due to raised water table and resultant acidification of ground water and changes in Eh which cause the reduction, mobilization and re-precipitation of iron and manganese sesquioxides (Leenheer, 2002). The overlying crudely laminated sandy unit and assorted gravel horizon suggests gradual strengthening of the hydrological regime. Thinner gravel horizon suggests short lived ephemeral floods leading to sediment mobilization. Overlying light-grey sand unit further indicates prevalence of high energy hydrological regime. The overlying crudely laminated sands and bedded calcrites suggest channel proximal flood plain environment of a meandering river system (Goudie, 1983). The top-most aeolian sand suggests weakening of hydrological condition.

c) *Moti Akhol:*

Conspicuous presence of bedded calcrites in the lower units at Moti Akhol suggests channel proximal flood plain deposition in a meandering channel (Goudie 1983). The overlying weathered silty-sand units with rhizoliths and nodular calcrites suggests weathering of the flood plain fines in a lateral migrating alluvial channel (Kraus and Aslan, 1993). The succeeding laterally persistent pedogenised and calcretised fluvial sediment (occurring as distinct bench) suggests a prolong phase of non deposition probably caused due to lateral migration of the channel that may happen due to increase in sediment supply from the upper catchment (Kraus and Aslan, 1993). The upper most aeolian sand represent onset of aridity (dwindling hydrological system).

d) *Juna-Deesa:*

At Juna-Deesa, the lower most unit exposed is dominated by medium to fine sand and the overlying laminated coarse sand with bedded and nodular calccrete in an alluvial river suggests deposition under channel proximal environment. The overlying pedogenised unit (red soil) indicate periods of oxidation and soil drying, probably associated with a falling water table or good drainage. In general, red palaeosols develop on better drained sites reflecting higher elevation and/or more permeable parent material. The overlying sandy unit with rolled calcrites suggest erosion of pre-
existing alluvial carbonate from adjoining banks by migrating channels (Juyal et al., 2000 and reference there in). The overlying aeolian sand sheet points towards the onset of aridity and weakening of the fluvial regime.

Overall, the sedimentary sequence exposed at Juna-Deesa provides a detailed insight into the temporal changes in the hydrological condition. For example, the dominantly fluvial succession represents fluctuating hydrological conditions, lateral migration of the channel and eposidic high energy fluvial discharges. In the upper part, there seems to be a significant decrease in the water discharge, finally there seems to be complete disruption of fluvial system as indicated by the gradual onset of aeolian sedimentation.

e) **Goliya:**

At this location, part of the sequence that is exposed at Juna-Dessa is exposed in an amplified manner. With the exception that apart from the presence of laterally persistent fluvially modified pedogenised bench and the red soil, the horizon contain mud-balls and bedded calcretes. These are indicative of low energy meandering river system and presence of mud-balls suggests semi-permanent pools on the flood-plains (Mariott and Wright, 2004).

f) **Gotnath:**

The location is proximal to the Little Rann of Kachchh, hence dominance of fine sand along with the silty-clay indicate significant decrease in the stream power due to the decrease in the river gradient. However, presence of gritty to coarse sand sandwiched between silty-clay represents very short-lived flashy flood condition. Sudden flash flood could have been generated by sudden heavy rainfall or increase in the slope. Overall the dominance of fine sand and silty-clay suggests deposition under waning flood in a meandering channel. Since the location is proximal to the Little Rann of Kachchh, incision of the sediment succession can be speculated due to the change in the sea-level. The upwarping seems to be a synsedimentary deformation caused due to the loading viz. the sediment density gradient.

5.4.2. **Saraswati basin:**

At Siddhpur, presence of lowermost gritty to coarse massive sand suggests flashy hydrological discharge-a characteristic of the unstable climatic condition in
semi-arid environment (Graff, 1988). The overlying laminated sand with bedded calcretes indicate laminar flow under consistent fluvial discharge with seasonality. The bedded calcretes indicate episodic evaporative condition in a channel proximal flood plain environment. This was followed by the onset of aridity as indicated by the deposition of 4 m thick, medium to fine pale yellow aeolian sand sheet which show evidence of moderate pedogensis.

