CHAPTER 8
DISCUSSION

Evolution of a landscape to the present form and its characteristics are the major focus of the modern geomorphological research (For eg. Gilchrist et al., 1994; Kooi and Beaumont, 1994; Beaumont et al., 2000; Elliot et al., 2012, 2017; Nones, 2019; Bilal et al., 2020). The history of geomorphic evolution is reconstructed on the basis of analysis on geomorphic data collected from field investigations and absolute dating techniques (For eg. Cockburn et al., 2000; Campanile et al., 2008; Salgado et al., 2014; Mandal et al., 2015; Beauvais et al., 2016). The present landscape and structural setup of the Kachchh basin has evolved through the geomorphic processes that took place during Tertiary and Quaternary periods (Biswas, 2016a; Maurya et al., 2017). The fault bounding scarps are one of the most notable and significant landforms of the terrain that evolved with the present landscape. Therefore, these landforms are the key to the understanding of the long-term geomorphic evolution of the basin. The scarps are predominantly erosional, however sedimentary records of the uplifts are missing for the Tertiary and also greater part of the Quaternary periods. The KMF is the largest fault that forms a flexure zone in the upthrown block. The KMF is believed to be active during the Quaternary and Tertiary periods (Biswas, 1993). The scarp characteristics and development along the KMF was studied during the present study to understand the long term geomorphic evolution of the KMF. The main objective of this chapter is to reconstruct the evolutionary history and classify the fault scarps along KMF on the basis of morphological, field and chronological data presented in the previous chapters.

SCARP MORPHOLOGY AND CLASSIFICATION

The north facing scarps along the KMF form the geomorphic expression of the fault. The exposed scarps along the KMF have a height ranging between 6 and 190 m amsl. By definition of the fault scarp, the observed relief of the scarp should be equal to or less than the cumulative offset of the generating fault, but will not exceed it (Nash, 2013). In other words, height of the scarp is considered as direct evidence for throw of the fault. However, in the case of KMF there exist no direct linkage between the throw and the scarp height. Along the KMF, the Jhurio dome located in the eastern side of the KMF is believed to have the highest stratigraphic throw of approximately 1200m (Biswas, 1993). However, the scarp height in the location is around 50 to 60m. In the Jumara dome in the western side, having a comparable throw similar to the Jhurio dome, the scarp height is 20-30m amsl. The scarps along the KMF is evolved through multiple phases of reactivation during the Cenozoic inversion phase of the basin. The twin parallel scarps along the KMF is the direct geomorphic evidence for the multiple phases of reactivation and landscape development. Generally, in terrains where denudational activity is high the tectonic signatures will be obliterated. Along the KMF, the tectonic displacement is not matching with the height of the scarp suggesting severe denudational activity on the scarps in the region. However, a portion of the topographic expression is preserved in the form of scarp suggesting that on a long-term scale the tectonic uplift was relatively higher than the denudation rate. Therefore, it can be concluded that the present landform is a product of different phases of tectonic uplift and denudation. However, it is notable that the scarp height varies along the different segments of the KMF. Variation in the height of the scarps indicate along strike variation in the tectonic uplift in various segments of the KMF.

The morphology of the fault scarp not only addresses the deformational event but also give insight into the geometry of the fault and possible segmentation along the fault (Yeats et al., 1997; Klinger et al., 2006; Lin et al., 2009). However, once produced the scarps will recline over time as a result of degradation. The recline of the fault scarp is evidence for extensive denudational activity on the surface of scarp face over time. The available geophysical and geological studies carried along the KMF confirms that it is near vertical normal fault in nature (Maurya et al., 2017; Mohan et al., 2018). Considering the near vertical nature of the fault the initial morphology of the fault scarp has to be vertical. However, the present scarp angle varies between 40 to 85 degrees. The present scarp angle is an indication of the severity of denudation and erosion to which the landform has undergone. However, near the Jhuran anticline towards the eastern part of the KMF the scarp is near vertical with a scarp slope angle of 85 degrees. The scarp outcropping at the Jhuran anticline could be considered as an analogue of the initial scarp morphology along KMF. The higher slope angle of the scarp face will promote gravity driven erosion and debris-controlled erosion. The colluvio-fluvial deposits along the KMF and at the base of the scarp attest to the gravity controlled and debris-controlled erosion along the scarp. The bedrock scarps do not essentially follow the diffusion law similar to the scarp formed in the soft sediments. The angle of slope depends on the threshold strength of the lithology that make the scarp (Cellek, 2020). Therefore, present slope angle of the scarps cannot be considered as representation of surface rupture feature or fault geometry. The slopes could be classified into three categories based on topographic slope and bedding planning intersection angle, cataclinal slopes, orthoclinal slopes and anaclinal slopes (Powell, 1875; Cruden, 1988, 1989; Cruden and Hu, 1996; Meentemeyer and Moody, 2000). The cataclinal slopes are those in which the bed plane dips in the same direction of the slope. The slope is classified as anaclinal slope if the bed dips opposite to the slope. If the azimuth of dip direction is perpendicular to the azimuth of slope direction it is classified as orthoclinal slopes. Cataclinal slopes is classified into underdip, dip slope and overdip slope. The overdip cataclinal slopes are those in which the slope is steeper than the bedding plane, dip slope follows the bedding plane and underdip will have a slope less than the bedding plane. The similar to cataclinal slopes, anaclinal slope is further classified into normal escarpments, steepened escarpments and subdued escarpments. Normal escarpments are those with slope perpendicular to bedding plane, whereas, steepened escarpment will have slope steeper than the bedding plane. In the case of subdued escarpments, the slope will be less than the bedding plane. According to this classification the KMFS formed in the steep northern limp of the flexure can be included in the category of over dip and dip slope cataclinal slope. At the same time the KHS and JMS can be included in the category of steepened or normal escarpment in the anaclinal category.

The scarps along the KMF have variably retreated along the segments of the KMF. Retreat is a common degradational phenomenon occurring in the bedrock scarps. The retreat of the scarp and displacement are directly related to each other (Elliot et al., 2017). The highest displacement and more frequent reactivation of fault over time result in the higher amount of retreat. However, in the case of KMF such relationships are not fully satisfying. It is also common along the faults that the highest amount of retreat occurs at the central portion of the fault and minimum amount of retreat at the tips of the fault. However, a general relation could be established that the scarps along KMF have suffered higher amount of retreat at the center of the domes than at the tip. Considering the highest amount of throw, the Jhurio and Jumara dome show maximum displacement along the KMF. However, the amount of retreat of the scarp is less than 500m in the vicinity of the domes. At the same time, the Devisar dome in the eastern most portion of the KMF, where the stratigraphic offset is expected to be low in comparison with the Jhurio and Jumara, the scarp is retreated to more than 400m. These evidences from the KMF suggest that the amount of retreat of the scarp is not completely controlled by tectonic influence. The lithology comes into consideration in the absence of role of climate in the region. Previous researches on scarp retreat have also highlighted that lithology could secondarily influence the scarp retreat in a tectonically active setting (Aden, 1984; Menges, 1988). The climatic regime has been the same along the strike of the KMF. Therefore, variable retreat of the scarp is secondarily controlled by the influence of lithology.

