CHAPTER - 4
ISLAND BELT AND WAGAD
4.1. Introduction:

Landscape analysis providing critical constraints on rates and spatial distribution of earth deformation is an important aspect to understand geodynamics of any terrain (Kirby and Whipple, 2001). Such studies may be accomplished by segmentation of the terrain into discrete blocks in order to ascertain the comparative scenario of ongoing active deformation. Though there have been the advents of high-precision space geodesy for estimating vertical component of surface deformation, however these geodetic determinations require continuous GPS measurements or traditional leveling surveys which are reasonably challenging and time-consuming (Kirby and Whipple, 2001). Although, such studies are significant in terms of inter-seismic strain accumulation; while long-term deformation rates and their pattern of occurrence remains unrevealed. This can be addressed by studies pertaining to geologic structures and geomorphic markers (Lave and Avouac, 2000). Present study encompasses the tectonically active Kachchh rift basin which is characterized into discrete blocks, which is known to behave differently. Six major uplifts describing the structural evolution of the Kachchh basin are: Pachcham, Bela, Khadir, Chorar, Wagad Highland and the Kachchh Mainland (Biswas, 1974) (Fig. 4.1A). The ‘Mainland’ uplift is the largest which is followed by the ‘Wagad-uplift’ occurring in en-echelon fashion with ‘Island-Belt’ in the north and ‘Mainland’ in the south (Biswas, 1974).

Present study is an attempt towards understanding of the role of seismicity in shaping the ephemeral fluvial landforms, describing the rate and spatial distribution of deformation in the different blocks of the Kachchh basin, viz., Pachcham, Bela (forming parts of ‘Island Belt’) and Wagad (Fig. 4.1). In order to achieve the objective, the study involves sedimentological investigations supported by optical chronology followed by estimation of steepness index ($k_s$) and morphotectonic indices.

4.1.1 Island Belt:

Pachham, Khadir, Bela and Chorar islands are located linearly towards the northern fringe of the Kachchh peninsula and are separated by the salt encrusted eastern Great Rann. These rocky islands have a steep northern escarpment and southward dipping gentle back slopes which eventually merges into the Rann surface
(Fig. 4.1A). In addition to this, fault bounded domes and faulted anticlines are present which are considered to have played significant role in the uplift of the Island belt (Biswas, 1974).

Figure-4.1(A): Map of Kachchh showing location of Island Belt Fault Zone (Blue dotted box). Major faults are marked in red. (B) Geology of Island Belt Fault Zone. Note that the IBF zone is segmented into discrete patches along the E-W direction (modified after Biswas and Deshpande, 1970).

(I) Structural Framework of Pachcham and Bela island:

The Pachcham Island which is the westernmost segment of the Island Belt Fault (IBF) consists of two east-west running hills viz., Kaladongar and Goradongar ranges and are separated by a Central-valley (Fig.4.2A). The Kaladongar Range runs along the northern margin of the island with an escarpment facing the Rann to the north and a high plateau sloping gently down to the south into the Central-valley. Goradongar range runs along the southern margin of the island. These two ranges form parts of a system of step-faults trending NW-SE with down-throw to the north. Kaladongar and Goradongar ranges are considered to be the northern and southern steps respectively (Biswas, 1993).
Babia, Dingy, Flamingo, Raimalro, Gadaputa, Kank and Modar hills are the domal uplifts. Kuar bet dome is a major dome to the northwest of Pachcham which is surrounded by Gangta bet and Karabir, Gorabir and Kakindia domes. Stratigraphically, the Pachcham Island is characterised by a distinctive suite of rocks, consisting of three parts: the lower part of the succession is mostly arenaceous, limestones and shales occur at the middle part of the succession. Arenites and rudites, with subordinate argillites and carbonates are also present. The upper part is mostly arenaceous. In addition to this, innumerable dykes and sills, omnipresent in the terrain have strongly baked the rocks. None of these are exposed in the mainland area. The crystalline basement, underlying the Kaladongar formation occurs at shallow depth. (Biswas, 1993). The rivers originating from the Kaladongar hill range flow towards south and then either turn towards the east and west on approaching the central-valley before debouching into the Rann (Fig. 4.2A).

In a similar structural set-up, the Bela Island is characterized by a hill range to the north forming a prominent escarpment, termed as Bela Hills (Fig. 4.2B). This east-west trending hill range runs throughout the Bela Island and also form a distinct domal segment along the east (e.g. Mouana Dome; Fig. 4.2B). The stratigraphy of the Bela Island comprises of the Mesozoic and Tertiary rocks (Biswas, 1987). This scarp is sub-vertical to vertical and exposes rocks of the Mesozoic formations. Mesozoic rocks of the Bela escarpment are folded into southern limb of the Lodrani anticline. The escarpment acts as a drainage divide with majority of the rivers originating from the upland draining towards the south into the Balasar lowland. Sharan, Khalwa, Gommery and Lodrani river are the major rivers draining this island (Fig.4.2B).
Unlike the mainland of Kachchh, the Island belt were least investigated. The limited studies carried out in the past suggest that this terrain is tectonically active (Biswas, 1982). More recently, Chowksey et al. (2010), based on the occurrence of raised marine notches and abraded platforms in Khadir, Bela and Banjhada islands, suggested that the terrain was block uplifted after 2 ka.

(II) Drainage pattern and river terraces (Pachcham island):

Pipri, Kiska and Bandi are the three major rivers of the Pachcham Island (Fig. 4.3).

![Figure 4.3: Drainages and major faults (Kaladongar and Goradongar) of the Pachcham island. Detail sedimentological studies have been carried out at locations-1to 7 along Pipri, Bandi and Kiska rivers.](image)

All the rivers in this island originating from the northernmost Kaladongar either gets deflected towards west or east once they reach the Central-valley (Fig.4.3). The diversion (deflection of stream course) is observed from around Semri-wandh which constitutes the foothill region of the Kaladongar fault scarp (Fig.4.3). Rivers have appreciably incised the bedrock consisting of Mesozoic limestone and sandstone which are geomorphologically expressed by the occurrence of multiple terrace surfaces.
The late-Quaternary sediment although scanty and dominated by hyperconcentrated debris-flows occurs as discrete capping on the weathered and beveled bedrock. The sequential evolution of landforms along the Pipri, Bandi and Kiska rivers can be observed in the development of distinct terrace surfaces. Based on the classification of Bull (1990), these terraces fall under the category of strath-terrace implying their development due to dominant tectonic control facilitated by subordinate climatic contribution. Observations were made pertaining to the nature and extent of the development of terrace system at 7 locations along the Pipri, Bandi and Kiska rivers. The oldest strath terrace is topographically confined to the eastern part of the island along the Kiska river. Along the Bandi river, a total of three terrace (T₁, T₂ and T₃) surfaces were carved during the late-Quaternary. Out of these terraces, T₃ is the most widespread and observed at all 7 localities. Compared to this, terrace T₂ is more distinct towards downstream (Fig. 4.3; location-3 and 4) whereas the youngest terrace T₁ is patchy in occurrence and is observed at locations 5 and 7 (Fig. 4.3). Below is the description of the sediment successions observed at multiple locations (locations-1 to 7) along the Pipri, Bandi and Kiska rivers (Fig. 4.3).

**Pipri:**

In the Pipri river, the sedimentary section has been investigated at the location shown in figure 4.3. The sediment succession studied lies along the right flank of the Pipri river (Location-1, 23°49'31.9''N and 69°50'12.8''E, Fig. 4.4). Emerging from the Kaladongar scarp, Pipri river flows ~5 km to reach the Central valley towards the south (Fig. 4.3). At location-1, the river has incised its valley forming terraces. From location-1, the Pipri river takes a southeasterly turn and flows towards the Rann. A number of tributaries originating from the Goradongar hills also join the Pipri river before it meets the Rann (Fig. 4.3).

