CHAPTER 4

SCARP DEGRADATION AND NEOTECTONISM

Normal faulting leads to breaking of surface and generation of scarps. The scarp formed in alluvium or soft unconsolidated sediments degrades predictably through diffusion process (Wallace, 1977). Therefore, time since scarp formation or age of the scarp formation can be inferred from the study of scarp profiles and morphological dating technique (Wallace 1977; Colman and Watson, 1983). However, scarp formed in bedrock degrades differently from the alluvial scarps or scarps formed in unconsolidated sediments. Hence, the age-slope angle relation for scarp developed in bedrock is entirely different from that of the alluvium scarp. Also, the geomorphic process operating in bedrock scarp evolution is significantly different from the alluvial scarp (Wallace, 1977). Moreover, the slope replacement and degradation stages of bedrock scarp erosion takes much longer period of time, perhaps millions of years. The bedrock scarp degradation in a tectonically active terrain passes through more complex geomorphic cycles due to periodic reactivation of fault and temporal change in the degradational processes. The operation of complex geomorphic processes on the evolution the scarps make it difficult to determine the time taken since its formation. Nevertheless, the persistence of bedrock scarps or escarpments provides some of the best evidences of past earthquakes, sediment generation, mode of landscape evolution in a given region (Goodall et al., 2021; Godard et al., 2019; Wang and Willet, 2021).

The data generated on the previous chapter on scarp morphology suggests that scarps along the KMF is extensively degraded and retreated several hundreds of meters south of the active fault trace. Therefore, detailed investigation and mapping of the scarp generated deposits are essential in addressing the scarp development. The KMF scarp is characterized by thick Quaternary colluvial deposits in the fore end, generally confined to a zone between the scarp base and the Rann. The lateral variation in colluvial thickness and geometry is significant characteristics of the deposits. In this chapter data generated from field investigation, available secondary data on Quaternary deposits and GPR data were combined to describe the scarp degradational process along KMF during the Late Quaternary period. Refining our understanding of scarp degradational processes in Late Quaternary period may ultimately give clues on the degradational processes and helps in framing an effective model of scarp degradation and landscape evolution on a long-term scale. This chapter also address the major phases of the Late Quaternary scarp derived colluvial generation, primary factor controlling the scarp degradation and also the stages of degradation and retreat of the scarps.

QUATERNARY COLLUVIO-FLUVIAL DEPOSITS ALONG KMF

Parallel scarp retreat is one major element of scarp degradation process in many landscapes (Dikau et al., 2004; Braun, 2018). Lateral retreat of escarpment is common a phenomenon in dryland landscapes (Dutton, 1882; Bryan, 1940; King, 1953). However, the geological processes that lead to escarpment retreat may vary from place to place. The lateral retreat of the scarp can be influenced by many factors including climate, rock strength, structural dip and tectonic forces (McCarroll et al., 2021; Forte et al., 2016; Elliott et al., 2012). The weathering and retreat of the scarp over time leads to deposition of scarp derived detritus at the base of the scarp; this phenomenon over time results in the formation of colluvial wedges (Christie et al., 2009). The colluvium or talus deposits along the lower slopes or base of the escarpment are long considered as a natural archive for understanding the long-term evolution of the escarpments (McCarroll et al., 2021). A precise definition for colluvium is given by French (1992). He postulated colluvium as a loose, non-stratified, poorly sorted, heterogenous mixture of various size grades found at the base of the slopes. The deposits that accumulate at the base of the fault scarp are distinctive signature of ancient dip slip earthquakes (McCalpin, 2009). Therefore, mapping of these deposits could shed light on to the historical or past tectonic events that occurred in the region.

Mapping and field observation studies along the KMF zone suggest multiple phases of colluvio-fluvial deposits along the KMF. The deposits are called as colluvio-fluvial deposits because of the fluvial reworking of the originally deposited colluvial sediments (Choksey et al., 2011b). In the eastern Kachchh in a stretch between segment I and segment IV or from Nirona to Khirsara, the deposits are well exposed. The deposits are encountered in almost all the north flowing rivers or at the base of the scarps (Fig. 4.1). While the outcrops of the deposits are well exposed in the eastern segments of the KMF, less outcrops of the deposit are exposed in the western half of the KMF. However, subsurface studies along the western KMF zone reveals that these deposits are buried under thin cover of Holocene sediments (Shaikh et al., 2022) (Fig. 4.2). Thorough investigation on these deposits is essential in understanding the past mechanism of landscape development, phases of tectonic uplift and scarp degradation along the KMF in

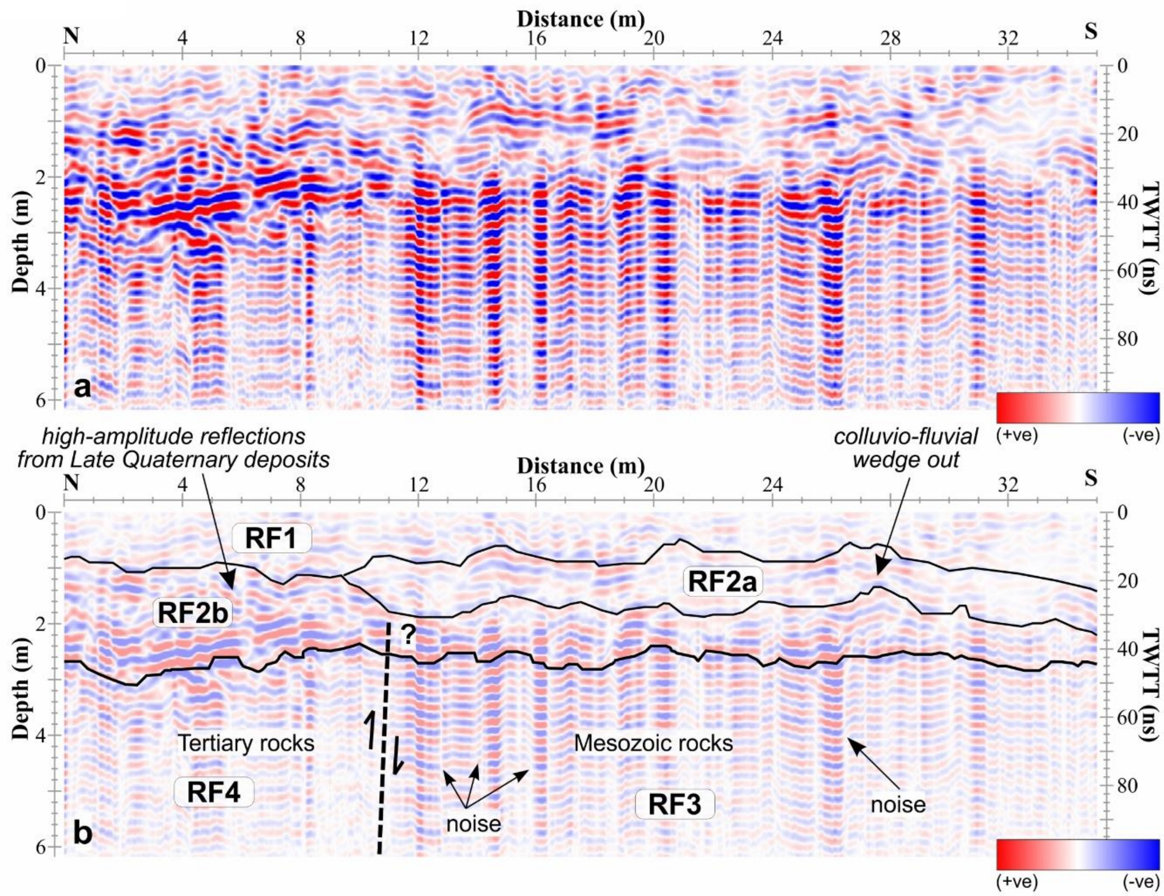

Figure 4.1 GPR profile of eastern KMF indicating the subsurface nature of the KMF zone (After Maurya et al., 2022). Here, RF1: Holocene sediments, RF2a: colluvio-fluvial wedge out deposits, RF2b: Late Quaternary deposits, RF3: Mesozoic rocks, RF4: Tertiary rocks.

