CHAPTER – 9

DRAINAGE REORGANIZATION INDUCED BY SURFACE FAULTING

Drainage reorganization involves modification of drainage lines and this may be caused by tectonic activity (Bishop, 1995). Drainage patterns have a tendency to get preserved once established, so they incorporate noteworthy information about the past and present tectonic regime (Seeber and Gornitz, 1983; Oberlander, 1985; Gupta, 1997; Twidale, 2004; Yanites and Tucker, 2010; Castelltort et al., 2012). The patterns of river channels in tectonically active regions may contain important signals for understanding fault movement and its interaction with stream development (Jackson et al., 1996; Burbank and Anderson, 2011). The majority of the studies of drainage reorganization encompass large temporal and spatial scales with a reported range in age from 100 ka to more than 20 Ma (Prince at al., 2011; Zheng et al., 2013; Antón et al., 2014; Aslan et al., 2014; Bracciali et al., 2015; Robl et al., 2017; Authemayou et al., 2018), where, the processes of river incision and river basin reorganization are difficult to observe (Yanites et al., 2013; Zheng et al., 2013; Antón et al., 2014; Bracciali et al., 2015; Shugar et al., 2017). Some features, such as river elbows and barbed tributaries, can persist for millions of years, but they do not reveal much about the diversion process and its effects. Some studies have elaborated the impact of river diversions on the upstream drainage in medium-sized catchments (Mather, 2000; Stokes et al., 2002; Giletycz et al., 2015; Authemayou et al., 2018). Studies of drainage reorganizations in smaller scale drainage basins and sub-basins are generally rare (Harel et al., 2019).

In this chapter, drainage realignment on a sub basin-scale as a consequence of tectonic tilting caused by multiple events of surface faulting along the range bounding the Katrol Hill Fault (KHF) located in western India (Figure 9.1) during the last ~30 ka B.P. is described. The objective here is to constrain the mechanisms and causes of drainage disruption and reorganization in the small drainage basins of the Gunawari and Gangeshwar rivers that show highly anomalous channel characteristics.

STRUCTURAL INFLUENCE ON GUNAWARI RIVER BASIN

A major part of the area of Gunawari river basin lies in the Katrol Hill Range (KHR) (Figure 9.2a), located ~8 km upstream of its confluence with the Dharawa river. The Gunawari river basin shows influence of two domal structures in Mesozoic rocks, the eastern one with a higher elevation is the Ler dome and to the west is the Gangeshwar dome with relatively lower elevation (Figure 9.2a).

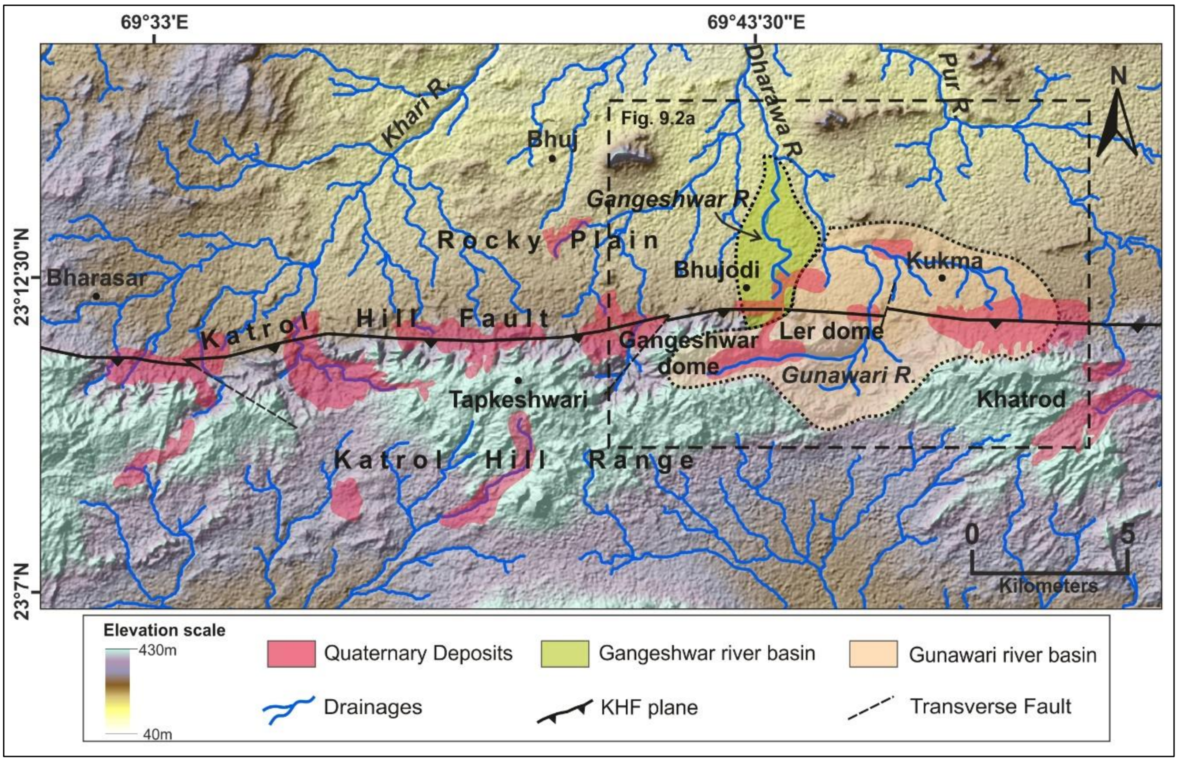

Figure 9.1 DEM of Katrol Hill Fault (KHF) zone (modified after Patidar et al., 2008). Note the rugged hilly topography of the Katrol Hill Range bounded by the KHF in the north. Also seen are the north and south-flowing drainage lines. Boxed area in dashed lines show the area covered in Figure 9.2a. Red colour indicates Late Quaternary miliolite deposits.

The domes are asymmetrical as the northern limbs have steep dips (~60°-80°) while the southern limbs have moderate dips (~25°-35°) that progressively become gentle up to ~5° towards south. The Ler dome largely exposes the Jumara Formation while the Gangeshwar dome comprises of the younger Jhuran Formation (Figure 9.2a). The eastward flowing Gunawari river flows around the Ler dome to flow northward along the saddle at its eastern margin (Figure 9.2a). Between the Ler and Gangeshwar domes is a buried paleo-valley filled by Late Quaternary miliolite deposits that is presently drained by the narrow and incised channel of the Gangeshwar river. The paleo-valley extends southwards into the wind gap, which is also filled by miliolite deposits (Figure 9.2a). The term 'wind gap' is defined as fragment of an abandoned channel that is filled with sediments of mainly fluvial origin (Bishop, 1995; Clark et al., 2004).

Topographic profiles drawn from the topographical maps illustrate a strong influence of structure on the geomorphic set up of the Gunawari basin (Figure 9.2a). The profiles were drawn from the Survey of India topographical maps to 1:50,000 scale. Three profiles oriented in N-S, NE-SW and E-W directions and marked as a-a', b-b' and c-c' respectively are shown in Figure 9.2a.

