CHAPTER 5

DEVELOPMENT OF TWIN SCARPS: JARA-JUMARA SECTOR

Landscape evolution in a region is regarded as the combined effect of various geomorphic factors like tectonics, lithology, structure, climate and time (Chorley et al., 1984; Morisawa, 1985; Bloom, 1998; Burbank and Pinter, 1999; Miliaresis and Iliopoulou, 2004; Trauerstein et al., 2013). The tectonic imprints on the landscape get preserved in the form of valley form, drainage pattern terraces, fault scarps, paleochannel etc. (Jorden, 2003; Thakkar et al., 2012; Taloor et al., 2021; Maurya et al., 2021). However, due to the erosional dominance during periods of lesser tectonic activity or tectonic quiescence, the tectonic signatures will be wiped out from the topography. In such cases, the drainage systems are effective tool in extracting the tectonic signal from the landscape (Bishop, 2007). In that category, the bedrock rivers have been proven to be useful in understanding the landscape evolution (Whipple et al., 2004). The drainage networks also help to establish the relation between the surface process and structural deformation in a tectonically active terrain (Burbank and Anderson, 2001; Delcaillau et al., 2006). The tectonic dominance in a region can control the relief generation and hillslope processes in a region (Bloom, 1998). Research on escarpment originating rivers have proved that they are effective tool in evaluating the geomorphic evolution of the escarpment (Kale and Shejwalkar, 2007; Harbor and Gunnell, 2007; Wang and Willet, 2021).

Twin parallel scarps along the western KMF is a significant feature in the landscape of the Jara-Jumara sector. This sector comprises the Jara dome and Jumara dome which exposes Mesoozic rocks. The Jaramara Scarp (JMS) is the prominent scarp of the terrain with numerous north flowing rivers originating from the scarp face. The scarp also forms a secondary drainage in the region. In the previous chapters the morphology and mode of degradation of the scarp was discussed. The morphological analysis on the previous chapters suggest that the scarp is predominantly erosional, however, the region lacks Cenozoic sedimentary record for evaluating the long term geomorphic conditions. The main objective of this chapter is to evaluate major controlling factors on the landscape that led to development and preservation of the JMS in the western KMF through detailed drainage analysis. For the purpose of quantitative reconstruction of the geomorphic evolution a systematic study on the drainage networks of Jara-Jumara was conducted. The study on drainage system will help to understand the nature, variation in relief and morphology of the JMS with respect to lithology, structure and tectonic uplift. The chapter will also demonstrate how the fluvial networks sculpted the present landscape of western KMF.

The area chosen for the present study covers western half of the KMF located between the villages of Shiyot and Bharebari in the Kachchh district (Fig. 5.1). The KMF in the study area is buried under the thick Rann sediments. However, the geomorphic expression of KMF is visible in the form of north facing scarp. The sector consists of two domes, the Jara and Jumara dome on the western and eastern end of the sector. The Northern Hill Range Flexure Zone (NHRFZ) forms the principal watershed for the rivers of the study area. The Jara-Jumara sector shows a very dense drainage network which is in contrast to the hyper arid climatic conditions of the region. Rivers of the region show an ephemeral character that remain dry most part of a year. Occurrence of dense drainage network in hyper arid climatic condition supports the influence of tectonic forces in the region. The major rivers that flow through the section includes the Gandi River, Jara River, Jumara River, a river flowing east of Gandi River (River 1), river flowing through the center of Jara dome (River 2), river on west of Jara River (River 3), river draining between Jara and Jumara River (River 4) (see Fig. 5.1). The rivers of the region are north flowing which originates from south of the Nothern Hill Range (NHR) and debouches in the Rann surface. The rivers in the study area are generally short with a length of 5-12 km and basin area of less than 10 km^2. However, the Gandi River has a basin area of 54km^2, the highest in the region (Table 5.1). The study area is characterized by three major type of drainage pattern, (a) annular drainage (formed between the cuesta girdles) (b) centripetal drainage system (formed at the core portion of the domes) (c) sub-parallel drainage, which covers major portion of the study area. Milliman and Syvitski (1992) reported that river basin can be subdivided into five categories based on the headward elevation- 1) high mountain rivers (>3000 m), 2) mountain (1000-3000 m), 3) highland (500-1000 m), 4) lowland (500-100 m), 5) coastal plain (<100 m) rivers. In the study area, all the rivers except River 1 fall into the category of Lowland River, whereas River 1 is included in the category of coastal plain rivers (Table 5.1).

The drainage system in the area is underlined by heterolithic suite of rocks which includes Jhuran, Jumara and Jhurio Formations of Mesozoic age. The lithologies of these formations includes various types of sandstones, fossiliferous to unfossiliferous clastic and non-

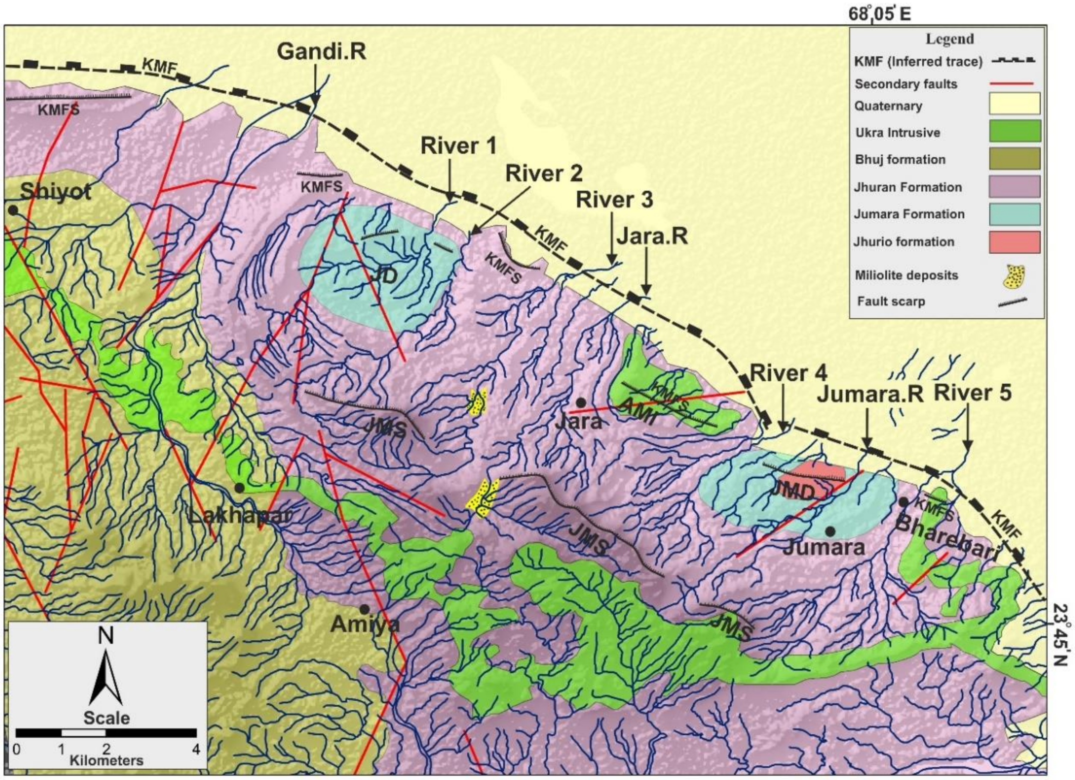

Figure 5.1 Drainage and geological map of the study area draped over DEM. Major structures and geomorphic units are also shown. All rivers analysed in the present study are marked by arrows. Unnamed rivers are numbered as River 1-5. Note that the oldest Mesozoic formation, the Jhurio Formation is exposed only in the centre of Jumara dome. Note that all drainages of Jara and Jumara domes flow towards north. KMF: Kachchh Mainland Fault, JD: Jara Dome, JMD: Jumara Dome, AMI: Amedi Intrusive, KMFS: KMF Scarp, JMS: Jaramara Scarp.

Table 5.1 Categories of rivers in the study area. River types are based on Milliman and Syvitski (1992).