the Late Quaternary period. There are two generations of traceable colluvio-fluvial deposits occur along the eastern half of KMF. These deposits were studied by Maurya et al. (2017) using Optically Stimulated Luminescence (OSL) dating technique. The colluvial deposits are rich in boulders, cobbles, gravels, pebbles and sand. The boulders, cobbles and gravel of colluvium can be observed in outcrop close to scarp base and grade into alluvial pebble-sand with increasing distance from the scarp. Furthermore, the deposits also display a northward dip or inclination. The rivers flowing through the colluvio-fluvial deposits show a decrease in the rate of incision towards north. These evidences further attest the northward inclination of the colluvio-fluvial deposits. The northward inclination of the colluvio-fluvial deposit could be linked to the post depositional deformation along the KMF (Maurya et al., 2017). Additionally, the colluvio-fluvial deposits also exhibit lateral variation in the sedimentary facies. Sedimentologically, the deposits are mainly matrix supported boulder-cobble, cobble-boulder-gravel and clast supported boulder-cobble-gravel. In the western KMF between the Nara and Lakhpat dome, the colluvial wedge is displaced by recent tectonic movements along the KMF (Shaikh et al., 2022). The displacement of the colluvium, incision and northward inclination along KMF points to the neotectonic active nature of the KMF.

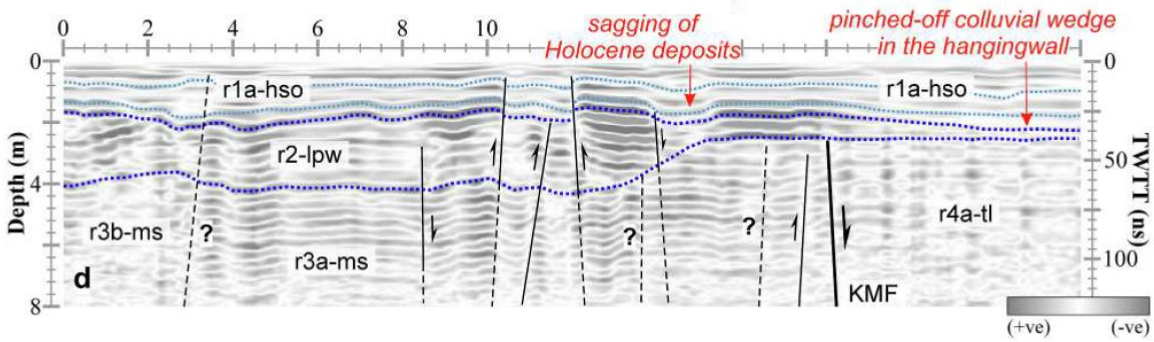

Figure 4.2 GPR profile recorded across the KMF zone near Jumara dome (western KMF) indicating the subsurface nature of the zone. (After Shaikh et al., 2022). Here, r1a-hso: loose Rann sediments, r2-lpw: Late Pleistocene colluvial deposits, r3b-ms: deformed Mesozoic sandstone/ shale, r3a-ms: Mesozoic sandstone, r4a-tl: Tertiary limestone.

SEGMENT-WISE CHARACTERISTICS OF QUATERNARY COLLUVIUM ALONG KMF

The eastern KMF along a stretch between Nirona and Lodai which covers segment I and II comprises of well-preserved colluvio-fluvial deposits (Fig. 4.3). The basement of the Quaternary sequence is generally Mesozoic SST or shale and Tertiary shale. The Mesozoic bedrock is covered by thick sequence of aeolian miliolite deposit suggesting a tectonically dormant phase and extensive aeolian activity along the zone of the KMF. The aeolian activity along Kachchh basin is extensive during a period between 130-30ka (Mid Pleistocene to Late Pleistocene (Baskaran et al., 1989). The commencement of the Late Pleistocene period is characterised by deposition of clast supported boulder gravel/coarse gravel/pebble gravel (Maurya et al., 2017). The Late Pleistocene period of deposition of clast supported gravelly deposits ceased by the deposition of sand rich units, mostly gravelly sand or massive sand. The sand rich units suggest that the region has underwent extensive fluvial erosion. The rivers are actively adjusting to the newly formed base level changes in the last phase of tectonic maximum