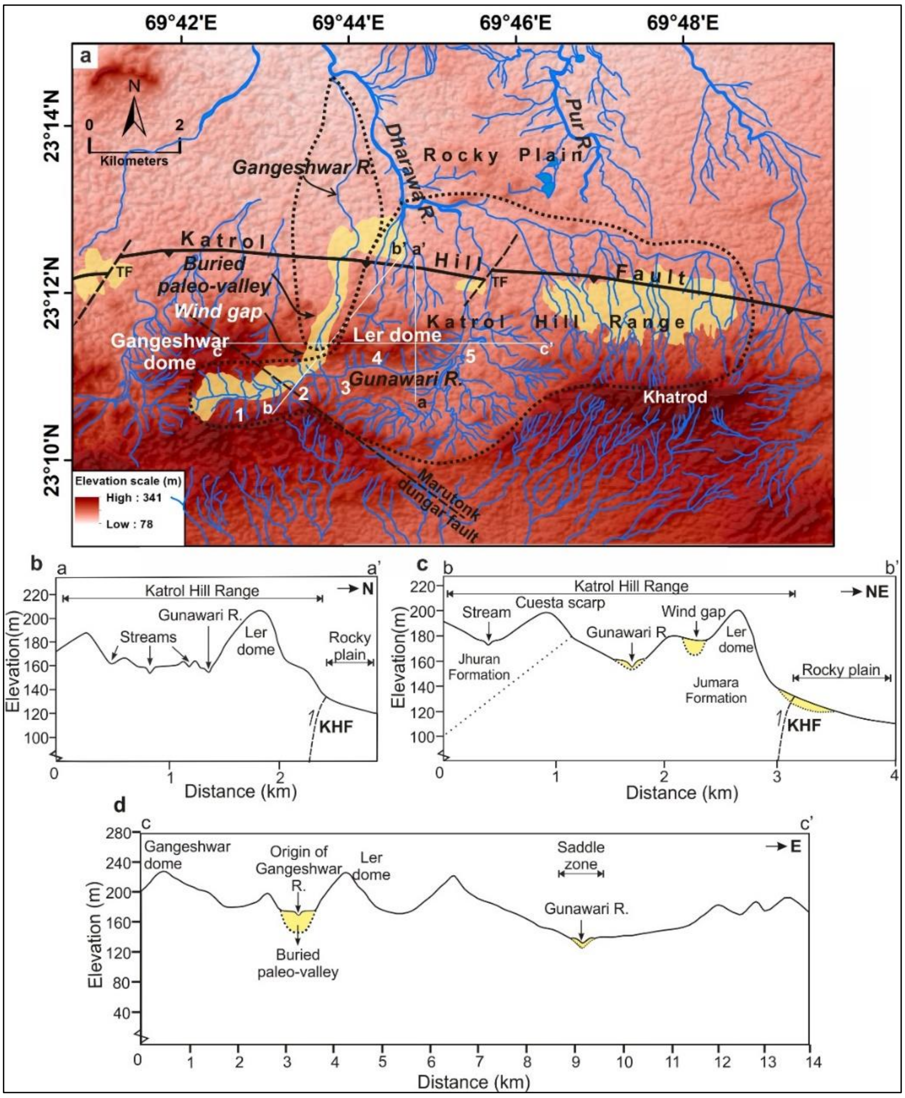

Figure 9.2 a. DEM image of the Gunawari river basin and Gangeshwar river basin. Note the anomalous nature of the Gunawari basin. Yellow colour denotes Late Quaternary miliolite sediments. The miliolite deposits occur along the valley including paleo-valley and wind gap in the Katrol Hill range and along the KHF zone. Thin white line shows the orientation of topographical sections – a-a', b-b', c-c'. **b.** N-S topographical section showing structurally controlled geomorphic setting of the area. Note the geomorphic contrast between the hilly topography of the Katrol Hill Range and the rocky plain in the north controlled by the KHF. **c.** NE-SW topographical section passing through the Gunawari river, wind gap and the KHF zone. Yellow colour indicates Late Quaternary miliolite deposits. **d.** E-W topographical section showing rugged topography, Gangeshwar river located in miliolite filled buried paleo-valley and Gunawari river in the saddle zone. (TF-Transverse fault).

The N-S profile (Figure 9.2b) shows the structurally controlled and rugged hilly topography of the KHR bounded by the KHF. The channel of Gunawari river to the south of Ler dome is formed along the E-W trending back-valley. The back-valley is formed along the E-W strike of the Mesozoic formations. The NE-SW oriented profile (Figure 9.2c) is drawn across the transect passing through Ler dome, buried paleo-valley, Gunawari river and the E-W trending cuesta scarp in the south that forms the drainage divide (Figure 9.2c). The wind gap occurs to the south of buried paleo-valley, through which the Gangeshwar river flows. The E-W trending profile (Figure 9.2d) is located within the Katrol Hill Range (KHR). The profile shows the positive relief developed over the Gangeshwar dome in the west and the Ler dome in the east. The structural evolution of the domes is attributed to multiple phases of post-Mesozoic tectonic deformation (Biswas, 1987; 1993) Between the two domes is the paleo-valley that is filled with Late Quaternary aeolian miliolite sediments that are exposed in the incised cliffs along the narrow channel of Gangeshwar river. To the east of the Ler dome is a wide saddle zone, through which the Gunawari river exits the KHR to flow northward. The rugged structurally controlled topography of the KHR and the confined nature of the Gunawari river channel is obvious in all the topographic profiles. The presence of a buried paleo-valley presently occupied by the north flowing Gangeshwar river and the wind gap are important geomorphic features suggesting existence of a paleo-drainage in the study area.

ANOMALOUS CHANNEL MORPHOLOGY

The major part of the course of the Gunawari river lies in the E-W trending back-valley located to the south of domal hills of the Gangeshwar and Ler domes (Figures 9.2a and 9.3a). The southern limit of the back-valley is formed by steep cuesta scarps consisting of south dipping, hard and compact Mesozoic rocks. The river arises and flows eastward through the back-valley to the south of the Ler and Gangeshwar domes. Along its length, the river channel shows straight to sinuous channel with several anomalous reaches (Figure 9.2a and 9.3a).

Starting from the origin, these channel reaches are – E-W trending sinuous channel (1), 'V'-shaped bend (2), 'S'-shaped bend (3), E-W trending straight channel (4) and the north flowing channel in the saddle region (5) up to the KHF zone. These channel reaches are shown as 1-5 in Figure 9.2a and 9.3a. From its origin up to the start of 'V'-shaped bend, the river shows a deeply incised meandering course. The depth of incision is 10-20 m (Figure 9.3b). The incised valley walls continuously expose miliolites with Mesozoic rocks at the base. The miliolites dominantly show aeolian characteristics. However, a few intervening horizontally stratified layers with clasts of Mesozoic rocks indicate very short phases of fluvial reworking. The deeply incised channel with vertical cliffs and narrow channel (~5

m) mimics the morphology of a typical gorge (Figure 9.3b). The river forms an inverted ‘U’-shaped bend (Figure 9.3a) as it cuts through a narrow NNW-SSE trending igneous dyke that is emplaced along the Marutonk dungar fault. The highly fractured nature of the dyke allows the river to carve out a ‘U’-shaped course around it. However, the depth of incision remains uniform, indicating that the Marutonk dungar fault was not reactivated in the post-miliolite time.