River	River length (km)	Drainage Area (km^2)	Headwater Elevation (m)	River type
Gandi R.	11.4	54.65	205	Lowland
River 1	4.7	8.33	85	Coastal plain
River 2	4.2	7.17	105	Lowland
River 3	5.8	9.68	166	Lowland
Jara R.	7	11.04	170	Lowland
River 4	4.1	4.34	184	Lowland
Jumara R.	5.2	5.15	145	Lowland
River 5	5.4	11.68	165	Lowland

clastic limestones, shales and igneous intrusive bodies. The stratification also caries from thick bedded to thin bedded. These lithologies show different degree of hardness thereby suggesting a difference in their erodibility. The Jhuran Formation covers a major portion of the study area. The rivers flowing through the western side of the sector such as the Gandi River which follows the trend of hard sandstone ridges of Jara dome suggest the structural control of cuesta girdles on the drainage networks. The Ukra intrusive in the region forms the principal drainage divide for the bedrock river in the region. At the same time, near the vicinity of the Jumara dome, the JMS forms drainage divide for few rivers that flows through the eastern side of the sector (see Fig. 5.1). The rivers of the sector display profound incision, characterised by gorges developed along their course. The severe incision and gorges are more common particularly in the upstream region and in the zone where the river crosses the scarp. Recent deposits are seen scattered along the river beds with fan shaped sandy alluvial deposits at the mouth of rivers. Amedi instrusive which forms a part of Ukra intrusive in the inter-domal saddle has developed short drainage networks with deeply incised channels which is peculiar in nature (Fig. 5.1). The rivers in the study area show an anti-dip directional flow, while those on the southern side (back slope) follows the general slope of the beds. In some instances, rivers originating from the back slope takes a sharp turn and flow northward. The Jara River in the study area were examples from this category, where they originate from the backslope and flow northward dissecting the JMS and KMFS. In the studied region it was observed that majority of the north flowing rivers dissects the KMFS, thereby making the KMFS more discontinuous in appearance. At the same time, the JMS is more continuous feature in the region. The Kachchh basin falls in the extreme arid climatic belt of western India with an average rainfall of less than 30cm per annum. The rivers of the region are ephemeral and remains dry throughout the summer seasons. Even though, the rivers considered for the present study remain dry during the summer season, they are characterised by deeply incised valleys, strath terraces, gorges and knickpoints.

DRAINAGE ANALYSIS

In the present study to understand the drainage characteristics, morphometric indices extracted from 30 m SRTM (Shuttle Radar Topography Mission) supplemented by field observations, geological mapping (incorporating lithologies, KMF, secondary faults) and geomorphological maps (combining major uplifts, saddles, knickpoints) prepared using of Survey of India (SOI) toposheet at 1:50000 scale were analysed. Dome-wise morphometric indices were computed to examine the drainage characteristics and landscape development owing to the active tectonic movements along the individual segments. A dome-wise comparison will also yield more information on the scarp modification on the individual domal units of western Kachchh. In the present study, those rivers which originate from the NHR and flows across the KMF are targeted.

Much importance has been given to the rivers originating from the scarp face of JMS for understanding the evolution of secondary scarp along KMF. The long profiles of the studied rivers were normalized for comparison and superposition of river of different length and source elevation. Elongation ratio (Re), Hypsometric Integral (HI), Hypsometric curve (HC), Bifurcation ratio, Drainage density and Stream frequency were the other indices computed for this purpose in the study area. The morphometric parameters were calculated using standard formulae as depicted in (Table 5.2). Most of the rivers in the study area were unnamed, therefore for the ease identification and correlation, these rivers were named from River 1 to River 5 (Fig. 5.1, Table 5.1). The drainage density can be defined as the degree of closeness of channels in a drainage basin. According to Smith (1950) and Strahler (1957), the values less than 5 represent coarse, between 5 and 13.7 represent medium, 13.7 and 155.3 represent fine and values above 155.3 represent ultra-fine drainage density. The bifurcation ratio can be described as the degree of branching within the hydrographic network. The bifurcation value above 3 indicates structural control on the river basins (Strahler, 1964). The stream frequency can be used as an index which describes the stages of the landscape evolution. Higher values of stream frequency are indication of higher tectonic uplift (Horton, 1932). The hypsometric analysis and elongation ratio describe the degree of maturation of the topography (Schumm, 1956; Ohmori, 1993). With the progression of time, the relief of the basin will be lowered and basin shape will become more circular in outline. This results in an increase in a progressive decrease in the values of hypsometric integral and increase in the values of elongation ratio. The SL index anomaly were calculated by dividing the SL index of each segment of stream by the total SL index (SL_{Total}). Depending on the values, the SL anomaly index classify the stream segments into different order of anomaly, such as no anomaly (SL anomaly <2), second order anomaly ($2>$ SL anomaly 10), and first order anomaly (SL anomaly>10) (Seeber and Gornitz 1983; de Araújo Monteiro et al. 2010). The analysis helps to pinpoint the gradient change and associate stream characteristics along the course of the river.

Table 5.2 Standard relationships used for the calculation of morphometric indices.

Morphometric Parameter	Formula	Reference
Stream order	Hierarchical rank	Strahler (1964)
Bifurcation ratio	Rb=Nu/Nu+1 Where, Rb= Bifurcation ratio Nu= Total number of streams of order u Nu+1= Number of streams of next higher order	Schumm (1956)
Drainage Density	Dd= Lu/A Lu= total stream length of all orders (Km) A= Area of basin (Km^2)	Horton (1945)
Stream frequency	Fs= ΣNu/A Fs= Stream frequency ΣNu= Total no. of streams of all orders A= Area of basin (Km^2)	Horton (1945)
Elongation ratio	Re=2√(A/Π)/L Re= elongation ratio A= Area of basin (Km^2) Π=3.14 L= length of basin (Km)	Schumm (1956)
Hypsometric integral	$\frac{Mean\ elevation - minimum\ elevation}{Maximum\ elevation - minimum\ elevation}$	Schumm (1956)

MORPHOMETRIC PARAMETERS

The rivers draining the Jara-Jumara sector were short with substantially higher drainage area. The presence of large proportion of 1st order streams in the river basins of the study area in contrast to the arid climatic condition points to tectonic significance. The region represents coarse drainage density. The calculated drainage density for the rivers varies between 2.8 and 4.4. Taking the extreme arid climatic condition into consideration the calculated density values infer to the tectonically active nature of the terrain. The rivers draining through the western part of the sector, notably the River 1, 2,3 and Jara River of the study area, show a slightly higher drainage density value, however the density values in the other segments do not alter much (Table 5.3). The stream frequency for the rivers range between 2.9 and 5.6. The higher stream frequency indicates higher tectonic influence in the terrain. The bifurcation ratio calculated for the rivers lies within the range of 2.7 – 5.9. Similar to the other morphometric parameters the bifurcation ratio also does not show a significant change in the segments investigated. The values computed for the study area, as per Strahler (1964) show the prominent role of structural control on the existing drainages of the region. The structural control or slope on the river networks clearly conveys the episodic movements along KMF. Overall analysis of the

Table 5.3 Summary of various morphometric parameters calculated for the rivers in the study area.

River	Stream Order	Bifurcation ratio	Drainage density	Stream Frequency
Gandi R.	5th	3.5	3.4	3.73
River 1	4th	3.6	4.3	5.5
River 2	4th	3.5	4.4	5.6
River 3	3rd	5.9	4.1	4.3
Jara R.	4th	3.6	4.2	5.0
River 4	3rd	3.8	3.9	4.1
Jumara R.	3rd	4.2	3.5	4.2
River 5	4th	2.7	2.8	2.9

morphometric indices points to the fact that the segments of eastern Kachchh are actively influenced by the neotectonics movements along the KMF (Table 5.3).