(a) **Location-1:**

**Stratigraphy:**

At this location, ~10 m thick sediment succession overlying 1–2 m incised Mesozoic bedrock is observed (Fig. 4.4). From bottom upwards a 60 cm thick platy Tertiary sandstone dominated lithoclast horizon (Unit-I) overlies a 100 cm thick
highly weathered Tertiary ferruginous sandstone. This is followed by 100 cm thick pedogenised, calcetised, massive,

Figure 4.4 (A): Incised channel-fill adjoining the Goradongar at location-1 along the Pipri river valley. The bedrock is concealed below water (B) Close-up of the sedimentological units of the channel-fill showing five major litho units. OSL sample is dated from Unit-II. The topmost unit (Unit-V) is divided into two subunits in figure-4.5.

medium to fine sandy horizon (Unit-II). Sand shows swelling and pinching character. Above this lies 500 cm thick debris flow consisting of thick randomly oriented sandstone dominated platy lithoclasts showing crude imbrication (Unit-III). This is followed above by 120 cm thick crudely laminated, light grey coarse to medium sand (Unit-IV) which is overlain by 220 cm thick platy gravels embedded in gritty to coarse sand matrix and show crude lamination (Unit-V). (Fig.4.4). The topmost unit (Unit-V) is divided into two subunits (details shown in Figure-4.5). Bottommost subunit: unit-V(a) consists of 90 cm thick platy boulders and occasional calcretes embedded in subordinate sand matrix. This is followed above by unit-V(b) which consists of 80 cm thick platy pebbles, crudely laminated embedded in coarse to medium sand (Fig. 4.5).
Depositional Environment:

Based on the lithoclast characteristics and sediment textures, two major depositional environments can be discerned. The sediment successions of unit-I overlying the Mesozoic bedrock and unit-III to V can be interpreted as deposition under short-lived high intensity rainfall event. Such events are known to occur in arid and semi-arid landscape which led to large-scale mobilization of assorted rocky lithoclasts from poorly vegetated catchment (Hassan, 1990; Tooth, 2000). Considering that a major part of the Pipri river catchment lies in the Kaladongar dominated by sheared and fractured lithology, the occasional rainfall events would have caused the mobilization of the sediments from relatively steep slopes towards the gentler Central-valley. Occurrence of pedogenized and calcretized massive sandy unit-II suggests that the sedimentation from the upper catchment was reduced (or stopped) which facilitated the weathering and pedogenesis of the unit-II sediment. Additionally, it can be argued that during the deposition and subsequent pedogenesis of unit-II, there was landform stability in the Pachham Island.

Figure 4.5: Sub-units of the topmost unit (Unit-V) of channel-fill along the Pipri river valley (ref. figure-4.4, location-1), also shown is the OSL sample dated from Unit-V(a).

Bandi:

In the Central-valley segment of the Bandi river, incised sedimentary sections have been investigated at four locations (Fig. 4.3). The Bandi river originates from the Kaladongar hills and has incised ~10 m deep valleys in the Mesozoic sediment in the Central-valley segment. The incision depth decreases as the river approaches the Rann in the west. River terraces that were investigated are located in the Central-valley (23°52′0.2″N and 69°48′04.4″E to 23°51′55.8″N and 69°47′52.9″E) at locations 2 to 5 (Fig.4.3). Inspite of their location at the Central-valley, the river has deeply
incised its course and has carved three paired terraces (T1, T2 and T3) (Fig. 4.6). Out of these three terraces, T1 and T3 are the fluvially modified debris flow terraces whereas the terrace T2 is a fluvially modified channel-fill deposits. In the Central-valley segment of the Bandi river, four locations (2–5) have been studied (Fig. 4.3). Stratigraphy of the terrace sequences is discussed below.

Figure 4.6: Field photograph showing three terraces (T1, T2 and T3) along the Bandi river, location-2. T1 and T2 constitute channel-fill deposits. Platy lithoclasts dominated units indicate flashy hydrological condition.

(a) Location-2:

At this location, three terrace surfaces are distinctly visible (Fig. 4.6). The stratigraphy of the oldest terrace (i.e., T3) is being discussed here. The bottommost unit consist of 100 cm thick coarse to medium endurated sand (Unit-I) overlying a 850 cm thick highly weathered limonitic and ferruginous Tertiary shale and sandstone. The unit contains high concentration of rhizoliths. Overlying this is a 150 cm thick (Unit-II) angular lithoclast dominated bouldery horizon which marks the termination of sedimentation at this location (Fig. 4.7).
At location-3, stratigraphy of the T2 river terrace commences with a 320 cm thick crudely laminated sub-rounded boulder with intervening gravelly sand (Unit-I) overlying 300 cm thick Tertiary bedrock. The boulders in the horizon show a decreasing trend from bottom upwards. The upper part of this unit contains 20–30 cm thick parallel laminated pebbly gritty sand. This is followed above by 300 cm thick medium to fine sand (Unit-II) which occurs as lensoidal body. Also the unit contains rhizoliths and disseminated pebbles. This unit is succeeded by 200 cm sub-rounded to platy lithoclast, crudely imbricated and are embedded in gravelly matrix (Unit-III) (Fig.4.8).
(c) Location-4:

T2 terrace at this location comprises of 200 cm thick intense weathered shaly, limonitic ferruginous Tertiary sandstone. This unit is also weathered and contains abundant rhizoliths. Above this, unit-I consists of 360 cm thick crudely laminated, subrounded to platy sandstone, dominated with subordinate gravelly matrix (Fig.4.9).

Depositional environment (Location 2-to 4):

Broadly, two major processes can be invoked during the deposition of sedimentary succession at location 2 to 4. The coarse, endurated sand of unit-II and III indicate subdued sediment supply from the catchment, probably associated with relatively stable hydrological condition and landscape stability. On the contrary, the crudely imbricated gravelly horizon with subordinate sandy matrix of unit-I suggests flashy hydrological condition under weak hydrological discharge and or terrain instability.
At location-5, T1 terrace is documented for the sediment succession which comprises of a 60 cm thick sediment unit containing randomly oriented, sub-rounded to platy assorted lithoclasts (Unit-I) overlying a 200 cm thick incised Tertiary bedrock (Fig.4.10). Above this lies a 140 cm thick gravelly, crudely laminated and poorly sorted sand (Unit-II) which is succeeded by a 80 cm thick coarse to medium, massive sand (Unit-III).

At location-5, the sedimentation initiates with a flashy discharge which led to the scavenging of sediments from poorly vegetated catchment (Fig.4.10). Occurrence of
lensoidal to massive sand horizon indicates relatively stable condition both in terms of discharge and landscape stability.