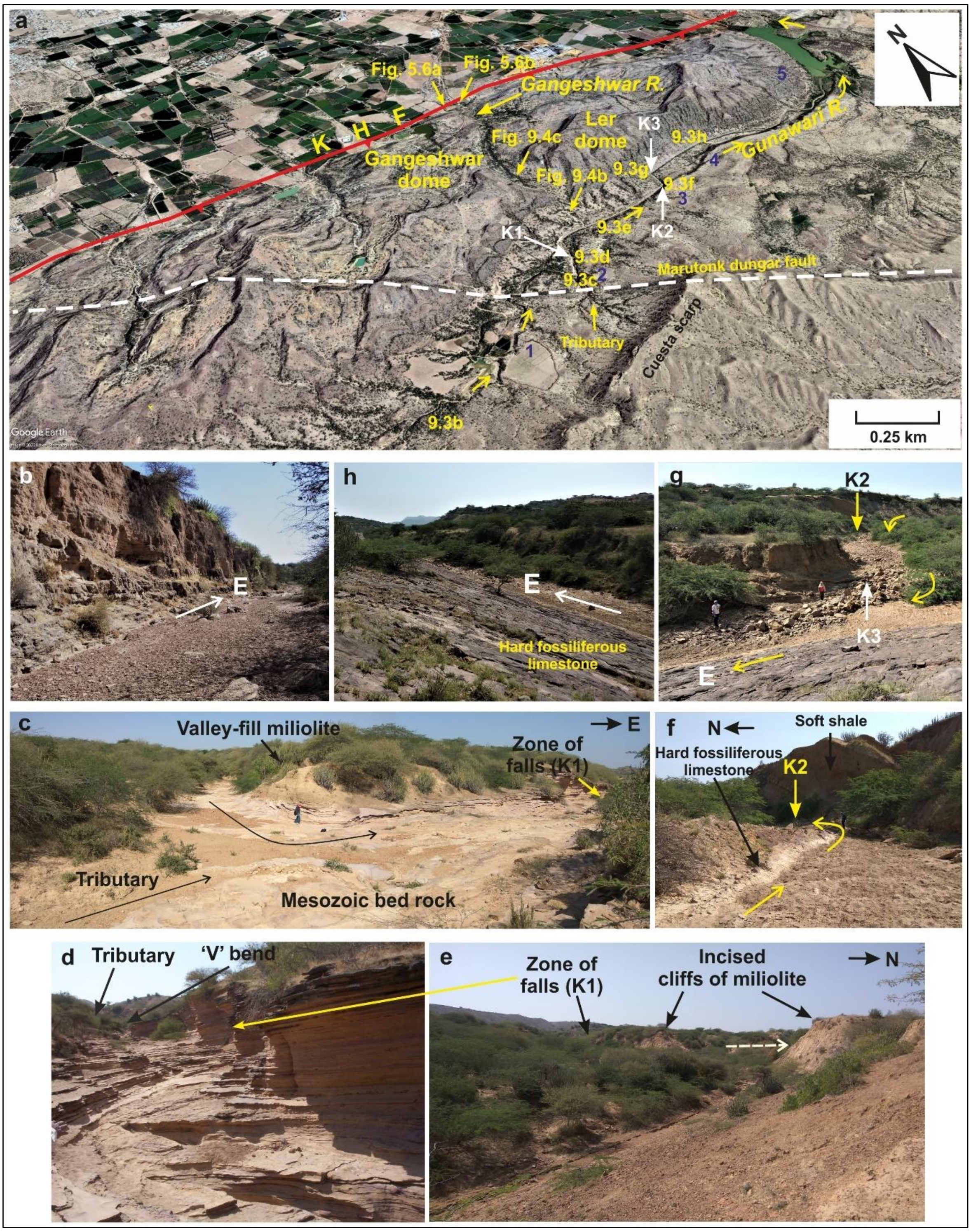

Figure 9.3 a. Satellite image of the area showing structurally controlled courses and anomalous channel characteristics of the Gunawari and Gangeshwar rivers (source: https://earth.google.com/). Major features and location of the field photographs included in Figure 4 and 5 are indicated. K1, K2 and K3 show the location of knickpoints. 1 – 5 are the anomalous channel segments of the Gunawari river. 1 – E-W trending incised meandering channel in the upstream reach of the Gunawari river. Note that most of the cliffs are formed on the southern bank of the river. 2 – 'V'-shaped bend of the Guawari river. Note the tributary stream joining at the apex of 'V'-shaped bend. The eastern arm of the 'V'-shaped bend is in alignment with the trend of the tributary stream. 3 – 'S'-shaped bend of Gunawari river. The bend is formed by two oppositely oriented right-angled bends. 4 – E-W trending straight channel after the Gunawari river emerges out of the 'S' -shaped bend. 5 – Channel of Gunawari river in the saddle zone to the east of Ler dome. **b.** Downstream view of the narrow, incised channel of the Gunawari river in its upper catchment in back-valley. The cliffs expose Late Quaternary miliolite sediments with Mesozoic rocks at the base. Note the absence of channel alluvium. **c.** View of the anomalous 'V'-shaped bend developed in Mesozoic rocks overlain by miliolites. The tributary coming from south and joining at the bend is also shown. **d.** Upstream (southward) view of the eastern arm of the 'V'-shaped bend showing zone of falls with multiple falls/knickpoints (K1). Location of the tributary indicated in (**c**) is also shown. **e.** Upstream (westward) panoramic view of the Gunawari channel. Thick white arrow points to the direction of buried paleo-valley towards north. The extremely narrow, straight, shallow eastward flowing channel in the foreground is formed after the river abandoned the paleo-valley due to river diversion. **f.** Downstream view of the eastward flowing straight channel of Gunawari river as it enters the 'S'-shaped bend. The channel is formed along the soft shales exposed in the cliff at the bend seen at the far end. The ~10 m height of the cliff is a reflection of the elevation of the drainage divide breached during phase of drainage reorganization. Also note the knickpoint (K2) at the 'S'-shaped bend. **g.** South facing view showing the 'S'-shaped bend showing narrow bedrock channel and knickpoints (K2, K3). **h.** Eastward (downstream) view of the narrow, straight channel of the Gunawari river after the 'S'-shaped bend shown in (f). Note the south dipping Mesozoic rocks (Jumara Formation) comprising the southern limb of the Ler dome.

A large and sharp 'V'-shaped bend (Figure 9.3c) is the most conspicuous channel bend along the course of the Gunawari river. The eastward flowing Gunawari river takes an abrupt turn towards the north to form the western arm of the 'V'-shaped bend. This segment of the channel shows the presence of several knickpoints (Figure 9.3d) in its downstream direction, which corresponds to a sharp drop in the river bed elevation in eastern arm of the 'V'-shaped bend. Further downstream, the incision is ~10 m deep within the miliolites and the underlying Mesozoic sandstones. This appears to confirm the gentle southward dip of the bedrock.

The straight reach further eastward (Figure 9.3e) continues up to the 'S'-shaped bend (Figure 9.3f). This bend is not exactly 'S'-shaped but is formed by two right angle bends of the river. The river takes a sharp right angle turn towards the north, however after a short distance of ~100 m it again makes a right angle turn towards east (Figure 9.3f). The channel remains extremely narrow and flows through Mesozoic rocks exposed in the river bed and valley sides. The incision also remains low. Downstream of this bend, the channel is remarkably straight, narrow and shallow (Figure 9.3h). Further in the downstream, the river swerves around the eastern limb of the Ler dome and flows northwards into the KHF zone. The channel becomes broader as it flows in the structurally controlled saddle region (Figure 9.3a). The channel shows a marginal increase in gradient as it emerges out of the range front scarp and crosses the KHF zone. Incision of ~3.5 m is observed in miliolites in this zone. Further northward oriented narrow channel of the river is found to be shallow but incised into the sandstones of Bhuj formation till it meets the Dharawa river.

The Gangeshwar river flows northward along an extremely narrow but deeply incised channel along the central part of the buried paleo-valley (Figure 9.4b).

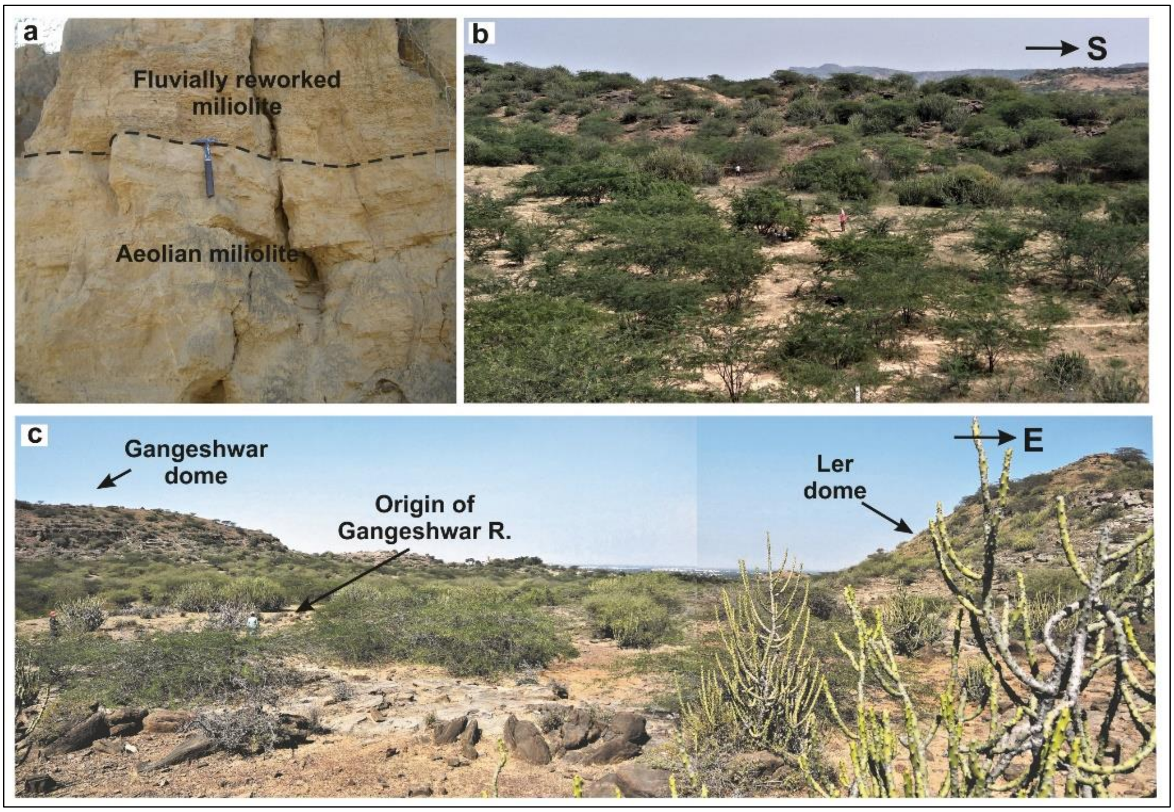

Figure 9.4 a. Close view of the incised river cliffs showing aeolian and reworked Late Quaternary miliolite deposits. **b.** Eastward view of the wind gap. The light-coloured flat surface is developed over the Late Quaternary miliolite deposits in the wind gap. The rocky hill slope at the far end is comprised of Mesozoic rocks of the Ler dome. **c.** Northward view of the buried paleo-valley. Location of the channel of northward flowing Gangeshwar river is indicated. Note the nature of the rocky plain in the distant background visible through the buried paleo-valley. Location of photographs in b and c are shown in Figure 9.3a.

There are no tributary channels joining this stream along its course. The stream originates at an elevation of ~166 m at the southern end of the paleo-valley (Figure 9.4c) with a very rapid increase in incision depth to ~15 m. All along the incised valley walls, reworked (fluvial) miliolites are exposed. Before the KHF, the river shows two small knickpoints. The channel is very shallow with negligible incision after it crosses the KHF. The small shallow channel is almost imperceptible in the rocky plain until it joins the Dharawa river (Figure 9.4c). Deformation and offset in aeolian miliolite deposits are observed at the location where the Gangeshwar river crosses the KHF zone (Figure 5.6a, b, location is marked in Figure 9.3a).

Morphometric river meander parameters were calculated for 25 reaches comprising the channel of Gunawari river and 04 reaches comprising the channel of Gangeshwar river (Figure 9.5) for characterizing spatial variations in channel properties (Table 9.1). Overall, the parameters are found to vary within a limited range of values, which is consistent with the small size of the drainage basins.