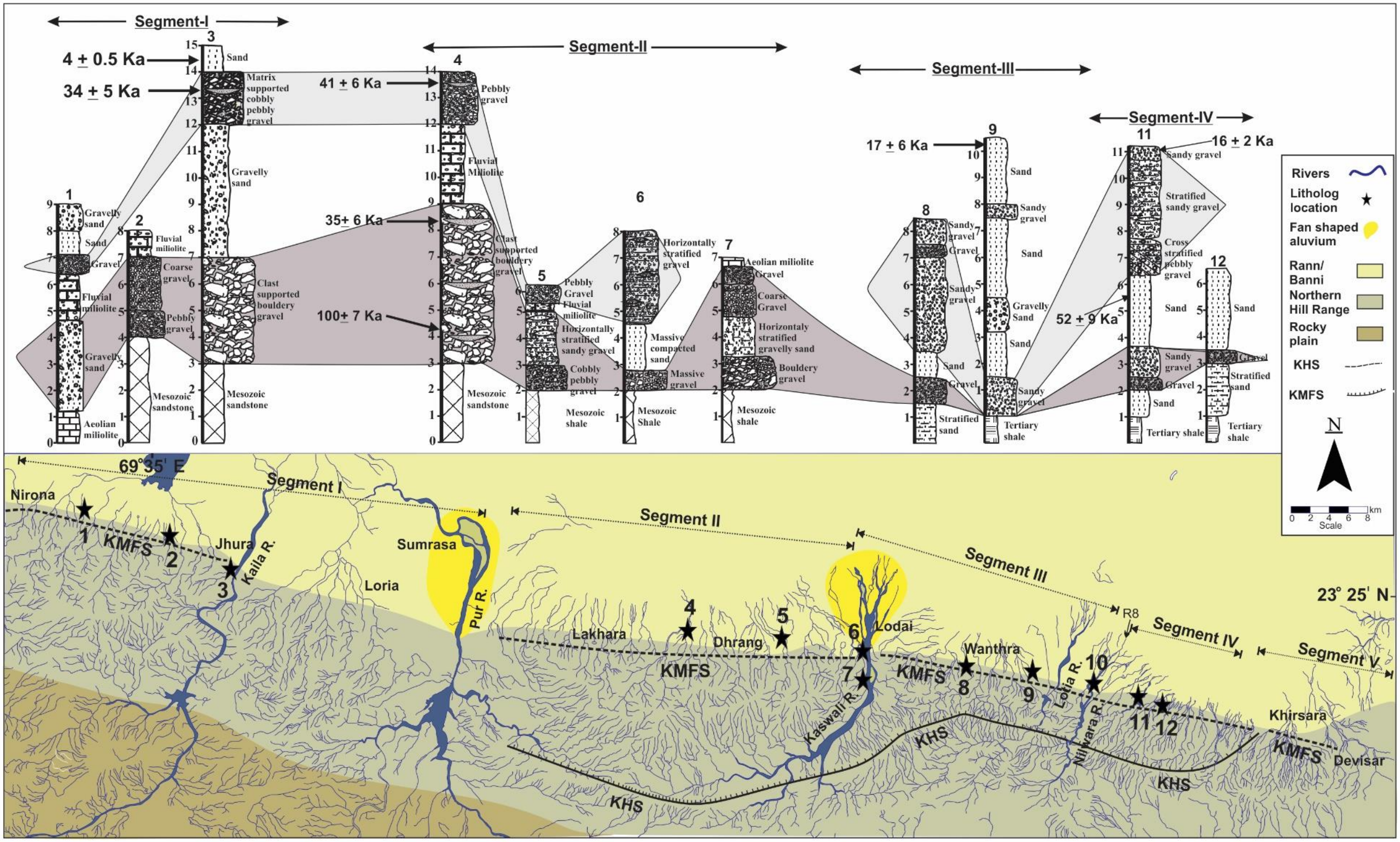

Figure 4.3 Lithologs of Late Quaternary sediments along various segments of eastern KMF (after Maurya et al., 2017). Note the progressive variation in the sedimentary facies from segment I to segment IV. Colluvio-fluvial deposits are negligible in segment V. The vertical scale is in meters.

by actively scouring the landscape. This phase in the KMF scarp could be linked to active gully erosion and fluvial modification of the scarp. The amount or rate of retreat will be comparatively less in comparison to the previous phase. This period is again succeeded by a period of elevated tectonic uplift. The phase is marked by deposition of comparatively small sized gravely units suggesting an enhanced tectonic activity, however several magnitude less than the previous events. This period of tectonic uplift is surpassed by enhanced deposition of fluvially reworked valley fill miliolite and fluvial sediments along the KMF zone. This suggests that an elevated phase of uplift is succeeded by a phase of fluvial erosion in the landscape. This stage continued to the recent time period in the stretch.

The stretch between Lodai-Khirsara is characterised by comparatively different sedimentation pattern as revealed by the sedimentary deposit. The grain size of the colluvio-fluvial deposit is significantly less than that of the previous stretch. The sedimentary unit is dominated mainly by sand rich units. However, intermittent boulderly gravel, gravelly and sandy gravelly units are also common in the stretch. The intermittent gravelly units are indication of heightened tectonic activity. The sedimentary units in the stretch not only have higher sand proportion but also displays comparatively better stratification than the previous stretch. Horizontally stratified gravel, gravelly sand, sandy gravel sand and cross stratified pebbly gravel are common textural and sedimentary structural characteristics in the stretch. All these evidences univocally points to the fluvial dominance in the landscape in response to the tectonic reactivations along the KMF.

In the western KMF, the colluvial deposit overlain the Mesozoic and Tertiary age rocks similar to the previous segments of the eastern KMF (Shaikh et al., 2022). Well exposed outcrops of the colluvial or the colluvio-fluvial deposits are missing along the KMF and the scarp base. However, colluvial deposit including boulders and gravelly units can be traced at the base of the Jaramara Scarp. This makes the study to rely more on the available geophysical data. In the geophysical study using GPR, Shaikh et al. (2022) identified that the colluvial deposits makes a sharp erosional surface with the bedrock and the Holocene sediments overlying the colluvial sediments. The average thickness of the deposit is 2-3m in the western part of the KMF. The Holocene sea-level rise and submergence of the area caused the deposition of the Holocene sediment on the top of the colluvial deposit (Kumar et al., 2021). Overall characteristics of the sedimentary deposit along KMF indicates that the period of heightened tectonic activity in the area is manifested by rock fall and gravity collapse and periods of tectonic quiescence by massive sand deposits.

Along strike variation in nature of colluvio-fluvial deposits

The KMF displays a strike variation in the sediment character of colluvio-fluvial deposits (Fig. 4.2). In the eastern segments of the KMF, the colluvio-fluvial deposits are well exposed and therefore, the variation in the sedimentation nature could be differentiated from one another in a more pronounced manner. Lateral variation in the grain size and thickness is observed along the eastern segments of the KMF. The segment I and II are characterised by deposits with higher proportions of boulders and gravelly units (Fig. 4.3). However, towards further east, grain size reduces dramatically to sandy gravel, finer gravel and massive sand units. The difference in the sedimentary facies in the eastern segments of the KMF can correlated with the strike variation in the tectonic activity along the KMF (Chowksey et al., 2011b; Maurya et al., 2017). The presence of more massive sand units confined to the eastern segments, particularly segment III and IV are indication of extensive periods of tectonic quiescence between periods of tectonic reactivation or comparatively lower magnitude of tectonic reactivation towards the easternmost segments. The western KMF also the colluvio-fluvial deposits are overlain by well stratified Holocene deposits (Shaikh et al., 2022).

Thickness variation of colluvio-fluvial deposits

Thickness of the colluvio-fluvial deposit is one of the key geological evidence for understanding the degree or level of historical tectonic activity operated in a region (McCalpin, 2009). The higher thickness is an indication that more frequent and higher magnitude of tectonic disturbance in the region. The thickness of colluvio-fluvial deposit is highest in the eastern portion of the KMF. Which shows decent thickness of colluvial deposits ranging from 5-12m. However, the colluvial deposits are mostly buried under the recent deposit in the western part of KMF. As mentioned previously, the rise in sealevel and subsequent submergence of the western portion of the KMF during Holocene resulted in a thick cover of the Holocene sediments over the colluvial deposit in the western KMF. However, subsurface survey of the KMF zone using GPR in the region revealed substantial quantity of colluvium deposits (Shaikh et al., 2022). The thickness of the deposit is 2-3m. The eastern segments of the KMF also display a lateral variation in the thickness of the colluvial deposits other than the vertical variation in the sedimentary characteristics. The greater thickness of the colluvial deposits are observed in the eastern part of KMF especially in the vicinity of Jhurio and Habo located in the segment I and II. This suggests that more frequent and higher level of tectonic activity operated in the region during the historical time. The thickness decreases to minimum in the segment V. The height of the fault scarp is more or less the representation of displacement along a fault (Nash, 2013). The scarp height along the KMF is 60-80 m. This suggest that the displacement along the KMF should be ~80m. However, based on stratigraphic offset data the total displacement along the Jhurio dome is ~1200m (Biswas, 1993). However, the scarp height is less than the tectonic displacement. The mismatch in the scarp height and displacement is an indication of extensive denudation in the region. However, the available data on the scarp derived sediments point to a maximum thickness of 10-15m. This might be because of active fluvial processes in operation in the region. If the action of fluvial processes is high in a terrain or area it will carry the deposits further away from the scarp base and fault zone. However, with the existing scarp derived Late Quaternary sedimentary record, it is possible to draw a conclusion that the relative level of tectonic activity was highest in the eastern segments of the KMF, more specifically in the segments I and II.