The term fault scarp is used for a linear topography formed from the displacement along a fault (Nash, 2013). The scarps along the KMF can be classified based on the morphology, appearance and nature. Biswas (1993) has categorised the scarps along the major fault systems of the Kachchh basin as resequent faultline. However, considering the morphology and nature of the scarps along the KMF, all the scarps cannot be included in the category of faultline scarp. In-depth field investigation and morphological studies carried out in the scarps along the KMF reveal that they could be included in different types based on their morphological characteristics. The fault scarps along the KMF comes under two different configurations (1) Residual range front normal scarp, (2) Simple range front normal scarp. The KMF is a normal fault with near vertical dip (Maurya et al., 2017; Mohan et al., 2018). Considering the occurrence of the scarps at the northern limp of the flexure it could be included in the category of range front scarp. Most of the scarps along the KMF do not coincide with the present active

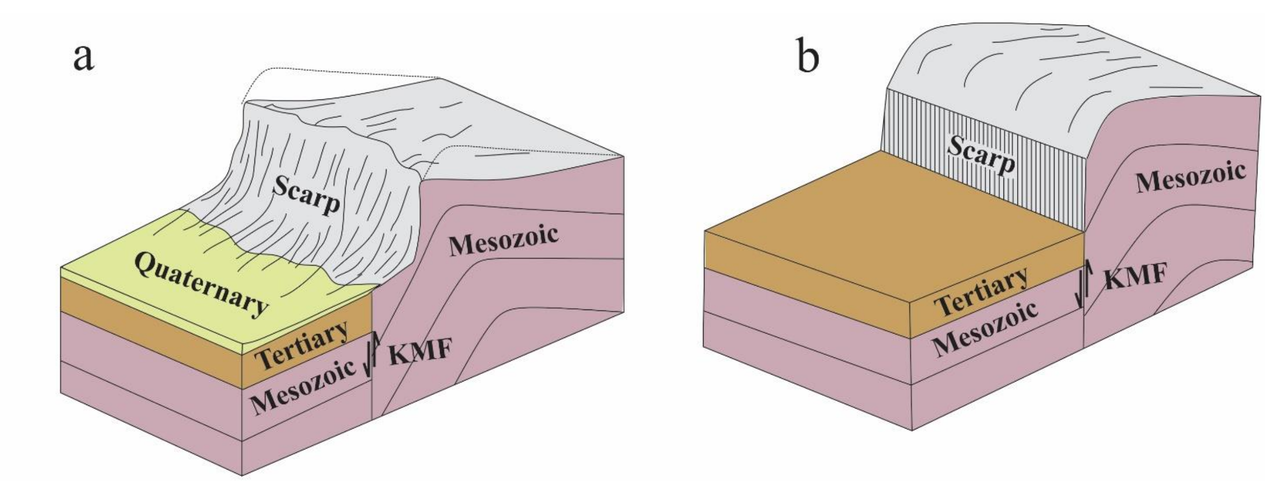

Figure 8.1 Classification of scarps along KMF. (a) Residual range front normal scarp which includes majority of the scarps along KMF, including KHS and JMS (b) Simple range front normal scarp (eg. Khirsara scarp).

fault trace. Furthermore, no trace of the original scarp or faulting remains persevered other than the ragged morphology. The term residual scarp is given to all mature scarps from which the original tectonic surface is removed by geomorphic modification (Steward and Hancock, 1990). Considering all the characteristics of the scarp it could be included in the category of residual range front normal scarp (Fig. 8.1 a). Most of the scarps along the KMF fall in this category. Additionally, simple range front normal fault scarp can be observed along the eastern most segment of KMF (Fig. 7.1 b). The scarp is characterised by preserved fault plane and is coincident with the fault line. Considering the mentioned characteristics, the Khirsara scarp outcropping in the eastern end of the Jhuran anticline could be included in the category of simple range front normal fault scarp.

SCARP DEVELOPMENT ALONG KMF

For long-term scarp development along KMF two domains of the study area were investigated in detail. These domains were investigated in detail due to the presence of twin parallel scarps along the KMF; which is unique along the entire KMF. The two domains are Jara-Jumara sector and Kas Hill sector. North-facing Jaramara Scarp and Kas Hill Scarp represents the most distinctive feature of Jara-Jumara and Kas Hill sector on KMF's western and eastern sides, respectively. Topographical response to perturbations in boundary conditions were examined in the two domains with regards to the landscape evolution.

Kas Hill sector – Eastern KMF

The sector is located in the eastern part of Kachchh and includes areas from Kunaria to Khirsara. The major physiographic division of the region includes- 1) Kas Hill Scarp, 2) KMFS, 3) Northern Hill Range, 4) Alluvial Surface, 5) Banni Plain. The Kas Hill Scarp (KHS) forms the dominant feature in the sector with elevation much higher than the KMFS. Here, the KMFS lies 1200-600 m south of the subsurface trace of KMF, whereas the KHS is located 3000-2000 m south of KMFS. The Kas Hill Scarp forms the prominent feature of the sector with elevation several times higher than the KMFS. Formation of twin scarps in the location is peculiar in nature. The scarps in the sector do not consistently coincide with the active fault trace. To understand the scarp evolution and preservation in the sector drainage characteristics along with cosmogenic exposure dating of the landforms in and around the scarp was attempted.

Drainage characteristics

The present study emphasizes on drainages originating from the scarp face and those cutting across the scarps. Rivers show predominance of parallel to sub-parallel drainage patterns. In addition to this, rivers show annular and radial drainage pattern at the vicinity of domes. The rivers originating from the scarp face generally shows parallel to sub-parallel drainage pattern. The drainage density is very high which strongly contrasts with the hyper-arid desertic climate of the region. The high drainage density in contrast to the hyper arid climatic condition is the direct indication to tectonic control on the landscape. The major drainage divides in the sector includes- the Kas Hill Scarp and Northern Hill Range. The river originating from the scarp face of KHS is characterized by well-developed 3rd to 4th order streams. The well-developed hillslope drainages are geomorphic evidences that implies that the KHS is older in comparison with the KMFS. Rivers flow northward in the anti-dip direction which is another geomorphic evidence suggesting that the landscape has evolved through long-term tectonically driven fluvial erosion. Majority of the rivers do not show any large knickpoints, however the gradient of the river profile is very steep and the channels are highly incised. Normalized stream profiles or dimensionless curves (ratio of elevation to ratio of distance) of the major rivers in the study area show L-shaped nature of the curves representing deep downcutting in the upper medial portion of the basin. Compared to other rivers in the sector, those rivers which originate from the scarp face have more pronounced concavity of the long profile or L-shaped nature. The L-shaped nature of the profiles suggest that the zone of fluvial erosion is concentrated in the scarp face of KHS. Severe downcutting of the upper middle reaches of the scarp-derived rivers point to the fact that major component of erosion is focused on the scarp face and therefore have significant influence on the present morphology of the scarp. Similar nature of longitudinal profile can be seen in river originating from the Western Ghats (Kale and Shejwalkar, 2007). The rivers show concave up to S-shaped average hypsometric curve, indicative of an early to late developing stage of geomorphic cycle. The above-mentioned characteristics represent the dynamic nature of major scarp originating drainages in the sector. In addition, the hypsometric integral versus elongation ratio plot indicates that rivers in the sector are actively increasing drainage area in the headward direction. The headward advancement of drainage area has important connotation to the long-term retreat and degradation of the fault scarps in the region. However, the portion of the scarp where the scarp face gains the highest elevation, the rivers typically display lateral advancement in drainage area than longitudinal advancement. The lateral advancement in drainage area promotes lateral retreat of scarp instead of dissecting the scarp face. Other than tectonics, the rivers are actively responding to lithological changes. The Upper Jhuran Formation which is predominantly arenaceous forms the top portion of the Jaramara Scarp. The lower and middle Jhuran Formation have predominantly softer lithologies of shale and sandstone intercalation. The softer lithologies at the base promote higher fluvial erosion compare to the upper resistant unit. The present geological setting will favour the backwearing or lateral retreat of scarp erosion than downwearing. Modelling by Forte et al. (2016) have shown that faster rate of propagation of erosional wave into the softer rock will lead to undermining of the upper hard rock and thereby resulting in the higher erosion and retreat of the scarp. In short, it can be concluded from drainage analysis that the erosional retreat of the KHS is controlled by tectonically induced fluvial erosion and backwearing process with periodic reactivation of the KMF.

