CHAPTER - 3
KACHCHH MAINLAND
3.1. Introduction

In actively uplifting areas, the bedrock rivers are dominantly involved in incising the underlying resistant bedrock (Whipple, 2004). Therefore, such rivers lack laterally continuous alluvium cover, instead, discrete sedimentary patches can be found along their courses (Howard et al., 1994). In seismically active and monsoon dominated regions, studies suggest that on millennial time scales, the bedrock rivers oscillate between incision and valley aggradation. This is ascribed to the changes in monsoon intensity and sediment flux (Pratt-Sitaula et al., 2004). In view of this, the morphology and sedimentary successions of the bedrock rivers can be used to reconstruct the history of seismicity and climate variability.

The Kachchh peninsula in the western India is one such region where the interplay between climate and tectonics can be discerned through the fluvial successions which is preserved in various bedrock river valleys. Presently, all the major rivers in the Kachchh peninsula are actively incising the Mesozoic and Tertiary bedrocks (Thakkar et al., 1999; Maurya et al., 2003; Patidar et al., 2007; 2008; Bhattacharya et al., 2013). However, the presence of valley and channel-fill deposits of varying thicknesses preserved in different river valleys is suggestive of the fact that there were periods of tectonic stability in the geological past (Mathew et al., 2006; Patidar et al., 2007). Further, the temporal changes in the pattern of fluvial aggradation suggest that the region responded to the ISM variability during the late Quaternary (Bhattacharya et al., 2013). The tectonically active nature of the Kachchh peninsula is adequately expressed by the presence of E–W trending major faults viz. the Kachchh Mainland Fault (KMF), Katrol Hill Fault (KHF), South Wagad Fault (SWF), Island Belt Fault (IBF) and Gedi Fault (GF) (Biswas, 2005, Fig-3.1A). Seismically active nature of these faults is manifested by major earthquakes during the late Quaternary (Morino et al., 2008; Kundu et al., 2010) which continued even during the recent historical times e.g. 1819 Allah Bund earthquake, 1956 Anjar earthquake and 2001 Bhuj earthquake (Rajenderan and Rajenderan, 2001).

The geomorphic configuration and the drainage network of the Kachchh mainland are controlled by the KMF and KHF (Biswas, 1974; 1987). The surface expression of the KHF is manifested in the form of the north facing steep escarpment (Thakkar et al., 1999) (Fig.3.1B).
The KHF is the major tectonic structure in the study area which is geomorphologically expressed as a linear scarp and acts as a drainage divide between the north and south flowing rivers in the Katrol Hills (Patidar et al., 2007; Fig. 3.1A). According to Biswas (1974), tectonic activity along the KHF was responsible for the...
development of the cyclic planation surfaces in the southern Kachchh and the present day rivers flow on the early Quaternary surface. Based on the fault plane solution, Chung and Gao (1995), suggested that the KHF is a reverse fault. These were further supported by the study of Thakkar et al. (1999). Further, the area is traversed by lineaments, anticlines, and domes (Thakkar et al., 1999; Figs.3.1A and D).

The rivers in the vicinity of the KHF have incised deep gorges along with the development of knick points indicating continued tectonic activity during the Holocene (Thakkar et al., 1999). Majority of the north flowing rivers originate from the narrow valleys that lie south of the KHF (Fig.3.1D). At these places the rivers have carved reasonable accommodation surfaces on the Mesozoic bedrocks for the late Quaternary fluvial sedimentation (Thakkar et al., 1999; Patidar et al., 2007). The fluvial sediments are dominated by reworked aeolian miliolites (Biswas, 1974; Thakkar et al., 1999) with subordinate contribution from the Mesozoic sandstone and shale. Considering that the fluvial sediments are incised to the depth of the present day river channel, two major phases of Quaternary tectonics have been suggested by Thakkar et al., (1999). The older uplift phase which was assigned an early Quaternary age was attributed to the uplift along the E-W trending KHF whereas the younger phase of uplift (late Pleistocene to Holocene age) was attributed to the activity along the NNE-SSW to NNW-SSE trending transverse fault systems. In a more recent study, Patidar et al. (2007) invoked two major events of seismicity viz. earlier one was during the deposition of colluviums immediately above the beveled Mesozoic bedrock and the later one was after the valley-fill aggradation. Considering the structural configuration of the southern Kachchh and infrequent earthquakes, it is reasonable to assume that the incision was tectonically governed. However, rivers can also incise due to climatically induced base level changes so that local incision does not necessarily equal local tectonic uplift (Lave and Avouac, 2000). It has been suggested that in the tectonically active region, in a shorter time scales (≤10^5 years) the rivers oscillate between bed rock incision and valley alluviation owing to the changes in monsoon intensity and sediment flux (Pratt-Sitaula et al., 2004).

Studies carried out in the past suggest that the terrain has the potential for reconstructing the late Quaternary seismicity and climate variability. However, due to
lack of detailed sedimentological observations and limited chronometric data, the inferences drawn remained speculative (Patidar et al., 2007 and reference therein). Although the earlier studies presented a broad picture of climate-tectonic interaction in the southern Kachchh, however, these studies lacked detailed sedimentological observations and absolute chronometric data. As a result it is difficult to quantify the factors responsible for channel and or valley-fill aggradation and their subsequent incisions. In view of this, the present thesis is an attempt to ascertain the role of climate and seismicity in the evolution of the channel and valley-fill sequences in the upper catchment of the Khari river (south of KHF; Fig. 3.1).

Climatically, Kachchh region of Gujarat in the western India lies in the arid and hyper arid climate zone (Juyal et al., 2006, Fig.3.1C). The major source of precipitation is the southwest summer monsoon (~80%) which occurs during the months of July and September (Pramanik, 1952; Sontakke et al., 2008). The terrain experiences high average temperature and low humidity as a result of which the potential rate of evaporation is exceedingly high (Glennie and Evans, 1976). Due to the arid and semi-arid climatic conditions, the present day fluvial processes are largely ephemeral in nature.

3.1.1. Channel-fill sequence in Khari river:

(I) Study area and stratigraphy:

Along the Khari river, a channel fill deposit (23°10′56″ N and 69°35′43″ E) which is transverse to the main Khari river has been investigated for sedimentology and optical chronology (Fig. 3.1D).
Figure-3.2(a) Field photograph showing SW-NE trending channel-fill sequence incised by NW flowing Khari river in the south of the KHF. (b) Cross-section profile showing the channel geometry and the channel fill stratigraphy, Unit-1= Cross stratified assorted angular gravels, Unit-2= Laminated miliolite (endurated), Unit-3= Laminated friable miliolite, Unit-4= Crudely laminated miliolite, Unit-5= Weathered miliolite, Unit-6= Mesozoic lithoclast dominated debris flow.