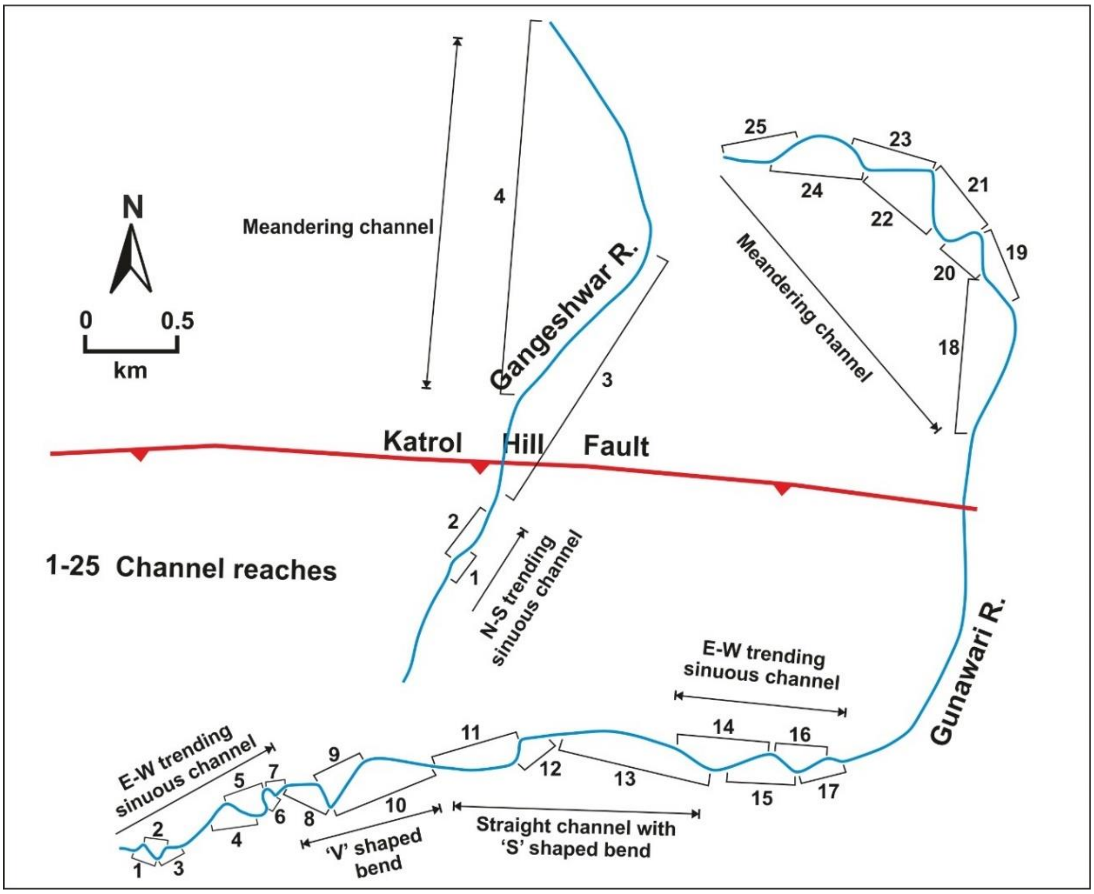

Figure 9.5 Map showing channels of Gunawari and Gangeshwar rivers with channel segments and reaches. Morphometric data generated for the channel reaches is shown in Table 9.1.

However, the variations correlate with the results of the field-based study of present-day channels described above. The Gunawari and Gangeshwar rivers show open meanders, which is reflected in low sinuosity values from 1.07 to 1.99 (Table 9.1). Values closer to 1 are from the straight segments of the river. The short Gangeshwar river is almost straight with few wide, open meanders with sinuosity values of 1.013 to 1.191. River segments with sinuosity values of 1.5 or greater are considered as meandering (Leopold and Wolman, 1960). The sinuosity values suggest the tendency of the Gunawari river to flow straight with a few meandering segments, while the Gangeshwar river falls in the category of a straight channel.

In the Gunawari river, the W/D ratios range from 0.17 to 3.35, which is a reflection of the dominance of vertical incision in the morphology of the present river channel (Table 9.1). The minimum ratio of 0.17 is for the eastern arm of 'V'-shaped bend, which hosts the zone of falls (K1). The maximum ratio of 3.35 is found in the source region where the depth of incision is relatively low. The ratios are consistently <1 in the E-W trending narrow and straight channel segments on either side of the 'S'-shaped bend. The W/D values are relatively higher in the rocky plain to the north of KHF due to significantly lower incision in the channel reaches in this part. The Gangeshwar river has W/D rations <1, which conforms to its narrow, deep channel. Overall, the W/D ratios match field data, which show narrow and deeply incised bedrock channels in the Katrol Hill Range.

The structural lows within the Katrol Hill Range and along the KHF provided an ideal landscape for the deposition of Late Quaternary aeolian miliolites. The deep back-valley, wind gap and range front scarps provided suitable sites for substantial accumulation of miliolites. The deposition of miliolites occurred in phases spanning relatively long period of time. Several $^{230}Th/^{234}U$ dates of miliolites are available from the Kachchh region (Baskaran, 1989a; Chakrabarty et al., 1993). However, the location of samples is not precisely marked. A critical evaluation of sparse chronological data on miliolites from exposures in and around Gunawari basin gives a broad idea of the miliolite depositional phase. These dates indicate a relatively large period of deposition time, from 167±17 to 42.4 ±4 ka B.P. (Baskaran, 1989b; Chakrabarty et al., 1993). The absence of other Quaternary deposits is significant. Intervening layers of reworked miliolites within the aeolian miliolites seen in incised sections (Figure 9.4a) along Gunawari basin suggests that the river continued to exist during episodic accumulation of aeolian miliolite sediments. However, the nature of channel must have been very different from the present day.

Table 9.1 Morphometric parameters of the Gunawari and Gangeshwar rivers. The channel segments and reaches are shown in Figure 9.5.

Gunawari river											
Geomorphic Domain	**Channel segment**	**Reach ID**	**River Width (W) (m)**	**River Depth (D) (m)**	**Radius of Curvature (R) km**	**Axis Length (A) km**	**Meander Neck Length (L) km**	**Flow Length (S) km**	**Sinuosity (C)**	**W/D Ratio**
Katrol Hill Range	E-W trending sinuous channel	1	4.9	2.5	0.021	0.044	0.11	0.153	1.391	1.96
		2	6.7	2	0.037	0.068	0.11	0.187	1.7	3.35
		3	5.52	3	0.027	0.041	0.16	0.185	1.156	1.84
		4	4.12	7	0.057	0.099	0.29	0.36	1.241	0.59
		5	4.69	9.5	0.063	0.142	0.23	0.387	1.683	0.49
		6	5.37	10.5	0.037	0.071	0.1	0.199	1.99	0.51
		7	4.72	7	0.039	0.041	0.1	0.112	1.12	0.67
	'V' shaped bend	8	3.45	8	0.047	0.085	0.29	0.34	1.172	0.43
		9	5.2	14	0.044	0.178	0.28	0.497	1.775	0.37
		10	5.24	30	0.108	0.179	0.62	0.734	1.184	0.17
	Straight channel with 'S' bend	11	4.86	9	0.049	0.123	0.48	0.548	1.142	0.54
		12	3.59	10	0.023	0.029	0.1	0.121	1.21	0.36
		13	4.76	7	0.564	0.107	0.97	1.002	1.033	0.68
	E-W trending sinuous channel	14	5.16	5	0.126	0.109	0.5	0.553	1.106	1.03
		15	6	4	0.064	0.095	0.36	0.42	1.167	1.50
		16	7.48	5	0.064	0.09	0.31	0.362	1.168	1.50
		17	5.23	5	0.077	0.042	0.27	0.289	1.07	1.05
Rocky Plain	Sinuous channel	18	6.66	4	0.604	0.193	0.91	1.025	1.126	1.67
		19	6.75	4	0.386	0.072	0.45	0.479	1.064	1.69
		20	3.72	3	0.06	0.159	0.27	0.449	1.663	1.24
		21	6.5	3	0.104	0.203	0.45	0.64	1.422	2.17
		22	8.49	3	0.092	0.246	0.52	0.73	1.404	2.83
		23	10.7	4	0.069	0.12	0.53	0.604	1.14	2.68
		24	9.8	3	0.205	0.177	0.51	0.672	1.318	3.27
		25	7.57	4	0.201	0.086	0.399	0.473	1.185	1.89
Mean			5.88	6.66	0.127	0.112	0.376	0.457	1.305	1.38
Standard Deviation			1.79	5.62	0.158	0.059	0.232	0.251	0.254	0.924
Minimum			3.45	2	0.021	0.029	0.1	0.111	1.07	0.17
Maximum			10.7	30	0.604	0.246	0.97	1.025	1.99	3.35
Gangeshwar river											
Katrol Hill Range	N-S trending sinuous channel	1	3	8.5	0.15	0.017	0.15	0.152	1.013	0.35
		2	3.5	7	0.042	0.026	0.12	0.13	1.083	0.50
Rocky Plain	Sinuous channel	3	1.25	1.5	0.9	0.19	1.47	1.53	1.04	0.83
		4	1	1	1.17	0.7	2.25	2.68	1.191	1.00
Mean			2.19	4.5	0.56	0.23	0.99	1.12	1.08	0.67
Standard Deviation			1.08	3.29	0.48	0.27	0.9	1.06	0.06	0.25
Minimum			1	1	0.15	0.017	0.12	0.13	1.013	0.35
Maximum			3.5	8.5	1.17	0.7	2.25	2.68	1.191	1

LONGITUDINAL RIVER PROFILES

The longitudinal river profile is a curve, which represents the variation of elevation with the downstream distance of a river (Hack, 1957), where the Y-axis represents elevation in a linear scale and the X-axis represents downstream distance. These profiles are sensitive to the ongoing uplift process and can be used to recognize active structures (Seeber and Gornitz, 1983; Merritts et al., 1994; Lavé and Avouac, 2001; Kirby and Whipple, 2001). The long profile of the Gunawari river (Figure 9.6a) shows variable characteristics in its various channel segments as described above (Figure 9.3). In the vicinity of the source, the river shows very steep gradient (Figure 9.6a). This part of the course lies in the Mesozoic rocks. Further downstream, the gradient is relatively gentle, but, remains steep.