The aeolian sand is channelized in which a 4 m thick crudely-beded fining upward gritty sand is deposited which represent the onset of flashy hyrological condition after the aeolian activity. Lithoclast dominated the bottom of this horizon, followed by crudely laminated gritty to coarse sand suggests that there was a gradual decline in the flash flood intensity. This is succeeded by a short-lived aeolian sedimentation implying temporary reversal towards the dryness followed by a phase of landscape stability (in terms of aeolian sedimentation) which is manifested by the development of soil (humus rich layer) on top of the aeolian sand. A renewed phase of fluvial activity can be inferred based on the occurrence of crudely laminated planer to cross-stratified sand on the top. Overall the channelized sediment (within the aeolian sand) represents high frequency fluctuating climatic conditions.

5.5. Chronology:

5.5.1. Banas basin

For optical dating six exposed sections along the Banas river (covering the piedmont zone, the middle and lower alluvial plain have been sampled. The middle assorted gravel unit-III at Iqbalgarh is dated to 5±0.3 ka. At Dantiwada, the uppermost assorted gravel unit-VII is dated to 6±0.3 ka and lowermost unit-I consisting of crudely laminated mottled sand is dated to 26±2 ka. These sites are located in the Pedimont zone of the Banas river basin. In the middle alluvial plain, at Moti Akhol, the calcretized sandy unit-II is dated to 25±2 ka. Further downstream, at Juna-Deesa which preserves one of the most detailed sedimentary record of fluvial and aeolian succession, a total of eight samples were dated. The lowermost coarse to medium friable sand is dated to 37 ± 2 ka, unit-III consisting of coarse sand containing friable calcretes is dated to 22 ± 2 ka, unit-IV dominated by pedogenised massive sand is
dated to $18 \pm 2$ ka, unit-V containing medium to fine friable sand interspersed with nine fluvially reworked rolled calcrete gravels is dated to $12 \pm 1$ ka to $11 \pm 1$ ka, unit-VI consisting of aeolian sands is dated to $6 \pm 0.5$ ka to $3.5 \pm 0.1$ ka. At the downstream segment of the river, at Goliya, unit-I consisting of crudely laminated, highly indurated pedogenised sandy horizon is dated to $37 \pm 2$ ka and unit-II containing highly calcretised reddish brown sandy-silt is dated to $31 \pm 3$ ka. At Gotnath, unit-I comprising of silty-clay with dispersed nodular calcretes is dated to $20 \pm 2$ ka and unit-IV dominated by dark-brown pedogenised silty-clay is dated to $1 \pm 0.1$ ka. Flood-plain units adjoining Juna-Deesa is dated to $0.8 \pm 0.2$ ka.
Table 5.1: Showing radioactivity, equivalent dose and ages for the samples from the Banas river

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<th>Sample no.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K %</th>
<th>ED (CAM) Gy</th>
<th>ED (MAM) Gy</th>
<th>DR</th>
<th>OD %</th>
<th>Age (CAM) ka</th>
<th>Age (MAM) ka</th>
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<td>1.09±0.02</td>
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<td>3±1</td>
<td>4±0.1</td>
<td>50</td>
<td>76±108 (a)</td>
<td>76±25 (a)</td>
</tr>
<tr>
<td>DW-1</td>
<td>9.8±0.49</td>
<td>0.99±0.05</td>
<td>1.75±0.03</td>
<td>98±4</td>
<td>56±4</td>
<td>3.7±0.2</td>
<td>25</td>
<td>26±1.6</td>
<td>15±1</td>
</tr>
<tr>
<td>DW-2</td>
<td>12.1±0.60</td>
<td>0.82±0.04</td>
<td>2.14±0.05</td>
<td>25±1</td>
<td>25±1</td>
<td>4.5±0.2</td>
<td>33</td>
<td>5.5±0.3</td>
<td>5.5±0.3</td>
</tr>
<tr>
<td>GN-1</td>
<td>2.3±0.11</td>
<td>9.87±0.49</td>
<td>0.94±0.02</td>
<td>80±3</td>
<td>42±3</td>
<td>2±0.1</td>
<td>40</td>
<td>39±2</td>
<td>20±2</td>
</tr>
<tr>
<td>GN-2</td>
<td>2.09±0.10</td>
<td>9.25±0.46</td>
<td>1.14±0.02</td>
<td>2.2±0.1</td>
<td>2±0.1</td>
<td>2±0.1</td>
<td>56</td>
<td>1±0.1</td>
<td>1±0.1</td>
</tr>
<tr>
<td>OG-1</td>
<td>2.06±0.12</td>
<td>13.1±0.65</td>
<td>1.45±0.03</td>
<td>98±2</td>
<td>97±2</td>
<td>2.7±0.1</td>
<td>45</td>
<td>59±4</td>
<td>31±3</td>
</tr>
<tr>
<td>OG-2</td>
<td>1±0.05</td>
<td>5.2±0.3</td>
<td>0.8±0.02</td>
<td>82±4</td>
<td>43±4</td>
<td>1±0.06</td>
<td>45</td>
<td>9±0.4</td>
<td>5.0±0.3</td>
</tr>
<tr>
<td>IQB</td>
<td>2.42±0.12</td>
<td>16.72±0.83</td>
<td>2.61±0.05</td>
<td>37±1</td>
<td>20±1</td>
<td>4±0.1</td>
<td>40</td>
<td>9±0.4</td>
<td>5.0±0.3</td>
</tr>
<tr>
<td>MA</td>
<td>0.94±0.05</td>
<td>6.59±0.32</td>
<td>0.62±0.01</td>
<td>62±2</td>
<td>33±2</td>
<td>1.3±0.1</td>
<td>40</td>
<td>48±3</td>
<td>25±2</td>
</tr>
</tbody>
</table>