The channel geometry was prepared by measuring the horizontal and vertical profiles at fixed intervals (Figs. 3.2A and B). Khari river flows N 40°E and the tributary channel meets it at N 300°W (Fig. 3.1b). The Khari river has incised ~6 m of the channel fill sediment and 3 m of the Mesozoic bedrock belonging to the Bhuj Formation (Figs. 3.2 and 3.3).

Using the conventional sedimentological criteria (structure and texture), a total of six sedimentary units have been identified (Figs. 3.2B and 3.3). The sediment succession overlying the bed rock is characterized by a 170 cm thick assorted, angular, crudely laminated ferruginous sandstone dominated by gravels with subordinate platy miliolite clasts (unit-1). The upper 50 cm of this horizon shows trough cross stratification (unit-1). This is succeeded by a 80 cm thick parallel laminated and endurated miliolite containing angular lithoclasts of ferruginous sandstone that are dispersed preferentially along the bedding plane (unit-2). Above this, a 80 cm thick parallel laminated (mm to cm thick) friable miliolite containing discrete angular lithoclasts can be observed (unit-3). At places, desiccated clay laminae can be seen along the bedding plane. This horizon

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Optical ages</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.9 ± 1.4</td>
<td></td>
<td>Mesozoic sandstone (crushed and sandstone alteration)</td>
</tr>
<tr>
<td>9.4 ± 1.5</td>
<td></td>
<td>Laminated miliolite with lithoclast of sandstone decomposed</td>
</tr>
<tr>
<td>8 ± 1</td>
<td></td>
<td>Parallel laminated fragile miliolite with chromatic angular lithoclasts and decomposed rocky structure</td>
</tr>
<tr>
<td>7.5 ± 1</td>
<td></td>
<td>Weathered miliolite sand with matrix carbonates</td>
</tr>
<tr>
<td>5 ± 1</td>
<td></td>
<td>Crudely laminated miliolite sand with ferruginous sandstone lithoclasts</td>
</tr>
<tr>
<td>Unit-6</td>
<td></td>
<td>Assorted angular gravel with sandstones and platy miliolite above upper part trough cross stratified</td>
</tr>
<tr>
<td><strong>Unit-5</strong></td>
<td></td>
<td>Weathered miliolite sand with matrix carbonates</td>
</tr>
<tr>
<td><strong>Unit-4</strong></td>
<td></td>
<td>Crudely laminated miliolite sand with ferruginous sandstone lithoclasts</td>
</tr>
<tr>
<td><strong>Unit-3</strong></td>
<td></td>
<td>Parallel laminated fragile miliolite with chromatic angular lithoclasts and decomposed rocky structure</td>
</tr>
<tr>
<td><strong>Unit-2</strong></td>
<td></td>
<td>Laminated miliolite with lithoclasts of sandstone decomposed</td>
</tr>
<tr>
<td><strong>Unit-1</strong></td>
<td></td>
<td>Cross stratified assorted angular gravels</td>
</tr>
</tbody>
</table>

Figure-3.3: Detail stratigraphy of the channel fill deposit along with optical ages.
is overlain by 1 m thick crudely laminated miliolite sand embedded with ferruginous sandstone lithoclasts (unit-4) which in turn is succeeded by 1 m thick weathered miliolite with discrete marly carbonate layers (unit-5). The succession terminates with the deposition of 1 m thick massive platy lithoclasts gravels embedded in miliolite matrix (unit-6).

(II) Depositional environment:

The erosional contact between the bedrock and the thin channel-fill sediment (~6 m) suggests that sedimentation occurred on beveled Mesozoic bedrock basement similar to the strath terrace as defined by Bull (1991). The beveled planar surfaces develop when there is a change in the ratio of vertical incision to lateral planation in a down cutting river (Hancock and Anderson, 2002) during low sediment flux (Lave and Avouac, 2001). The deposition of unit-1 indicates that the initiation of channel fill sedimentation occurred under hyper-concentrated sediment gravity flow (Wasson, 1979; Miall, 1996). Further, presence of trough cross stratified gravels in unit-1 indicates deposition of sediment as bedload, a characteristic feature of intermittently flowing dryland rivers which are subjected to occasional floods. Sediment mobilization in such rivers occurs on the rising limb of the flood hydrograph (scouring) and the sediment deposition occurs during the recession phase of the flood (filling). Such scours and fills give rise to cross-stratification in the dry land fluvial environment (Hassan, 1990; Tooth, 2000). The overlying parallel-laminated miliolite in unit-2 (both endurated and friable) suggest their deposition under aqueous condition. Kachchh miliolite are primarily aeolian deposits (Biswas, 1971; Thakkar et al., 1999) which would imply that the channel fill miliolites are in their secondary context (fluvially transported). Sporadic occurrences of platy lithoclasts with long axes preferentially oriented along the bedding planes indicate short transport distance during increased flow intensity. The overlying mm to cm thick parallel laminated friable miliolites along with desiccated clay lamina (unit-3) can be suggestive of low energy flood plain environment (Thomas et al., 2007). A weakening of the hydrological condition can be suggested by the occurrence of angular ferruginous sandstone lithoclasts embedded in miliolite matrix (unit-4). The overlying weathered miliolite (unit-5) indicates prolong sub-aerial exposure following their deposition, implying subdued water activity. The poorly sorted and platy clast dominated topmost
(III) Chronology:

Samples for optical dating were collected from freshly exposed sections in opaque metal pipes. Basic principles of luminescence dating can be found in Aitken, 1998; Duller, 2008 and Rhodes, 2011. Considering that the sediments have been transported by the fluvial system, there is significant variability in sediment water ratio (discussed in chapter-2). For the estimation of De, we used the Central Age Model (CAM) of (Galbraith et al., 1999), Minimum Age Model (MAM) suggested by Galbraith and Laslett (1993) and the minimum plus two sigma approaches from Juyal et al. (2006). Except for BM-1, the MAM and Minimum plus two sigma ages (within errors) gave near identical ages whereas CAM ages were not only overestimated but show inversion as well (sample BM-5). This was expected because during fluvial transport, sediment grains receive an attenuated flux of sun light on account of water column, turbidity and duration of the transport (Srivastava et al., 2001).