Kiska

Kiska is a small river as compared to the Pipri and Bandi rivers and drains towards east into the Rann. The river originates from the piedmont zone of the Kaladongar range and flows southwards towards the Central-valley. Following this, it turns towards east at Jeta-Pir (Fig.4.11 and 12; Location-6 and 7) where it has incised a~13 m deep valley. In the downstream, at location 6 and 7 (Fig. 4.11 and 12), the river flows along the foothills of the Kaladongar. Although these location are proximal to the Rann (2–3 km inland from the Rann), however, the river has incised appreciably into the Tertiary rocks. Several tributary streams that emanate from the Kaladongar hills join the Kiska river on its left-flank (Fig.4.3). Two fluvial terraces viz. T4 and T1 present around location-6 and 7 are degraded and show the development of badland topography (intense weathering, erosion and gullying). The upper reach of the Kiska river bed is riddled with large boulders whereas in the downstream segment, south of Location-7, it becomes the localized alluvium dominated river. At this location (adjoining Location-6), the laterally persistent gravel-bed seems to have been vertically displaced giving rise to an impression of a normal sense of faulting (Fig.4.13). Considering that the terrain is currently under overall compressive regime (Biswas, 2005), it seems that the the events probably associated with the localized extension (discussed later). Stratigraphy and depositional environment of the sediment succession of locations 6 and 7 is discussed below:

Stratigraphy

(a) Location-6:

The oldest T4 terrace at location-6 consists of a 130 cm thick crudely imbricated platy lithoclast dominated, moderately compact horizon (unit-I) overlying a 10.5 m thick incised ferruginous Tertiary sandstone bedrock that show intense weathering with significant concentration of rhizoliths (Fig. 4.11). The lower 30 cm of this unit contains randomly oriented gravels and boulders of sandstones. This is overlain by 120 cm thick crudely laminated, calcrites and lithoclasts dominated
cemented gravel bed (unit-II). Additionally the unit also contains randomly oriented angular to sub-rounded gravelly lithoclasts.

**Depositional Environment:**
Lithoclast dominated moderately compact horizon of unit-I overlying the Mesozoic bedrock suggests rapid deposition under unstable hydrological condition. Presence of overlying crudely laminated unit-II indicates temporary stability in the hydrological discharge (less flashy condition) and probably landscape stability.

![Figure 4.11: Oldest river terrace (T4) along the Kiska river at location-6. OSL samples collected from the top part of Quaternary deposit. Bedrock concealed by vegetations.](image)

**(b) Location-7:**
At this location 140 cm thick (unit-I) is dominated by local slope wash debris (Tertiary sand stone). This is overlain by a 30 cm thick alternate fining upward gritty to coarse sandy horizon (unit-II). This is followed above by a 10 cm thick matrix supported angular gravel horizon (unit-III). The topmost unit-IV consists of 20 cm thick dark grey, coarse to medium sand mixed with angular gravel (Fig. 4.12A and B).

**Depositional Environment:**
The unit-I represents debris flow from the surrounding slope under localized rainfall event. However, following this deposition of unit-II to IV represent rather stable hydrological condition which allowed the crude segregation of sediments with occasional unstable condition, indicated by presence of intervening angular gravel of unit-III.
A total of two samples are dated along the Pipri river basin. The ages obtained range from 38±3 ka to 32±1 ka. Along the Bandi river, five samples are dated and ages range from 47±3 ka to 2±0.2 ka. The T3 terrace is dated to be ~ 47 ka, T2 ranges from 27-30 ka and T1 is dated to be 2-1 ka. Along the Kiska river, a total of three samples were dated, the oldest terrace is dated to be 62±5 ka to 65±3 ka. The alluvium along the youngest terrace (T1) of the Kiska river is dated to be 1 ± 0.1 ka. Details of the ages are given in Table-4.1.

The existing chronology is obtained for the overall dominantly assorted sediments which have been interpreted as deposition under hyperconcentrated debris flow from

Figure 4.12(A): T1 river terrace (youngest) at location-7 of Kiska river (B) Close-up of the terrace. OSL sample collected from unit-II (C)Kiska river choked with alluvium near Rann.

Figure 4.13: Gravel bed displaced by a normal fault adjoining Kiska river valley. (A) field photograph (B) the section drawn. Note highly weathered and ferruginised bedrock.

(III) **Chronology and Terraces along Pipri, Bandi and Kiska rivers:**

A total of two samples are dated along the Pipri river basin. The ages obtained ranges from 38±3 ka to 32±1 ka. Along the Bandi river, five samples are dated and ages range from 47±3 ka to 2±0.2 ka. The T3 terrace is dated to be ~ 47 ka, T2 ranges from 27-30 ka and T1 is dated to be 2-1 ka. Along the Kiska river, a total of three samples were dated, the oldest terrace is dated to be 62±5 ka to 65±3 ka. The alluvium along the youngest terrace (T1) of the Kiska river is dated to be 1 ± 0.1 ka. Details of the ages are given in Table-4.1.

The existing chronology is obtained for the overall dominantly assorted sediments which have been interpreted as deposition under hyperconcentrated debris flow from
the source proximal regions which in the present case is dominantly the Kaladungar hill with localized contribution from the Goradungar in Pipri river (Location-1). In terms of the regional climatic scenario, except for the Kiska river where the ages correspond to the cold but relatively wet Marine Isotopic Stage-4 (MIS-4; 65 ka - 62 ka) (Fontugue et al., 1986). The subsequent ages viz. between 47 ka and 32 ka (except for 2 ka) correspond to the wet Marine Isotopic Stage-3 (Juyal et al., 2006 and reference therein). This would imply that considering the arid and semi-arid characteristic of the northern Kachchh, the mobilization of the sediment from source proximal areas occurred during the period of relatively intensified Indian Summer Monsoon (ISM). However, the incision which post date the dispositional events (after MIS-3) indicate the stream power was augmented not by the increase in fluvial discharge (ISM) but was due to the enhanced surface uplift (over steepening of the bedrock). Thus the bedrock incision in the rivers studied can be ascribed to the dominance of tectonics with subordinate contribution from the ISM.

Table-4.1: Showing dose rates and ages of samples along Bandi, Kiska and Pipri rivers.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K(%)</th>
<th>CAM De (Gy)</th>
<th>MAM De (Gy)</th>
<th>OD %</th>
<th>Dose Rate (Gy/ka)</th>
<th>CAM Age (ka)</th>
<th>MAM Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN-1A</td>
<td>1.14 ± 0.07</td>
<td>4.93 ± 0.29</td>
<td>0.33 ± 0.02</td>
<td>51 ± 3</td>
<td>45 ± 2</td>
<td>40</td>
<td>1 ± 0.04</td>
<td>53 ± 4</td>
<td>47 ± 3</td>
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<tr>
<td>BN-2A</td>
<td>1.86 ± 0.04</td>
<td>10.8 ± 0.22</td>
<td>1.13 ± 0.01</td>
<td>67 ± 2</td>
<td>66 ± 2</td>
<td>25</td>
<td>2 ± 0.1</td>
<td>31 ± 1</td>
<td>30 ± 1</td>
</tr>
<tr>
<td>BN-3</td>
<td>1.9 ± 0.06</td>
<td>11.45 ± 0.3</td>
<td>1.14 ± 0.02</td>
<td>119 ± 5</td>
<td>60 ± 4</td>
<td>44</td>
<td>2 ± 0.1</td>
<td>53 ± 3</td>
<td>27 ± 2</td>
</tr>
<tr>
<td>BN-4</td>
<td>1.25 ± 0.03</td>
<td>6.29 ± 0.13</td>
<td>0.91 ± 0.01</td>
<td>6.5 ± 0.3</td>
<td>3 ± 0.3</td>
<td>43</td>
<td>1.6 ± 0.1</td>
<td>4 ± 0.2</td>
<td>2 ± 0.2</td>
</tr>
<tr>
<td>JP-2</td>
<td>2.04 ± 0.04</td>
<td>9.4 ± 0.19</td>
<td>0.57 ± 0.01</td>
<td>187 ± 7</td>
<td>101 ± 8</td>
<td>31</td>
<td>1.6 ± 0.1</td>
<td>114 ± 6</td>
<td>62 ± 5</td>
</tr>
<tr>
<td>JP-3</td>
<td>0.89 ± 0.02</td>
<td>10 ± 0.19</td>
<td>0.86 ± 0.01</td>
<td>110 ± 3</td>
<td>110 ± 2</td>
<td>20</td>
<td>2 ± 0.1</td>
<td>65 ± 3</td>
<td>65 ± 3</td>
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<tr>
<td>KR-1</td>
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<td>7.6 ± 0.24</td>
<td>0.74 ± 0.02</td>
<td>4 ± 0.2</td>
<td>2 ± 0.2</td>
<td>44</td>
<td>1.5 ± 0.1</td>
<td>2.6 ± 0.2</td>
<td>1 ± 0.1</td>
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<tr>
<td>PPR-1A</td>
<td>2.3 ± 0.05</td>
<td>11.59 ± 0.26</td>
<td>0.83 ± 0.01</td>
<td>144 ± 5</td>
<td>78 ± 6</td>
<td>34</td>
<td>2 ± 0.1</td>
<td>70 ± 4</td>
<td>38 ± 3</td>
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<tr>
<td>PPR-2</td>
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<td>1.23 ± 0.02</td>
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<td>39 ± 2</td>
<td>23</td>
<td>2 ± 0.1</td>
<td>32 ± 1</td>
<td>19 ± 1</td>
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</tbody>
</table>