Quaternary sedimentation and deformation along KMF

The eastern portion of KMF displays an apron of colluvio-fluvial and colluvial deposit along a zone that commences from the base of KMFS and overlaps the KMF. The colluvial deposits (5-15 m) of Quaternary age indicate high rate of Quaternary faulting and scarp degradation that has taken place in the region. Two major phases of Quaternary sedimentation occurred along the KMF zone. The first episode of colluvio-fluvial deposition occurred during 100ka, followed by the second episode during 50-35ka (Maurya et al., 2017). The subsurface survey using GPR also indicates the presence of well-developed colluvial wedge in the fault zone (Maurya et al., 2022). The colluvio-fluvial deposits are indication of the coupled action of tectonic and fluvial processes. The phases of colluvio-fluvial and colluvial deposition in the Late Pleistocene period can be related to the episodic reactivation along the KMF and associated scarp degradation. Aeolian miliolite deposition occurred along the KMF zone during the Late Pleistocene period (130-30ka) (Baskaran et al., 1989). The vertical dipping miliolite beds encountered in the vicinity of the KMF is another notable evidence from the region indicating to the post miliolite deformation to which the region has subjected to along the KMF. The Quaternary colluvial deposition and miliolite deformation in the KMF zone put forward direct evidence for multiple phases of reactivation during the Late Quaternary period. The eastern portion of the KMF display many direct evidence of Quaternary tectonic reactivation and uplift along the KMF. Thickness of the Quaternary sediments and elevation of sediments are the highest along the Habo dome. Considering the amount of retreat along the KMF, the scarps along the Habo dome has undergone the highest retreat. Evidence points to the higher amount of tectonic deformation in the vicinity of Habo dome.

Cosmogenic surface exposure dating

Majority of the scarps along the KMF are degraded and retreated from the faultline. The Khirsara scarp in the eastern most segment of KMF is less effected by erosion and hence making it a suitable location for surface exposure dating. The sandstone scarp here has faded striations visible on the surface indicating that scarp preserve the features of a fault plane. The scarp was sampled from top and bottom to establish the phases of reactivation of KMF. The cosmogenic exposure ages of top and bottom of the scarp are 318±43 ka and 249±52ka BP respectively. The exposure ages indicate that a major phase of reactivation of KMF occurred during Mid Pleistocene. The ages also indicate that a youngest phase of scarp formation occurred along the KMF during the Mid Pleistocene period. The reactivation of the KMF during this period must have resulted in the growth in the relief and erosional retreat of the relict scarps. The difference between the height of the samples collected for cosmogenic dating is 5m. This suggests that a minimum of 5m elevation growth has happened along the KMF during the Mid Pleistocene period.

The above-mentioned evidences reveals that the eastern Kachchh have gone through episodes of tectonic reactivation in the Quaternary period. The drainages are deeply downcutting in to scarp to adjust with the tectonic disturbances of the region. However, more frequent and higher tectonic uplift in the Habo dome led to the higher rate of degradation and retreat of the scarp face. The higher thickness of the colluvium and L shaped nature of the longitudinal profile are evidences of the more frequent tectonically driven fluvial erosion of the landscape. Also, the triangular facet in the Habo dome supports the finding that region was more active during the Quaternary period. Other than the tectonic influences the hard resistant lithology of the upper Jhuran Formation also plays a significant role in the preservation and erosional pattern of the scarp. The coupled effect of resistant upper Jhuran Formation and lesser tectonic deformation lead to the preservation of the Kas Hill Scarp in the segment III and IV of the eastern KMF.

A sequence of events following the Deccan intrusion and episodes of fault reactivation thereafter yielded the present geometry of the fault bounded footwall flexure in the Kachchh basin (Maurya et al., 2017). In the present geological setup, the transverse faults (TF) dissect the flexure into different segments, where the nature, appearance and retreat amounts of scarps in each individual segment differ from the other segments. Similar examples of footwall scrap evolution and degradation was addressed in tectonically active regions of the world, for example: fault scarps of Aegean region and range front scarps of western USA, Viking Graben, northern North Sea (Hesthammer and Fossen, 1999; Fraser et al., 2002; McLeod et al., 2002; Stewart and Reeds, 2003; Welbon et al., 2007; Elliott et al., 2012; Bilal et al., 2020). Such studies conducted around the world and its importance in understanding the geomorphic evolution have helped to develop a model for the fault scarps of the Kachchh basin.

The present location of the eastern Kachchh was investigated exclusively to understand the fault zone architecture that led to the development of twin parallel scarps along the KMF. Such twin parallel fault scarps along a single causative fault can be good type sections to understand the history of long-term fault scarp degradation and tectonic instabilities in a region. Also, this phenomenal landscape and its mode of development can shed light onto the long-term fault zone evolution and pattern of geomorphic modifications in the basin. Apart from the KHS discussed in this work, the KMF has a comparable scarp on the western side called the Jaramara Scarp, which stands parallel to the younger KMFS (Shaikh et al., 2019; Padmalal et al., 2021).

In seismically active regions, the reactivation of principal fault systems is the prime factor responsible for the development of landforms and topographic forms (Maurya et al., 2017). The previous studies carried out in the Mainland Kachchh points to the fact that the eastern part of the Mainland was more active during the Late Cenozoic period than the western counterpart. This view was supported by the recent colluvio-fluvial deposits exposed along the scarp base and north flowing river channels (Chowksey et al., 2011a, b; Maurya et al., 2017). In a more general point of view, the geometry of a fault scarp can be resultant of three main factors which include initial tectonic style, mass wasting and regional settings (Steward and Reeds, 2003). However, because of the constant degradation by active surface processes the final morphology of the scarp differs from the initial morphology. Here in the present case study, both the KHS and KMFS looks similar to an erosional scarp. Our field studies in the region confirms the absence of a secondary fault in the vicinity of Kas Hill Scarp, which could actually influence the present morphology and origin of the scarp in the region. Therefore, KMF should be the principal fault responsible for the development and degradation of KHS along the eastern Kachchh. The present asymmetrical posture of the anticlinal unit can promote a bed parallel slip and failure resulting in gravitational collapse and scarp degradation of along the KMF. Such deposition commonly occurs in other similar rift basins of the world, including the East African rift (Morley, 1999), Gulf of Suez (Sharp et al., 2000). Generally, the scarp degrades with advancement in time by reducing the height and rounding off the crest (Wallace, 1977). When compared to scarps formed on soft unconsolidated and recent lithologies, the bedrock rock scarp takes a slightly different path of degradation. The deposition of gravity driven colluvium at the scarp base occurs commonly with the degradation of the bedrock scarps (Welbon et al., 2007). In other words, the gravity driven hillslope processes play a major role in the degradation of bedrock scarp. Poor outcrop or mare absence of colluvio-fluvial deposits older than 100ka makes the long-term landscape modelling of the bedrock scarps along the KMF more challenging. Therefore, in the present modelling we attempted a holistic approach integrating the geological, stratigraphical, morphometric and chronological evidences for reconstructing the long-term twin parallel scarp evolution along the eastern KMF. A conceptual model highlighting the stages of scarp development is depicted in Fig. 8.2.