IMPLICATIONS FOR SLOPE PROCESSES ON SCARP DEGRADATION

Once a scarp is formed in any terrain, it undergoes a continues process of modification by denudation (Stewart and Hancock, 1990). Degradation of the scarp surface is mainly controlled by three types of erosional processes; gravity-controlled erosion, debris-controlled erosion and wash controlled erosion (Wallace, 1977). The erosional process that operates on the scarp face will ultimately lead to slope replacement, slope decline or retreat of scarp (Nash, 2013). The gravity-controlled erosion is manifested as block or fall from the scarp face (Wallace, 1977). This phenomenon occurs when the gravitational pull exceeds the threshold rock strength and results in the free fall of rock from the scarp face. On the other hand, debris-controlled erosion involves block falling and rolling down as pseudo plastic flow (Wallace, 1977). The wash-controlled erosion is characterized by erosional movement of smaller sized materials from the scarp surface (Wallace, 1977). The duration and rate of operation of these erosional processes vary considerably (Wallace, 1977). Over time, the erosional processes operating in the scarp face changes. In the initial period, the gravity-controlled erosion will be a dominant erosional process for scarp with slope angle greater than 45^0. As time advances with the decline in the slope angle the erosional process in operation shift to debris and then wash controlled (Wallace, 1977). However, in the case of scarp formed in fractured bedrock the gravity-controlled scarp erosion persists for a longer time duration until the scarp slope shallows (Wallace, 1977) (Fig. 4.4). The fault scarp along the KMF is mainly formed in Bhuj, Jhuran and Jumara Formations of Mesozoic of Kachchh. The hard resistant nature of the rock and the high scarp slope angle will favour gravity-controlled scarp erosion than debris-controlled erosion. However, at places the scarps are highly eroded and debris-controlled erosion is dominant. The numerous small drainages and gully channels arising the scarp face have essentially transported the talus deposits generated from the scarp face further to the north of the scarp face. The gullies and streams arising from the scarp face have important influence in the scarp degradational process (For eg. McCarroll et al., 2021).

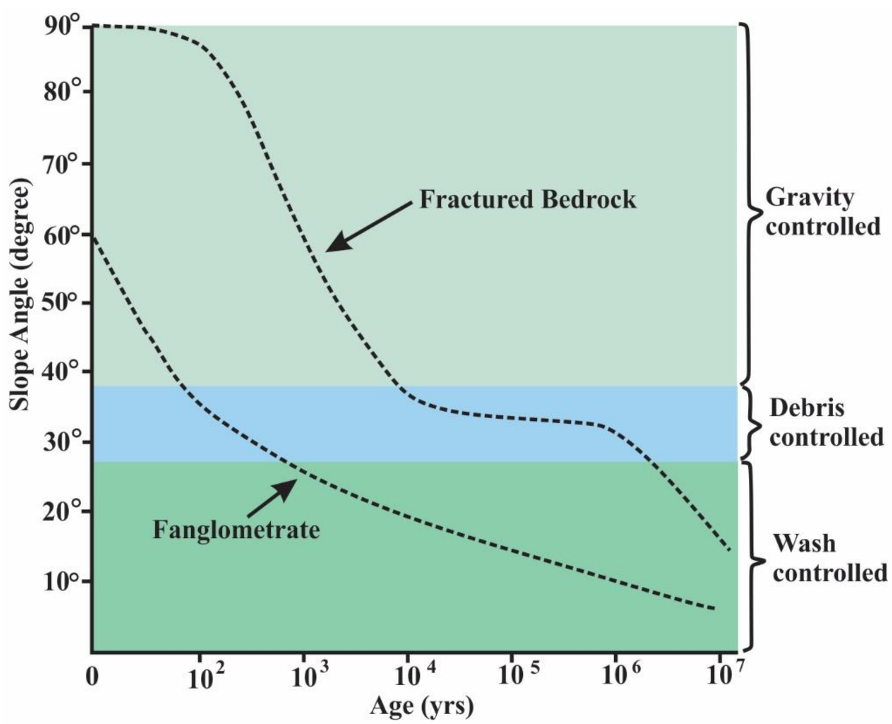

Figure 4.4 Slope versus age (Redrawn from Wallace,1977). Note that bedrock scarp with higher slope angle remains in gravity-controlled erosion for longer period of time.

The KMF zone is characterized by thick colluvio-fluvial deposits as mentioned earlier. However, as a result of fluvial reworking of the original scarp-derived talus and colluvium deposits, these deposits along KMF have been given the nomenclature of colluvio-fluvial deposits by Chowksey et al. (2011b). Mappable quantity of colluvio-fluvial deposits along the

KMF scarp points to the fact that scarp faces are modified from the original fault surface through series of erosional and scarp collapse events.

The scarps along the KMF are characterised by talus deposits at the base and all over the KMF zone. The colluvio-fluvial deposits along the KMF zone are typically unsorted, weakly graded and lacks sedimentary structure. The occurrence of unorganised big clast or massive boulders and pebbles with absence of sedimentary structure, poor sorting and sub angular nature of the deposit can be interpreted as product of rock fall, rock avalanche or debris flow (Rust 1978; Miall, 1996; Aziz et al., 2003). This suggests that periodic gravitational collapse/debris-controlled erosion and deposition of colluvial deposits in the base of the scarp is common slope erosional process to attain stability. The colluvio-fluvial deposits are overlain by medium to thin beds of sand locally. These deposits could be interpreted as slope wash deposits at periods of subdued tectonic activity. The region lacks older colluvium mantles of age greater than Late Pleistocene. The absence of the older colluvial deposits is peculiar for a landscape or scarp evolved by long-term term degradational processes. The absence of older colluvial mantles can be correlated with frequent tectonic movements along the KMF. The episodic tectonic uplift and frequent channel rejuvenations can result in poor preservation of the colluvial mantles. The frequent channel rejuvenation can erode and transport the colluvial deposits (for eg. Botha et al., 1992). Therefore, the absence of colluvium older than 100ka in the KMF zone points to the periodic activation of the KMF and effective fluvial transport in the Quaternary period.

The slope instability is mainly influenced by three factors that includes tectonic disturbances, climate-controlled weathering and relief (Botha et al., 1992). In the case of the KMF, it is known that the region had gone through multiple episodes of tectonic uplift and growth in relief. Therefore, the tectonic reactivation could be considered as the main process controlling the scarp evolution and modification. The lithology is another factor that is needed to be considered when colluvial generation and scarp degradation is concerned. The lithology can significantly influence the rate of colluvial generation (Botha et al., 1992). The northern limp of the NHRFZ is characterised by heterogeneous lithologies of varying resistance. The comparatively hard and resistant lithology can significantly lowers the generation of the colluvium and degradation of the scarp. Another important slope process that is to be considered is the gullying process. Gullying is a typical process that operates in arid climatic condition

(Twidale and Milnes, 1983). The gullying process together with tectonic disturbances can trigger the slope degradational process by generation of colluvial deposits. The period of uplift along the KMF can result in the relief growth of the scarp, which in turn can increase the gullying processes to several magnitudes and results in degradation and retreat of the scarp. Therefore, the present morphology of the Kachchh Mainland Fault Scarp (KMFS) is a result of complex interaction between periodic uplift and slope process. Fluvial action on the scarp degradation and retreat is minimum. However, considering the Kas Hill Scarp and the Jaramara Scarp, many medium sized drainage systems arise from the scarp face. Therefore, the scarp morphology and slope development in these scarps require consideration of fluvial erosional process other than tectonic uplift and slope process.