(IV) Incision and aggradation:

An attempt has been made to estimate the phases of incision and aggradation along the Bandi river of the Pachcham island. In tectonically active areas, long-term variations of climate and tectonics (>0.1-1 ka) might lead to gross changes in the
incision/aggradation behavior of the rivers (Schumm, 1969; Bull, 1991; Pazzaglia and Brandon, 2001). The rivers in the Pachcham island have been subjected to lateral/wide incision whereby the river channel incised downward and laterally, commonly into the bedrock, in order to generate a broad flat valley bottom. Following this, the river initiated aggradation which may be attributed to the increase in sediment load (Pazzaglia and Brandon, 2001). The aggradation has resulted in the formation of fill-terrace deposits along the Bandi river of the Pachcham island. The resultant of the process of incision developed strath terrace which is used to estimate rock uplift or incision-rate. We used height of terrace-tread and the OSL age obtained immediately above the bedrock in order to arrive at the incision-rate. Detail of the methodology can be referred from chapter-2.

Four strath terraces (Location-2 to 5) have been used along this river for estimating the incision-rate. Sediment succession above the bedrock strath is dated at three terrace surfaces along the Bandi river.

![Graph showing incision rate obtained from the strath terraces (T1, T2 and T3) along the Bandi river of the Pachcham island. Please note the phases of aggradation and incision.](image)

The linear regression drawn along the dated surfaces gave a slope of 0.1 which correspond to the incision rate (discussed in chapter-2). Strath terrace (T3) was carved prior to ~ 47 ka, which was an era of incision when the river incised the bedrock laterally generating broad flat valley bottom. Following this, the river initiated aggradation till it reached the topmost height of the terrace tread. Then the aggradation ceased giving way to incision due to surface uplift. This incision/ uplift generated the strath surface of the second terrace (T2) before ~30 ka. Aggradation
resumed till the third phase of incision which led to the formation of third and youngest strath terrace (T1) prior to 2 ka. The aggradation on the T1 terrace surface continued till 1 ka when it ceased and was replaced by re-incision of the river to its present level. An incision-rate of 0.1 ± 0.01 mm/yr or 1 cm/ka has been estimated for strath terraces along the Bandi river of the Pachcham island (Fig. 4.14).

**(V) Steepness-index analyses of Pachcham and Bela islands:**

In order to obtain relative estimate on the tectonic instability/stability, steepness-index analyses of Pipri, Bandi and Kiska rivers of the Pachcham island and Lodrani, Gommery, Khalwa and Sharan river of the Bela islands have been carried out. Detailed methodology is given in chapter-2.

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Figure: 4.15: DEM and distribution of normalized steepness index ($K_{sn}$, with $\theta=45^0$) values along (A) Bandi, Pipri and Kiska rivers of Pachcham (B) Lodrani, Gommery, Khalwa and Sharan rivers of Bela island.
It has been observed that overall steepness index values decrease systematically from north to south in Pachcham and Bela islands. However minor fluctuations have been observed in the vicinity of structural discontinuities.

In Pachcham Island, the normalized steepness index ($k_{sn}$), decreases from the northernmost Kaladongar fault zone (57) to the southern Goradungar fault zone (4.0) (Fig.4.15). The Pipri river while traversing through the Central Valley exhibits gradual decrease in $k_{sn}$ values (Fig. 4.15) which accords well with the morphology of longitudinal river profiles viz. the higher $k_{sn}$ values are associated with clustering of knickpoint (K1 and K2; Fig.4.16) which indicate differential movement/uplift as have been observed along most of the active orogens (Seeber and Gornitz, 1983; Whittaker et al., 2007).

Figure 4.16: Longitudinal profiles of Bandi, Pipri and Kiska rivers of the Pachcham island and knickpoint clusters (K1 and K2). Inset shows the concavities ($\phi$) obtained from the regression associated with the steepness index estimations.
In Bandi, Pipri and Kiska rivers, the $k_{sn}$ values vary from 7−46, 4−58, and 15−45 respectively. The variations of $k_{sn}$ values are consistent with the original Steepness index ($k_s$) values. Further, clustering of $k_{sn}$ values along the knickpoints implies that terrain is undergoing differential uplift (Fig. 4.15 and 4.16). However, the concavities along the slope vs. area plot show a non-uniform relationship along the major rivers of the Pachcham Island (Fig.4.16). Higher values of concavities are concentrated along the domal structures (Fig.4.17). Concavities in the Pachcham Island are on the higher side along the westernmost part (0.79) and decreases eastward (0.51 to 0.07) along Bandi and Kiska river valleys respectively (Fig.4.17).

Figure: 4.17: Distribution of concavities associated with the estimation of steepness indices along Bandi, Pipri, Kiska, Lodrani, Gommery, Khalwa and Sharan rivers of the Pachcham and Bela island. Mean concavity obtained is $\bar{\omega}=0.47$. Higher concavities observed towards the domal uplifts.

In the case of the Bela island, the normalized steepness index ($k_{sn}$) varies from (2−36) for Lodrani, (3−67) for Gommery, (4−98) for Khalwa and (9−29) for Sharan river. These values consistently decrease from northern escarpment to the south towards the Rann (Fig.4.15). Knickpoint clusters have also been observed towards the northern escarpment (Fig.4.18). Figure 4.19 show a correlation plot between the $k_{sn}$ values and the longitudinal profiles and show a reasonable correlation between the $K_{sn}$ values and the topographic relief.
The relative values of active tectonics have been ascertained by comparing the steepness indices with Stream-length gradient index (SL), Sinuosity index (SI) and drainage area. The SL values investigate stream power which is proportional to the product of stream discharge and slope (Hack, 1973). SI helps to identify minor deformation in the drainage basins as any tectonic deformation changing the slope of a river valley results in corresponding change in sinuosity to maintain the equilibrium channel slope (Keller and Pinter, 2002). SL values show a positive correlation with that of $k_{sn}$ values (Fig. 4.19A) and show an abrupt change in the vicinity of Kaladongar and Goradongar fault zones. SI values close to 1 have been observed along Kaladongar and Bela escarpments which accords well with its topography (uplifted segment) (Fig. 4.19B).
Figure 4.19: Comparative studies of normalized steepness indices (ksn) vs. SL, SI and drainage area of (A), (B), (C) of Pachcham island and (D), (E), (F) of Bela island. [Plus sign (+) indicates Ksn values].
Figure 4.20: Comparative studies between steepness indices and SL, SI, drainage area and elevation. Grey bar indicates zones of enhanced uplifts [Plus sign (+) indicates $K_{sn}$ values].
With respect to drainage area of the major rivers, overall $k_{sn}$ values show opposite trend. Drainage area vs. $k_{sn}$ plots, although at a smaller scale suggest equilibrium of the rivers with the topography (Fig. 4.19C). In case of Bela island, the steepness indices show less steep slope. $k_{sn}$ values are conformable with the slope variations and SL indices show concordant trend with the $k_{sn}$ values (Fig. 4.19D). Unlike the Pachcham island which is traversed by the two major structural discontinuities viz. the Kaladongar and Goradongar faults, the Bela island consists of a major scarp at its northern margin and hence $k_{sn}$ vs. SL plots differ along both these islands. SI values are close to 1 and are divergent with respect to $k_{sn}$ values in the Bela island (Fig. 4.19E). Drainage area vs. $k_{sn}$ plots indicate opposite trend as all the major rivers follow the topography and merge into the Rann towards south (Fig. 4.19F). A close correspondence between the steepness indices and SL, SI, drainage area and elevation indicates zones of enhanced uplifts along Pachcham and Bela islands (Fig. 4.20).