The Kachchh Rift Basin (KRB) has evolved through two major stages, the rift stage and the inversion stage. These stages led to development of landforms and tectonic feature in the basin. The first stage was characterized by a sequence of events in the Kachchh basin which includes the rift initiation, sedimentation, faulting and magmatism. The reactivation of pre-existing (basement) faults during this period happened in an extensional tectonic regime (Biswas, 1987, 1993, 1999, 2005; Maurya et al., 2017). The scarp formation along KMF under such a setting have plausibly commenced during this stage of rifting, when reactivation of the pre-existing fault took place with syn-rift sedimentation (Fig. 8.2 a). The syn-rift sedimentation happened during this period have shaded the scarp from forming a significant relief. Extensive basin fill sedimentation obscuring the scarps from generating a significant relief was demonstrated in rift basins across the world (Bilal et al., 2020). This event was succeeded by episodes of syn-magmatism and Deccan volcanism in the basin (Biswas, 2005; Sen et al., 2009). The emplacement of intrusions occurred along the weak faulted zones of the basin, including

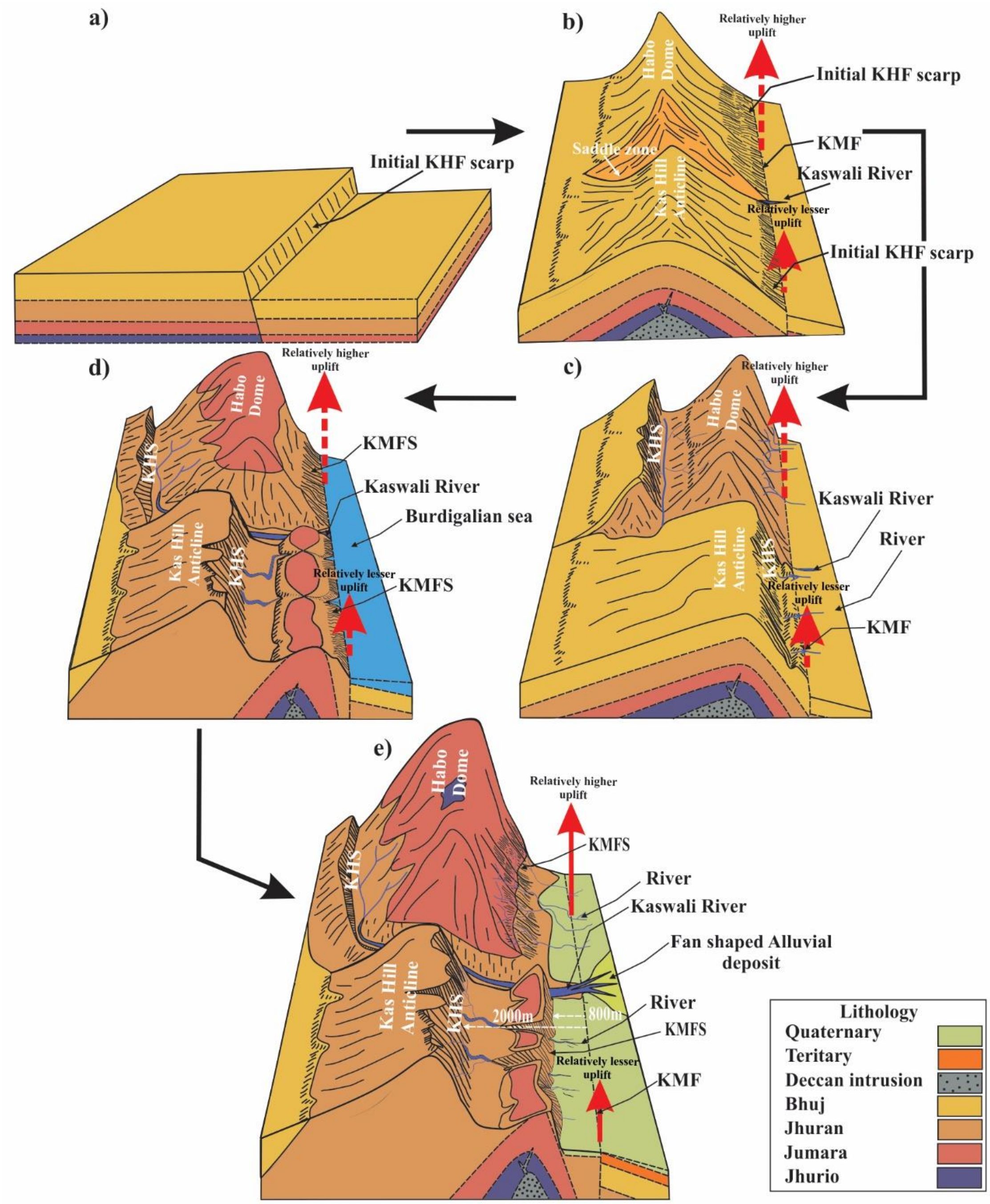

Figure 8.2 Schematic models showing the sequential development of scarp along the eastern KMF zone. (a) As the rifting progressed a minor scarp with low relief formed along the KMF zone. At the same time, thick synrift sedimentation during the period hindered the scarp from developing a prominent relief. (b) The main Deccan Trap eruptive phase in an extensional regime. The eruption rose upwards through the weak KMF zone uplifted and domed up the overlying Mesozoic sequence. The forced intrusion of the magma led to the vertical movements along the KMF, creating fault parallel footwall flexure and prominent north facing scarp in the KMF zone. The uneven emplacement of the intrusion in the domes resulted in variable

magnitude of uplift in the segments of KMF. The resulted in the development of wide saddle zone between the Habo and Kas Hill anticline. The saddle zone developed natured the ancestor of the present Kaswali River. The variable uplift imparted variable height and geometry for the flexure and scarp formed. (c) The domes started to deform further due to the onset of north-south compressive stress related to the Indian-Eurasian plate collision. The initially formed scarp started to degrade as a result of the periodic tectonic pulses along the KMF zone. The variable amount of uplift favored the variable rate of degradation of the scarp. The Habo dome with highest uplift favored higher scarp degradation. (d) Prolonged period of compressive stress along the fault zone resulted an increase in the rate of vertical movements along KMF and favored the development of younger and new fault scarp along the faultline. The older scarp retreated further southward forming the KHS. The variable rate of degradation and retreat towards south continued. The newly formed KMFS near the KMF zone acted as a barrier and further restricted the Burdigalian high sea from advancing to the inland areas. (e) The continuing tectonic activity to the present increased the amplitude of domal deformation and degradation of the scarps and the scarp reached the present location.

the KMF zone (Sen et al., 2009; Sen et al., 2016). The bulk of magmatic activity during Deccan intrusion occurred at 66±1 Ma (Sen et al., 2016). Maurya et al. (2017) demonstrated the significance of Deccan intrusion in doming and faulting of the flexure zone of the Kachchh basin. The reactivation of the KMF after the event (emplacement of intrusives) led to the formation of more prominent fault scarp along the displaced northern limb of flexure (Fig. 8.2 b). The emplacement of intrusion in the domes of the Kachchh basin have occurred in two phases, syn-rift phase(pre-deccan) and deccan trap eruption (Biswas, 2005). The magmatic bodies were emplaced at different volumes along the marginal faults (Sen et al., 2009). The uneven distribution of magmatic intrusions have resulted in a variable magnitude of uplift in the domes of the KMF. Biswas (2016a) also highlighted the importance of magmatic intrusion and control on the present shape of the domes along the intrabasinal faults. The variable uplift resulted in the development of wide saddle zone between domal units. The saddle zone developed have given accommodating space for the development of the rivers. The present Kaswali River was possibly formed during this stage of the landscape evolution (Fig. 8.2 b). The emplacement of magmatic intrusion, doming and vertical movements along the KMF zone resultant in the formation of scarp with significant relief.