OTHER NEOTECTONIC EVIDENCES FOR FAULTING AND TRANSIENT LANDSCAPE DURING QUATERNARY PERIOD

Kachchh is an active tectonic zone which possesses fault-controlled first-order topography and several geomorphic features indicating neotectonic activities (Maurya et al 2003). The basin was developed through varying stages of movement of Indian plate (Biwas, 2016a). Initiated as a rift basin in Early Jurassic, it passed through several tectonic cycles ending up as a seismically active zone in the present neotectonic cycle under compressive stress regime caused by plate collision and anticlockwise plate rotation (Biswas, 2005). Neotectonic activities along E-W trending master faults and transverse faults are reflected in morphotectonic features viz. horizontal offsetting streams, switching of streams, sharp angular turns in the courses, beheading of streams, knick points, alignment of fault scarp, unpaired terraces, alluvial fans, development of gorges and intense incision in bedrock and Quaternary deposits along faults (Thakkar et al, 2006; Chowksey et al., 2011b; Maurya et al., 2017; Maurya et al., 2021). The indication of the ongoing neotectonic activity in the study area is derived from geomorphological evidences such as presence of, anomalies in river courses, entrenched menders, intense incision, multiple knickpoints or knickzone, Quaternary deformation. A few evidences of neotectonism along the KMF are given below.

Incision

Incision or basefall in a river network can potentially affect scarp evolution and modification (McCarroll et al., 2021). Incision of the rivers in a topography is indication of transient topography. The faulting will change the gradient of any river crossing the fault.

Therefore, incision along the river course can be considered as an important geomorphic marker for neotectonism in the absence of climatic influence. Rivers flowing through the eastern and western domains of the KMF show significant incision along its course. The Quaternary sediments cover is common in the KMF zone. The incision of the Quaternary sediments is significant as it indicates post depositional tectonic reactivation along KMF (Fig. 4.5 a, b and c). The river basins show intense incision along its course; however, two major zones of incision are identified (a) upstream (b) in the zone of KMF. To understand the nature of incision in the landscape Lotia River and Nihwara River flowing through the eastern part of KMF were

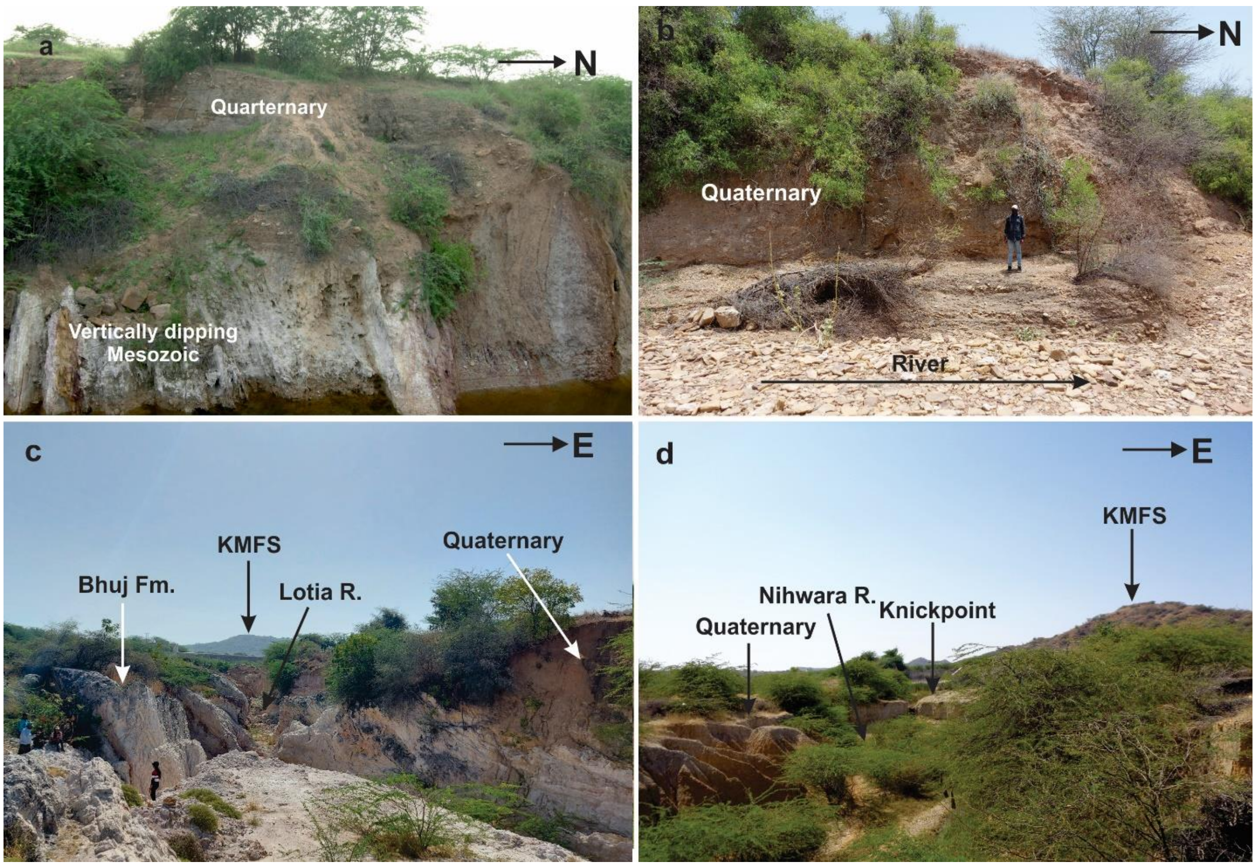

Figure 4.5 Photographs shows intense incision of north flowing rivers in the KMF zone. a) View of incised Quaternary sediments in the vicinity of KMF near Jhura dome (segment I). Here the Quaternary sediments rest uncomfortably over the steeply dipping Mesozoic rocks. b) View of incised colluvio-fluvial sediments in the Falay River near Habo dome (segment II). c) Intense incision by Lotia River in the vicinity of KMF near Lotia Dam dome (segment III). Here the river incises through the Bhuj Formation and Quaternary formation. d) Southward view of the KMF zone with KMFS in the background. Here the Nihwara River shows incision in the Quaternary miliolite and recent sediments. The river also forms knickpoint (3m fall) in Quaternary formation.

investigated in detail. The Lotia River originates from the backslope of the Northern Hill Range and flows northward dissecting the North Hill range. The zone of dissection of the hill range is characterized by intense incision and gorge like topography. In the downstream, close to the vicinity of KMF, the Lotia River incise through the bedrock forming 10-15m cliff section on the banks. Here the river forms narrow gorge like valleys in the Bhuj sandstone (Fig. 4.5 c). The narrow and deep valleys formed in the hard and resistant sandstone suggest neotectonic reactivation of the KMF during the recent past. Further downstream the river also incises the Tertiary and Quaternary deposits. The rate of incision decreases further north. The incision in the Quaternary sediments close to the KMF zone attest to the gradient changes associated with reactivation of KMF.