Figure-3.4: Radial-plots showing De distributions of OSL samples from unit-1 (BM-1), unit-2 (BM-2), unit-3 (BM-3) and unit-5 (BM-5) of the channel-fill along the Khari river. The grey horizontal bars represents 2-sigma.
Table 3.1A: Showing U, Th, K concentrations, cosmic ray dose rates and dose rates

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K(%)</th>
<th>Cosmic Ray Dose Rate (µGy/a)</th>
<th>Dose Rate (Gy/ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM-1 (Unit-1)</td>
<td>2.44 ± 0.04</td>
<td>13.42 ± 0.26</td>
<td>1.19 ± 0.02</td>
<td>88 ± 17.6</td>
<td>2.5 ± 0.09</td>
</tr>
<tr>
<td>BM-2 (Unit-2)</td>
<td>2.53 ± 0.05</td>
<td>14.81 ± 0.29</td>
<td>0.77 ± 0.01</td>
<td>103 ± 20.6</td>
<td>2.2 ± 0.08</td>
</tr>
<tr>
<td>BM-3 (Unit-3)</td>
<td>2.89 ± 0.05</td>
<td>19.63 ± 0.39</td>
<td>0.96 ± 0.02</td>
<td>120 ± 24.0</td>
<td>2.8 ± 0.10</td>
</tr>
<tr>
<td>BM-5 (Unit-5)</td>
<td>3.18 ± 0.06</td>
<td>18.12 ± 0.36</td>
<td>1.83 ± 0.04</td>
<td>169 ± 33.8</td>
<td>3.6 ± 0.10</td>
</tr>
</tbody>
</table>

Table 3.1B: Showing CAM, MAM and Min+2*sigma De values

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CAM (De in Gy)</th>
<th>MAM (De in Gy)</th>
<th>Min +2*sigma (De in Gy)</th>
<th>CAM (Age in ka)</th>
<th>MAM (Age in ka)</th>
<th>Min + 2*sigma (Age in ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM-1 (Unit-1)</td>
<td>69 ± 2.83</td>
<td>63 ± 1</td>
<td>49.35 ± 2.83</td>
<td>27.8 ± 1.5</td>
<td>25.4 ± 1.03</td>
<td>19.9 ± 1.4</td>
</tr>
<tr>
<td>BM-2 (Unit-2)</td>
<td>39 ± 3.28</td>
<td>20 ± 4</td>
<td>20.95 ± 3.28</td>
<td>17.4 ± 1.6</td>
<td>8.9 ± 1.82</td>
<td>9.4 ± 1.5</td>
</tr>
<tr>
<td>BM-3 (Unit-3)</td>
<td>35 ± 2.52</td>
<td>19 ± 1</td>
<td>23.00 ± 2.52</td>
<td>12.5 ± 1.0</td>
<td>6.8 ± 0.4</td>
<td>8.2 ± 0.9</td>
</tr>
<tr>
<td>BM-5 (Unit-5)</td>
<td>48 ± 2.85</td>
<td>25 ± 5</td>
<td>25.27 ± 2.85</td>
<td>13.4 ± 0.9</td>
<td>7.0 ± 1.4</td>
<td>7.1 ± 0.8</td>
</tr>
</tbody>
</table>

Particularly for dry-land sediments (as in the present case) which by virtue of their depositional pattern (as discussed above) are likely to suffer differential bleaching under same depositional environment. This is demonstrated in the radial plots (Fig. 3.4). In view of this, it is likely that the minimum dose subset is being the closest to the most bleached fraction in the sediment, hence we used the minimum plus two sigma ages (De falling under the grey bar of radial plot). Based on above, unit-1 is dated to 19.9±1.4 ka, unit-2 is dated to 9.4±1.5 ka, unit-3 is dated to 8.2±0.9 ka and unit-5 is dated to 7.1±0.8 ka (Table 3.1A and B).

(IV)Discussion:

Dryland rivers (ephemeral) from process point of view are primarily the selective transporter, which bury and re-excavate their own sediments under episodic flows. These rivers are comparatively insensitive indicators of subtle shift in climate, but respond too readily to long-term climatic pattern (Reid and Frostick, 1997). Therefore, based on the optical age obtained immediately above the beveled Mesozoic
bed rock it can be suggested that prior to ~20 ka due to the weak Indian Summer Monsoon (ISM), (Overpeck et al., 1996), there was insignificant sediment mobilization from the catchment. Thus the ambient fluvial energy was utilized for channel incision. The river gradient is considered most representative of the ability of a river to transport sediment and erode the bedrock (Lave and Avouac, 2001), which in turn can change either due to uplift or eustatic lowering of sea level. Considering that the ISM was weak around 20 ka (Overpeck et al., 1996; Juyal et al., 2009) and the sea level was around 100 m lower than present (Hashmi et al., 1995), it is reasonable to assume that the channel incision prior to 20 ka can as well be caused by eustatically lowered sea-level (over steepening of river gradient). In the present case, however, we negate this for the following reasons. (i) Khari river drains into the Banni alluvial plain instead of draining directly into the sea. (ii) Studies have shown that the extent of inland incision due to lowered sea strand is limited to the coastline (Leigh and Feeney, 1995). (iii) Further considering an extended shelf of the Gulf of Kutch (~100 km with average water depth of ~100 m; Chauhan and Almeida, 1993), the geomorphic effects of sea level lowering will be restricted to the shelf and deltaic areas (Blum and Salvatore, 1994; Koss et al., 1994; Miall, 1988; Schumm, 1993). Therefore, the pre 19.9 ka channel incision could not have been caused by the eustatic lowering of sea level; instead, we attribute it to the enhanced tectonic activity in the vicinity of the KHF and the associated transverse faults. Our observations accords well with the earlier study carried out in the lower reaches of Khari river by Mathew et al., (2006) indicating enhanced tectonic (uplift) activity prior to 19.9 ka (Fig. 3.5a).

The texture and sedimentary structures associated with the lower part of the unit-1 dated to 19.9 ka suggests that the deposition occurred during weak hydrological (monsoon) condition as hyper-concentrated sediment gravity flow. However, presence of the trough cross stratified gravels in the upper part of unit-1 suggest establishment of episodic channel activity (ephemeral). Absence of appreciable sediment thickness between 19.9 ka and 9.4 ka can be attributed to erosion caused by infrequent sediment mobilization due to frequent high magnitude floods (Hassan, 1990; Tooth, 2000) as indicated by the presence of cross-stratified horizon below unit-2 (Fig. 3.3). It was only around 9.4 ka (unit-2) sustained hydrological condition (strengthened monsoon) facilitated enhanced sediment flux which persisted until around 7.1 ka (Fig. 3.5b). During this period ~3 m thick sediment succession was
deposited implying that the channel fill aggradation was caused due to the sediment induced rise in base level. Chronologically constrained fluvial sequences are limited from the western India. Studies from the fluvial sequences from Sabarmati and Mahi rivers in the western India indicate intensified monsoon ~12 ka that persisted until around the mid-Holocene (Srivastava et al., 2001; Juyal et al., 2006). In the Ganga plain, Srivastava et al. (2003) observed development of dense channel network between 13 ka and 9 ka which was attributed to the enhanced precipitation. A recent study based on the fluvial terraces in the Alakananda and Ganga river system by Ray and Srivastava (2010) and Juyal et al. (2010) suggested prevalence of enhanced monsoon during 11 ka and 7 ka. A near continuous fluvial aggradation in the Alakananda valley was dated between 15 ka to 7 ka which was attributed to enhanced monsoon (Juyal et al., 2010).