Previous studies on the fault scarps of the world envisioned the view that a newly formed fault scarp can be the new erosional axis in a topography (Stewart and Hancock, 1988). Therefore, the initial scarp retreats southward by the geological action of pre-existing rivers and slope failure process (deposition of colluvium). The scarp slope failure process favouring the development of the drainage system in such footwall setting was previously demonstrated (Elliot et al., 2012). Thus, the initial fault scarp formed would have started degrading further south before the Early Miocene period. The breaks in the sedimentary record also indicates that the basin has gone through serval phases of uplift and simultaneous erosion in the Palaeocene to starting of Miocene period (Biswas, 1993). The spatial variability in the uplift rate led to differential rate of scarp degradation and retreat along the segments of eastern KMF (Fig. 8.2 c). The Habo dome with higher rate of uplift have promoted more degradation and retreat of the initially formed scarp. The collision of Indian and Eurasian plate occurred at 50 Ma, i.e, in the Eocene period (Pusok and Stegman., 2020). This resulted a tectonic inversion in the basin, followed by stress inversion and increase in tectonic uplift along the footwall of KMF. This phenomenon favoured the formation of relatively low elevation scarp close to the KMF zone.

The Kachchh basin witnessed Burdigalian transgression and advancement of sea up to scarps during the Mid Miocene period (Biswas, 2016b; Catuneanu and Dave, 2017). In the present stratigraphic settings these Burdigalian deposits were found close to the present KMFS zone (Fig. 8.2 d). The Burdigalian, a period of maximum transgression, where the sea advanced and flooded most part of the residual basins around the uplifts in the Kachchh basin (Biswas, 2016b; Catuneanu and Dave, 2017). The younger KMFS have hindered the Burdigalian sea from entering more inland into the Mainland Kachchh region (Fig. 8.2 d). The present position of the Burdigalian deposits (Chassra Formation) along the KMF zone support the view that the scarp acted as a barrier preventing the invasion of sea to the inland areas. Consecutive uplift and inversion of the stress (compressive) thereafter resulted in higher levels of folding and imparted more asymmetric appearance to the northern limb of the anticlines and domal units of the flexure zone (Maurya et al., 2017). The asymmetrical geometry with steeply dipping northern limb have augmented the slope failure process with consecutive tectonic uplift. The temporal variability in the magnitudes of tectonic uplift can also impact the linear trend of scarp development and degradation along a fault in a tectonically active terrain (Bilal et al., 2020). In the present setting, Habo dome at the higher elevation exposes the oldest lithologies (Jhurio Formatiom) suggesting a temporally higher rate of net uplift when compared to the Kas Hill anticline. This led to the augmentation of degradational process in the dome.

The tectonic pulses continued into the Late Quaternary period in the region. The present-day sharp channel gradient, broad and steep concave up long profiles and vertical incision in the recent sediments, in the channels of the region support continuation of tectonic instability to the recent times. Apart from this, the exposure ages for scarp and OSL ages of the colluvio-fluvial deposit establishes the Late Pleistocene peak in the tectonic activity along KMF. Despite the local linearity of KHS in the eastern side, the scarp is highly dissected and shifted more southward in the saddle zone through which the Kaswali River flows. This further attest to the dominance of fluvial processes and its influence in the present morphology of the scarp. The long profile analysis and morphometric analysis carried out along the segment II and III suggest that the fluvial network has a pivotal role in controlling the denudation rate and also in sculpturing the present morphology of the KHS. The Kaswali River and its tributaries at the same time have a major role in the development of the present morphology of the KHS in the saddle zone. The KHS attains its maximum elevation (approx. 190m) in the vicinity of Kaswali River basin. The long profile and other computed morphometric data through this study in the Kaswali River basin suggest a transient state for the river. This transient state of the river can be correlated to the Late Cenozoic reactivation along the KMF. The transient condition of Kaswali River subsequent to the periodic uplift have potentially affected the tributary streams that have its origin from the KHS and resulted more headward erosion and downcutting into the scarp face.

The present mode of operation of the geomorphological agents in the region have operated in the past as well after the formation of the scarp. However, the magnitude and intensity of operation of geomorphic agents could be proportional to the amount and rate of uplift at different time periods. In such a scenario, post-rift scarp collapse and degradation would have produced colluvial deposition at the base of the scarp. However, the area lacks a good exposure of colluvial deposits older than 100 ka. The older colluvium generated were buried under the thick blanket of Quaternary and Tertiary deposits or transported and deposited further north in the Rann basin as a result of active tectonically induced fluvial processes on the footwall block. The available lithology data of last 100k suggest that the intermittent reactivation of faults have caused instabilities in the region. These instabilities in landscape were eventually transferred to the north flowing rivers and resulted in higher denudational process. The younger sedimentary units are characterized by a few coarse gained gravelly beds with intercalation of sandy units. The presence of coarse-grained gravelly units suggests that episodic high magnitude event capable of transporting such coarse grained units from the surrounding slopes (scarp faces and NHR) have occurred intermittently during the last 100ka. The more gravelly type with little sand proportion in the litholog exposed near Kaswali River basin point to the unstable condition of the river during the last 100ka. This unstable condition of the rivers and intermittent tectonic events have augmented the degradation rate in the region and shifted the position of the scarp more southward over the past few million years and yielded the present morphology to the KHS (Fig. 8.2 e).

Jara-Jumara sector – Western KMF

This sector is located in the western part of Kachchh and includes areas in and around the Jara and Jumara domes. The Jumara dome is expected to have a throw comparable to Jhurio dome in the eastern KMF, which is highest throw in the entire KMF (Biswas, 1993). The oldest Mesozoic bed is exposed at the center of the dome similar to Jhurio dome in the eastern part of KMF. The sector can be divided into five tectono-structural zones- 1) Jaramara Scarp, 2) Jara dome, 3) Jumara dome, 4) Inter-domal saddle zone and 5) KMFS. The Jaramara Scarp forms the prominent feature of the sector with elevation many times higher than the KMFS similar to the Kas Hill Scarp in the eastern KMF. Similar to the scarps in the eastern KMF, the scarps in the present sector do not consistently coincide with the active fault trace. At present, KMFS lies ~400 m south of the subsurface trace of KMF, whereas the Jaramara Scarp (JMS) is located ~4000 m south of KMF scarp. The sector composes mainly of Mesozoic rocks that include Jhuran, Jumara and Jhurio Formations.

Drainage characteristics

The rivers originating from the scarp face generally shows parallel to sub-parallel drainage pattern similar to the Kas Hill sector in the eastern KMF. The drainage density is very high similar to the eastern Kachchh. The major drainage divides in the sector includes- the Jaramara Scarp and rugged hilly topography of the Ukra intrusive. The river originating from the scarp face of Jaramara is characterized by well-developed 3rd to 4th order streams. Major scarp deriving rivers are flowing northward in antidip direction similar to those rivers originating from the Kas Hill sector. The morphology of the longitudinal profiles varies from concave up to convex up nature even though the broad structural pattern is same in Jara and

Jumara domes. Long profiles of major north flowing rivers show L-shaped nature of the curve representing deep downcutting in the upper medial portion of the river basins. Compared to other rivers in the sector, those that originate from the scarp face have more pronounced concavity of the long profile or L-shaped nature. The L- shaped nature of the profile suggest that the zone of fluvial erosion is concentrated in the scarp face of Jaramara. The above-mentioned characteristics represents the dynamic nature of major scarp originating drainages in the sector. Hypsometric curves of rivers show S-shaped to concave up curve indicating early to late developing stage for the landscape according to Ohmori (1993). Relationship between hypsometric integral and elongation ratio indicate that the drainage basins are actively increasing the basin area longitudinally (in headward direction) rather than laterally. However, the rivers originating from the central part of the scarp face, where the scarp face shows highest elevation typically displays lateral advancement in drainage area than longitudinal advancement. The lateral advancement in drainage area promotes lateral retreat of scarp instead of dissecting the scarp face. The River 4 originating from the scarp and flowing through the interdomal saddle zone is more in an equilibrium stage where the fluvial erosion balances the tectonic uplift. As a result, the scarp in the vicinity of the River 4 drainage basin was preserved. However, rivers like Jara and Jumara with higher tendency of headward erosion have dissected the scarp face.