Another example from the eastern KMF is the Nihwara River. Similar to the Lotia River, the Nihwara River originates from the backslope of the NHR and flows towards north dissecting the NHR. This river also significantly incised in its upstream and in the downstream reaches. In the upstream the river incised through the Jhuran Formation at the zone of dissection of the NHR. The amount of incision in the N-S flowing river decreases towards the downstream side, however 10m incision in the Tertiary rocks exposed at the downstream supports tectonic rejuvenations. The river channel shows significantly higher amount of incision in the upstream side. This suggests that the incisional waves are propagating in the upstream direction as result of periodic reactivations along the KMF. Towards the downstream the river incises the Tertiary rock and Quaternary sediments which indicates that the incision is not too old (Fig. 4.5 d). The evidences point to a Late Quaternary tectonic reactivation of the KMF. The incision is attributed to accelerated tectonic uplift along the KMF. However, at the zone of KMF the river incises through the Quaternary and Tertiary formations. Another example from the eastern KMF is in the vicinity of Habo dome. The north flowing Falay River significantly incise through the Quaternary colluvio-fluvial sediments in the region (Fig. 4.5 b). Overall, it could be concluded that the river in the eastern portion of the KMF are undergoing significant incision in the landscape to cope up with the tectonic rejuvenations. In the western side of KMF also the rivers show similar trend of incision. Where the major zone of incision is concentrated in the upstream and in the zone of KMF. Incision in river channels is common phenomenon in a landscape that undergo tectonic uplift. River incision is the natural process by which a river cuts vertically downward into its bed, deepening the active channel. Though it is a natural process, it can be accelerated by tectonic reactivation and uplift. Therefore, incision in the river channels can be an indication of tectonic influence in the landscape in the absence of climate and precipitation. The severe incision in the study area in contrast to the hyper arid condition directly points to the tectonic reactivation.

Knickpoints

Knickpoints are steep reaches in the river caused by more resistant lithology or by an increase in shear stress or by surface uplift (Bishop et al., 2005). In each catchment, knickpoints mark the boundary between steady state and adjusting landscape. These anomalies in profiles can indicate either a stream in equilibrium where the upstream retreat communicates changes in base level to upstream valley (Bishop et al., 2005) or, in some cases a dynamic equilibrium between fluvial processes and tectonic movements (Snow and Slingerland, 1990). Similar to the pattern of incision along the north flowing rivers, two major zones of knickpoints are observed along the north flowing rivers (a) upstream and (b) zone of KMF. In the eastern Kachchh the rivers are characterised by multiple set of knickpoints. In order to understand the pattern and occurrence of knickpoints in the landscape a few rivers were selected and studied. In the case of Lotia River, knickpoints were identified in two major zones. The first set of knickpoints were identified at the lithological contact between the Jhuran and Bhuj Formations. The second set corresponds to the KMF zone. Considering the geological setting of the basin, it is composed of 70-80% of Mesozoic rocks. The Bhuj Formation is characterized by hard calcareous sandstone units, which is more resistant to erosion. On the other hand, the Jhuran Formation is the alteration of sandstone and shale beds. It can be concluded that the first set of knickpoints were developed due to the juxtaposition of hard and relatively softer lithology. Presence of such knickpoints points to the lithological control in the region. The second zone of knickpoints are observed at the vicinity of KMF suggesting influenced faulting or tectonism. The present position of the knickpoints in the Lotia River indicates that the formation of knickpoints are controlled by both lithology and active tectonism. Knickpoints are recorded along the Nihwara River also. The Nihwara River shows three knickzones. In the first zone, a series of knickpoints are formed in the Bhuj Formation in the upstream (Fig. 4.6 a, b). The largest of the knickpoint in this series is 10m. The second set of knickpoints are identified at the contact of Bhuj and Jhuran Formation in the upstream. The zone of zone is also characterised

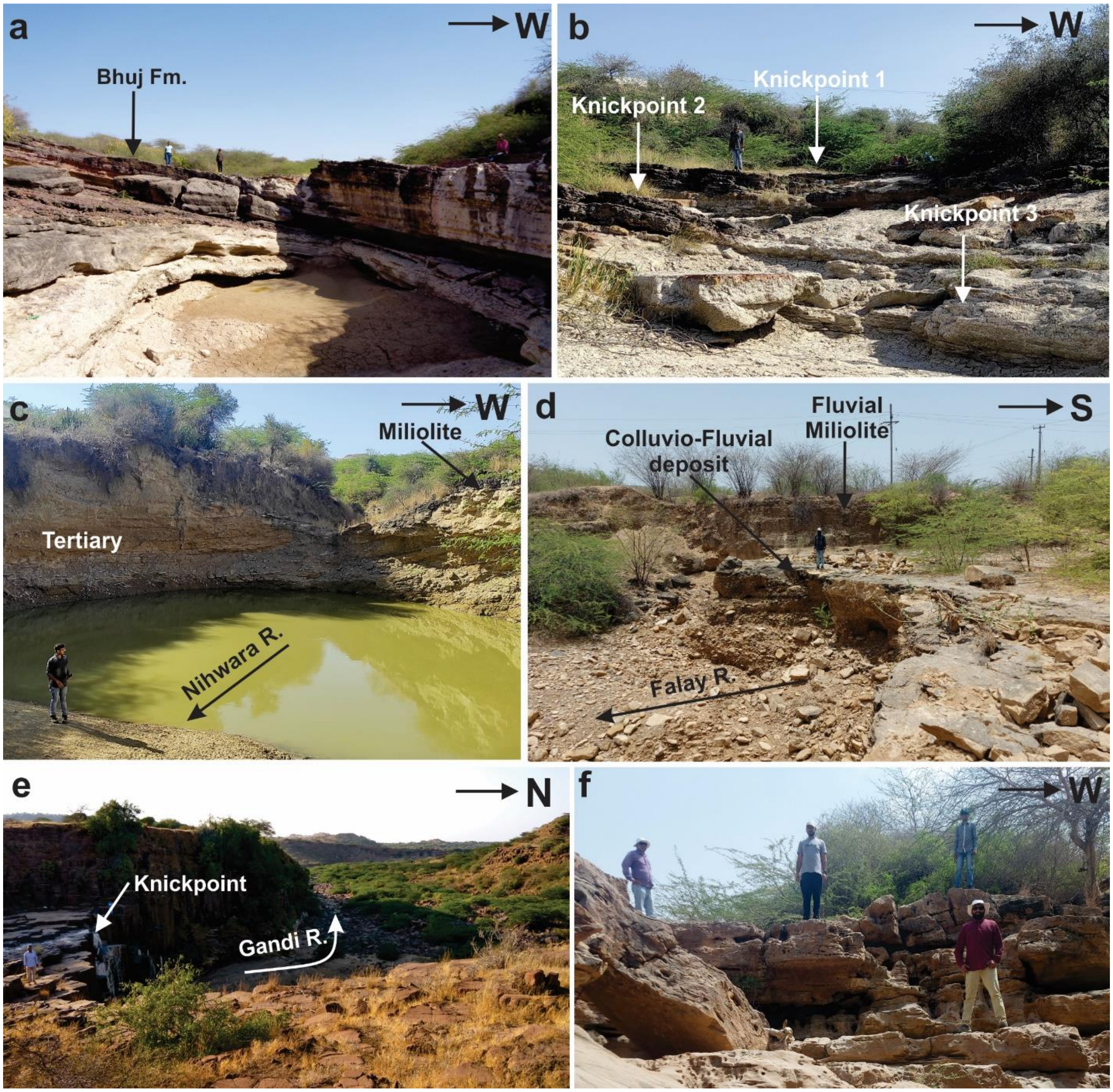

Figure 4.6 Photographs showing knickpoints along the KMF. (a) Photograph shows 10m fall in the upstream of the Nihwara River. (b) Multiple sets of knickpoint developed in the Bhuj Formation further upstream of the previous knickpoint in the Nihwara River. (c) Knickpoint (10m fall) in the downstream portion of the Nihwara River in the vicinity of KMF. (d) Photographs shows 5m fall formed in colluvio-fluvial deposit in the Falay River. (e) Gandi River forms multiple knickpoint in the zone of KMF. The photograph shows 20m fall near the KMF zone. (f) Jara River forms multiple sets in the upstream of the river in the hard sandstone unit of Jhuran Formation.