After around 7.1 ka, there seems to be a phase of non deposition in the channel during which the fluvially reworked miliolite with marly carbonates underwent pedogenesis suggesting overall decline in the monsoon strength after 7.1 ka as also observed both from the continental (Rajagopalan et al., 1997; Ray and Srivastava, 2010; Juyal et al., 2010), and marine records (Overpeck et al., 1996;). The channel fill along with the bedrock incision began sometime after 7.1 ka under weak monsoon. It is likely that the required stream power was precipitation deficient in that case it had to be supplemented by the uplift induced increased steepness of the channel gradient.
Figure 3.5: Depicting temporal changes in seismicity and channel fill aggradation during the last 20 ka. (a) Incision of the Mesozoic bed rock prior to 20 ka is attributed to the enhanced uplift (shown by the solid black arrows). (b) A phase of relative stability after 20 ka till 7 ka (subdued seismicity shown small solid black arrows). During this period a gradual strengthening of the summer monsoon is inferred. (c) A renewed phase of enhanced uplift (incision) began after 7 ka which seems to continue till today. A close correspondence of the monsoon based on present study with that of the Guliya ice core data from Tibet (Thompson et al., 1997) indicate that fluvial processes of Kachchh region were intimately associated with the southwest summer monsoon variability.

Trench investigation carried out by Morino et al. (2008) in the vicinity of KHF at Wandhay dam site revealed occurrences of at least three large magnitude seismic events. According to them these events occurred along 3 major fault strands F1, F2 and F3 representing the latest, penultimate and the older than penultimate events respectively and have displaced terrace units as well as the overlying younger channel-fill deposits. In the absence of absolute chronology, they suggested that the events had occurred during late Holocene or recent historic past. Considering that the facies do not change significantly in short distances and in same river valley, we speculate that the faulting activities at Wandhay dam site could be post 7 ka as the fault has displaced the upper sand layer which have been dated to 7.1 ka. In view of this, it can be argued that the second phase of enhanced uplift (incision) began after 7 ka and that probably continues till today (Fig. 3.5c).

3.1.2. Valley-fill sequence in Gunawari river:

(I) Geomorphology:

Gunawari river is located in the Katrol Hill Range (KHR) ~15 km south of Bhuj (latitude 23.17°-23.19°N and longitude 69.70°-69.75°E, Fig. 3.1D). Based on the landform characteristics and altitudinal variability, three broad geomorphic units can be discerned (Fig. 3.1B). These are from south to north (i) the KHR which rises to an elevation of 150–445 m, (ii) the central rocky plain (100-150 m) and (ii) the lower piedmont plain (<100 m), Fig. 3.1B). The Gunawari river which is a tributary of the Khari river originates in the KHR (~445 m asl). In the upper reaches, between the northern Satpura and the southern Marutonk domes, the river flows through a
meandering course (Fig. 3.6). After crossing the Marutonk dyke, the river becomes straight, following the E–W trending KHF and the valley becomes relatively wide.

The Gunawari river has incised 10–15 m deep E–W trending back valley (Fig. 3.1D) in which discrete but appreciable thickness of the late Quaternary valley-fill sediments overlying the incised Mesozoic and Tertiary rocks can be observed (Thakkar et al., 1999; Patidar et al., 2007). Based on their geomorphic position and sediment characteristics, these deposits can be divided into the (i) older valley-fills (OVF) and the (ii) younger valley-fill (YVF) deposits (Fig. 3.6). The older valley-fill deposits can be laterally traced along the northern flank of the Gunawari river. However, along the southern flank which is marked by the steeply dipping Mesozoic and Tertiary rocks corresponding to the hanging wall of the KHF, the older valley-fills are scanty or absent (Fig. 3.6). The 10–15 m thick sediments belonging to the older valley-fill succession is dominated by fluvially reworked miliolite whereas the 1–2 m thick younger valley-fill sediments are devoid of fluvially reworked miliolite. These deposits occur proximal to the river bed particularly in areas where river takes abrupt turn (Fig. 3.6). In addition to this, the northern flank of the Gunawari river consists of gullies which are developed on the older valley-fill successions by the southern flowing juvenile streams.

Figure 3.6: Map showing rocky upland, domes, piedmonts and locations of valley-fill deposits. Gunawari river in the west of Marutonk dyke follow a meandering course and becomes straight in the east of Marutonk dyke. The course of the Gunawari river (elbow bends, highlighted under red ellipsoid) is controlled by the NNW-SSE trending joint patterns (inset rose diagram).
(II) Stratigraphy

The valley-fill deposits can be laterally traced along the northern scarp of the KHR between latitude 23.18°-23.19°N and longitude 69.71°-69.75°E (Fig. 3.1D and 3.6). Detailed sedimentological investigations are carried out at Gunawari-1 (older valley-fill deposits; 23.18°N and 69.72°E) and at Gunawari-2 (younger valley-fill deposits; 23.18°N and 69.73°E; Fig. 3.6).

(i) Gunawari-1

At this location ~11 m thick alluvium succession overlying the 1.25 m thick incised Mesozoic bedrock is preserved (Fig. 3.7A and 3.8). Based on the facies architecture and textural attributes, a total of 9 units have been identified in the field (Fig. 3.7A). From bottom upwards, the sediment succession immediately above the beveled Mesozoic sandstone is represented by a 80 cm thick crudely imbricated angular gravel containing lensoidal silty-clay layer (unit-1). This is overlain by a 145 cm thick parallel laminated coarse to medium miliolite sand containing occasional pebbles and discrete clay lamina (unit-2).