(VI) Discussion:

(A) Paleoseismicity:

The oldest strath terrace along the Kiska river is dated to 65–62 ka and is parallel to the Kiska river trending NW-SE at location-6 and 7. This terrace consisting of beveled Mesozoic bedrock underlying the debris flow deposit suggests lateral planation of bedrock as well as regional tilting prior to its deposition. The absence of the oldest terrace at other locations (locations-1 to 5) suggests tectonic tilting prior to 62–65 ka at eastern part of the Pachcham island (Kiska river). The sediment deposits at location-7 (terrace T3) could be due its location in the Central valley and proximity to the Rann which provided the requisite accommodation spaces over the beveled and tilted Mesozoic rocks. The terrace sediment at Pipri river is dated to 38 ka implying the beveling of the bedrock predating 38 ka. The lesser thickness (2 m) of the incised bedrock and significantly thicker (10 m) of overlying sediments can be interpreted as relative landscape stability (subdued tectonic activity) after ~38 ka. Although speculative, we tend to suggest that the accommodation space for terrace sediment aggradation was probably facilitated by synsedimentary subsidence in Central valley. Three terraces (T1, T2 and T3) along the Bandi river is observed to have developed over the beveled Mesozoic bedrocks and sedimentation commences with the
deposition of slope-controlled debris flow. The most extensive and oldest planation surface corresponding to terrace T3 is dated to ~47 ka in the Bandi river valley. The younger terrace T2 is dated between 27–30 ka. Whereas the youngest terrace T1 in Bandi and Kiska rivers is dated between 2–1 ka respectively (Fig. 4.10 and 4.12). Based on the terrace morphology and optical chronology, it can be suggested that the river incision initiated with the development of oldest terrace at the eastern end of the Pachcham Island ~65 ka (MIS-4). Following this, the incision propagated through the central and western part at ~47 to 27 ka (MIS-3 and early part of MIS-2) giving rise to the formation of terrace T3 and T2 respectively. The youngest terrace T1 (2–2.6 ka) which occurs as discrete terrace treads can be suggestive of the youngest major tectonic event in the Island belt region. Considering that the Island belt is traversed by the geologically youngest NE-SW and NW-SE trending strike-slip faults (Biswa, 1995), we ascribe the landform deformation as observed in the present study to the activity along these faults.

(B) Paleoenvironment:

To summarize the evidence presented above, it can be suggested that the tectonically active nature of the terrain is recorded by the sedimentation pattern in the river terraces. The sediments that constitute the terraces are dominated by debris flow deposits. These deposits were derived locally from the surrounding slopes during the cold and wet MIS-4 and pluvial MIS-3. Following their deposition the assorted source proximal sediments were modified (terraced) by the impersistent fluvial activities. The terraces are virtually deprived of pure fluvial sediments which are invariably underlain by beveled Tertiary bedrocks. The textural characteristics of the terrace sediments (discussed earlier) indicate that the sedimentation occurred dominantly during the wet (pluvial) MIS-3, however considering the proximity of the sediment provenance, the textural attributes largely indicate flashy fluvial condition. Thus the pattern of sedimentation although reflect a very flashy (stormy discharge) condition, however, the incision of the fill sediment along with the variable thickness of the underlying bedrock invariably indicate role of surface uplift (discussed earlier). This is further supported by the morphometric indices, steepness index, geomorphology and sedimentation pattern, it can be suggested that the terrain along the Island belt was tectonically active during the last 65 ka and probably continued intermittently until around 2 ka.
4.1.2. Wagad

It has been suggested that the eastern part of Kachchh is a highly strained zone for potential earthquakes (Biswas and Khattri, 2002; Mathew et al., 2006) and is capable of generating large magnitude earthquakes in near future (Rastogi, 2001; Mandal et al., 2004). Data obtained on the magnitude of earthquakes in Kachchh by the Institute of Seismological Research (ISR), Gandhinagar, indicate that the seismicity is concentrated in the eastern Kachchh with two prominent clustering between the KMF and NWF and around the GF (Fig. 4.21) (source: ISR, Earthquake Catalogue).

There are some studies pertaining to the drainage basin analyses from Kachchh, (Biswas, 1974; Maurya et al., 2003a; Maurya et al., 2003b; Patidar et al., 2007; Thakkar et al., 2001; Thakkar et al., 2006) which provides a broad insight (at regional scale) on the role of tectonics in the landform evolution. However, at a smaller scale, such studies are lacking. In view of this, the present study is focused on a small area of 4000 sq. km in the eastern Kachchh between the North Wagad Fault (NWF) and the Gedi Fault (GF) (Fig.4.22). Using the basin morphology and drainage network, an attempt has been made to understand the role of seismicity (structure) in

![Figure 4.21: Map showing the distribution of earthquake epicentres in the NE Kachchh. Note two major clustering between the KMF and NWF and around GF. (Source: Earthquake data obtained from ISR, Gandhinagar catalogue 2006-2010).](image-url)
Structures of Wagad

The E-W trending faults in the eastern Kachchh are identified as the South Wagad Fault (SWF), NWF and GF (Biswa and Khattri, 2002; Rastogi, 2001; Mandal et al. 2004) (Fig. 4.22). In addition to this, Manfara Fault (MF) which trends NE-SW (transverse fault) has displaced the E-W trending faults suggesting its young age. The 2001 Bhuj earthquake was associated with the activity along the MF (Rastogi, 2001; McCalpin and Thakkar, 2003). Additionally, moderate earthquake of M_w 5.0 during 2006 was associated with the GF implying the active nature of this fault (Rastogi, 2008).

Geomorphology and drainage network:

Wagad upland is the second largest upland area in Kachchh (Biswa and Deshpande, 1970; Biswas, 1987) which extends from latitude 23^020’N and 23^045’N and longitude 70^015’E and 71^010’E. The area is surrounded by Rav basin to the north and the Little Rann of Kachchh to the south-east. Lithologically, the terrain is dominated by Jurassic and Cretaceous sand stone, shale and lime stone with some out
crop of Tertiary lime stone and sand stone in the north and southeast of Wagad (Biswas and Deshpande, 1970) (Fig. 4.23).