Cosmogenic surface exposure dating

Considering the basic principle of cosmogenic nuclide, the JMS summit was sampled. The scarp face was avoided as it was highly eroded and weathered. Such highly eroded surfaces are not suitable for cosmogenic exposure dating. The second sample was taken from the Jara River gorge. This was to understand the formation of gorge in the present tectonic settings. The gorge was sampled from few meters above the river bed from the left bank. The exposure age of the Jaramara Scarp summit is 102$\pm$15ka. The exposure age suggests that the surface of the scarp got exposed to cosmic rays in the Late Pleistocene. The exposure age for sample collected from Jara river gorge is 1003$\pm$ 15ka. The exposure age from the western sector suggest that the Jara gorge formation initiated during the Late Pliocene period and the Jaramara Scarp reached its present elevation in Late Pleistocene period. The ages from the cosmogenic nuclides matches with the Late Pliocene to Early Pleistocene uplift and erosion in the Kachchh basin as suggested earlier by Biswas (1993). The Late Pleistocene exposure of the Jaramara Scarp submit can be correlatated with colluvio-fluvial deposition along the eastern part of the KMF. The gorge formation and uplift of Jaramara Scarp indicates that multiple phases of reactivation along KMF occurred in the Quaternary period.

Considering the drainage characteristics and the cosmogenic dates it is clear that the western part of KMF and the Jaramara Scarp have gone through significant changes in the Quaternary period. The available chronology from the Jara River gorge suggests that the gorge formation along the sector commence in the later part of Tertiary period. This points to the tectonic active nature of the KMF during the Late Tertiary period. Biswas (1993) also pointed that the Kachchh basin have undergone significant uplift and subsequent erosion during the post Miocene and Late Pliocene to Early Pleistocene period. The data generated from the present work along the KMF also lies in the agreement with the post Miocene active nature of the KMF (Biswas, 1993). The frequent reactivation of the KMF can significantly affect the base level changes in the rivers and thereby causing severe incision in the topography to cope up with the tectonic disturbances. The base level changes in river can result in the tectonically induced fluvial erosion into the Jaramana scarp face. Many previous workers have illustrated the erosion and retreat of the escarpment by fluvial processes (Braun, 2018; Wang and Willet, 2021). An example for escarpment retreat from Indian context is the great western Ghat escarpment. Kale and Shejwalkar (2007) have demonstrated the influence of fluvial systems in carving the present morphology and retreat of western Ghat escarpment. Generally, two evolutionary scenarios are addressed for escarpment evolution associated with river incision and base level changes. The first model describes downcutting and stationary escarpment scenario (Gunnel and Fleitout, 1998). In the model, the rivers will incise into the escarpment, causing a change in relief and steepening of escarpment slope over time. However, the position of the escarpment will remain stationary. In the second scenario the fluvial erosion retreats the escarpment inland. Headward erosion of the escarpment rivers involve in the retreat of the escarpment further inland (Tucker and Slingerland, 1994; Willet et al., 2018). In the second scenario of escarpment evolution, the overall morphology and height of the escarpment remains constant. Considering the geological settings of the Kachchh Rift Basin and the KMF, a hybrid scarp evolution model is proposed for the KMF. The periodic reactivation of the KMF can result in baselevel changes of the rivers and could significantly affect the geomorphic processes in operation. The possible scarp degradation model with the Jara River gorge evolution is illustrated below and in Fig. 8.3.

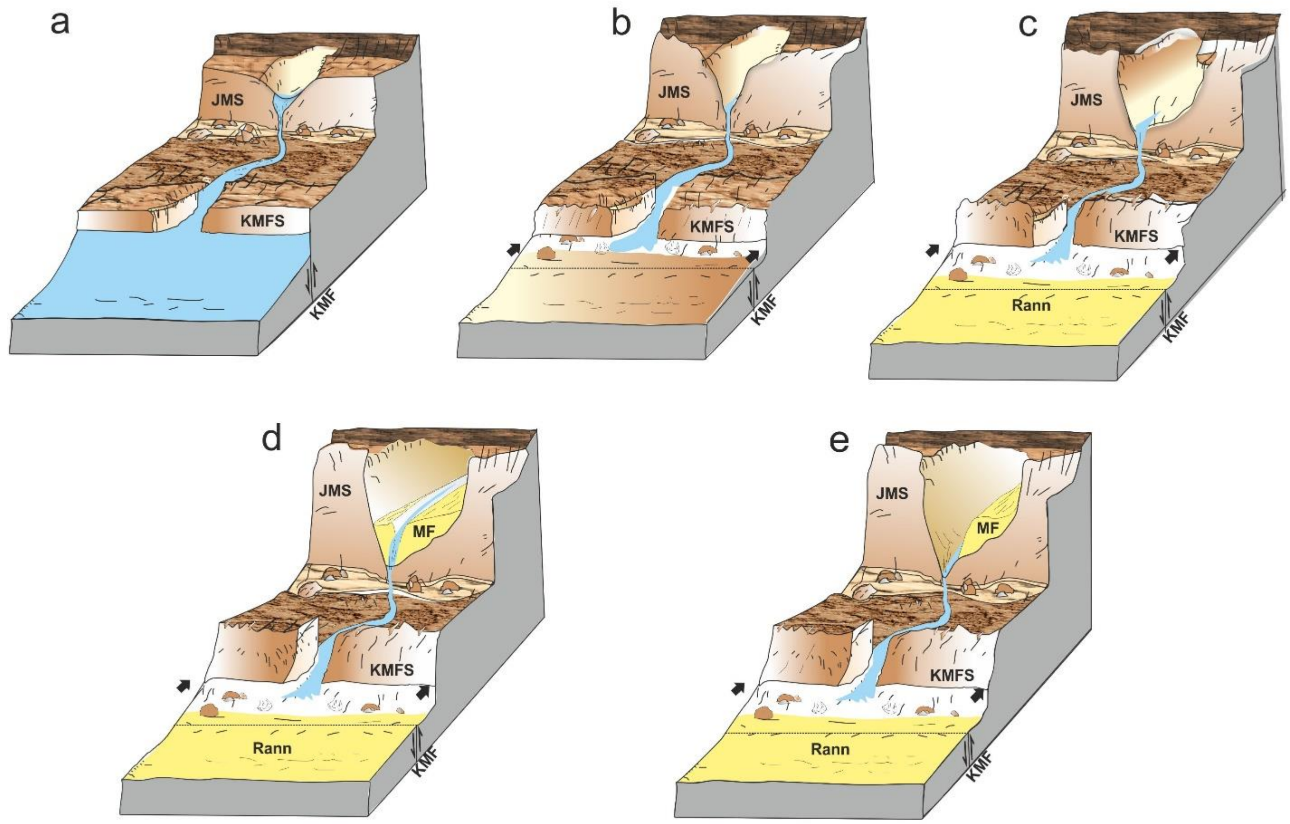

Figure 8.3 Schematic models showing the sequential development of scarp along the western KMF zone from the Miocene period. (a) The low relief KMF scarp prevented the Burdigalian sea from advancing to the inland area. The Jaramara Scarp in the background existed as the prominent feature of the landscape (b) The post Miocene tectonic uplifts led to the vertical movements along the KMF. The uplift continued to the Late Pliocene and the Early Pleistocene. The heightened level of uplift led to the incision and commencement of gorge formation along the KMF. The uplift along the KMF led to overall growth of topography and degradation of KMFS and Jaramara Scarp; result of tectonically induced erosion (c) The period of heightened tectonic uplift along the KMF is followed by a period of reduced tectonic uplift or tectonic quiescence. The tectonic quiescence led to valley widening along the Jara River (d) Late Pleistocene period is marked by extensive deposition of aeolian Miliolite Formation across the valley. The region was undergoing tectonic uplift indicated by the exposure of the present Jaramara Scarp submit (e) The continuing compressive stress to the present increased the amplitude of domal deformation, degradation of the scarps and incision of the valley. The continued uplift and fluvial erosion led to the degradation and retreat of the scarp to the present position. Here, JMS: Jaramara Scarp, KMF: Kachchh Mainland Fault, KMFS: Kachchh Mainland Fault Scarp, MF: Miliolite Formation.