![Figure 3.7: Detail stratigraphy of the valley-fill deposits at (A) Gunawari-1 and (B) Gunawari-2. Red rectangles and circles represent locations of OSL and geochemistry samples respectively.](image)

This is followed by the deposition of a 260 cm thick faintly laminated miliolite sand, which grades into massive miliolite in the upper part and contain marly carbonate
(unit-3). This is overlain by a 125 cm thick laminated coarse to medium miliolite sand which is punctuated by sandy-clay intercalation (unit-4). This horizon is overlain by a 180 cm thick pedogenised clayey-silt containing dispersed calcretes in the upper part (unit-5) and is succeeded by a 60 cm thick laminated miliolite horizon. This horizon contains multiple sandy-clay units and is capped by clay layer towards the upper part (unit-6). This is overlain by a 110 cm thick massive pedogenised clayey-silt containing platy litho-clasts at the bottom (unit-7) and is succeeded by a 40 cm thick crudely laminated platy lithoclast dominated miliolite (unit-8). The succession terminates with the deposition of ~90 cm thick poorly organized platy litho-clast dominated gravels (unit-9).

(ii) Gunawari-2

At this location, 2.5 m thick sediment succession rests over ~3 m thick beveled and incised Tertiary limestones and shales (Figs. 3.7B and 3.9). From bottom upward, the sediment succession begins with the deposition of a 40 cm thick angular to sub-rounded litho-clast (Bouldery layer; unit-1) which is overlain by a 2.0 m thick massive, medium to coarse sand. The upper 20–50 cm of this horizon contains an impersistent platy litho-clast layer (unit-2).
(III) Optical dating

Samples from freshly exposed sections were collected in aluminum pipes from five sedimentary units (viz. unit-1,3,4,9 at Gunawari-1 and from unit-2 at Gunawari-2; Fig. 3.7A and B). Since the over-dispersion in De was >30%, the Minimum Age Model (MAM) suggested by Galbraith and Laslett (1993) has been used for age estimation. Fig. 3.10 gives a growth curve (3.10A) and a shine down curve (3.10B) for the lower most sample (unit-1,) and the radial plots of all the five samples (3.10C to G). From the older valley-fill sequence the lowermost sample dated from unit-1 at Gunawari-1 gave an age of 17.4±1.7 ka, unit-3 is dated to 11.8±1 ka, unit-4 is dated 7.8±0.6 ka whereas the topmost unit-9 gave an age of 3±0.6 ka (Fig. 3.11A). The younger valley-fill sequence (unit-3) at Gunawari-2 is dated to 0.9±0.04 ka (Fig. 3.11B). Table 3.2A and B provides the details of the radioactivity, equivalent dose, dose rate and ages computed using MAM and CAM.

Table-3.2A: Showing details of the radioactivity and dose rate.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Sample No.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K(%)</th>
<th>Dose Rate (Gy/ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunawari-1</td>
<td>Unit-1</td>
<td>1.63 ± 0.05</td>
<td>10.2 ± 0.02</td>
<td>0.66 ± 0.02</td>
<td>1.67 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Unit-3</td>
<td>2.37 ± 0.02</td>
<td>9.55 ± 0.09</td>
<td>1.18 ± 0.01</td>
<td>2.20 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Unit-4</td>
<td>2.03 ± 0.02</td>
<td>9.10 ± 0.09</td>
<td>1.42 ± 0.01</td>
<td>2.30 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>Unit-9</td>
<td>1.94 ± 0.06</td>
<td>9.87 ± 0.02</td>
<td>0.69 ± 0.02</td>
<td>1.70 ± 0.1</td>
</tr>
<tr>
<td>Gunawari-2</td>
<td>Unit-3</td>
<td>2.0 ± 0.04</td>
<td>14.75 ± 0.29</td>
<td>1.0 ± 0.02</td>
<td>2.30 ± 0.1</td>
</tr>
</tbody>
</table>

Figure 3.9: Section at Gunawari-2 showing ~2.5 m thick sediment succession overlying the beveled southerly dipping Tertiary limestone and shale.
Figure 3.10: (a) Typical growth curve and (b) shine down curve of the sample from unit-1 at Gunawari-1. Radial plots showing De distributions of unit-1 (c), unit-3 (d), unit-4 (e) and unit-9 (f) at Gunawari-1 and (g) unit-3 at Gunawari-2. The grey horizontal bars represent 2-sigma.

Table-3.2B: Showing ages computed using MAM and CAM

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>CAM De (Gy)</th>
<th>MAM De (Gy)</th>
<th>CAM Age (ka)</th>
<th>MAM Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gunawari-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit-1</td>
<td>52 ± 1.6</td>
<td>29 ± 2.0</td>
<td>31 ± 2.3</td>
<td>17.4 ± 1.7</td>
</tr>
<tr>
<td>Unit-3</td>
<td>48 ± 1.5</td>
<td>26 ± 2.0</td>
<td>22 ± 1.5</td>
<td>11.8 ± 1.0</td>
</tr>
<tr>
<td>Unit-4</td>
<td>35 ± 1.0</td>
<td>18 ± 1.1</td>
<td>15 ± 1</td>
<td>7.8 ± 0.6</td>
</tr>
<tr>
<td>Unit-9</td>
<td>19 ± 0.6</td>
<td>5.2 ± 1.0</td>
<td>11 ± 1</td>
<td>3.0 ± 0.6</td>
</tr>
<tr>
<td>Gunawari-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit-2</td>
<td>4.1 ± 0.1</td>
<td>2.1 ± 0.06</td>
<td>1.8 ± 0.07</td>
<td>0.9 ± 0.04</td>
</tr>
</tbody>
</table>
Figure 3.11: Chronology of the valley-fill sequence at Gunawari-1 and 2.

(IV) Geochemistry

It has been suggested that the synchronous variation in major oxides such as Al$_2$O$_3$, FeO, TiO$_2$ and SiO$_2$ mimics the temporal changes in detrital input (provenance) and thus can be used as a measure of past rainfall and runoff (Lisitzin, 1996; Peterson et al., 2000; Juyal et al., 2009). Therefore, in order to ascertain the temporal changes in valley-fill aggradation, each unit at Gunawari-1 is sampled (except unit-7 and 8, due to inaccessibility) for geochemical analyses (major oxides). From each unit, two to three sub-samples were collected and homogenized so as to obtain an average/representative concentration values. Attempt has also been made to ascertain the relative change in weathering intensity by using the conventional Chemical Index of Alteration (CIA) technique in decarbonated samples. CIA is defined as CIA = 100 × [(Al$_2$O$_3$)/(Al$_2$O$_3$+CaO+Na$_2$O+K$_2$O)] (Nesbitt and Young, 1982). It has been observed that there is a gradual increase in Al$_2$O$_3$ from 9.77% (Unit-1) to 11.89% (unit-6) followed by a marginal decline to 11.1% (unit-9). Maximum value of 11.89%
is obtained from unit-6. Identical trend is observed for FeO, TiO$_2$ and SiO$_2$ (Table-2, Fig. 3.12). Compared to this, we observed a gradual decline in CIA from unit-1 (84.71) to unit-4 (69.55) followed by an increase in the value towards unit-6 (86.82) (Table-2; Fig. 3.12). At Gunawari-2 we observed relatively high concentration of Al$_2$O$_3$ (13.36%), FeO (7.36%), and TiO$_2$ (0.9%) and significantly low concentration of CaO (6.61%) (Table-2).