by meandering of the channel. The meandering of the channel and knickpoints are indication of the lithological control on the landscape other than tectonics. The multiple set of knickpoints are identified close to the vicinity of the KMF zone (Fig. 4.6 c). Here the river forms multiple knickpoints in the Tertiary and Quaternary formations. Among these series three major knickpoint of 5m, 7m and 10m are prominent one. Knickpoints developed in the Quaternary colluvio-fluvial sediments is also observed in the vicinity of the Habo dome in the Falay River (Fig. 4.6 d). Here, the river displays significant incision in the Quaternary colluvio-fluvial and miliolite deposits close to the knickpoints. The knickpoint developed in the Late Pleistocene colluvio-fluvial sediments are direct evidence for Late Pleistocene tectonic reactivation and baselevel changes across the north flowing the river. In the western KMF also knickpoints are common fluvial feature. The Gandi, Jara and Jumara Rivers are characterised by multiple knickpoints along its course (Fig. 4.6 e, f). Similar to the eastern Kachchh the region has knickpoints developed in the lithological contact. Several factors may co-exist at the same location and their geomorphologic expressions will overprint each other. Critical analysis through field mapping reveal that knickpoints generated are not only by tectonics but by lithology as well. However, most of the knickpoint in the region are not having any direction relation with the lithology. Therefore, the knickpoint generation in the region can be linked with the tectonic reactivation of the KMF. Many previous workers have linked the generation of knickpoint to the passage of incision wave upstream. Clark et al., (2005) and Stock et al., (2004) interpreted knickpoints as signals of accelerated incision in the landscape as a result of accelerated uplift.

Deformed miliolite deposits

Quaternary sediments along the KMF are archives that can yield important clues for reconstructing the neotectonic history. Among the Quaternary deposits aeolian and valley fill miliolite have been found useful in identifying the phases of neotectonic activity. Miliolite deposits are most extensively occurring deposits along the Kachchh basin other than Saurashtra. The miliolite outcrops are seen in the southerly directed slope of the highland areas and as isolated pockets at the base of the northfacing range front scarp. These rocks are generally absent in the low-lying areas surrounding the Rann. The topographic depressions of the hilly areas are the favourite places for their occurrence. Such depressions are usually the valleys, ravines, wind gaps and plains surrounded by ridges. Other than the aeolian variety of the miliolite the region is characterised by occurrence of horizontally miliolite deposits containing cobbles, pebbles and boulders. These are fluvially reworked miliolite deposits referred to as

Figure 4.7 (a) Vertical miliolite beds exposed close to the vicinity of KMF in the segment III. Deformed miliolite beds suggest tectonic movements along KMF during the post miliolite phase. (b) Another view of steeply dipping miliolite in the vicinity of KMF.

valley fill miliolite (Thakkar et al., 1999). The chronologic data available for the aeolian miliolites suggests that a rather prolonged period of aeolian activity and miliolite deposition occurred in the basin during the Late Pleistocene. $^{230}Th/^{234}U$ ages of the miliolites in the Katrol Hill Range (south to NHR) vary from 130 to 30 ka, suggesting a Late Pleistocene age for these deposits (Baskaran et al. 1989; Chakrabarti et al. 1993; Somayajulu, 1993). Along the KMF, the miliolites outcrops were identified very close to the fault zone. In the eastern KMF, the KMF zone close to the Nihwara River shows miliolites deposits with vertical dip. The vertical dip of rock suggest post depositional deformation of the miliolite rocks in the region (Fig 4.7 a, b). The deformation and vertical dip of the miliolite deposits are previously reported from the basin, in the vicinity of Katrol Hill Fault (KHF) (Maurya et al., 2021). Here, the vertical dip of the miliolite deposits were interpreted as post miliolite deformation along the fault. The deformation in the miliolites is a crucial evidence to constrain timing of the fault reactivation along KMF. Similar to the KHF, the deformed miliolite close to KMF zone attributes to the post miliolite reactivation of KMF.

LATE QUATERNARY REACTIVATION AND LANDSCAPE EVOLUTION ALONG NHRFZ

The tectonism has played a major role in relief growth and Quaternary topographic development in the KMF zone. The deeply incised fluvial networks, gorges, knickpoints and deformation in Quaternary sediments attest to the major role of tectonism in landscape evolution along KMF in comparison to the role of climate. River incision of the Late Pleistocene and recent sediments suggesting the continuation of the tectonism to the present. The tectonically driven baselevel changes results in incision waves moving through the river networks. The Quaternary deposit along KMF also suggests degradation and lateral retreat of the scarp along the KMF with successive tectonic phases. The colluvio-fluvial deposits are remnants of colluvial deposits derived from the scarp face by gravitational collapse in successive faulting events. The sediment generated by hillslope process are generally transported to drainage system by gullies or smaller streams arising from the scarp face. The gully erosion and lateral retreat of the scarp with talus deposition is a common mechanism of scarp erosion observed in the semiarid to arid climatic condition (Schumm and Chorley, 1966; Pinheiro and Neto, 2017; McCarroll et al., 2021). Maurya et al. (2017) proposed two major phases of colluvial deposition along the eastern KMF. The major event of scarp degradation and retreat of scarp in the Late Pleistocene to recent period is discussed below and in Fig. 4.8.

Mid Pleistocene -Late Pleistocene

The extensive aeolian activity occurred in the Kachchh basin during the Mid Pleistocene to Late Pleistocene period. The aeolian activity led to deposition of layers of miliolite deposit along the face and base of the scarp. The scarp acted as a barrier for the windblown deposits, which eventually led to reduction in wind speed and deposition of the miliolite at the face of the scarp and also in the fore-end of the scarp. The deposition of the miliolite followed by a heightened tectonic event along the KMF in the Late Pleistocene. This event is marked by deposition of colluvial material at the scarp base. Large boulders and cobbles were deposited at the scarp base. The deposition of the larger boulders and cobbles suggest a major phase of gravity-controlled collapse of the scarp face along the KMF during the time. This event led to the significant degradation and retreat of the scarp. The collapsed material was latter carried to the drainage systems by gullies or small channel originating from the scarp faces. Overall, this period can be elucidated as a period of tectonic dominance and maximum scarp degradation and retreat. The heightened tectonic uplift or event could lead to relief growth of the topography.

Late Pleistocene: 100-50ka

Period is characterised by extensive fluvial and gully erosion in the scarp face. The effect of these processes in the scarp degradation and modification were very less compared to the previous event. However, scarp degradation and modification were happening along the

KMF at lesser magnitude. The fluvial erosion of the landscape continued to cope up with the tectonic disturbances or extremities produced in the previous event. The extensive fluvial erosion in the landscape led to the deposition of massive sand in the channels and reworking of the colluvium generated in the previous event. The gravity-controlled erosion was operating in scarp faces at a lower magnitude. However, the gullying process active on the scarp faces have modified the scarp morphology and led to degradation of the scarp faces at a much lower scale. The period could be marked a period of minimal scarp degradation and retreat in comparison to the previous event.