Geomorphologically, the study area can be divided into three major geomorphic units. These are (i) the upper planation surface dominated by juvenile streams (ii) the middle incised slopes with piedmont and (iii) the lower Rann plain. The upper planation surface represents early Quaternary erosional event, the middle incised slopes with terraces developed during the late Quaternary which together supplied sediment to the lower peripheral areas (Biswas, 1974). There are five fifth order ephemeral streams which originate from the Wagad Upland. These streams follow the regional tilt of the Wagad upland which is towards the north and drains into the Great Rann (Fig. 4.23).
III) Morphometric studies

(a) Stream length-gradient ratio (SL)

High relief areas with higher SL values > 200 are located towards south (proximity of NWF) whereas the lower SL values (<50) are observed around low relief areas located towards the north (proximal to GF).

(b) Asymmetric Factor (AF) and Drainage Basin Asymmetry (DBA)

In a stable setting the AF is ~50, implying absence of abnormal tilting and values smaller or larger than 50 indicates tilting (Keller and Pinter, 1996; Burbank and Anderson, 2001). The AF of >50 and <50 of the rivers in the present study suggests preferential tilt in the river valleys. This is further indicated by the preferred westward shift, except the Karaswali river which show eastward tilting (Fig. 4.24). In addition to this, the Drainage Basin Asymmetry (DBA) analyses further helps in understanding the role of tectonics in the evolution of basin morphology (Cox et al. 2001). DBA values indicate direction of regional migration which is the manifestation...
of ground tilting (Keller and Pinter, 1996). The DBA values of 1 indicate that the rivers are flowing symmetrically whereas value <1 indicate asymmetrical nature caused due to tilting (Cox et al., 2001) All the five rivers show DBA values <1 suggesting tilting.

(c) Sinuosity index (SI)

Any tectonic deformation that changes the slope of a river valley results in a corresponding change in sinuosity to maintain the equilibrium channel slope (Keller and Pinter, 1996). Thus, the sinuosity index (SI) helps in identifying minor deformation in the drainage basin. Sinuosity index close to 1 indicate actively deforming area (Burbank and Anderson, 2001). The high sinuosity values are observed in the upper planation surface (proximal to the NWF) dominated by juvenile streams. This indicates that the area is undergoing active deformation (Figs. 4.24a, b and c). Tectonic movements change the gradient of a river and modify the valley.

(d) Elongation Ratio (Re):

Elongation Ratio (Re) is a morphometric variable that quantitatively describes the planimetric shape of a basin, thus provides information about the degree of basin maturity. It has been observed that the rivers draining through tectonically active basins are more elongated and become more circular with the cessation of uplift (Kale et al. 2008; Burbank and Anderson, 2001). Elongation Ratio of the five rivers that are investigated has a Re <1, indicating elongated shape of the rivers hence tectonically active. Narelawali river is the most elongated of all the five rivers, with a Re value of 0.44.

(IV) Sedimentological studies

Detail sedimentological investigations have been carried out along Karaswali, Dharawali and Bhimguda rivers flowing through the Wagad highland. These rivers originate from the Wagad hills consisting of innumerable domes and anticlines and embark on their journey towards the Rann in the north (Fig. 4.23). Overall, the rivers form parallel drainage pattern. Bhimguda river is the only river which has got deflected towards the west at Trambau (Fig. 4.23). Sediment successions along
Karaswali, Dharawali and Bhimguda river valleys (Location-1 to 5) are discussed below.

**Karaswali**

*a) Location-1:*

Along the Karaswali river, debris flow deposits aprons the horizontally bedded, beveled bedrock surface (Fig. 4.25). At location-1 abrupt lowering of topography and termination of Wagad upland has been observed. E-W trending small tributaries incise through the debris flow deposits (~5 m) and meet the present Karaswali river. The river has carved a terrace surface which laterally extends towards the north.

![Field photograph and stratigraphy of the fluvial terrace observed along the Karaswali river of Wagad.](image)

The sedimentological investigation is carried out along the right flank of the river (with a single terrace surface), while in the left flank, two terraces have been observed. The older terrace is presently under cultivation while the younger terrace is filled with debris flow. The sediment succession at this location consists of 2 m thick massive, gritty, coarse sand, dark brown in color containing angular dispersed sandstone lithoclasts overlying 6 m thick fractured, ferruginous parallel laminated sandstone form the bedrock (Fig. 4.25). Deposition of this unit could be attributed to sudden gravity flow.
Dharawali

b) Location-2:

Dharawali river form the extreme eastern branch of the Phalku river of the Wagad Highland. (Fig. 4.23).

Figure 4.26: Field photographs and stratigraphy of the fluvial terrace of the Dharawali river of Wagad Highland. (A) Longitudinal cross-section of the Dharawali river showing three major stratigraphical units underlain by bedrock. Please note the positions of Location-A, B and C along the river valley (B) Stratigraphical records of Location-A (C) Stratigraphical records of Location-B and (D) Field photograph and cross-section of a transverse channel along the Dharawali river.

Locations A, B and C demarcate the sediment sequences of the river terrace observed along this river (Fig. 4.26). Location-A exhibits near complete stratigraphic sequence, terrace deposit at Location-B is situated downstream. At location-C, an incised channel-fill section is preserved.

At location-A, the bottommost unit-I which is 250 cm thick overlies a 310 cm thick incised bedrock. The sediment succession comprises weathered, fractured clay
containing ferruginous sandstone and quartz, angular to sub-rounded gravel and pebbles (Fig. 4.26A and B). This is followed above by a 70 cm thick (Unit-II) dominated by angular to sub-rounded ferruginous sandstone and gravel embedded in crudely laminated gritty sand. This is overlain by 230 cm thick massive, gritty sand with angular and sub-rounded ferruginous sandstone gravel (Unit-III).

At location-B, a 200 cm thick angular to sub-rounded gravel and pebble dominated horizon embedded in fractured and weathered clay, forms unit-I above the 330 cm thick Mesozoic bedrock (Fig. 4.26A and C).

At location-C, a channel-fill sequence consists of 50 cm thick crudely laminated gravelly unit with sub-rounded to angular ferruginous sandstone lithoclast (Unit-I) (Fig. 4.26A and D). This is followed above by a 70 cm thick crudely laminated, gritty sand with angular gravels (Unit-II). The uppermost 100 cm thick (Unit-III) is dominated by massive gritty sand.

*Depositional environment*

*Location-A and B:*

Gravelly and pebbly horizon of unit-I of location-A suggests its deposition under sudden gravity flow which is followed upward by crudely laminated gritty sand of unit-II which indicates fluvial regime. Overlying massive units indicates rapid deposition and the topmost deposits of crudely laminated gritty sand reflect resumption of the fluvial regime.

*Location-C:*

Overall the deposition appears to have occurred under variable sediment water ratio (weak to moderate hydrological discharge).

*Bhimguda*

*(Location-3 to 5):*

Along the Bhimguda river, the sediment succession in the terraces demonstrates crude, cross stratified angular gravels. These sediments are deposited above the Mesozoic bedrock and debris flow units (Fig. 4.27). Samples for optical dating is collected from the river terrace (Location-3 and 4) and from the downstream section (Location-5). A variable depth of incision is observed along this river which ranges from 50 cm to > 3 m. Locations 3, 4 and 5 are situated in the vicinity of Trambau,
where the river abruptly deflected towards west (Fig. 4.23). A 2 m thick incised scroll-bar dominated with medium to fine sand with occasional silty-clay is exposed in the right bank of the river.

**Stratigraphy**

*(c) Location-3:*

At location-3, sedimentation commences with deposition of a 150 cm thick cross stratified; angular gravelly horizon (Unit-I) dominated by ferruginous sandstone. The sediment was deposited over a 250 cm thick incised Mesozoic sandstone. Overlying this unit is a 360 cm thick fluvial sediment (Unit-II) mixed with angular to sub-rounded lithoclasts (Fig. 4.27A).