LONGITUDINAL RIVER PROFILE ANALYSIS

Longitudinal profile of rivers crossing the Jara-Jumara sector shows variable gradients with several knickpoints and convex up reaches. Longitudinal profiles of the major rivers that drains through the sector can be categorized into two major types: 1) Convex up type and 2) Concave up type. Among these two, the convex up type profile is common in the rivers draining through the sector (Fig. 5.2). On the contrary, the rivers flowing through the eastern region of the sector have more concave type profile in comparison with the rivers in the western part of the sector (Fig. 5.2). The rivers 4 which originates from the central portion of JMS has a regular and well-developed concave up profile. The Jumara river, that flows through the center of Jumara dome, is an exception in the eastern side, as it shows a convex up type profile. The Gandi River and Jara River draining through the Jara dome, show convex up segments in the profile. The Jara River, which flows through the eastern end of Jara dome reveals high gradient similar to the rivers that flow through the center of dome. The dimensionless curves show that the maximum concavity does not exceed 20% of the normalized distance for the rivers that originates from the JMS. While the other rivers show maximum concavity after 35% of the normalized distance (Fig. 5.3). Rivers generally shows a decrease in channel incision throughout the river course. The greatest incision in the study area is shown by the Jara River which shows ~25 m gorge like channel cut into the Mesozoic Jhuran Formation.

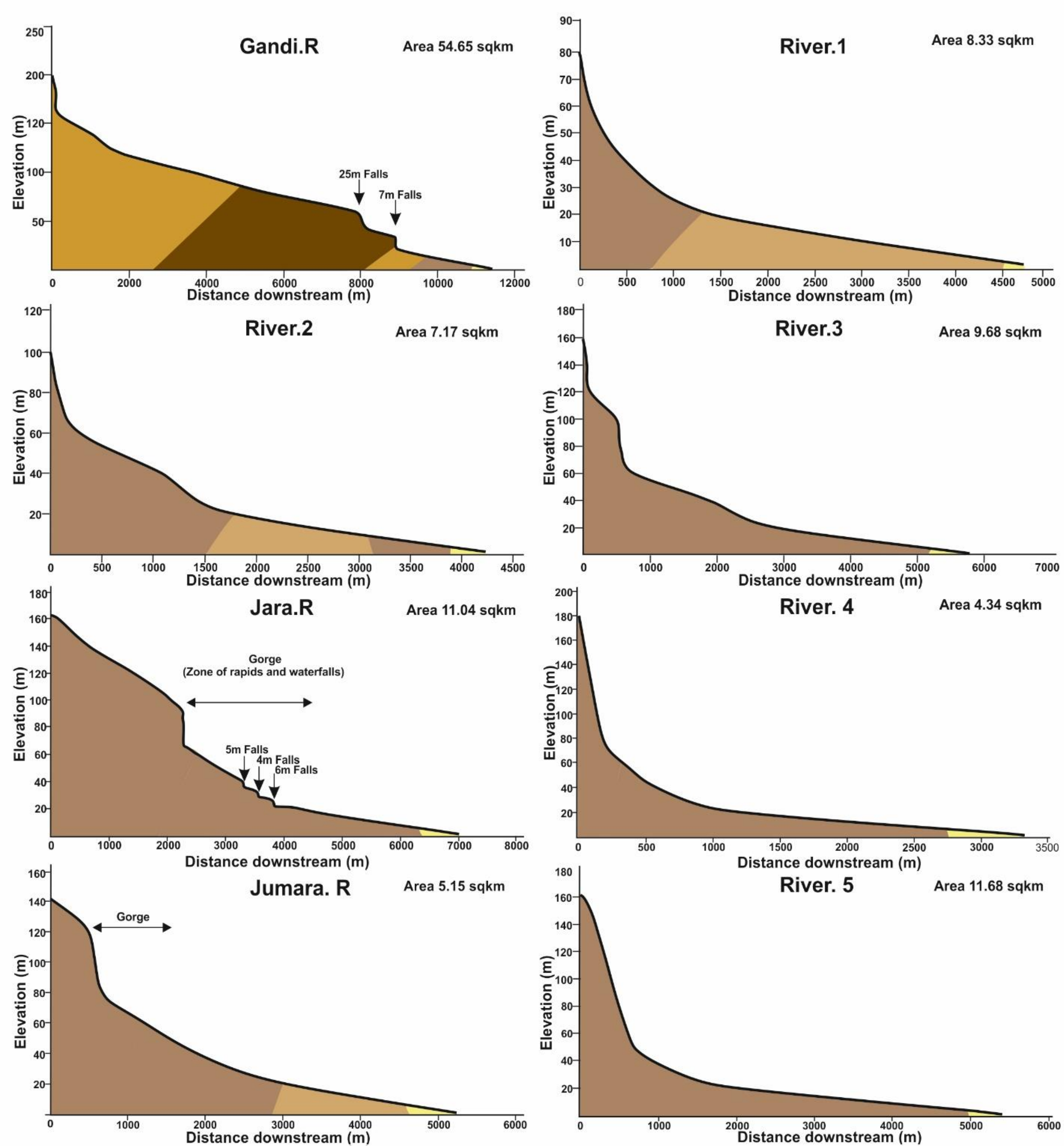

Figure 5.2 Long profiles of the rivers flowing perpendicular to the major structures and geomorphic units. Elevation is based on Survey of India topographical map (survey year-1960-1966). The morphology of the river profiles varies from concave up to convex up nature even though the broad structural pattern is same in Jara and Jumara domes. Note that the gradient changes correspond to lithological variations.

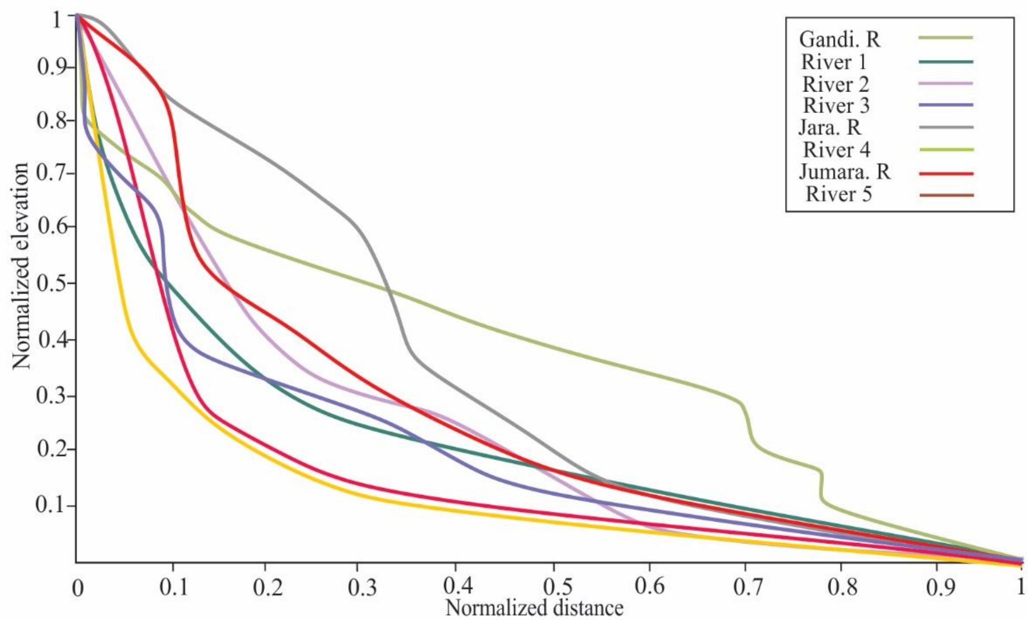

Figure 5.3 Normalized stream profiles or dimensionless curves (ratio of elevation to ratio of distance) of the major river in the study area. Note the 'L' shaped nature of the curves representing deep incision in the upper to medial portion of the curve.

Hack's profile

All rivers flowing through the Jara-Jumara sector show strong upwarping from the ideal gradient profile with the exception of River 4. River 4 is practically graded in comparison with the other rivers in the sector (Fig. 5.4). The rivers show an average index of gradient (K) between 8 and 21. The rivers 1 and 2 have a slightly lower value of K (Fig. 5.4). Rivers that drains through the sector shows deviation between 20 and 175. The Gandi River shows abnormal high deviation i.e. (175) followed by Jara River (155) which passes through the inter-domal saddle region. A comparatively higher convexity is shown by the rivers draining across western sector (i.e., the rivers draining through the Jara dome). However, this difference is not that much prominent. The convexity so produced in the river profiles is not lowered yet to produce an equilibrium (steady) state. We infer that the uplift rate in the area exceeds the denudation rate. The markedly low slope of the River 4 suggests that denudational rate and uplift rate are in equilibrium. We attribute this to the location of the river in the saddle zone between the Jara and Jumara domes as the amount of uplift is expected to be minimum in this part. This also is suggestive of the structural attributes contribute to the variable erosional effects as seen in the river channels.