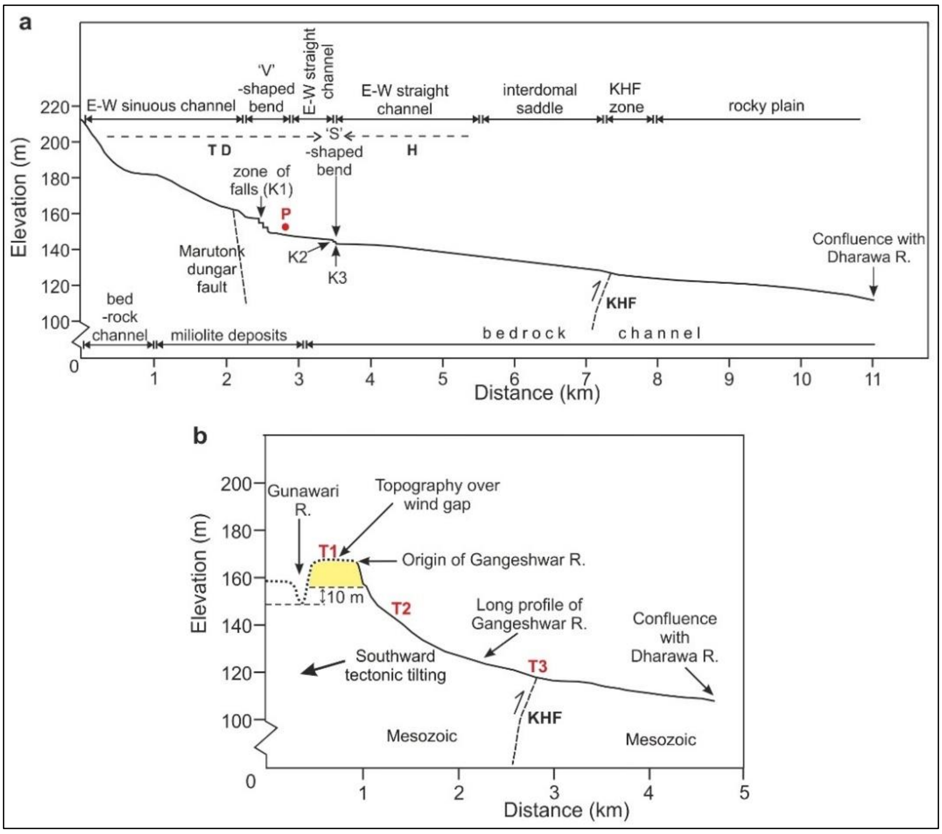

Figure 9.6 a. Longitudinal river profile of the Gunawari river. Location of characteristic channel reaches and anomalous segments described in the text are indicated. K1, K2 and K3 denote knickpoints in the river profile. The point on the long profile closest to the headwaters of the Gangeshwar river is marked as P. Note the abrupt break in channel gradient in the anomalous 'V' and 'S'-shaped bends. The Marutonk dungar Fault does not show any effect on the river profile indicating its inactive nature. **b.** Longitudinal river profile of the Gangeshwar river. Note the origin of Gangeshwar river at the margin of the floor of the buried paleo-valley. The elevation difference of the floor of the wind gap and the present-day channel of Gunawari river is also shown. T1, T2 and T3 indicate the location of the transects of GPR profiles shown in Figures 6.2, 6.3 and 6.4.

The effect of the Marutonk dungar fault is not seen in the long profile (Figure 9.6a). The 'V'-shaped channel segment has several closely spaced knickpoints (K1), which corresponds to the sharp drop in river bed elevation in the eastern arm of the bend as described earlier (Figure 9.3d, 9.6a). Further downstream, the profile (Figure 9.6a) has a gentle gradient throughout. This part of the profile encompasses the straight E-W trending bedrock channel and the northward oriented channel in the saddle zone and further in to the rocky plain. This part of the profile also matches the significantly low incision as discussed in the previous section. The anomalous 'S' -shaped bend in the centre of this reach shows two small knickpoints (K2, K3) exactly at the anomalous turns of the river (Figure 9.3f, 9.3g and 9.6a).

The long profile of the Gangeshwar river (Figure 9.6b) has concave upwards morphology that is typical of a rejuvenated river. The profile is remarkably steep in the upper part and progressively reduces in the downstream direction (Figure 9.6b). The gentle slope of the profile continues as the river crosses KHF and flows further in the rocky plain. The profile downstream of KHF corresponds to the shallow indistinct channel in the rocky plain as mentioned in the previous section (Figure 9.4c).

CHI (χ) ANALYSIS

The chi (χ) factor analysis was carried out for the Gunawari river (Figure 9.7) to determine its state of drainage stability. Horizontal dynamics of the drainage divides of river networks can be understood from chi (χ) map (Willett et al., 2014; Struth et al., 2020) in Figure 9.7a. Differences in chi (χ) across drainage divides indicate disequilibrium conditions, which induce migration of drainage divides from low to high chi (χ) values to achieve equilibrium (Willett et al., 2014; Fan et al., 2018; Struth et al., 2020). The chi (χ) map of Gunawari and Gangeshwar river basins shows mostly equilibrium condition (Figure 9.7a). However, the chi (χ) values are highest in the source region of Gunawari river (Figure 9.7a). This is interpreted as a possible reduction of its drainage area by the movement of the divide as water divides generally move in the direction of higher chi (χ) to achieve equilibrium. The drainage divide between the Gangeshwar and Gunawari rivers appears in equilibrium as there is not much difference in the chi (χ) values across the drainage divide (Figure 9.7a). The χ -elevation plot of a channel in steady state is always characterized by a straight line and deviation from this linear trend can be used to compare different drainage basins and also profiles within a single drainage basin (Whipple and Tucker, 1999; Perron and Royden, 2013; Lague, 2014). Figure 9.7b shows the chi (χ) -elevation plot of the

Gunawari river and its tributaries. It can be seen that the general slope of the chi (χ) plot broadly appears to follow the average slope line suggesting that the channel is in an overall steady state. However, the chi (χ) plot slope varies in several segments. This is observed in a number of successive linearized segments of differing steepness (Figure 9.7b).

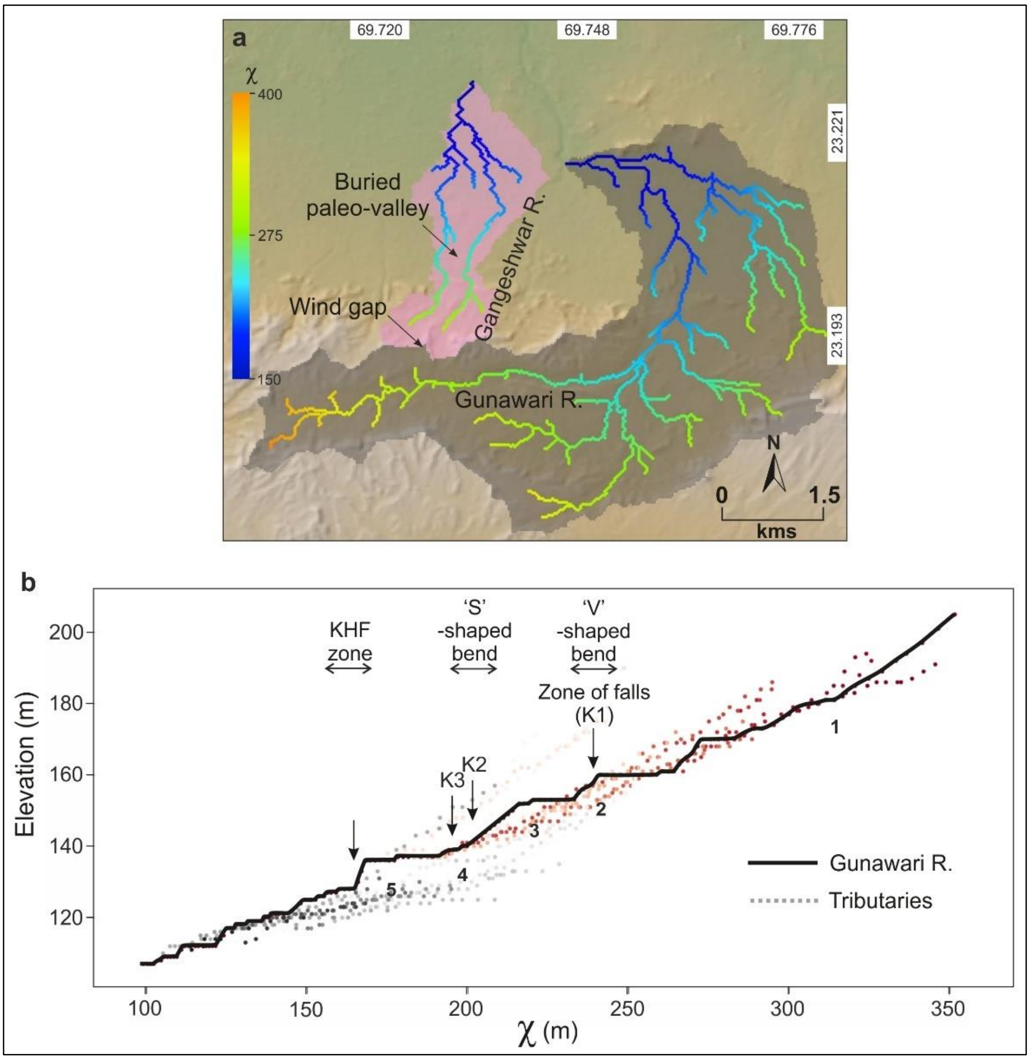

Figure 9.7 a. Chi (χ) map of Gunawari and Gangeshwar river basins. Note the high chi (χ) values in the source region of Gunawari river and almost identical values across the divide between the two rivers. **b.** Chi (χ) plot of the Gunawari river channel from origin to its confluence with Dharawa river. Note the abrupt slope variation that corresponds with the anomalous channel reaches and the KHF zone.

These segments are found to correspond to the anomalous reaches along the channel of Gunawari river. Also, the absence of collinearity of the main trunk and tributaries is observed in the lower reach of the channel that is in close proximity to the KHF. In contrast, collinearity can be observed for the upper reach of the river as the tributaries are well aligned with the main channel. It is interpreted that the deviations of the segments of chi (χ) plot from the linear trend, indicates transient state of the Gunawari river channel in the anomalous ‘V’ and ‘S’-shaped bends and the KHF zone, which is also indicated by the knickpoints (K1, K2, K3) located in these bends (Figure 9.3).