5.5.2. Saraswati basin:

A total of six samples are optically dated from the sediment succession at Siddhpur along the Saraswati river basin. Stratigraphic successions have been investigated at two locations for studying lower and upper sequences. Optical dating of unit-I of the lower part of the sequence consisting of gritty to coarse massive sand with bedded calcretes is dated to 32 ± 2 ka, unit-III consisting of pale yellow, medium to fine sand is dated 27 ± 2 ka to 20 ± 1 ka. The upper part of the sequence is investigated at adjoining downstream location, of which unit-VI is a channel deposit which has cut into unit-V of the lower sequence and it is dated to 3 ± 0.1 ka, unit-VII with pedogenised aeolian sand is dated to 2 ± 0.1 ka, overlying unit-IX which is massive buff-colored aeolian sand is dated to 0.2 ± 0.01 ka.
Table 5.2: Showing radioactivity, equivalent dose and ages for the samples from the Saraswati river.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K %</th>
<th>ED (CAM) Gy</th>
<th>ED (MAM) Gy</th>
<th>Dose Rate</th>
<th>OD %</th>
<th>Age (CAM) ka</th>
<th>Age (MAM) ka</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDS-1A</td>
<td>1.57±0.03</td>
<td>14.52±0.21</td>
<td>2.1±0.02</td>
<td>103±3</td>
<td>57±4</td>
<td>3.2±0.1</td>
<td>29</td>
<td>32±1.5</td>
<td>18±1</td>
</tr>
<tr>
<td>SDS-.OSL-3A</td>
<td>1.66±0.04</td>
<td>10.67±0.20</td>
<td>1.65±0.02</td>
<td>136±6</td>
<td>71±6</td>
<td>2.6±0.1</td>
<td>40</td>
<td>52±3</td>
<td>27±2</td>
</tr>
<tr>
<td>SDS-.OSL-3B</td>
<td>1.95±0.04</td>
<td>12.8±0.20</td>
<td>2.05±0.02</td>
<td>119±5</td>
<td>62±3</td>
<td>3±0.1</td>
<td>40</td>
<td>38±2</td>
<td>20±1</td>
</tr>
<tr>
<td>SDS-.OSL-4B</td>
<td>1.6±0.03</td>
<td>11.89±0.19</td>
<td>1.90±0.02</td>
<td>9±0.3</td>
<td>9±0.3</td>
<td>2.9±0.1</td>
<td>28</td>
<td>3±0.1</td>
<td>3±0.1</td>
</tr>
<tr>
<td>SDS-OSL-5</td>
<td>1.13±0.03</td>
<td>7.72±0.15</td>
<td>1.30±0.01</td>
<td>4±0.1</td>
<td>4±0.1</td>
<td>2±0.1</td>
<td>10</td>
<td>2±0.1</td>
<td>2±0.1</td>
</tr>
<tr>
<td>SDS-OSL-7</td>
<td>1.38±0.03</td>
<td>9.43±0.20</td>
<td>1.26±0.03</td>
<td>0.49±0.02</td>
<td>0.49±0.02</td>
<td>2±0.1</td>
<td>20</td>
<td>230±12</td>
<td>(a)</td>
</tr>
</tbody>
</table>