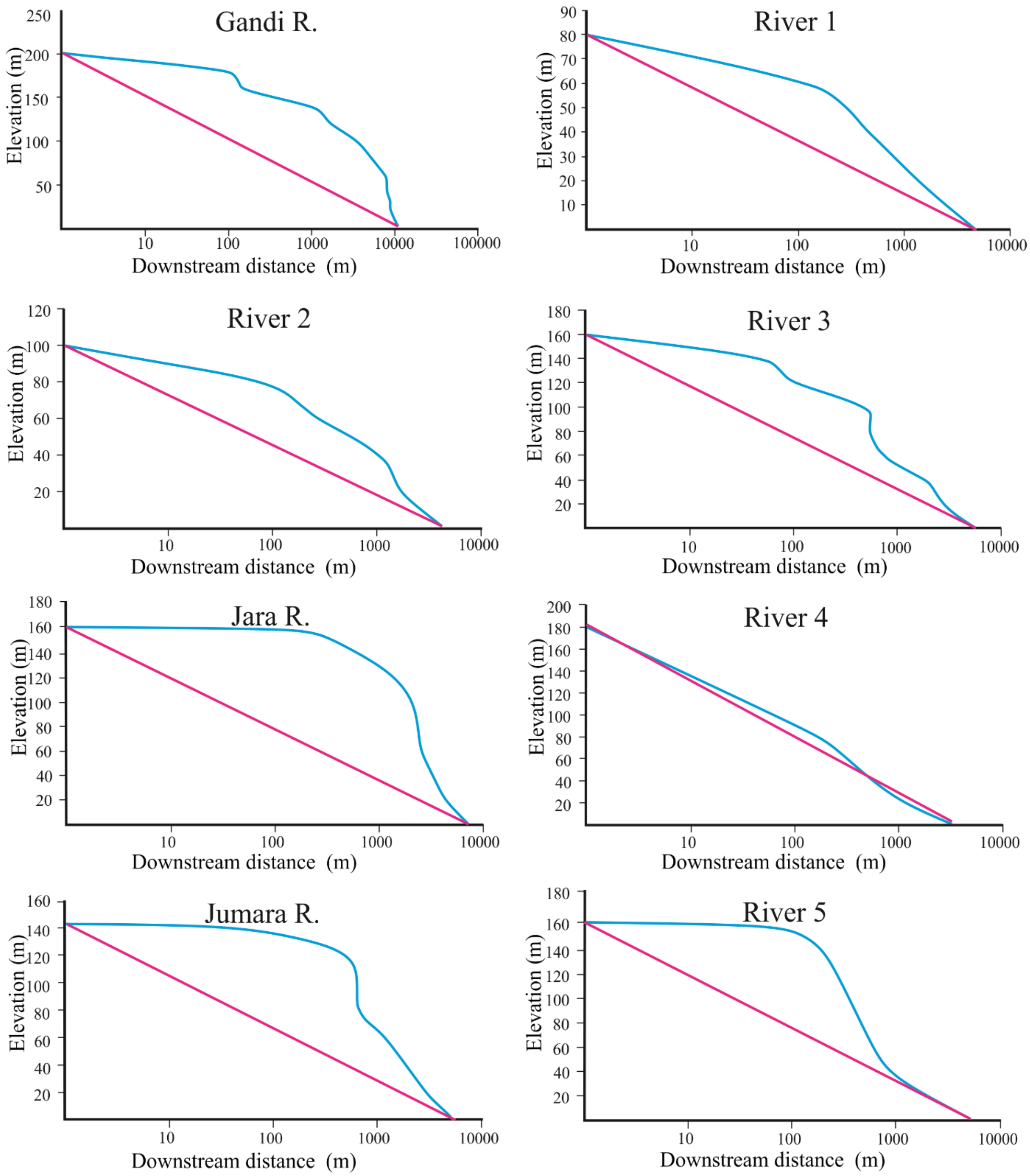

Figure 5.4 Hack profile/semi-logarithmic profiles showing the zones of major break in slope and deviation from the graded profile. Note: All rivers expect the River 4 show a major upwarping above the equilibrium line.

Stream length-gradient index (SL)

Stream length gradient index (SL index) calculated for the rivers shows variation throughout their length. However, significant changes in SL values are in general confined to the upstream reaches of the rivers draining the study area, with the exception of Gandi river. The correlation between SL and longitudinal profile shows distinct peaks of high SL value. The sudden slope breaks are associated with lithological variation, knickpoints and presence of fault. The average SL values calculated for all the rivers flowing from west to east are 197, 13, 19, 52, 84, 29, 42 and 30 respectively (Fig. 5.5). The Gandi River that flows through the western side of the sector has the highest average SL value (Fig. 5.5). Two prominent peaks observed to the downstream of Gandi River is due to 25 m and 7 m knickpoints. This is followed by the Jara River (average SL-84) which flows through the inter-domal saddle region. The SL value of Jara River ranges between 13 to 215, with an abrupt peak at the zone of gorge. The changes in the SL values along different segments of a river is represented in a plot of SL index as a function of stream length downstream (Fig. 5.5). The NSL obtained for the rivers reveal that the Gandi River has the steepest gradient among the other rivers draining the area with a value of 8.82 followed by Jara River, River 3 and Jumara River with values 5.16, 2.76 and 2.61 respectively. The River 4 is characterized by gentler reaches with NSL values less than 2 (Table 3).

VALLEY FLOOR WIDTH TO HEIGHT RATIO (VF)

Vf ratio ranges between 0.30 and 1.67, where rivers originating from the scarp shows low value compare to other rivers. River 4 and 5 draining in the eastern side of the sector show slightly higher values i.e. 1.67 and 1.1 suggesting transition in valley morphology from narrow V-shape to broad U-shape. In contrast, the Jara and Jumara Rivers exhibit low Vf values (0.30 and 0.50) near the JMS. This is indicative of rivers incising actively to their respective reaches to tune with the tectonic disturbances. Gandi River, River 1, 2 and 3 shows low Vf values (0.60 to 0.72) also suggestive of V-shape valleys resulting from river incision. This lower Vf values suggest that these rivers are actively incising their valleys.