GEOMORPHIC EVIDENCE OF DRAINAGE REORGANIZATION

Drainage rearrangement is known to occur on variable spatial scales ranging from badlands to regional to sub-continental scale river systems (Bishop, 1995; Brookfield, 1998; Clark et al., 2004; Rossetti and Góes, 2008; Mantelli et al., 2009; Zhang et al., 2017; Fan et al., 2018). River capture is the most obvious and common form of drainage rearrangement, which occurs through capture of a river by an adjacent river through aggressive headward erosion, river diversion and beheading. The primary evidence for identification and reconstruction of drainage reorganization is mostly morphological (Bishop, 1995) such as the elbow of capture, wind gap etc. The point of river capture is called the elbow of capture, which can be identified by sharp change in channel direction (Bishop, 1995; Fan et al., 2018). The above-described present-day channel planform characteristics and valley morphology of the Gunawari river show a highly abnormal nature. Given the small size of the Gunawari drainage basin, the occurrence of all three known forms of drainage reorganization (capture, diversion and beheading) is significant. While the elbow of capture is important evidence for the occurrence of drainage reorganization, other evidences in the Gunawari river supports this including the wind gap and buried paleo-valley. Tectonic deformation and offset in aeolian miliolite deposits overlying the KHF zone provides evidence for establishing the causative factor of drainage reorganization in the study area (Figures 5.6).

The most prominent evidence of drainage reorganization in the Gunawari river basin include the anomalous ‘V’ and ‘S’-shaped bends (Figure 9.3c and 9.3g), wind gap (Figure 9.4b) and the buried paleo-valley (Figure 9.4c) presently, occupied by the Gangeshwar river. The sharp ‘V’-shaped bend and multiple falls (K1) in its eastern arm (Figure 9.3d) reflect the adjustments made by the river during drainage reorganization. The deeply incising Gangeshwar river flowing northward in the buried paleo-valley appears to be a misfit first order stream (Figure 9.3a). The N-S trending miliolite filled wind gap connects the present channel of the Gunawari river and the origin point of the Gangeshwar river at its northern end (Figure 9.3a). Such a sediment filled valley is a consequence of drainage rearrangement and occurs upstream of the elbow of capture (Bishop, 1995). The geomorphic setting of the Gangeshwar river in the buried paleo-valley and the wind gap with the same orientation at its origin point (Figure 9.3a) indicates that it is the beheaded (victim) remnant of drainage rearrangement.

The anomalous ‘S’-shaped bend of the Gunawari river (Figure 9.3f, g) located downstream of the wind gap, is identified as the elbow of capture. The two knickpoints (K2, K3) at this bend (Figure 9.3a, 9.3f and g) reflect the height difference between the involved rivers necessary for river capture to take effect. The role of the aggressor stream (headward erosion) is attributed to the paleo-Gunawari (Figure 9.8a, b) that occupied the broad saddle zone to the east of Ler dome as seen in the topographic cross section profiles in Figure 9.3. This is evident in the abrupt right angle turns formed by the two straight channel segments (Figure 9.3g). The channel downstream of the bend (paleo-Gunawari) is the one, which is associated with headward erosion (bottom-up process), while the straight channel upstream of the bend (paleo-Gangeshwar) was the one, which was forcing its way in the downstream direction (top-down process) as shown in Figure 9.8b. The presence of two knickpoints (K2, K3) exactly at the right angle turns clearly show that the ‘S’-shaped bend formed the elbow of capture (Figure 9.8b).

The geomorphic evidences combine to suggest that the paleo-Gangeshwar river previously flowed northward through the wind gap, buried paleo-valley, and present course of the Gangeshwar river (Figure 9.8a). The drainage rearrangement caused the river to abandon its northward course in the wind gap and buried paleo-valley. Establishment of a new drainage system was influenced by the two tributary streams that already existed prior to and during the depositional phase of miliolite (Figure 9.8a). The existence of Tributary 1 and Tributary 2 before the drainage rearrangement is supported by aeolian miliolite deposits along their channel. The process of drainage rearrangement involved abandonment of the northward course of the paleo-Gangeshwar river, formation of the western arm of a ‘V’-shaped bend in down dip (south) direction to join up with Tributary 1, formation of an E-W trending channel along the strike between the ‘V’-shaped bend and the ‘S’-shaped bend through flow reversal and extension of the course of Tributary 2 and along strike headward erosion to the west up to the ‘S’-shaped bend by paleo-Gunawari river (Figure 9.8b). The straight, narrow E-W trending channels reaches on either side of the ‘S’-shaped bend were formed along the easily erodible lithology of soft shales while the hard, compact lithology of fossiliferous limestone lines the northern bank (Figure 9.3f). The relative higher relief in the zone of the present day ‘S’-shaped bend indicated by the 10-12 m cliff sections (Figure 9.3f), facilitated the headward erosion. Both along strike and parallel, but misaligned channels advancing towards each other by headward erosion (bottom-up process) joined up to produce the ‘S’-shaped bend, which formed the elbow of capture as shown in Figure 9.8b. However, the short south flowing western arm of ‘V’-shaped bend was formed by a top-down process, as defined by Bishop (1995), in terms of the down dip direction of Mesozoic rocks. It is elaborated further in the section on GPR studies, the drainage reorganization was triggered by surface faulting along the KHF, which led to southward titling of Katrol Hill Range (KHR) during the last ~30 ka B. P.

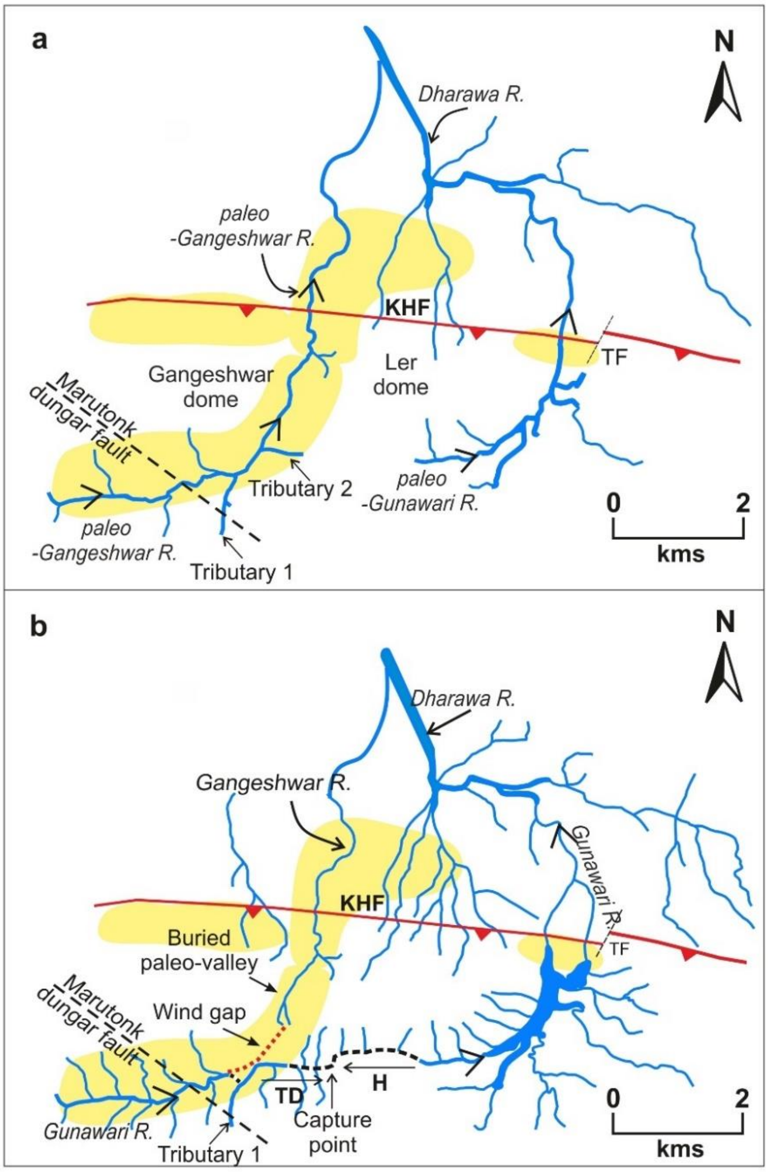

Figure 9.8 a. Reconstructed paleo-drainage lines inferred from geomorphic evidences. Note that the paleo-Gangeshwar was a larger river while the paleo-Gunawari was a short river that drained the area around the eastern fringe of Ler dome. This drainage existed prior to and during the deposition of phase of miliolite lasting up to ~40 ka B.P. This drainage set up was reorganized in the last ~30 ka B.P. due to tectonic tilting attributed to surface faulting along KHF. **b.** Map showing present day drainage lines in the study area. The channel segment of Gunawari river shown in black dashed line was formed due to reorganization of drainage in last ~30 ka B.P. The channel marked dark by red dots indicates the drainage line (paleo-Gangeshwar river) that existed previously during and before the deposition of miliolite sediments as shown in (a).

Deep incision by the beheaded north flowing Gangeshwar river was primarily influenced by tectonic uplift. The river flows through the northernmost margin of the fault bounded Katrol Hill Range (KHR), which experienced relatively more tectonic uplift (due to south directed tectonic titling due to faulting along the Katrol Hill Fault). Also, the incision occurred in the softer miliolite sediments and not in hard, compact Mesozoic rocks. The Gangeshwar river, therefore, could incise deep in spite of its reduced source area and consequent low stream power.