As mentioned in the model for the Kas Hill Scarp shown earlier in this chapter, the Miocene period in the Kachchh basin is marked by a major transgression and advancement of sea to the inland areas. The present position of the Burdigalian deposits is located close to the KMF (Fig. 8.3 a). This suggests a barrier existed hindering the advance of sea further inland during the Tertiary period. The barrier must be the newly formed KMF scarp along the faultline as a result of uplift that continued to the Miocene period. The post Miocene period in the basin is characterised by major tectonic uplift and erosion. The uplift and erosion are usually marked by major erosional breaks in the sedimentary record (Biswas, 1993). Post-Miocene and Late Pliocene to Early Pliocene uplift and erosion along the KMF resulted the initiation of the Jara river gorge. The uplift along the KMF will result in the growth of relief in the sector and base level changes of the rivers, promoting fluvial erosion in the scarp (Fig. 8.3 b). The vertical incision of the Jara River also points to fact that the rivers during this time was actively scouring the landscape in the headward direction. The headward erosion and downcutting of the river in the region resulted in increase in relief and retreat of the Jaramara Scarp. The presence of hard resistant upper Jhuran Formation that make up the upper portion of Jaramara Scarp also favoured an effective backwearing type of erosion of the Jaramara Scarp. The later part of Early Pleistocene period uplift in the region is succeeded by a period of the tectonic quiescence. The tectonic quiescence will result in the lateral erosion of the Jara gorge (Fig. 8.3 c). This period of tectonic quiescence will be characterised by reduced level of fluvial erosion and degradation of the Jaramara Scarp. The Late Pleistocene period in the region is marked by the deposition of miliolite deposits (Fig. 8.3 d). The uplift in the region resulted in the downcutting and incision of the miliolite deposit. This suggests that region has underwent elevated scarp degradation during the Late Pleistocene period. The colluvium deposits in the KMF zone similar to the eastern KMF also indicates the Late Pleistocene tectonically induced landscape degradation in the region. The periodic uplift and reactivation of the scarp during later part of Late Pleistocene and Holocene resultant the degradation and retreat of the scarp face away from the faultline (Fig. 8.3 e).

LATERAL PROPAGATION OF KMF

The analysis on north flowing rivers along the segments of eastern KMF including segment I and V indicates progressive decrease in fluvial dissection and degree of downcutting into landscape towards eastern segments of KMF. In addition, the average hypsometric curves for the segments of eastern KMF show a general trend of younger geomorphic stages for eastern segments. These evidences from the fluvial channel supplemented by fining of sedimentary facies towards eastern most segments of KMF strongly point to a younger topography towards the eastern side of eastern KMF. The younger topography towards the eastern segments is direct indication for lateral propagation of the KMF. The cosmogenic dating of the Khirsara scarp in the eastern most segment of the KMF further confirms the finding of the drainage and geomorphic analysis. The cosmogenic ages of the Khirasra scarp are giving an age of Mid Pleistocene. This suggests that the KMF has propagated towards the east during the Late Quaternary period; more precisely in the Mid Pleistocene period. The eastward propagation of the KMF resulted in the formation three phase of scarp formation along the KMF. The eastward propagation of the KMF resulted in the dislocation of ground surface and generation of comparatively younger fault scarp along the eastern most segment of the KMF. The third phase is the youngest of all the scarp forming events along the KMF. The decrease in scarp height and the elevation of the NHRFZ correlate well with the progressive younging of topography towards east. The exposed lithological units in the domal units and scarps are another evidence of lateral propagation of the KMF. Towards the eastern segments more younger Mesozoic lithologies are exposed. The scarp along the eastern segments of the KMF also shows a similar trend in which, the scarp are formed in younger Mesozoic rocks, i.e. the Bhuj Formation. The lateral propagation of the KMF has a major control on the scarp development along the KMF. Therefore, the lateral propagation of the KMF is to be considered while proposing a conceptual model for scarp development along the KMF.

MORPHOTECTONIC EVOLUTION OF SCARPS ALONG KMF

The available geological data from the basin and data generated from the present work was synthesised to propose an evolutionary stage for scarp development along the KMF. The stages of the scarp evolution along the KMF is presented in Table 8.1.

Middle Jurassic to Late Cretaceous: Rift initiation began in the basin with reactivation of pre-existing faults in an extensional setting (Biswas, 1987, 2005, 2016a). This was accompanied by extensive syn-rift sedimentation in the basin. The displacement along with footwall uplift has produced primitive fault scarp along the KMF. However, the excessive syn-rift sedimentation during this period shaded the scarp from developing a significant relief.

Therefore, during rifting phase scarp with insignificant height/no scarp existed along KMF (Fig. 8.2 a).

Late Cretaceous to Palaeocene: The period is marked by Deccan eruption in an extensional setting with the passage of Indian plate over the Reunion hotshot (Sen et al., 2009, 2016). Flexure zones (footwall anticline and hanging-wall syncline) originated with emplacement of intrusive along the weak marginal fault zones of KMF (Maurya et al., 2017). The augmented vertical displacements resulted in the development of more prominent scarp with significant relief on the footwall of KMF (Fig. 8.2 b). The available sedimentary record suggest that region has gone through a major phase of uplift and erosion during the Paleocene period (Biswas,1993). The uneven doming along the KMF resulted in the development of saddle zones between domes. The saddle zone had given accumulation space for structurally controlled drainages to develop and nurture.

Eocene-Oligocene: Compressive stress commenced in the basin (Maurya et al., 2017). In the new stress regime, progressive increase in topographic relief and further southward retreat of KMF scarp occurred. Scarp became the new axis of erosion in the topography. The degradation of the initial fault scarp morphology begun with footwall gravity collapse and talus production. The prolonged phases of slope failure along the evolving scarp caused development of numerous scarp derived channels in the landscape. Due to the dynamic nature of the river systems, the sediments were carried further north to the present Great Rann basin. The uneven uplift caused the scarps generated along the different segments of KMF to degrade and retreat at variable rates (Fig. 8.2 c). On the other hand, the rivers in the saddle zone become well-developed with entrenched channels.

Miocene: During this period the basin witnessed a sequence of events. The prolonged phases of uplift that continued to the Miocene period resulted in the development of a new scarp along the KMF. The present KMFS formed along the KMF as a relatively lower elevation scarp near the fault line. At the same time, the higher rate of footwall uplift favoured erosion and retreat of the older scarp (i.e., the JMS and the KHS). The flexure zone had attained a more asymmetric geometry as result of the ongoing compressive stress regime in the basin (Maurya et al., 2017). Thereafter, a major marine transgression (the Burdigalian transgression) occurred (Biswas, 2016a; Catuneanu and Dave, 2017). The Miocene marine transgression inundated the

Table 8.1 Summary of morphotectonic evolution of the twin parallel fault scarps along KMF.