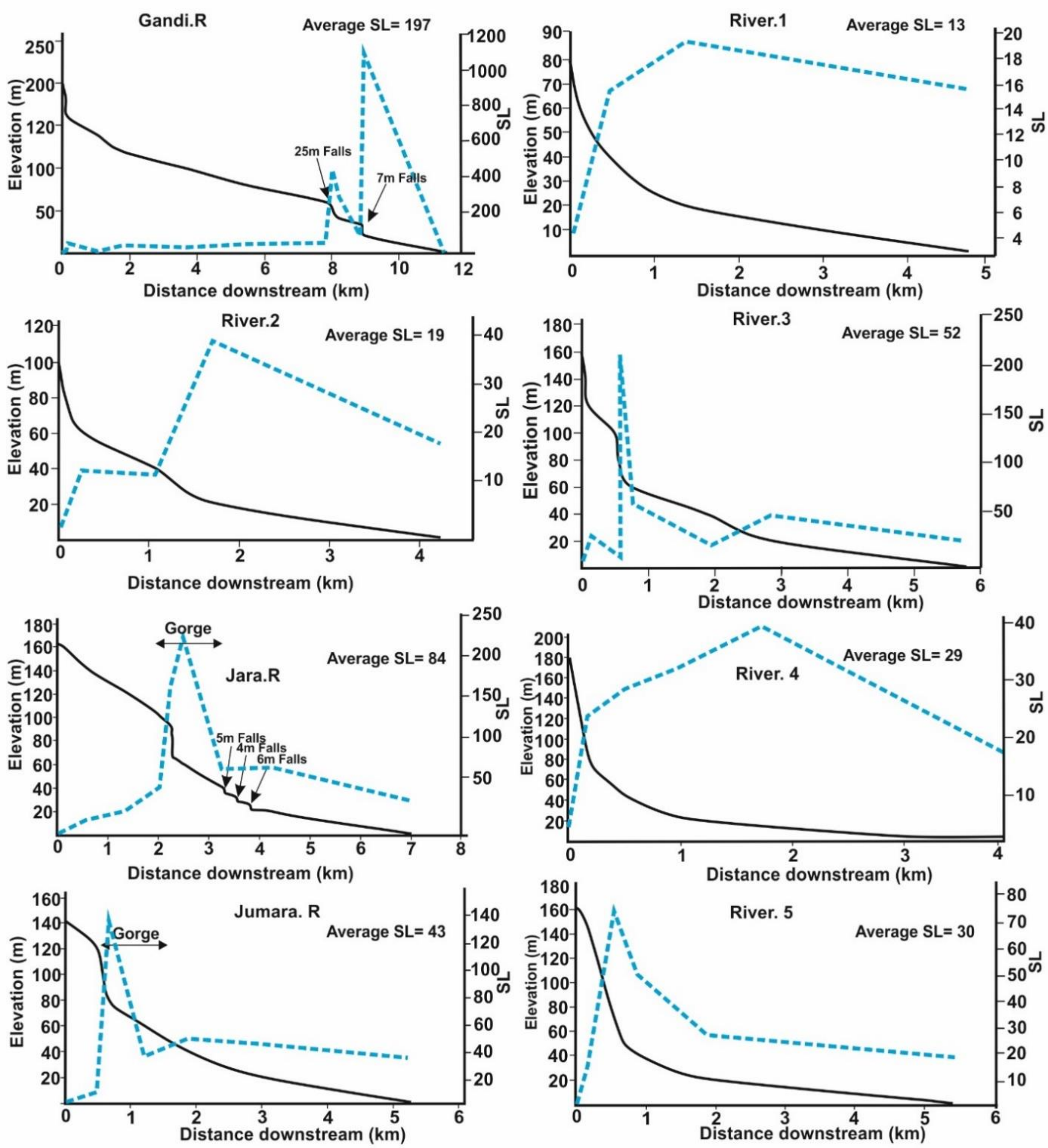

Figure 5.5 Plots of SL index (dashed lines) as a function of downstream distance overlapped on longitudinal profiles (solid line) of the rivers. Note that the anomalous peaks of SL index correlate with changes in river gradients including knickpoints.

HYPSOMETRIC CURVE AND HYPSOMETRIC INTEGRAL

Hypsometric curve (HC) and hypsometric integral (HI) for major north flowing rivers that drains through the study area is calculated. Even though the river basin of the study area is

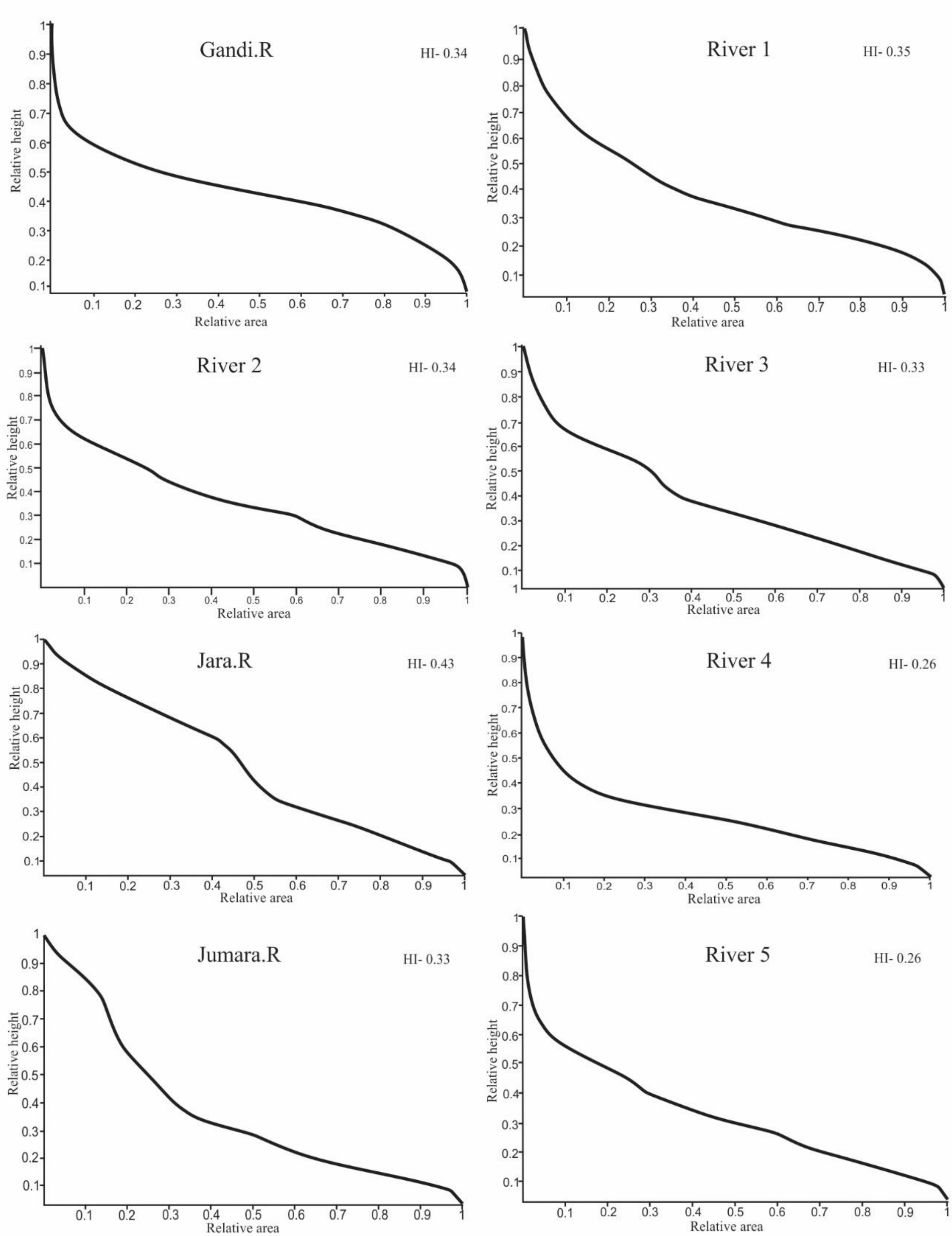

Figure 5.6 Hypsometric curves of rivers in the study area. The Gandi River, River 1 and River 2 show S-shaped curves indicating a mature stage of the landscape. Whereas River 4 and River 5 show concave up curve indicating late mature or old stage of the basin. Note the break in slope of the hypsometric curves of River 3, Jara River and Jumara River caused by the lithological contrast between the lower and upper Jhuran Formation.

affected by same fault, the KMF, these rivers do not display similar hypsometric curves. This is attributed to different rates of uplift across the domal structures or tectonic control or both. In the western side the major rivers exhibit the hypsometric integral ranging between 0.34 and 0.31, while those flowing through the eastern side show values between 0.32 and 0.26. Rivers 4 and 5 show lowest hypsometric integral with the concave shaped curve. In contrast, the Jara river shows a comparatively higher hypsometric integral value of 0.43. The rivers that drain the Jara dome forming the western side of the sector show more or less smooth S-shaped curves (Fig. 5.6). These rivers also show change in the slope of the curve as they cross over from upper Jhuran Formation comprising mostly sandstones to the lower Jhuran Formation consisting mainly of shales (Fig. 5.6). The hypsometric curves of rivers flowing through Jumara dome show prominent concave up profile suggesting higher erosion than the Jara dome in the west. This correlates with the stratigraphic evidence of comparatively greater amount of uplift of the Jumara dome.

ESCARPMENT SINUOSITY AND ELONGATION RATIO

For escarpment sinuosity, 120 m and 80m contours were selected because these contours are more continuous from the east to the west. The ES values are more close to 1 at the source of River 4 (Fig. 5.7 a). This value is highly deviating near the source regions of Jumara and Jara Rivers. Previous calculated morphometric parameters and ES entirely suggest the fact that river 4 is undergoing a more uniform and steady state erosion which is in consonance with uplift. Other segments have higher sinuosity values due to their higher erosional rate. This is evident from the Jumara River gorge that dissects the scarp. In order to have a better picture about the basin geometry and erosional nature of the region, the elongation ratio (R_e) of each river basin is compared with the hypsometric values (Kale and Shejwalkar, 2007). The calculated parameters clearly shows that the basins have undergone a higher degree of fluvial erosion in an elongated fashion (Fig. 5.7 b).