5.6. Geochemistry

Weathering processes affecting the upper continental crust is a function of climatic changes and provides a direct evidence of the past weathering conditions (Young and Nesbitt, 1999; Young, 2001; Scheffler et al., 2003; Dobrzinski and Bahlburg, 2007). Sediments and rocks are subjected to variable degrees of chemical and physical weathering leading to loss of Ca \(^{2+}\), K\(^+\), Na\(^+\) and Sr (Fedo et al., 1995; Bland and Rolls, 1998; Minyuk et al., 2014). The concentration of these elements and various ratios between them have effectively been used and compared to create time-series of changing environments (Wei et al., 2004; Li et al., 2003; Zabel et al., 2001; Arnaboldi and Meyers, 2003; Benson et al., 1998; Jahn et al., 2001).

Al\(_2\)O\(_3\) could be considered to be immobile during weathering and acts as a proxy to determine temporal changes in detrital input such as in Ruxton Ratio, SiO\(_2\)/Al\(_2\)O\(_3\) (Ruxton, 1968). Similarly, detrital input from the catchment indicating transportation due to adequate precipitation is indicated by ratios viz., Fe\(_2\)O\(_3\)/Al\(_2\)O\(_3\), Rb/Al\(_2\)O\(_3\), Sr/Al\(_2\)O\(_3\), Zr/Al\(_2\)O\(_3\) and TiO\(_2\)/Al\(_2\)O\(_3\). For example, warmer periods are characterised by higher mobility of Sr and Rb and lower concentrations of Zr (Melles et al., 2007). The reason being Sr is a mobile element and it tend to show depletion during chemical weathering, therefore, Rb/Sr ratios can be used to determine
weathering histories of a sedimentary succession (Gallet et al., 1998; Goldberg et al., 1987). On the other hand, Zr variability is being used (mostly in aqueous environment) as a surrogate for aeolian contribution (Minyuk et al., 2007).

Further, the degree of chemical alteration (weathering) can be ascertained using the ratios of major elements such as the Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA) and Chemical Index of Weathering (CIW). Nesbitt and Young (1982) demonstrated CIA = \[ \frac{Al_2O_3}{(Al_2O_3+CaO+NaO+K_2O)} \] *100, where CaO is considered to be associated with the silicates only. CIA measures the ratio of \( Al_2O_3 \) versus more labile oxides and reflects amount of feldspars and clay minerals in the sample. PIA indicates weathering intensity of plagioclase and is given by (Fedo et al., 1995): PIA = \[ \frac{[Al_2O_3-K_2O]}{(Al_2O_3+CaO+Na_2O*K_2O)} \] *100. Chemical Index of Weathering (CIW) reflects the ratio of immobile \( Al_2O_3 \) to the labile CaO and NaO. CIW is calculated using the equation (Harnois, 1988), CIW = \[ \frac{Al_2O_3}{(Al_2O_3+CaO+NaO)} \] *100, here K is not considered in the estimation as it may be leached or accumulated in the residual weathering products.

In the present study, major element ratios have been used to ascertain the temporal changes in the sedimentation and weathering. Towards this a total of 43 samples from Juna-Deesa (Banas river) and 21 samples from the Siddhpur (Saraswati river) were analyzed.

5.6.1. Banas basin:

Geochemical indices

The geochemical indices representing degree of weathering show low frequency high magnitude fluctuations (Fig. 5.14). SiO\(_2\)/Al\(_2\)O\(_3\) varies between 6.0 to 8.8, Fe\(_2\)O\(_3\)/Al\(_2\)O\(_3\) varies from 0.11 to 0.23, Rb/Al\(_2\)O\(_3\) varies from 9.3 to 11, Sr/Al\(_2\)O\(_3\) varies from 10.7 to 16.7, Rb/Sr varies from 0.61 to 0.91, Ti/Al\(_2\)O\(_3\) varies from 0.035 to 0.053, Zr/Al\(_2\)O\(_3\) varies from 15.9 to 43.6, CIA varies from 64 to 82\%, PIA varies from 70 to 80\% and CIW varies from 72 to 90\%. There is a reasonable concordance between the lithostratigraphic units and the weathering proxies.
Figure 5.14: Plots of geochemical indices associated with different units at Juna-Deesa of the Banas river basin.