(V) Depositional environment

Incised sedimentary succession at Gunawari-1 provides detail facies variability in the Gunawari river valley. On the basis of sedimentological observations, it can be suggested that sedimentation occurred on the beveled Mesozoic bedrock surface implying that before the deposition of unit-1(Fig. 3.11), beveling of the bedrock surface occurred due to the change in the ratio of vertical incision to lateral planation, a typical feature in a down cutting river (Hancock and Anderson, 2002). Once the sediment supply increases, the lateral planation of the bedrock is prevented due to the overlying sediment cover (Lave and Avouac, 2001). Thus, it can be suggested that the accommodation space for the valley-fill sedimentation on the Mesozoic bedrock surface was created during low sediment supply. Deposition of crudely imbricated, angular to sub-rounded lithoclasts of unit-1 (above the bedrock) dated to 17 ka suggests their deposition under hyperconcentrated sediment gravity flow caused by episodic

Figure 3.12: Concentration variability of major oxides and Chemical Index of Alteration corresponding to different units at Gunawari-1 (older valley-fill deposits).
discharge (Wasson, 1979; Miall, 1996; Knighton and Nanson, 1997). Sediment characteristics (laminated coarse to medium miliolite sand with occasional pebbles and clay lamina) of unit-2 suggests improved hydrological condition. Presence of subordinate pebbles indicate that optimum segregation of the sediments was not achieved in the main channel before the floods spilled over the banks during the higher magnitude flood events (Thomas et al., 2007). Occurrence of faintly laminated to massive miliolite along with marly carbonate in unit-3 indicates deposition in the localized flood plain environment (Goudie, 1983; McCarthy and Metcalfe, 1990). The massive miliolite towards the upper part of unit-3 can be ascribed to the flashy hydrological condition (ephemeral) which prevented textural differentiation (Thomas et al., 2007). Overall it can be suggested that deposition of unit-1 to 3 dated between ~17 ka and ~12 ka (Fig. 3.11a) occurred with the gradual intensification of the ISM which is also indicated by a steady increase in the detrital proxies of rainfall and runoff (viz. Al₂O₃, FeO, TiO₂ and SiO₂) (Fig. 3.12). The increase in CaO concentration in unit-2 can be interpreted as enhanced contribution from easily erodible primary miliolite (aeolian) (Fig. 3.12). Deposition of unit-4 to unit-7 containing two pedogenised horizons (viz. unit-5 and 7; Fig. 3.11) and two fining upward horizons (viz. unit-4 and 6) suggest their deposition under consistent hydrological condition on a flood plain environment by a laterally avulsing river channel (Kraus, 1997; Juyal et al., 2000). These units were deposited after 8 ka and prior to 3 ka. Improved hydrological condition during the deposition of these units is also manifested by the increase in the major oxides except for CaO particularly during the deposition of unit-4 to unit-6 (Fig. 3.12). The decrease in CaO could be due to reduction in the aeolian miliolites in the Gunawari river catchment. Deposition of crudely laminated platy litho-clast dominated miliolite (unit-8) can be interpreted as weakening of the hydrological condition (onset of dryness) which seems to be further enhanced during the deposition of poorly graded and platy gravels dominated unit-9 dated to 3 ka (Fig. 3.11A). The textural attribute of this unit suggests that the sediments were transported as debris flows (Iverson, 1997; Griffiths et al., 2004). Compared to the major oxides, CIA shows a decreasing trend until the deposition of unit-4 (Fig. 3.12). This we attribute to the primary weathering that occurred in the river catchment. Whereas an increase in CIA corresponding to unit-5 (pedogenized horizon) and 6 (dominance of clay) can be ascribed to the post depositional weathering caused due to frequent and prolong sub-areal exposures (Fig. 3.12) caused
due to the existence of laterally avulsive fluvial system during the deposition of unit-5 and 6.

At Gunawari-2, the beveled Tertiary bedrock can be laterally correlated with that of the Gunawari-1. However, absence of older valley-fill at Gunawari-2 can be attributed to the post depositional erosion in the lower reaches of the river valley. The angularity of the boulders and their lithology which immediately overlies the Tertiary bedrock suggests their deposition during the short-lived storm surge flood event from the surrounding slopes (Fig. 3.11b). However, the overlying massive, medium to coarse sand horizon dated to 1 ka can be interpreted as deposition under low energy condition from the upper catchment (Fig. 3.11b). The high concentration of Al₂O₃, FeO, TiO₂ and low concentration of CaO in the sand horizon is ascribed to a change in the sediment provenance from aeolian miliolites to the Mesozoic and Tertiary rocks of Katrol hill range.