<table>
<thead>
<tr>
<th>Location-3</th>
<th>Location-4</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Location-3" /></td>
<td><img src="image2" alt="Location-4" /></td>
</tr>
</tbody>
</table>

Figure 4.27: Field photograph and stratigraphy of (A) Location-3 (B) Location-4 and (3) Location-5 along the Bhimguda river of the Wagad highland.

*(d) Location-4:*

At location-4, two sedimentary units have been identified. The lower unit-I which is 260 cm thick is dominated by crudely laminated, cross-stratified gravel. This is overlain by a 300 cm thick colluvial unit dominated by boulders of Mesozoic ferruginous sandstone (Unit-II) (Fig. 4.27B).

*(e) Location-5:*

At location-5, four sedimentary units have been identified which were deposited on a 50 cm thick incised Tertiary bedrock (Fig. 4.27C). From bottom upwards the unit-I consists of 50 cm thick coarse to medium sand with platy lithoclasts of ferruginous sandstone interspersed within laminated gritty sand and
clayey silt. Overlying this is a 10 cm thick parallel laminated, endurated clayey-silt (Unit-II). Above this is a 75 cm thick parallel laminated and endurated medium to fine sand (Unit-III). This unit consists of disperse pebbles. Following this above is the 50 cm thick brownish massive sand (Unit-IV).

Depositional environment:

Location 3 and 4:

The pattern of sedimentation indicates that short-lived high energy fluvial environment persisted during the deposition of unit-I and II.

Location 5:

Sedimentation of Unit-I and II indicates stable fluvial condition which deposited parallel laminated gritty sand and clayey silt. It appears that the hydrological condition became gradually strengthened with the deposition of laminated sand of unit-III and IV.

(V) Chronology of the river terraces:

A total of nine samples have been optically dated from the sandy horizons. The sediment succession along the Karaswali river is dated to 0.8±0.1 ka, 1±0.1 ka. The river terrace along the Dharawali river valley is dated to 15±1 ka. Channel-fill along the Dharawali river is dated to 2.7±0.1 ka and 1.7±0.1 ka. The river terrace overlying the Tertiary bedrock along the Bhimguda river is dated to 29±2 to 24±2 ka. The sediment succession at the downstream of this river is dated to 2±0.2 ka to 1±0.04 ka (Table-4.2). Scrol bar deposited along the Bhimguda river is dated to 0.2 ±0.02 ka.

Table-4.2: Showing dose rates and ages of the OSL samples of the Wagad upland

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K(%)</th>
<th>CAM De (Gy)</th>
<th>MAM De (Gy)</th>
<th>OD %</th>
<th>Dose Rate (Gy/ka)</th>
<th>CAM Age (ka)</th>
<th>MAM Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGD Loc2_1</td>
<td>1.8 ± 0.04</td>
<td>11.3 ± 0.23</td>
<td>1.06 ± 0.01</td>
<td>10 ± 0.8</td>
<td>4.5 ± 0.5</td>
<td>71</td>
<td>2 ± 0.1</td>
<td>4.6 ± 0.4</td>
<td>2 ± 0.2</td>
</tr>
<tr>
<td>BGD-1</td>
<td>0.85 ± 0.02</td>
<td>5 ± 0.1</td>
<td>0.33 ± 0.003</td>
<td>40 ± 1.4</td>
<td>22 ± 1.4</td>
<td>30</td>
<td>1 ± 0.03</td>
<td>44 ± 2</td>
<td>24 ±2</td>
</tr>
<tr>
<td>BGD-2</td>
<td>1.38 ± 0.03</td>
<td>9.7 ± 0.19</td>
<td>0.59 ± 0.01</td>
<td>44 ± 2</td>
<td>44 ±2</td>
<td>30</td>
<td>1.5 ± 0.1</td>
<td>29 ± 2</td>
<td>29 ± 2</td>
</tr>
<tr>
<td>BGD2- Loc2</td>
<td>1.44 ± 0.03</td>
<td>9.75 ± 0.20</td>
<td>1.26 ± 0.01</td>
<td>1.5 ± 0.08</td>
<td>1.4 ± 0.09</td>
<td>48</td>
<td>2 ± 0.1</td>
<td>1 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>BGBS-1</td>
<td>4.06 ± 0.08</td>
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<td>1.49 ± 0.01</td>
<td>1.2 ± 0.07</td>
<td>1.2 ± 0.07</td>
<td>62</td>
<td>4.3 ± 0.1</td>
<td>276 ± 0.02 (a)</td>
<td>276 ± 0.02 (a)</td>
</tr>
<tr>
<td>KRD-1B</td>
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<td>17 ± 0.39</td>
<td>0.88 ± 0.02</td>
<td>3 ± 0.15</td>
<td>3 ± 0.14</td>
<td>40</td>
<td>2.4 ± 0.01</td>
<td>1.3 ± 0.08</td>
<td>1.3 ± 0.08</td>
</tr>
<tr>
<td>KRD-2</td>
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<td>16 ± 0.26</td>
<td>0.94 ± 0.01</td>
<td>5 ± 0.4</td>
<td>2 ± 0.2</td>
<td>66</td>
<td>2.4 ± 0.01</td>
<td>2 ± 0.2</td>
<td>830 ± 0.1 (a)</td>
</tr>
<tr>
<td>KRS-Loc2</td>
<td>2.2 ± 0.04</td>
<td>16 ± 0.26</td>
<td>0.94 ± 0.01</td>
<td>37 ± 1.5</td>
<td>19 ± 1.4</td>
<td>37</td>
<td>2.4 ± 0.1</td>
<td>15 ± 1</td>
<td>7.8 ± 0.6</td>
</tr>
<tr>
<td>KRS Ch-bottom</td>
<td>2.26 ± 0.05</td>
<td>16.4 ± 0.32</td>
<td>0.63 ± 0.02</td>
<td>6 ± 0.18</td>
<td>5 ± 0.19</td>
<td>24</td>
<td>2 ± 0.1</td>
<td>2.7 ± 0.1</td>
<td>2.3 ± 0.1</td>
</tr>
<tr>
<td>KRS Ch-top</td>
<td>1.75 ± 0.05</td>
<td>9.37 ± 0.26</td>
<td>0.75 ± 0.01</td>
<td>3.2 ± 0.18</td>
<td>3 ± 0.15</td>
<td>40</td>
<td>1.7 ± 0.1</td>
<td>1.8 ± 0.1</td>
<td>1.7 ± 0.1</td>
</tr>
</tbody>
</table>
(VI) Incision and aggradation:

Three strath terraces (at Location-A, B and C) along the Dharawali river and two strath terraces (at Location-3 and 5) along the Bhimguda river have been used for estimating the incision-rate. Strath terrace at location-A and B along the Dharawali river were carved prior to ~15 ka, indicating phase of incision. Following this, the river initiated aggradation till it reached the topmost tread height. Prior to 2.7 ka, there were channel activities which cut into the bedrock incising the overlying alluvial deposits and created accommodation space for the channel-fill deposits (Fig. 4.26A). Aggradation of the channel-fill deposits continued from ~3 to 2 ka. Dharawali river resumed its phases of incision post ~2 ka when it incised its own deposits as well as the transverse channel-fill deposits (Fig. 4.26 and 4.28). Long-term incision rate is estimated to be 0.1 ± 0.01 mm/yr or 1 cm/ka.