Figure 5.15: Plots of CIA, PIA and CIW associated with different units of Juna-Deesa of the Banas river.
For example SiO$_2$/Al$_2$O$_3$ shows a decreasing trend corresponding to the coarse to medium sand viz. unit-I and II dated to around 37 ka. Following this, it shows an increasing trend in the moderately weathered unit-III (dated to 22 ka) and become consistently high in the pedogenised red soil dated to 18 ka (unit-IV). An abrupt decrease in the weathering proxies can be seen with the beginning of fluvially reworked aeolian sand horizon dated between 12 ka and 11 ka (unit-V). Towards the top in aeolian unit-VI, there is a monotonous increase in SiO$_2$/Al$_2$O$_3$, FeO/Al$_2$O$_3$, Sr/Al$_2$O$_3$ and Rb/Al$_2$O$_3$. This unit is dated between 6 ka and 3.5 ka. Interestingly, the aeolian proxies viz. the TiO$_2$/Al2O$_3$ and Zr/Al$_2$O$_3$ show an opposite trend (compared to the weathering proxies), which in fact is expected because these proxies represents the aeolian contribution, hence during the events of high weathering (intensified monsoon) it is expected that the aeolian contribution should decrease and vise-versa (Fig. 5.14). The more robust proxies viz. the CIA, PIA and CIW reflects more vividly the temporal changes in the weathering intensity. A consistently high CIA, PIA and CIW is observed in the red soil dated to 18 ka (unit-IV) as also in the upper most aeolian sand (dated between 6 ka and 3.5 ka) and is punctuated by the low values in unit-I, II and V dated to 37 ka, 22 ka and 12 to 11 ka respectively (Fig. 5.15). The increase in these proxies are ascribed to the post depositional weathering of the sediments associated with different units.

5.6.2. Saraswati Basin:

Geochemical indices

Near Sidhpur, the alluvial section exposed in Sarswati river was sampled for geochemical studies. The limited samples analyzed show a reasonable correspondence with that of the different lithostratigraphic units (Fig. 5.16). The geochemical proxies of weathering show a wide temporal variability. For example SiO$_2$/Al$_2$O$_3$ varies between 5.0 to 9.4, Fe$_2$O$_3$/Al$_2$O$_3$ varies from 0.04 to 0.25, Rb/Al$_2$O$_3$ varies from 10.3 to 16, Sr/Al$_2$O$_3$ varies from 10.6 to 16.6, Rb/Sr varies from 0.62 to 1.4, Ti/Al$_2$O$_3$ varies from 0.037 to 0.056 and Zr/Al$_2$O$_3$ varies from 18.1 to 54.4, CIA varies from 65 to 78%, PIA varies from 70 to 76% and CIW varies from 73 to 90%. More specifically, the ratios of SiO$_2$/Al$_2$O$_3$, Fe$_2$O$_3$/Al$_2$O$_3$, Rb/Al$_2$O$_3$, Rb/Sr and
Sr/Al$_2$O$_3$ show an increase associated with the moderately weathered fluvial sand dominated unit-I and II (dated between 32 ka and <27 ka).
Following this a decrease is observed associated with the very fine aeolian sand dominated unit-III (dated between 27 ka and 20 ka). The upper fluvial and partly aeolian units that were deposited after incising the aeolian sand and dated between 3 ka and 0.2 ka (unit-VI-IX) show an overall increase with a decrease around 2 ka (pedogenized aeolian sand (unit-VII)).

Similar trend is observed in the more robust weathering proxies viz. the CIA, PIA and CIW (Fig. 5.17). A consistently high CIA, PIA and CIW is observed in the lower fluvial units (I and II) dated between 32 ka nd <27 ka, followed by a decrease in unit-III (fine aeolian sand dated between 27 ka and 20 ka). This was succeeded by a sharp increase in the unit-IV. A temporary drop followed by a consistent increase is observed till unit-VII dated between 3 ka nd 0.2 ka (Fig. 5.17).