EVIDENCE OF DRAINAGE REORGANIZATION FROM GPR SURVEYS

The GPR profiles of Transect 1, 2 and 3 described in the Chapter – 6 fall within the Gunawari river basin and provide important evidence of Late Quaternary drainage reorganization, which complements the geomorphic evidences described above. Overall, the GPR profile of the wind gap (Figure 6.2) suggests the existence of a bed-rock channel in the subsurface filled up by aeolian miliolites with episodic reworking by an ephemeral stream. The nature of reflector patterns along with erosional troughs provide conclusive evidences for the northward flow of the river through the paleo-valley during the phase of miliolite deposition. However, the prominent erosional truncation surface at the top of the sediment fill (Figure 6.2b) clearly suggests the river ceased to exist that led to dominantly slope wash-dominated depositional activity. Further northward extension of the wind gap into the buried paleo-valley strongly indicates the presence of a northward flowing river. The geomorphological and GPR data and lack of climatic data from the Kachchh region do not allow to infer climatic conditions during the fluvial reworking of the miliolites. However, the active nature of the KHF (Patidar et al., 2008; Maurya et al., 2017) points to the strong role of tectonic activity on the geomorphic development of the Katrol Hill Range (Patidar et al., 2007).

The reflection patterns in the GPR profile of Transect 2 (Figure 6.3) located in the paleo-valley are similar to the GPR data along Transect 1 (Figure 6.2) across the wind gap in the south. The presence of reworked miliolites along with sediment filled erosional troughs suggest the existence of a river flowing northward through the wind gap and buried paleo-valley. It is inferred that the Gangeshwar river during and prior to the phase of miliolite deposition extended further south with the catchment comprising the area covered by the present Gunawari river (Figure 9.9a, b). This suggests that the presently short Gangeshwar river occupying only the paleo-valley (Figure 9.9b) is a beheaded remnant stream of the former paleo-Gangeshwar river that had a larger catchment in further south (Figure 9.9a, b).

The GPR data along Transect 3 (Figure 6.4) to the south of Bhujodi shows that the aeolian miliolites overlapping the KHF in front of the north facing range bound scarps are offset due to post-miliolite tectonic activity. The radargram clearly shows that the KHF fault plane extends up to the surface through the thin cover of aeolian miliolite (Figure 6.4). This suggests that the tectonic slip along the KHF offset the topography during post-miliolite times. The amount of offset is determined from the positions of stratigraphic layers on either side of the fault plane as has been done by Patidar et al. (2008) for the case of the KHF. In the study area, miliolite sediments are the only Quaternary deposits. Moreover, the compositionally homogenous nature of the aeolian miliolite mean that correlatable layers are difficult to identify across the fault plane. Because of these reasons the amount of offset cannot be estimated from the GPR profile. This indicates post-miliolite surface faulting along KHF from the GPR data.

The GPR data and interpretation matches previous data that have shown three surface faulting events in the last ~30 ka B.P. (Patidar et al., 2008; Kundu et al., 2010). The three surface faulting events are not discernible in the Gunawari basin as the only Quaternary sediment found here is aeolian miliolite. However, the field and GPR data presented, show that the multiple surface faulting events reported from ~20 kms to the west in the Khari river basin, did extend up to the study area. The findings also mean that the active fault trace of the KHF is at least 20 km in length.

PHASES OF DRAINAGE REORGANIZATION

Drainage rearrangement leads to obliteration of previous drainage divides and formation of new divides and channels (Bishop, 1995). Evidence for drainage realignment in the present study area is mainly geomorphological rather than sedimentological, due to the rocky mountainous landscape and absence of alluvial sediments. The only Quaternary deposit occurring in the study area is the Late Quaternary aeolian miliolite, which buried the pre-existing river channels. Several $^{230}Th/^{234}U$ dates from miliolite sediments in Katrol Hill Range and KHF zone indicate that the depositional phase extended from ~167 ka B.P. to ~42 ka B.P., that correlates with a similar phase of miliolite deposition in the Saurashtra region in the south (Baskaran et al., 1989a, b; Chakrabarty et al., 1993). Geomorphic evidence for drainage rearrangement in the area include the wind gap, buried paleo-valley (Figure 9.8) and the presence of anomalous 'V' and 'S'-shaped bends (Figure 9.3c and 9.3g) without any apparent geological reason. Offsetting and deformation of miliolites overlying the KHF (Figure 5.6), confirmed by GPR (Figure 6.4) and incised cliff sections of miliolite along river banks clearly suggest that the drainage realignment occurred in post-miliolite time due to southward directed tectonic tilting of the Katrol Hill Range in response to multiple events of coseismic surface faulting during the last ~30 ka B.P. (Patidar et al., 2008; Kundu et al., 2010). the sequence and mechanism of drainage rearrangement in the Gunawari basin is elaborated as it occurred in different phases (Figure 9.9). The entire phenomenon occurred in three distinct phases during the Late Quaternary. These are the pre-miliolite, syn-miliolite and the post-miliolite phases (Figure 9.9). These three phases are documented in detail in the following paragraphs.

Pre-miliolite phase

The mode of occurrence of miliolite deposits permits estimation of some geomorphological characteristics of the Gunawari river basin before the miliolite depositional phase (Figure 9.9a). The miliolites occur in the E-W trending central depression in the back-valley. The extension of miliolite deposits is continuous from the vicinity of the range to the end of the 'V'-shaped bend of the river. The river continued eastward with an extremely narrow and relatively shallow bedrock channel devoid of miliolites or any other alluvial deposits (Figure 9.3h). However, the miliolite deposits continue to occur northward in the wind gap and paleo-valley (Figures 9.2a and 9.9). Thereafter, the miliolites are encountered in the KHF zone that extends in E-W direction in front of the range front scarps (Figure 9.2). The GPR data show that the miliolites overlap the KHF in the shallow subsurface (Figure 6.4). Significantly, other Quaternary deposits like alluvial sands are not seen in the entire Gunawari basin as the miliolite deposits are found to directly unconformably overlie the Mesozoic rocks (Figure 6.4).

In Figure 9.9a, pre-miliolite and pre-capture situation is shown by initially separating the channel into two independent drainages: paleo-Gangeshwar and paleo-Gunawari rivers. The Figure 9.9a shows the path drained by the two rivers before the event of miliolite deposition, tectonic uplift, headward erosion and river capture. It is inferred that paleo-Gangeshwar river in the pre-miliolite times was a bedrock river all through its course (Figure 9.9a). The geomorphologic and GPR data shows that it flowed northward through the wind gap (Figure 6.2) and the paleo-valley (Figure 6.3) in the KHR before entering the rocky plain. The channel was incised and relatively wider as suggested by the width of the paleo-valley (Figure 6.3), which is distinctly larger than the present-day channel of the river. The 'V'-shaped bend did not exist in pre-miliolite time (Figure 9.9a). However, a predecessor of the present tributary (Tributary 1) joined the Gunawari channel from the south along the eastern arm of the 'V'-shaped bend (Figure 9.3c, d). The E-W shallow channel downstream of the ‘V’-shaped bend also did not exist at that time as it is devoid of miliolite deposits (Figure 9.9a). This suggests that this part was an elevated rocky surface, which was responsible for the paleo-Gangeshwar river to turn northward and flow through the wind gap and paleo-valley (Figure 9.9a). Another small tributary (Tributary 2) also existed that joined the eastern bank of paleo-Gangeswar river. The presence of Tributary 1 and 2 in pre-miliolite time is indicated by the occurrence of aeolian miliolites in their valleys (Figures 9.8a and 9.9a). As elaborated earlier and later in this section, these tributaries played important role in the formation of ‘V’-shaped bend and the E-W trending straight channel between ‘V’ and ‘S’-shaped bends (Figure 9.9).

Syn-miliolite phase

This phase includes a relatively long-time interval of miliolite deposition (Figure 9.9b). A major proportion of miliolite deposits in the Gunawari river basin are aeolian. Exposures of miliolites along the incised cliffs in the back-valley reach up to the ‘V’-shaped bend (Figure 9.3e) show aeolian characteristics. These deposits show uniformly fine-grained size with thick cross-bedded to massive nature. Few discontinuous centimetre scale horizontal layers with gravel to pebble sized rock fragments of Mesozoic rocks are observed. These layers suggest brief episodes of fluvial reworking between the phases of aeolian deposition (Figure 9.4a). Small thickness, discontinuous nature and general lack of distinct sedimentary structures indicate their deposition by short duration episodic flows that typically occur in ephemeral streams. The data shows that the fluvial system in the study area was strongly ephemeral throughout the phase of miliolite deposition. This is in agreement with the present hyper-arid climatic setting of the Kachchh region (Figure 9.1). Presently, the fluvial activities are minimal as the channel remains dry for most part of the year due to hyper-arid climate of the region. This slightly contrasts with the back-valley reach of the Khari river basin, further west of the study area (Figure 9.1). Here too, the back-valley is filled with miliolites, but a large part of it along the river is fluvially reworked (Patidar et al., 2007). The aeolian miliolite is found in the upper parts of the valley slopes (Patidar et al., 2007).

The Khari river is a much larger river (Figure 9.1) as indicated by its greater width and depth of the channel, which allowed reworking of a large part of the aeolian miliolites deposited in the valley. Evidently, the very small proportion of the reworked miliolites in the back-valley reach of the Gunawari river is an indication of much subdued fluvial activity as elaborated above. This contrast is attributed to the smaller drainage area of the Gunawari river and hyper-arid climate. The fluvial reworking of miliolites is relatively more obvious in the cliff sections along the present-day Gangeshwar river flowing through the paleo-valley.