(VI) Discussion
Paleoenvironment

The amplified geomorphic and sedimentological responses of the dry-land fluvial system make them suitable archives for reconstruction of the past hydrological conditions (Nanson and Tooth, 1999). For example, a river that is adjusted to carry the sediment loads during the enhanced and persistent discharge (wet condition) undergoes changes in form and function during cold and dry phases (Williams et al., 1998). Studies carried out in western India show that the sedimentary architecture of the dry-land fluvial systems can be used to reconstruct the past ISM variability (Tandon et al., 1997; Juyal et al., 2000; Srivastava et al., 2001; Juyal et al., 2006). The present study is a new contribution from the extreme western part of India for which the post-LGM monsoon reconstruction based on fluvial archives are virtually non-existent.
The sedimentary characteristics of unit-1 which overlies the beveled Mesozoic bed rock and dated to 17 ka (Fig. 3.11A), suggests that deposition occurred under hyperconcentrated sediment gravity flow implying the onset of the monsoon activity following the LGM (Duplessy et al., 1980). Similar observation was made in the adjoining channel-fill sequence in Katrol hill by Bhattacharya et al. (2013). The valley-fill sediments are derived from the biogenic carbonates (miliolite) which were primarily deposited as obstacle dunes (aeolian) on the southern face of the Katrol hill (Biswas, 2005; Mathur, 2005; Fig. 3.1D). This would imply that prior to the deposition of unit-1, the terrain was experiencing enhanced aridity which progressively weakened as indicated by the initiation of the valley-fill sedimentation around 17 ka. Occurrences of overlying parallel laminated coarse to medium miliolite sand and enhanced concentration of CaO along with marginal increase in Al₂O₃ after 17 ka (unit-2) is suggestive of a steady increase in moisture condition (Fig. 3.12). The facies architecture corresponding to unit-3 to unit-6 and the overall increase in the detrital proxies (viz. Al₂O₃, FeO, TiO₂ and SiO₂) dated between 12 ka to <8 ka suggests an overall strengthened monsoon condition with fluctuations (Figs. 3.11A
Evidence similar to this was obtained by Mathew et al. (2006) from the northern part of the study area and the present study accords well with the continental and marine records which show an early Holocene strengthened monsoon followed by a gradual decline after the mid-Holocene (Sirocko et al., 1993). For example, the early Holocene humid phase was characterized by revival of fluvial activity in the Indian subcontinent and increased weathering and fluvial erosion in many parts of the peninsular India (Kale, 2007). In the adjoining channel-fill section, this period is represented by the presence of laminated miliolite and weathered fluvial sediments which are optically dated between 9 ka and 7 ka (Fig. 3.13) and was attributed to strengthened monsoon in the region (Bhattacharya et al., 2013). Compilation of the paleoclimatic data obtained from lakes and peat bogs from Thar desert, Ganga plain and Himalaya, indicates overall strengthened monsoon with fluctuations during 12 ka to 8 ka (Chamyal and Juyal, 2008 and reference therein). The texture and pattern of sedimentation corresponding to unit-8 and 9 indicate gradual decline in the monsoon intensity which is also supported by the decrease in major oxide concentration (Fig. 3.13). Combining the chronometric data from channel-fill sequence (Bhattacharya et al., 2013) with that of the valley-fill sequence, the decline in monsoon strength can be bracketed between 7 ka and 3 ka (Figs. 3.11A and 3.13). Comparing the valley-fill succession with that of the channel-fill deposits, a broad similarity in the time contemporaneous sedimentation pattern was observed (Fig. 3.13) implying the basin-wide response to ISM variability in the southern Kachchh.

The continental record of monsoon variability suggests arid to ephemeral lake condition after the mid-Holocene implying overall weakened monsoon (Chamyal and Juyal, 2008). Absence of valley-fill sediments younger than 3 to >1 ka suggests decrease in the river’s carrying capacity which can be ascribed to the prevalence of weak monsoon as observed in semi-arid Penner river of southern India (Thomas et al., 2007), in the Narmada and Tapi river basins of the Central India (Kale et al., 2003). In view of this, it is reasonable to suggest that the re-incision of the valley-fill sediments and the underlying bedrock occurred during the weak monsoon that began after 3 ka and continued until around >1 ka. The younger valley-fill sequences that were deposited around 1 ka suggest resumption of a short-lived strengthened monsoon phase in the region. Observation similar to this was made in the southern Penner river
(Thomas et al., 2007), Narmada and Tapi river basins, Central India (Kale et al., 2003) and Luni river in western Thar desert (Kale et al., 2000).

**Palaeoseismicity**

Studies pertaining to late Quaternary seismicity from the region are limited, however, the existing studies suggests that the terrain proximal to the KHF experienced major earthquakes in the past (Morino et al., 2008; Kundu et al., 2010) and which continued during recent historical times (Rajenderan and Rajenderan, 2001). Considering the seismically active nature of the KHF (Patidar et al., 2007; Bhattacharya et al., 2013), we looked for the morphological expression of seismicity using the conventional geomorphology supported by structural and joint pattern analysis. The joint pattern analysis provided an insight into the pattern of stress regime prevailed through time whereas the optical chronology of the sedimentary successions helped in quantifying the incision/uplift rates.

Seismically active nature of the study area is manifested by the presence of joints in the Mesozoic bedrocks. Structural analyses indicate that the joints are of conjugate type and the rose diagram plots suggest two major joint trends viz. NNW-SSE and NNE-SSW (Fig. 3.6; inset rose diagram). These conjugate sets of joints on the Mesozoic bedrock suggest their origin during the phase of tectonic inversion following the formation of the Kachchh rift when strike-slip/oblique-slip movements dominated the terrain (Biswas, 2005). The joint patterns seems to dictate the course of Gunawari river as indicated by sharp elbow bends of the rivers which are sympathetic to the NNW-SSE and NNE-SSW joint trends (Fig. 3.6). Further, the ongoing process of domal up-warping in the area is manifested by development of knick points where the Gunawari river cuts across the Marutonk dome in the west and the Ler dome in the east (Fig. 3.14). The differential movement along the river course can be suggested by the change from meandering course (in the west of Marutonk dyke) to a straight course in the east till it reaches the Ler dome (Fig. 3.6). A river flowing through varying degree of valley slopes tends to meander in higher slope segment in order to dissipate its energy, whereas in the lower slope segment, the river follows a rather straighter course (Schumm, 1993). The morphometric indices such as drainage density (Dd) and valley floor width ratio (Vf) are used to ascertain the tectonic instability/stability of a river valley. Increase in Dd and decrease in Vf ratio are
considered as an expression of tectonic instability (Keller and Pinter, 1996). The higher Dd values of 2.9 km/km² is observed in the west of Marutonk dyke which decreases 1.9 km/km² in the eastern part of the Gunawari valley.

Figure 3.14: Major discontinuity in the longitudinal river profiles of (a) Gunawari (b) Khari rivers are observed where these rivers cut across the KHF. In addition to this, the rivers also show deviation from the graded profile on encountering the domal and anticlinal structures.

Similarly, the valley floor width ratio (Vf) show an increasing trend from west (0.5) to east (3.5). These indices supports the observation that the western part of the Gunawari river is experiencing relatively higher uplift compared to its eastern counterpart and the uplift and the incision are coupled processes (Keller and Pinter, 1996).

Based on the morphology of the landscape and the optical chronology obtained on the valley-fill sequences, we tend to suggest that the terrain experienced two major events of enhanced seismicity. The older event which is assigned >17 ka led to the vertical incision and lateral planation of the Mesozoic bedrocks which subsequently accommodated the post-LGM valley-fill aggradation. Morphotectonic considerations suggest that the incision of the southern scarp surface (below the piedmont zone; Fig. 3.6) and the development of transverse gorge would have started during the older
event of enhanced seismicity. However, the southern draining juvenile first order streams (Fig. 3.1D) seems to be the later phenomena as these streams were responsible for the transportation and deposition of primary miliolite (aeolian) from the southern slopes of south-dipping KHF during the phase of relative stability.