IMPLICATION FOR STRUCTURALLY CONTROLLED FLUVIAL DISSECTION

The rugged topography, highly incised channels, knickpoints and gorges developed in the rivers shows the neotectonic significance of the western KMF and nearby areas (Shaikh et al., 2019). The western part of the NHR generally has a low relief than its eastern part (Chowksey et al., 2011a, b; Maurya et al., 2017; Shaikh et al., 2019) but the terrain is highly

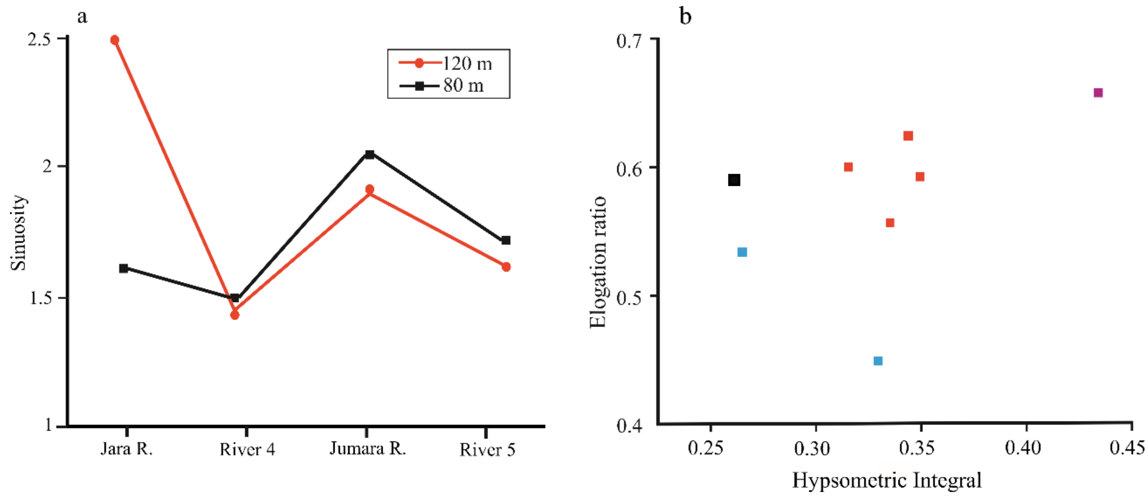

Figure 5.7 (a) Plotted values of escarpment sinuosity of the crest (red colour) and base (black colour) of the JMS. The x-axis corresponds to the lateral extent of the scarp with location of rivers draining through the scarp. Note that the pattern of dissection of the rim (120m) and base (80m) of the scarp is similar suggesting that the dissection carried out by the rivers is in phase with the retreat of scarp. (b) Relationship between hypsometric integral and elongation ratio. Blue squares-eastern rivers (Jumara River and River 5), red squares- western rivers (Gandi River, River 1, River 2), violet squares- Jara River, Black square- River 4. The parameters indicate that the major drainage basins are increasing their basin area longitudinally rather than laterally. However, the River 4 with lower hypsometric integral and moderate elongation ratio is increasing the drainage area laterally.

dissected by the river networks. The relatively higher drainage density of river network is in contrast to the hyper arid climatic condition which indicates tectonic uplift as the main factor in shaping of the fluvial networks, especially the Jara-Jumara sector. The anti-dip northward flow direction of all rivers is a manifestation of the long term influence of tectonics and fluvial erosion in the region. In the present study, the river networks of the Jara-Jumara sector is separated into three groups with a view to investigate the formation of rugged topography with two parallel scarps. The drainage lines have been divided into rivers flowing through the (a) Jara dome (b) inter-domal saddle (c) Jumara dome.

Rivers flowing through the Jara dome

The rivers under this category includes Gandi River, River 1, River 2, River 3 and Jara River. These rivers originate from the large Ukra intrusive or the back slopes of the JMS and flow northward dissecting through the Jara dome.

The Gandi River with the largest drainage area (54.65 sq. km) flows through extreme west of the Jara-Jumara sector and follows a path confined to the cuesta ridges of the Jara dome. The long profile of the river shows several convexities along its course downstream. The Hack profile is convex and show the maximum deviation amongst the equilibrium profiles of all rivers draining through the sector. The river has an average NSL value of 8.82, which again points to immensely steep reaches of the river. This is the only river in the entire study area with such a high NSL value. Another peculiar characteristic of the Gandi River is the S-shaped hypsometric curve. This type of curve, which is concave up at the higher elevation (head region) and concave down at the lower elevation (toe region) suggests that the river is flowing through a terrain that is tectonically, lithologically or structurally controlled terrain (Giaconia et al. 2012; Tepe and Sözbilir 2017). The Jara dome shows a comparatively more dominant structural control on drainage in comparison to the Jumara dome in the eastern side of sector. This higher structural control on the drainage resulted in an S-shaped curve for the rivers. The Gandi River which originates from the western part of Ukra intrusive flows initially in northwest direction and then takes a sharp turn towards north circling around the western fringe of the Jara dome. This peculiar nature of the river course supports the structural control of the fluvial network in the area. The calculated hypsometric integral values suggest that the river basin had undergone higher degree of fluvial erosion and in its early mature stage of landscape evolution.

River 1 and River 2 flow through the center of Jara dome. These rivers also possess convex up Hack profile. However, the relatively lower deviation of these rivers (River 1 and River 2) from equilibrium line suggests weaker denudational power of these rivers, a process also observed elsewhere (Chen et al., 2006; Ambili and Narayana, 2014). River 1 and 2 also have slightly lower values of average NSL pointing to the gentle nature of the channel reaches. But these rivers are also characterized by few segments having NSL values >2. The S-shaped hypsometric curve and hypsometric integral values (0.35 and 0.34) calculated for these rivers suggest an early mature stage for the river basin.

The River 3 originates from the western most extension of the JMS (Fig. 5.1). This river forms incised channels in the eastern side of the Jara dome. The normalized SL index (>2) values also suggest steeper reaches for the river. The hypsometric integral (0.33) and curve show a higher degree of fluvial erosion of the basin. The deflections in Hack profile are produced when the river encounters with more resistant thin sandstone bed in the southward limb of Jara dome (Fig. 5.4). This is also reflected well in the SL index plot showing sudden changes in SL values (Fig. 5.5), a feature also reported at Great Falls in the Potomac River (Hack, 1973). Overall, the steep channel gradient, convex up Hack profile, low hypsometric integral and elongated basin suggests that the River 3 is actively undergoing fluvial erosion to adjust to the tectonically induced disequilibrium.

The Jara River originates from the backslope of the JMS and flows northward dissecting the JMS. The region of dissection is characterized by 25-30 m gorge within the miliolites deposits of Late Quaternary origin (Baskaran et al., 1989). This primarily suggests that the river is actively incising through the litho-units to adjust to the tectonic uplift during the post-miliolite period. The Hack profile of the river is highly convex and deviates significantly from the equilibrium profile (Fig. 5.4). Kale and Shejwalkar (2007) opined that the segment or portion of river above the equilibrium line has high energy promoting erosion and downcutting. At the same time, the hypsometric curve shows a break (Fig. 5.6). The hypsometric curve is more concave down at the upper elevation followed by a break and concave up toe. This type of curve may be attributed due to the lithological difference, a process observed earlier by Ciccacci et al. (1992). Briefly, the calculated parameters suggest that the river is more in a transient state of evolution where fluvial erosion in the upper segment differs significantly from the lower reaches due to the lithological diversities of the region. The upper segment of river characterized by hard sandstone of upper Jhuran and is marked by less erosion in comparison with the lower Jhuran Formation in downstream. The higher hypsometric integral value (0.45) suggest an early mature stage for the river basin.