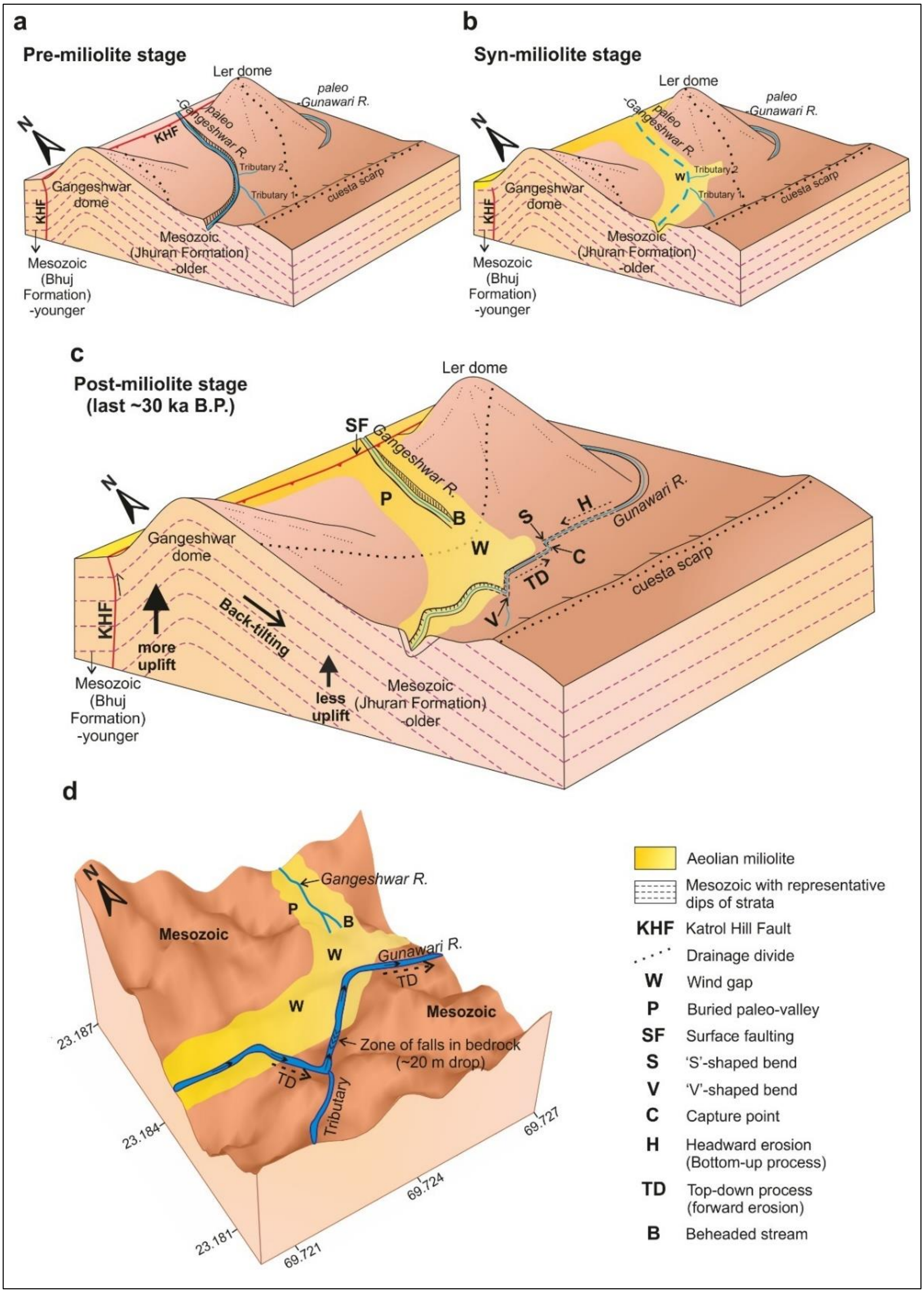

Figure 9.9 Schematic models showing stages of drainage rearrangement in the study area (a-c) and formation of the anomalous 'V'-shaped bend (d). **a.** Drainage set up prior to the deposition of Late Quaternary miliolite sediments. Note the absence of deposits younger than Mesozoic rocks. Dotted lines indicate inferred drainage divides. paleo-Gangeshwar and paleo-Gunawari rivers are the ancestors of present-day Gangeshwar and Gunawari rivers respectively. Note the Tributary 1 and Tributary 2 meeting the paleo-Gangeshwar river. **b.** Drainage set up during the Late Quaternary depositional phase of miliolite sediments. Notice the deposition aeolian miliolite sediments in the river channels including wind gap and in front of north facing KHF scarps. Rivers continued to maintain their courses (denoted by dashed line) during this phase resulting in short and episodic reworking of aeolian miliolite sediments. **c.** Phase of drainage rearrangement after the depositional phase of miliolite (last ~30 ka B.P.). Dotted line denotes the present-day drainage divides. Multiple surface faulting events along the KHF under compression led to uplift of the Katrol Hill Range in tilted manner, which triggered drainage rearrangement. Southward tilting caused greater uplift of the wind gap, which led to beheading paleo-Gangeshwar river. Channel segment of the catchment was diverted eastward along the easier path of the E-W strike of the Mesozoic rocks forming straight E-W oriented channel up to 'S'-shaped bend through reversal of Tributary 2 and top-down (TD) process. The paleo-Gunawari at the eastern margin of Ler dome extended its course upstream through along strike headward erosion towards east along the strike forming E-W trending straight channel. Both straight channels oriented in same direction and progressing towards each other joined up producing the 'S'-shaped bend, which formed the capture point. **d.** Model depicting the formation of the anomalous 'V'-shaped bend during the phase of drainage realignment in the last ~30 ka B.P. Prior to drainage realignment, the river flowed in a straighter path along the wind gap marked as 'W'. Southward tectonic tilting due to surface faulting along the KHF forced the river to flow southward through top-down process (TD), forming the western arm of 'V'-shaped bend. The new channel met up with the pre-existing tributary (Tributary 1) that flowed northward after arising from the Marutonk dungar hill located in the south. The development of 'V'-shaped bend is therefore attributed to the drainage rearrangement that was strongly influenced by tectonic activity and the reach specific conditions i.e., availability of the channel of Tributary 1.

The upper slopes of the paleo-valley are covered by aeolian miliolites. GPR data across the western slope of paleo-valley up to the river bank shows transition of aeolian miliolites to fluvial miliolites (Figure 6.3b, c). In general, the entire reach of the paleo-Gangeshwar river including those of Tributary 1 and 2 in the Katrol Hill Range were filled with aeolian miliolite (Figure 9.8 and 9.9b).

The KHF zone in front of the north facing range bounding scarps is completely overlapped by aeolian miliolites (Figure 9.2a). These were deposited as obstacle dunes against the slopes of the Gangeshwar and Ler domes. This is evident from the large scale aeolian cross stratification and uniform grain size. GPR data across the miliolites clearly brings out its aeolian nature in this zone (Figure 6.4). Offsetting and deformation of the miliolites suggest post-miliolite tectonic activity along the KHF (Figure 6.4b, c). Available chronological data in and around the study area indicates that the miliolite deposition extended over a period from 167±16 ka B.P. to 42.2±4.0 ka B.P. (Baskaran, 1989a). No occurrences of miliolite sediments corresponding to the Last Glacial Maximum (~20,000 ka B.P.) are reported from Kachchh or Saurashtra. The present study of these deposits in the Gunawari basin shows that the deposition occurred in phases separated by short lived pulses of weak fluvial activity in middle and upper reaches during this time.

Post-miliolite phase (last ~30 ka B.P.)

This phase includes the time period after the depositional phase of miliolites over the last ~40 ka. The present geomorphic and drainage setup of the study area, which includes the Gunawari river and Gangeshwar river, was attained during this period (Figure 9.9c).

Previous neotectonic studies along the KHF have revealed three events of surface faulting dating back to 30.1, 29.5 and 3.0 ka B.P. (Patidar et al., 2008; Kundu et al., 2010). The events are identified from a well exposed Quaternary sediment succession exposed along an incised cliff along the Khari river in the west, comprising of colluvium, fluvial miliolites and alluvium in the KHF zone (Patidar et al., 2008). Field evidence shows that the KHF offset the topography during each faulting event (Patidar et al., 2008). The field investigations revealed evidence of deformation in aeolian miliolites overlapping the KHF in the present study area also. The miliolite beds show sub-vertical dips along a narrow E-W trending zone along the KHF (Figure 5.6a, b). This suggests that the surface faulting due to reactivation of the KHF extended in to the Gunawari basin. Upward propagation of the KHF as a steep southward dipping reverse fault through the offset miliolite section is obvious in the GPR data (Figure 6.4). The deformation is seen as offsetting and abrupt steepening of aeolian cross stratification against the fault plane (Figure 6.4b). The southerly directed tilt block structure of the Katrol Hill Range is attributed to vertical movements along the KHF in compressive environment (Maurya et al., 2003b; 2017a). Multiple surface faulting events along KHF in the last ~30 ka B.P. induced southward tilting of the Katrol Hill Range. This resulted in relatively greater uplift of the course of the paleo-Gangeshwar river located in the wind gap compared to its upstream part further south. It is suggested that tectonic tilting induced changes in gradient became progressively more pronounced through multiple surface faulting events along KHF forcing the processes of drainage realignment (Figure 9.9c) in the Gunawari river basin. The mechanism of drainage reorganization in response to the surface faulting events in post-miliolite time is elaborated in the following sub-section.