Late Pleistocene-50-35ka

Period is marked by second episode of deposition of colluvio-fluvial deposits along the river channels. Therefore, the period marks the second heightened event of tectonic activity along the KMF. Large boulders, cobbles, pebbles were deposited at the base of the scarp and later carried to the channels. The deposition of the boulder cobbles and pebbles in the river networks suggest that gravity-controlled erosion in the scarp faces. The elevated level of collapse of the scarp face led to the modification of scarp morphology and retreat. The heightened tectonic event also led to the deformation and tilting of the Quaternary miliolite deposit along the KMF zone. As a whole, this period can be elucidated as second major phase of maximum scarp degradation and retreat along the KMF in the Late Pleistocene to recent landscape evolution.

35 ka to recent

Period is characterised by relatively lower tectonic activity in comparison to the previous event. The rivers being sensitive component of a landscape and will respond to such lower tectonic pulses or disturbances. However, the hillslope process including gravitational collapse of the scarp requires a minimum threshold magnitude of tectonic uplift to respond. The continued lower magnitude of tectonic reactivation along the KMF led to baselevel changes in the river networks. The rivers were actively incising the landscape with incision of previously deposited Late Quaternary sediments to cope up with the baselevel falls. Extensive fluvial and gully erosion occurred in the scarp face. However, gravitational collapse and retreat of the scarp wasalso operating at a much lower magnitude. The gullying process and fluvial erosion active on the scarp faces modified the scarp morphology and led to degradation of the scarp faces to

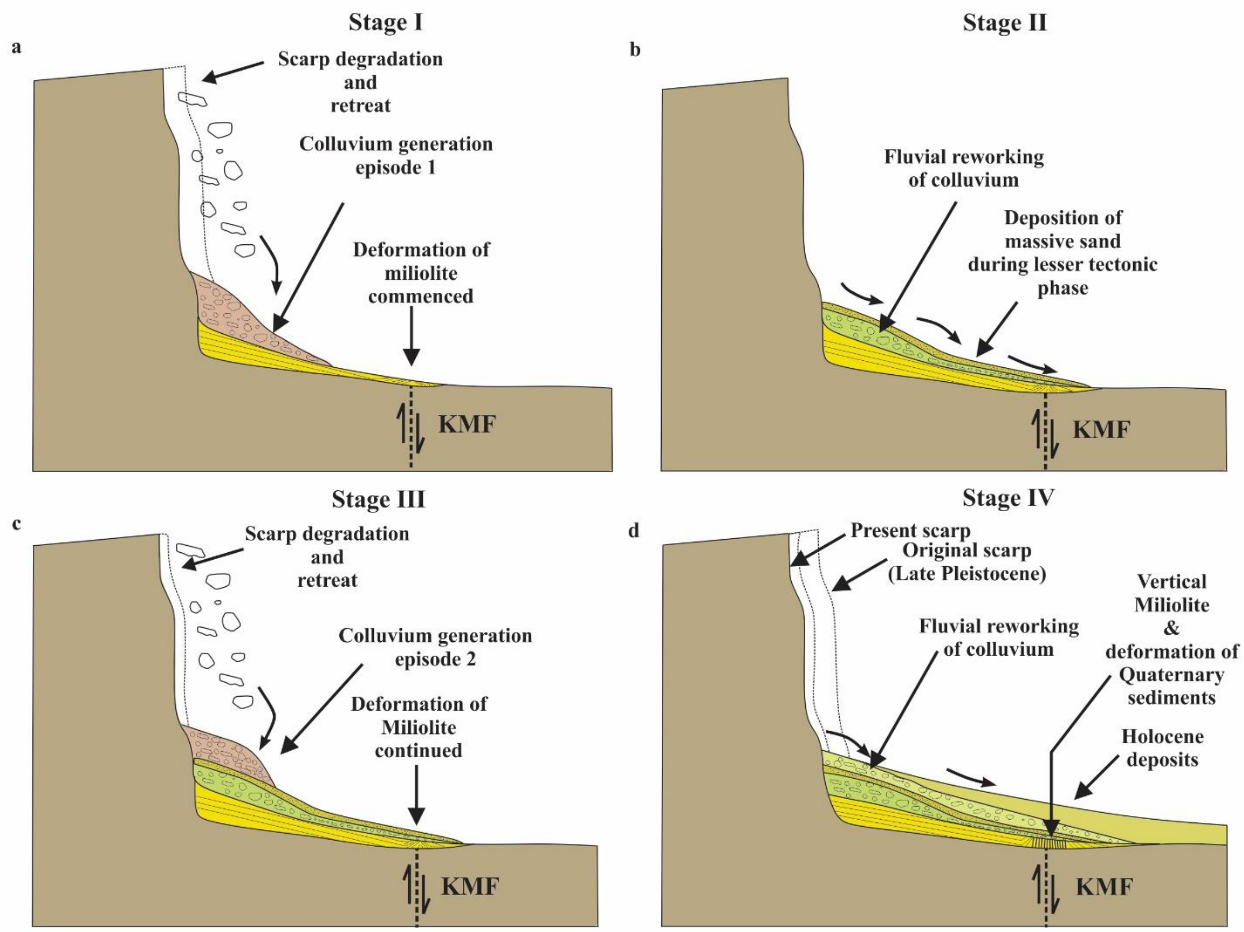

Figure 4.8 Schematic diagram depicting the stages of scarp degradation and sedimentation along the KMF zone. (a) The aeolian activity and miliolite deposition was common along the KMF zone during the Mid to Late Pleistocene period. This led to deposition of the miliolite in front of the scarp. The first episode of heightened tectonic activity during 100ka results in the collapse of scarp face and generation of colluvium at the base of the scarp. (b) The active fluvial reworking and gullying activity led to the transportation of the colluvium generated further north into the KMF zone. The dominance of the fluvial activity also led to the deposition massive sand along the KMF zone (c) The second episode of heightened tectonic activity along the KMF resulted in the collapse of the scarp and generation of colluvial deposit along the base of the scarp. (d) The periodic base level changes as a result of continuation of the tectonic activity to the recent times lead to the fluvial reworking of the colluvial deposit. The continued neotectonism to the recent times lead to the incision of the colluvio-fluvial deposits and generation of the knickpoints in the vicinity of the KMF. The baselevel changes results in the headward growth of stream and augmented the gullying activity in the scarp face. The processes will eventually lead to the degradation and retreat of the scarp face.

some extent. The continued tectonic activity in the Early Holocene to recent time led to continued deformation of the Quaternary sediments along the KMF zone. This ultimately led to steeply dipping miliolite and northward tilt of the colluvio-fluvial deposits in the KMF zone. Overall, the period could be marked as a period of minimal scarp degradation and retreat in comparison to the previous events.

Taking into consideration of the known facts and events in the Late Quaternary it can be elucidated that the heightened tectonic events along the KMF resulted in the gravitational collapse of the scarp and adjoining landscape. These phases have witnessed the maximum scarp degradation along the KMF. During periods of the lower intensity tectonic events following the heightened event, the fluvial erosion in the landscape dominated. The rivers eroded the landscape to the cope up with the disturbances produced in the previous event. The dominant fluvial erosion of the landscape continued till the next phase of the heightened tectonic event.