Tributaries of the Jara River which originates from the JMS have a major role in the development of the present morphology of JMS. Even though the trunk stream (Jara River) originates from Ukra intrusive, the river is joined by tributaries that originates from the JMS. The continuous adjustment of Jara River caused the tributary streams to erode in the upstream to adjust the base level changes produced by the trunk stream. As a result of this, the strike of the Jaramara Scarp face shifts slightly from its general trend of E-W to NE-SW direction (Fig. 5.1).

River flowing through inter-domal saddle zone

The River 4 and its tributaries constitute a basin area of 4.34 sq. km located in the eastern side of the sector. This river originates from the central portion of JMS, which is characterized by highest elevation. The river has 14 low order steams originating from the JMS. The JMS forms the drainage divide for the river and its tributaries in the study area. The River 4 shows marginal change in the SL values and low NSL values suggesting more gentle and graded profile for the river. Hack profile for the river is almost close to a state of equilibrium. However, some portion of the profile lies below the equilibrium line suggesting that the uplift and denudational process are more or less in the same phase, a feature also observed in the Kuthirapuzha, a tributary of the Chaliyar draining through the Western Ghats (Ambili and Narayana, 2014). The Vf ratio for the river is 1.67 indicating the broad nature of the river valley, characteristic of mature age topography (Keller and Pinter, 2002). Concave up hypsometric curve and low hypsometric integral connote that the river had underwent a high degree of fluvial erosion and attained a late mature stage of erosion. Moreover, L-shaped profile of the river and its tributaries points to the fact that the river has used its energy acquired from tectonic disturbance essentially for headward erosion (see Fig. 5.3).

Rivers flowing through the Jumara dome

The Jumara River originates from the backslope of JMS and flows northward dissecting the scarp through the center of Jumara dome. This river shows slightly different fluvial character, compared to the River 4 and River 5. The hypsometric curve and Hack profile of this river is characterized by a break in profile (Fig. 5.4 and 5.6). This reiterates the differential erosion taking place in the lithological contact i.e., the more resistant upper Jhuran and relatively softer lower Jhuran. The Hack profile and average NSL value (>2) signify that the river is steeper than the previous river and actively undergoing fluvial erosion.

The River 5 even though originates from the Ukra intrusive, has a few tributaries that originating from the eastern most part of the JMS (Fig. 5.1). The Hack profile of this river is closer to equilibrium line at the lower reaches and slightly convex up in the upper reaches. This abrupt changes in the profile is a result of the lithological contrast between upper reaches (more resistant upper Jhuran) and the lower reaches (weaker lithologies of lower Jhuran Formation). Overall, the moderately high Vf ratio, slightly elongated nature of basin, L-shaped profile and concave up hypsometric curve suggest that the river basin is actively undergoing fluvial erosion and is in the late mature stage.

Overall, the morphometric studies carried in the river networks of the Jara-Jumara sector suggest that the rivers are in an early to late mature stage of landscape evolution. The major controlling fault in the area is the KMF which is located north to the present study area and at present, buried under the recent Rann sediments. The present morphometric studies carried out in the Jara-Jumara sector in the western Kachchh rule out the control of minor fault systems in the present morphology of the landscape. This is evident from the calculated morphological parameters of the rivers which are not showing any significant changes when they crosses these minor structures. The faulting at different times during the past has a significant role in molding geometry of domes in the flexure zone of Kachchh basin (Maurya et al., 2017). Moreover, the occurrence of multiple knickpoints along the course of Gandi River, incision in present channels, effect of rejuvenation (incision through Late Pleistocene miliolite deposit) are strong indicators of river response to tectonic uplift.

Generally, in tectonically active terrains a youthful nature of topography is imminent. However, the rivers in the study area are in late mature to early mature stage of evolution. This might be because of tectonic quiescence after phase of tectonic uplift which is common for tectonically evolved terrains. During the period of tectonic uplift, the uplift overrides the denudational process and vice versa. Geological setting of the present study area shows that the older Jhurio Formation are exposed at the center of Jumara dome in the eastern side, which is absent in the western side and more younger formation of Jumara rocks are exposed at core of Jara dome (Biswas, 1993, 2016b). This suggests that the Jumara dome has experienced relatively higher net uplift in comparison to the Jara dome. Relatively lower net uplift in Jara dome produced drainages exhibiting more prominent structural influence as they flow around cuesta girdles comprising compact lithologies.

Local controls of lithological variations

Lithological variation can potentially affect the results of morphometric analysis, so it's important to have a region wide assessment of lithological factor (Strahler, 1956). Moreover, the lithological factor can intervene in the evolution of landscape in different ways. The lithology can significantly control the shape of the landform (Adams, 1984; Chorley et al., 1984). The harder resistant lithology with high erosional resistance can significantly affect the scarp morphology and degradational process (Dikau et al., 2004). Laure (2008) reckoned that river channel slope fluctuates with the lithological change. Therefore, analysis on the river systems could reveal the lithological control on the landscape. In our study area, the rivers mainly flow through the sedimentary successions of Mesozoic era, of which, the Jumara, Jhuran and Bhuj are the major lithology exposed in the NHRFZ. The SL index calculated for the river

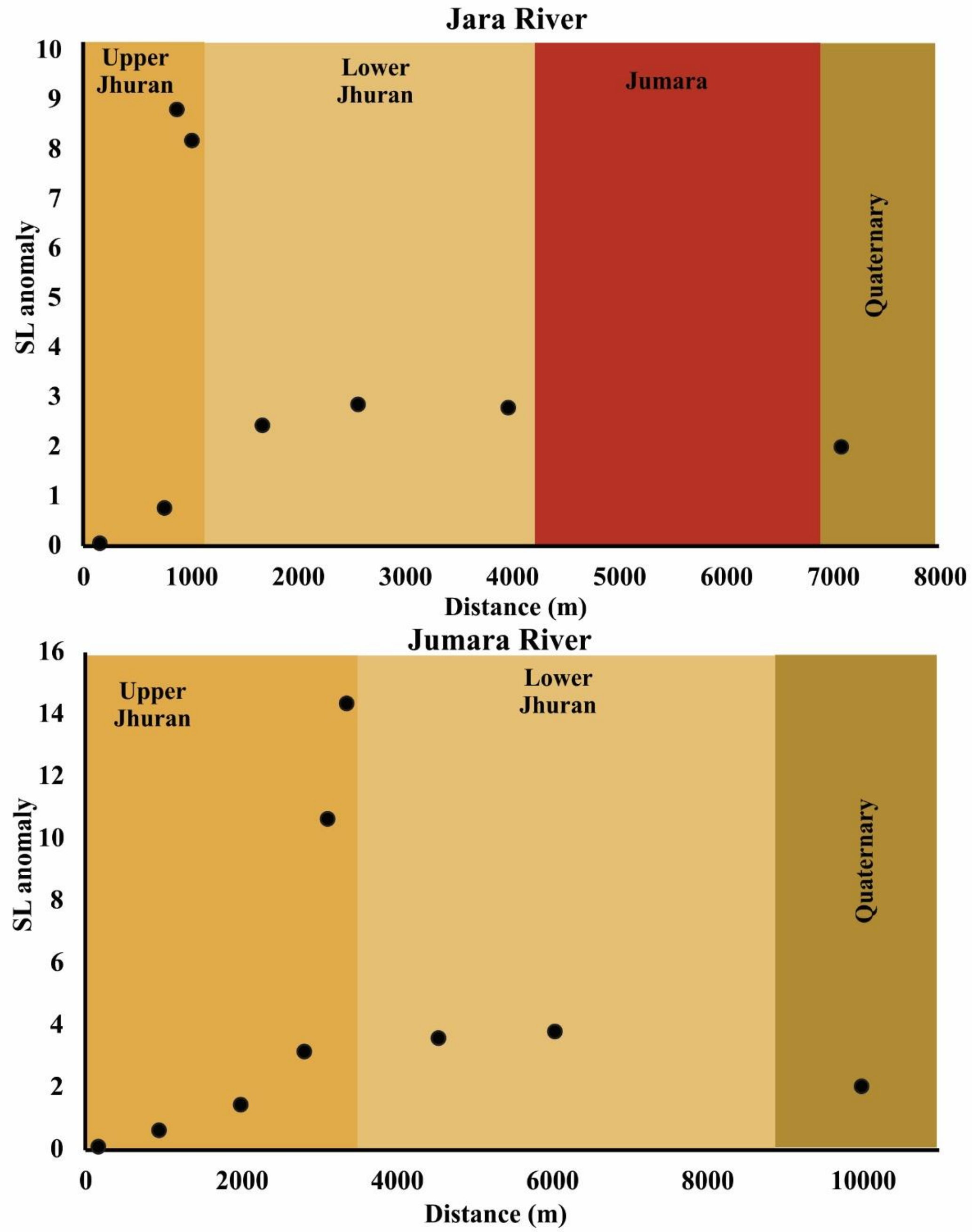

Figure 5.8. Plot displays SL anomaly index along the course of the Jara and Jumara River. The parameters indicate that the river gradient is changing at the contact between upper and lower Jhuran Formation. The variation in the SL anomaly index of the north-flowing river basin indicates lithological control on the landscape and is having an important connotation in the retreat of the scarp in the region.