In the adjoining Bhimguda river, at location-3, the strath terrace is carved prior to ~29 ka. Aggradation in the form of platy-lithoclast dominated, high energy fluvial deposits continued from ~29 to 24 ka. Post this phase of aggradation, the river mostly engaged in the process of incision till ~2 ka when there were stable hydrological regimes which deposited parallel-laminated sandy and silty-horizons at location-5. The aggradation lasted ~1 ka which was finally followed by incision of the river to its present level. Incision rate is obtained to be 0.2 ± 0.01 mm/yr or 2 cm/ka long the Bhimguda river.
(VII) Discussion:

The non graded nature of the stream, low Vf ratio (Fig. 4.24), and AF values >50 and <50, low sinuosity (~1) and <1 DBA together suggests strong tectonic control on the drainage basin evolution in the study area. As mentioned above the area is bounded by Gedi Fault (GF) in the north and North Wagad Fault (NWF) in the south. These faults run more or less parallel to each other and strike E-W. Based on fault plane solutions, the NWF is a south dipping blind fault and the Wagad uplift is considered to be associated with the NWF (Rastogi, 2001; Mandal et al., 2004). During March 2006, an earthquake of magnitude 5.0 was associated with the GF (Rastogi, 2008). The seismological observations made by the ISR Gandhinagar show that following the 2001 Bhuj earthquake, there is a significant increase in the aftershocks particularly between the KMF and the NWF and around the GF (Fig. 4.21). The morphotectonic setting and the earthquake activities together suggests that the study area is seismically active; hence it is reasonable that the drainage basins are responding to the ongoing tectonic activity associated with the NWF, GF and their subsidiary splays (Fig. 4.24). Geomorphic indices allowed us to infer the linear structures which seem to be splays of the major faults viz. the NWF and GF (Lineament L1) and the N-S trending basement high (Lineament L2) (Fig. 4.24). In addition to this, our data suggests that the NWF is displaced by the N-S trending lineament (L2) implying that L2 is very young structure in the study area probably developed in response to the activity along the MF (Figs. 4.22). Further, the Asymmetric Factor (AF) and Drainage Basin Asymmetry (DBA) indicate that rivers are preferentially deflected towards west that would imply a left lateral displacement along the NWF (Fig. 4.24). Evidence of active deformation particularly in the upper planation surface (proximal to the NWF) is indicated by the low sinuosity values (Figs. 4.24a, b, and c). Development of knick points in competent Wagad sandstones (Figs. 4.24) and associated incision (3–9 m) in an arid fluvial system further suggests that the incision is associated with the high uplift in the area. Based on the existing data it can be speculated that compared to the GF, the NWF seems to be more active during the recent geological past.

The limited field observations carried out in Karaswali and Malan river valleys (23.57°N, 70.65°E) near Gedi and Sangadh villages indicate that these rivers before meeting the GF flow towards NW-SE and as they approach the GF, they
Figure 4.29: Satellite data (source Google) showing meandering segments of Karaswali and Malan Rivers. White arrows along the two rivers indicate their flow directions.

follow the trace of GF which is E-W (Fig. 4.29). In addition to this, a localized ponding on the Karaswali River bed (Fig. 4.30a) suggest obstruction of river course due to sediment mobilization from the surrounding. Such sediment mobilization leading to river ponding was associated with the active tectonics (Sundriyal et al., 2007). Further, differential incision (~4 m) on the SW flank of the Karaswali river (Fig. 4.30b) indicate tectonically assisted enhanced stream power of an ephemeral river. The incision is absent on the NE flank and river has deflected towards the SW direction with a tilt of 8-10° (Fig. 4.30b). Evidence for the tectonic instability in the area is further suggested by the presence of ~100 m long and 6–20 cm wide fissures along Karaswali river course which penetrated well below the tertiary sandstone (Figs. 4.30c and d).

Although the present study is preliminary in nature, however, it has been demonstrated that the there have been tectonic signatures in the Wagad highland in the form of river terraces. In addition to this morphometric indices also suggest tectonic intervention. The tectonic phases developing the river terraces have been dated prior to ~29 ka and ~15 ka. From the morphometric and drainage pattern studies these tectonic disturbances could be attributed to the activities along the NWF and GF. However based on sedimentology, climatic imprints have been observed along the river valleys where enhanced monsoon condition could be suggested post ~29 and 15 ka. Climatic signatures have been overprinted by tectonic signatures which intervened with the uniform development of fluvial deposits.
Stress-scenario:

Differential uplift pattern associated with the terrain of IBF zone can be attributed to the stress pattern along the strike-slip faults (striking NW-SE and NE-SW). In order to understand the status of the island belt fault zone, the regional scenario needs to be considered. The Kachchh basin evolved through three tectonic phases: (1) Rift phase during the break-up from the Gondwanaland, (2) Late rift divergent wrench phase during drifting of the Indian plate, and (3) post rift convergent wrench phase during the collision (Biswas, 2005). Due to the predominance of the near-vertical fault planes, the Kachchh became a shear zone during the inversion stage following collision. Post-collision compressive regime is responsible for present active neotectonic movements. The drift motion and the counter-clockwise rotation induced strike-slip movements giving rise to positive flower structures (Biswas, 2005).
in Kachchh. Horizontal stresses developed associated with strike-slip movements controlled the major evolution. These strike slip faults have also been known to serve as conduits for magma migration to the surface. In addition to this, effects of strike-slip faulting is also observed by Ziegler (1992) who pointed out that wrench-induced pull-apart basin and oblique slip rift zones often display high level of volcanic activity. Positive Bouguer gravity anomalies suggest that the Island Belt Uplift consisting of PU, KU, BU and CU are the basement highs (Biswas, 1987). Several NE-SW and NW-SE strike-slip faults have been observed to dislocate the primary faults.

It can be suggested from the above discussion that the strike slip faults were generated during the collision stage and controlled the landform evolution since then. The isolated patches of the island belt seems to be the resultant of these faults due to broad N-S compression and E-W extension by simple shear associated with the active strike-slip faulting. The extension following the compression resulting into strike-slip movements by simple shear have been recorded in active orogens (Wilcox et al., 1973; Sylvester and smith, 1976). Normal faults displacing the gravel beds have been observed along the Kiska river supporting the evidence of extension (Fig. 4.13).

Figure 4.31: Conceptual model suggesting evolution of Island Belt Fault Zone. Please note NNE-SSW compression and ~E-W extension indicated by the arrows. Beachball indicates focal mechanism solutions of M>4.0 earthquakes along these islands which show dominant strike-slip faulting. The red dotted circle is deformed by simple shear into the ellipse resulting into strike-slip faulting producing discrete patches of islands along the IBF Zone.
faults (NE-SW and NW-SE) developed which probably had segmented a uniform patch of landform into discrete patches of island, viz., PU, KU, BU and CU. The horizontal movement recorded by the GPS data suggests the present stress condition which is compression in the N-S and extension in the E-W directions (ISR Annual report, 2012-13). Focal mechanism solution also refers to the strike-slip movements along the recent major earthquakes (Mw > 4.0) associated with Island Belt Fault Zone (ISR Annual report, 2011-12). It can be suggested that the stress pattern during the inversion and post collision stages segmented the Island belt zone and developed discrete patches in the form of PU, KU, BU and CU. These strike-slip movements are still active to the present day, producing moderate to large magnitude earthquakes and the same is being expressed in the river morphology.

4.1.3. Summary:

The present study is accomplished by segmentation of Kachchh into discrete blocks consisting of northernmost IBF and central Wagad highland in order to ascertain the comparative scenario of ongoing active deformation. It can be suggested from the present study that indeed the Kachchh, overally, is behaving in a segmented manner with northernmost part responding more to the NE-SW and NW-SE trending strike-slip faults, whereas the Wagad highland is more sensitive to the E-W trending NWF, SWF and GF.