The terrain experienced second phase of enhanced seismicity ~3 ka that led to the deposition of topmost debris-flow which led to the re-incision of the valley-fill and the underlying Mesozoic bedrock. Our observations are in conformity with the structural evidence obtained by Morino et al. (2008); they have suggested presence of active faults in the vicinity of Wandhay dam site which is located ~7 km northwest of the present study area. According to them, at least three large magnitude seismic events along 3 major fault strands F1, F2 and F3 representing the latest, penultimate and the older than penultimate events respectively. These events have displaced terrace units as well as the overlying younger channel-fill deposits. Based on the stratigraphic position and the sediment texture, this unit is comparable with the 3 ka debris-flow event of the Gunawari river (Fig. 3.13). This further supports our suggestion that the terrain was tectonically active as recent as <3 ka. However, the tectonic intervention was rather low between 17 to 3 ka, when monsoon was adequately strengthened.

In a down-cutting river, the rock uplift is equal to the river incision as measured from the elevation of the fill surface above the present day river channel (Burbank et al., 1996; Lave and Avouac, 2001). Ideally, uplifted bedrock strath terraces are considered best geomorphic features for estimating the incision/uplift rates as tectonic analysis of the strath is not susceptible to climate-induced effects (Avouac, 2003). However, in the present case, due to the variable sedimentary succession overlying the bedrock strath, we considered the total thickness that include the valley-fill and the incised bedrock and divided it with the topmost age to get the time averaged long-term incision rate (Lave and Avouac, 2001). Based on this, the long-term incising rate of 4.0 ± 0.8 mm/a is obtained for the valley-fill sequence. This is comparable with that of the channel-fill section along the Khari river, where an incision rate of 3.1 ± 0.4 mm/a is estimated. However, compared to the Mathew et al. (2006) who obtained ~10 mm/a from KMF and the recent GPS based instantaneous crustal shortening rate of ~12 mm/a (Jade et al., 2002), our estimate are on the lower side. We speculate the
higher incision rate obtained by Mathew et al. (2006) on KMF could (i) be due to that the fact that KHF is undergoing lesser degree of deformation compared to KMF and the later is the principle active fault in the Kachchh Mainland (Biswas, 2005) which is likely to assimilate the major strain during the regional deformation (Burbank and Anderson, 2001). (ii) Similarly the higher crustal shortening obtained based on the GPS measurements are instantaneous shortening rates (Mathew et al., 2006) and could be an artifact of the short time averaged expression of the cumulative slip of the four major faults like the KMF, IBF (Island Belt Fault), Allah Bund Fault and KHF (Kundu et al., 2010).

Figure-3.15 summarizes the observations made during the present study. Fluvial sedimentation commenced around 20 ka and persisted until around 1 ka. During this period monsoon driven hydrological variability led to significant changes in the pattern of fluvial processes. Onset of the ISM after the LGM led to the development of braided fluvial system that persisted until around 17 ka. A gradual strengthening of ISM followed by overall strengthened monsoon with fluctuation was observed after 12 ka and 8 ka. This led to the development of meandering river system and development of flood plains. It was after 7 ka the declining ISM monsoon facilitated the development of avulsive fluvial system which facilitated the development of flood plain pedogenesis. A dwindling hydrological condition seems to set in ~3 ka, when the slope-induced processes (debris flow) overwhelmed the fluvial sedimentation implying the onset of the aridity in the region. This phase was punctuated by a short-lived enhanced ISM before the onset of present day aridity ~1 ka that led to the deposition of the younger valley-fill sequence proximal to the river bed.

Two major events of enhanced seismicity are inferred. The older event which is dated to >20 ka was responsible for the creation of accommodation space for valley and channel-fill sedimentation. Compared to this, the younger event which is assigned <3 ka led to the re-incision of the fill sediment along with the underlying bedrock as also the evolution of the present day fluvial landforms in Gunawari river valley. The time averaged incision rate indicates that the terrain in the vicinity of the KHF is uplifting at ~ 4 mm/yr.
3.2. Summary

A broad correspondence of the monsoon reconstruction based on the valley-fill and the channel-fill deposits with that of the regional climate pattern indicates that the Kachchh peninsula in the western India responded in accordance with the regional climatic variability during the post-LGM period.

![Composite stratigraphy and optical ages obtained on the valley-fills and channel-fills](image)

Figure 3.15: A composite stratigraphy and optical ages obtained on the valley-fills (after Bhattacharya et al., 2014) and channel-fills (after Bhattacharya et al., 2013). The inferred fluvial processes based on facies architecture accords well with the isotopic proxy of monsoon variability reconstructed from the Guliya ice core data (Thomson et al., 1997). The two major events of enhanced seismicity (uplift/incision) are assigned >20 ka (older event) and <3 ka (younger event). The solid black arrow mimics the relative magnitude of uplift. OVF- Older valley-fill, YVF- Younger valley-fill.

The study indicates that channel-fill aggradation occurred during the early Holocene strengthened monsoon whereas the incision was dominated by the tectonics during periods of reduced monsoon activity. The study demonstrates a close correspondence between the summer monsoon and channel aggradation. Most
importantly, the recent study suggests two major events of enhanced seismicity (tectonic uplift). The older tectonic activity pre date ~20 ka whereas the younger activity began sometime after 7 ka and probably continued till today. An extended phase of landscape stability (subdued tectonic activity) can be bracketed between after 20 ka and 7 ka during which the channel aggradation responded to the regionally enhanced monsoon particularly which is bracketed between 9 ka to 7 ka.

The valley-fill sequence supplement the events that were not preserved in the channel sequence and provide a more extended and expanded record of climate and seismicity. For example, a progressive strengthening of monsoon was observed between 17 and 12 ka and an overall strengthened monsoon with fluctuation is inferred between 12 ka and <8 ka. This was followed by a steady decline in monsoon strength during after 8 ka to 3 ka. These evidence broadly accords well with the channel-fill stratigraphy. However, additionally, the younger valley-fill deposit which is located proximal to the modern Gunawari river dated to ~1 ka suggests a short-lived phase of renewed strengthened ISM before the onset of present day aridity.

Similar to the channel-fill sequence, the older event of seismicity pre date 17 ka which was responsible for the vertical incision and the lateral planation of the Mesozoic bedrocks in the Gunawari river valley. Whereas the younger (<3 ka) event of enhanced seismicity (which seems to continue till present) was responsible for the re-incision of the valley-fill and the channel-fill sediments along with the bedrock incision.

Further, the time averaged incision rate indicates that the terrain is uplifting at a rate of ~ 4 mm per year. Considering that the Kachchh peninsula is under compressive stress (Biswas, 2005), we attribute the periods of enhanced seismicity as observed in the present study to the episodic release of the compressive stress which seems to be intensified after 3 ka and is probably associated with the transverse faults.