networks changes with the variation in lithology. However, a prominent variation in the computed parameters is observed at the contact zone between the upper and lower Jhuran Formation. For example, Jara River draining the region shows sharp variation or peaks in the

SL anomaly index at the contact of lower and upper Jhuran (Fig. 5.8). The contact zone is also characterised by severe incision and development of gorge like fluvial landform. Similarly, the Jumara River also displays variation in the SL anomaly index at the contact of Upper and Lower Jhuran. The Jhuran formation can be classified further into lower and middle and upper members. The lower Jhuran is composed of hard shale altered with sandstone. The lithology is relatively soft and are prone to higher erosional activity. While the upper Jhuran rock are predominantly arenaceous units that is hard and resistant to the erosion (Biswas, 1993). These evidences suggest the region has a secondary influence of lithology in landscape evolution other than tectonics. Therefore, the lithological control has to be taken into consideration while proposing a landscape evolutionary model for JMS.

IMPLICATION FOR SCARP DEVELOPMENT

The ~12 km long JMS is a prominent feature and drainage divide for few north flowing streams in the Jara-Jumara sector of the western KMF. The present location of the study serves an ideal example for a landscape formed by long-term tectonic and erosional activity. The presence of numerous well-developed drainages in the sector corroborate the long-term tectonic and erosional dominance in the landscape. The development and preservation of the JMS in the present landscape is so far not been well understood, however, it has been suggested that the scarp is a product of tectonic reactivation and retreat of original KMF (Shaikh et al., 2019). The morphological characteristics and presence of numerous well-developed streams arising from the Jaramara Scarp face indicates that the scarp is much older in comparison to the KMFS. The periodic reactivation of faults is a major influencing factor in the landscape development and relief growth in the seismically KRB (Biswas, 1987; Biswas, 2005; Biswas, 2016a; Maurya et al., 2017). The previous structural, seismic investigations and morphological studies along KMF suggest that the fault was active both in the Quaternary as well as in the pre-Quaternary time (Biswas, 2005; Maurya et al., 2017; Shaikh et al., 2019; Shaikh et al., 2022). Our high-resolution study on the drainage networks in the Jara-Jumara sector provides crucial insights into scarp evolution and strengthening the understanding of tectonic control along the western KMF. The critical analysis carried on the drainage morphometric parameters and long profiles led to the following interpretations (a) the region has undergone uplift during the Late Cenozoic period which is well supported by the steep gradient and transient nature of the rivers (b) the headward cutting and growth of drainage area occurred in the upstream direction is evident from elongated nature of basins of the region (c) scarps attains the maximum relief in the source region of River 4 and the tributary of Jara River that originate from the scarp face (d) the River 4 which has reached an equilibrium stage, balanced the erosion and uplift (e) region is secondarily controlled by lithology other than tectonics (f) the rivers are in different geomorphic stages of development.

The long profile analysis and morphometric studies on the scarp deriving rivers indicate that the fluvial network has a significant role in controlling the regional denudation rate and in carving the present morphology of the JMS. Normalized profile of the rivers that originate from the scarp face is L-shaped with short and steeper upper reaches and comparatively gently sloping downstream reaches (Fig. 5.3). The shape suggests erosion is concentrated in the scarp face of the JMS. The Hack profile of the major river systems, except the River 4 flowing in saddle zone, is convex up in nature, which suggest the dominant role of tectonically induced fluvial erosion in the region. The observation is further substantiated by the occurrence of well-marked rapids and gorges in the study area. However, the River 4 originating from the scarp face and flowing through the interdomal saddle displays a more equilibrium Hack's profile. The equilibrium Hack's is an indication that uplift and fluvial erosion are balancing each other in the river basin (Hack, 1957; Ambili and Narayana, 2014). These evidences unequivocally point to the influence of River 4 in the development of the present morphology of the scarp in the vicinity of the interdomal saddle. The episodic movements along the KMF during the Late Cenozoic period have caused significant disturbance in the river network, the present transient stage of the river systems in the sector are a result this periodic reactivations. The reactivation of the KMF during the Late Quaternary period is also indicated by the episodic deposition of the colluvio-fluvial and incision of Late Quaternary miliolite deposits in the region (Shaikh et al., 2022). However, the River 4 with comparatively lesser uplift in the interdomal saddle have balanced the tectonic uplift and eroded the scarp more in a uniform fashion.

Sharp change in the gradient is common for the all the rivers that crosses the JMS, this clearly points to the lithological control in the study area. Knickpoints and rapids are common at the zone of lithological change. Morphometric parameters such as the SL, HC vary along the major lithological units confirms the control of lithology other than structure and tectonics in the area. The variation in the HC also indicates the variation in the erosion rate of lower and upper Jhuran formations. Generally, the scarp or hillslope erosion takes place through by two fundamental processes, the downwearing and backwearing (Dikau et al., 2004). The downwearing is process in which the hillslopes become gentler with time. On the other hand, in backwearing the scarp face or slope retreat parallel to the original form. The presence of geomorphologically resistant lithology will favor the process of backwearing than downwearing (Shejwalkar, 2007). In the present study, the drainage analysis unequivocally confirms the lithological control on the landscape. Moreover, the resistant sandstone forms the scarp face and crest of the JMS. The presence of the hard and erosion resistant lithology will favor the backwearing process than downwearing in a escarpment or scarp (Nash, 2013; Shejwalkar, 2007). Similar geomorphic processes and backwearing of the escarpment face could be seen in the Western Ghats. Here, in the escarpment, the backwearing process dominates due to presence of hard and erosional resistant lithological units at the scarp top.

The major morphometric parameters like drainage density, frequency and bifurcation ratio are not indicating a significant change in the vicinity of the JMS and the Jumara dome. However, the computed parameters signifies the role of tectonics in the region. The Jara and Jumara domes of the western KMF are composed of similar lithologies, however the JMS is more prominent and significant only in the vicinity of the Jumara and interdomal saddle. Two major reason is possible for the development and preservation of the JMS in the location. First, the rivers draining the vicinity of the Jumara and interdomal have undergone higher degree of fluvial erosion in response to the higher net uplift. Taking into consideration of the stratigraphic throw, the Jumara dome is uplifted more in comparison to the Jara dome. The older Jhurio formation is exposed at the center of Jumara dome as an inlier. However, the Jhurio formation is not exposed at the center of the Jara dome. This signifies to the fact that the Jumara dome had undergone higher net uplift when compared to the Jara dome. The greater net uplift will ultimately lead to growth in relief and subsequent fluvial erosional process over the course of time. Secondly, the River 4 is eroding the scarp face more uniformly. The morphometric and long profile analysis for the river indicates that tectonic uplift induced fluvial erosion is happening more likely in a balanced manner. The river also displays a tendency to increase the drainage area laterally than longitudinally. The lateral increase in the drainage area favors the parallel retreat of slope or scarp face. In contrast to the River 4, the other rivers of the study area show a tendency to increase the drainage area longitudinally than laterally. The longitudinal advancement of the drainage area results severe headward erosion and dissection of the scarp. For example, the Jumara River is undergoing severe headward erosion. The elongated shaped of the basin and gorge in the upstream is a result of the severe headward erosion. Thirdly, the stronger and more resistant lithology of the upper Jhuran sandstone led to parallel retreat and preservation of the JMS scarp face. The coupling of above-mentioned factors led to the development of present morphology of the JMS.