5.7. Summary:

The present study is an attempt to reconstruct paleoenvironmental condition of the Banas and Saraswati river valleys by integrating sedimentological, geochemical and chronometric data of fluvial and aeolian sequences. The composite stratigraphy of the sediment succession at Juna-Deesa along the Banas river valley and Siddhpur along the Saraswati river valley suggests deposition of overbank facies by meandering river system initiated at ~37 ka and persisted until around 27 ka. This period correspond to the later part of the pluvial Marine Isotopic Stage-3 (MIS-3). Existence of persistent hydrological condition can be inferred by the presence of well developed parallel laminated coarse to medium sands with bedded calcretes which continued till ~27 ka. Following this, the sedimentological and geochemical data suggests a decline in the riverine hydrology. Incidentally, this period equates with the onset of the relatively drier condition corresponding to the beginning of the MIS-2 (Duplessy et al., 1980) when the strength in the fluvial discharge diminished. Though channel proximal deposits due to occasional floods/ avulsive river system show their appearances, as has been recorded at Juna-Deesa along the Banas river valley. Following this, the event of weakened monsoon has been regionally recorded (Tandon et al., 1997; Juyal et al., 2006). In Saraswati river valley, this event is manifested in the form of fine and well sorted aeolian deposits. The forcing factor of the aeolian
activity could be attributed to the aridity associated with the last glacial maxima (Duplessy et al., 1980). This event continued up to ~22 ka with depletion in major and minor elemental concentrations during the phases of aridity (27-22 ka). A gradual strengthening of the monsoon can be suggested during the development of the red soil dated to 18±2 ka. Considering the large uncertainty in the age this can as well be equated with the onset of the monsoon following the LGM around 16 ka (Sirocko et al., 1993). The onset of early Holocene strengthened monsoon in the study area is manifested by the deposition of fluvially reworked aeolian sand. Presence of distinct layers of rolled calcrete in this horizon which is dated between 12 ka and 11 ka indicate the competency of the surface runoff to erode the preexisting pedogenized and calcretized red soil substratum (Juyal et al., 2000) in the catchment area of Banas river basin. The above inference is also eloquently supported by increase in the geochemical ratios and the weathering proxies. Following this, a significant decrease in the monsoon precipitation can be suggested at around 6 ka and the weak monsoon condition prevailed until around 3 ka.

Following this, the terrain experienced episodic monsoon surges during overall weak monsoon phase around 3 ka that led to the deposition of assorted cross stratified gravelly sand dated to around 3 ka. This was followed by a very short-lived phase of aridity which is manifested by the aeolian sand around 2 ka. Pedogenesis of the aeolian sand indicate a phase of landscape stability. Presence of historical flood sequence at Banas river dated to 0.8 ka indicate an overall strengthened monsoon condition which led to the temporary rejuvenation of the fluvial system. This period correspond to the medieval warm period during which it has been observed that the Indian Summer Monsoon was relatively improved (Chauhan et al., 2000; Bhattacharya et al., 2014). Following this, the terrain seems to have undergone climatic amelioration (aridity) and is being continued till today.

Paleomonsoon reconstructions of the Gujarat alluvial plain can be well demonstrated from fluvial and aeolian records along rivers traversing through the northern and southern parts of this plain. A broad correspondence is observed between continental record of the north Gujarat Alluvial plain and the Arabian Sea core data (Schulz et al., 1998; Leuschner and Sirocko, 2003).
Figure-5.18: Composite stratigraphy of Banas and Saraswati rivers of the North Gujarat alluvial plain is being compared with the Age vs. TOC % Arabian sea core data from Core KL-111 of Schultz et al., 1998. Corresponding depositional environment and inferred climate of the North Gujarat alluvial plain since ~37 ka has been shown in separate columns.

Comparing the chronostratigraphic data from Orsang, Mahi (Juyal et al., 2006), with that of the Banas and Saraswati basins, suggest that the alluvial sequences are variably incised at different sites along these rivers in their respective basins. Quaternary deposits exposed in the Orsang basin is dated to 98 ka, whereas, in the Mahi Basin, the oldest sediment has been dated to ~70 ka (Juyal et al., 2006). The Banas and Saraswati basins, further northwards comprises of Quaternary sedimentation from 37-1 ka. This non-uniform distribution of sedimentation pattern is ascribed to the differential movement along the Cambay rift segments. This is in accordance with the study of Maurya et al. (1995) where they have suggested that south of Mahi river subsided at a much faster rate than the north. On the basis of the present incision scenario and fluvial dynamics, it may be suggested that the southern rivers of Gujarat alluvial Plain (Mahi, Sabarmati and Orsang) have been subjected to higher tectonic perturbation leading to incision of their own deposits as compared to
the northern rivers (Banas and Saraswati). In addition to this, preferential clustering of the earthquake epicenters have been found more towards the south. However, scarcely present earthquake epicenters at Banaskantha and Patan would definitely invoke feeble tectonic perturbations at north Gujarat Alluvial Plain as well. The study ascribe the differential incision in the region to a combination of tectonics associated with the Cambay rift and the sea level fluctuations during the last 40 ka.