Morphotectonic Phase	Kas Hill sector			Jara-Jumara sector			Geologic time
	Geomorphic character of scarps	Fluvial characteristics	Sedimentation	Geomorphic character of scarps	Fluvial characteristics	Sedimentation	
Uplift induced erosion of Northern Hill Range (upthrown block)	Increase in topographic relief in response to uplift along KMF, degradation and retreat of both scarps	Fluvial incision and gorge formation by rivers	No sedimentation in KMF zone, all sediments carried in to the Banni-Great Rann basin	Increase in topographic relief in response to uplift along KMF, degradation and retreat of both scarps	Fluvial incision and gorge formation by rivers, Deepening of the Jara River gorge	Deposition of Holocene sediments burying the colluvio-fluvial deposit	Holocene
Uplift induced erosion with sedimentation in KMF zone	Degradation and retreat of both scarps, Quaternary sediment cover extends up to the base of the KMFS, KMF buried under thin sediment cover	Depositional drainages, shallow and braided fluvial sedimentary facies deposited.	Colluvio-fluvial, aeolian and reworked miliolite dating back to ~100 ka BP deposited in the KMF zone in front of the scarps	Degradation and retreat of both scarps, KMF buried Banni-Great Rann shallow marine sediments	Erosional drainages, Deepening of Jara River gorge.	Colluvio-fluvial deposited in the KMF zone in front of the scarps. Aeolian miliolites deposited in small pockets	Late Pleistocene
Uplift induced erosion with intermittent periods of tectonic quiescence	Third and youngest phase of scarp development along eastern segments of	Fluvial incision and gorge formation continued at periods of	No fluvial sedimentation in KMF zone, all sediments carried northward into	Uplift phases with higher erosion and retreat of scarps and tectonic	Enhanced incision in phases of elevated tectonic uplift and valley	No fluvial sedimentation in KMF zone, all sediments carried in to the Banni-	Middle Pleistocene

	the KMF as a result of lateral propagation.	elevated uplift and valley widening during period of reduced or minimum uplift.	the Banni-Great Rann basin. Aeolian miliolite deposition	quiescence by reduced erosion and retreat.	widening during tectonic quiescence.	Great Rann basin, Aeolian miliolite deposition	
Uplift induced erosion of Northern Hill Range (upthrown block)	Increase in topographic relief in response to uplift along KMF, degradation and retreat of both scarps.	Fluvial incision and gorge formation by rivers	No sedimentation in KMF zone, all sediments carried in to the Banni-Great Rann basin	Increase in topographic relief in response to uplift, fluvial incision along KMF.	Fluvial incision and gorge formation by rivers, Deepening of the Jara River gorge, degradation and retreat of both scarps	No sedimentation in KMF zone, all sediments carried in to the Banni-Great Rann basin.	Early Pleistocene
Uplift induced erosion	Deformation of Miocene sediments due to reactivation of KMF, uplift and erosional retreat of KMFS and KHS	Incising drainages, enhanced erosion of scarps (both KMFS and KHS) due to headward erosion by streams and gullies or smaller	Sediments carried to the Banni-Great Rann basin in the downthrown block	Deformation of Miocene sediments due to reactivation of KMF, uplift and erosional retreat of KMFS and JMS	Incising drainages, Initiation of Jara River gorge formation, enhanced erosion of scarps (both KMFS and JMS) due to headward	Sediments carried to the Banni-Great Rann basin in the downthrown block	Pliocene

		streams arising from scarps.			erosion by streams and gullies arising from scarps		
Marine transgression	Relatively lower elevation KMF scarp near the faultline with retreated scarp (KHS) further south	Rivers and streams with shorter courses as the sea extended up to the KMF scarp	Deposition of marine sediments in the downthrown block of Banni-Great Rann basin up to the KMF scarp	Relatively lower elevation scarp near the faultline with the retreated scarp (JMS) further south	Rivers and streams with shorter courses as the sea extended up to the KMF scarp	Deposition of marine sediments in the downthrown block of Banni-Great Rann basin up to the KMF scarp	Miocene
Prolonged phase of uplift induced erosion (Compressive stress regime)	Progressive growth in topographic relief and retreat of initially formed KMF scarp, variable magnitude of retreat in different segments, Jhurio and Habo dome uplifted more than eastern domes	Well entrenched channels in saddle zones, formation of scarp derived streams	Sediments carried to the Banni-Great Rann basin in the downthrown block	Progressive growth in topographic relief and retreat of initially formed KMF scarp, variable magnitude of retreat in different segments, Jumara dome uplifted more than Jara dome	Well entrenched channels in saddle zones, formation of scarp derived streams	Sediments carried to the Banni-Great Rann basin in the downthrown block	Eocene-Oligocene

Deccan Trap (Extensional stress regime)	Formation of Northern Hill Range and north facing scarp due to preferential emplacement of intrusive bodies along faultline in upthrown block leading to doming up of Mesozoic sediments and faulting. Scarp with significant relief formed.	Initiation of structurally controlled drainage in interdomal saddles	Uplift and erosion in the NHRFZ, Minimal sedimentation	Formation of Northern Hill Range and north facing scarp due to preferential emplacement of intrusive bodies along faultline in upthrown block leading to doming up of Mesozoic sediments, Scarp with significant relief formed.	Initiation of structurally controlled drainage in interdomal saddles	Uplift and erosion in the NHRFZ, Minimal sedimentation	Palaeocene
Rift phase (Extensional stress regime)	Faulting along primordial faults, Insignificant scarp height	Multiple phases of syn-sedimentary activity along fault along with rift sedimentation	Shallow marine to fluvio-deltaic conditions	Faulting along primordial faults, Insignificant scarp height	Multiple phases of syn-sedimentary activity along fault along with rift sedimentation	Shallow marine to fluvio-deltaic conditions	Middle Jurassic to Late Cretaceous

Kachchh basin. Presence of KMFS at the forefront have hindered the Tertiary Sea (Burdigalian) to further advance into the inland areas (Fig. 8.2 d and 8.3 a). The withdrawal of the sea led to deposition of marine sediments in the downthrown block of Banni-Great Rann basin upto the KMF scarp. Drainage evolution and headward erosion of the rivers continued in the footwall block to cope with the tectonic disturbances.

Pliocene: Uplift induced erosion continued along the KMF. Deformation of Miocene sediments occurred along the KMF due to continued reactivation of KMF. Uplift and erosional resulted in the retreat of scarps along the KMF. The elevated uplift rate changed the fluvial characters of the region. Incision and enhanced headward erosion were some fluvial characteristics during the time. The enhanced level of fluvial erosion in the headward direction result in the retreat of JMS and KHS. The Jara River gorge commenced during this period in the western sector (Fig. 8.3 b). At the same time, gravitational collapse and gully erosion were common in the KMFS. The sediments generated from the scarp were carried further north to the Banni-Great Rann basin.

Early and Mid Pleistocene: The continuing uplift induced erosion along the footwall block of the KMF. The continued uplift induced erosion led to degradation and retreat of KMFS, KHS and JMS along the KMF. The dynamic nature of the river system resulted in the effective transportation of the sediments to the into the Banni-Great Rann basin. Fluvial incision and gorge formation by rivers continued in the footwall block of the KMF. The lateral propagation of the KMF initiated in the eastern most part of the KMF. The lateral propagation led to formation of much younger scarps along eastern KMF. These scarps are younger to all the existing scarps along KMF. Therefore, the period marks the third phase of scarp development along the KMF. Thereafter, extensive phase of aeolian activity in the region during Mid to Late Pleistocene (Baskaran et al., 1987). The extensive aeolian caused the miliolite deposition along the scarp face and at the depressions in the footwall of the KMF.

Late Pleistocene: During the Late Pleistocene to Holocene period the region has gone through two major phases of the heightened tectonic activity along the KMF (Maurya et al., 2017). The heightened tectonic phases led to the degradation and retreat of scarps (all scarps including KMFS, JMS and KHS) along the KMF. Sedimentation occurred along the scarp base and KMF zone. The enhanced degradation and collapse of the scarp face resulted in the sediment production and deposition in the form of colluvium at the base of the scarp. The enhanced fluvial activity in the region resulted in reworking of colluvial generated and deposition further north to the scarp, in the Rann basin. The second episode of heightened tectonic activity during the Mid-Late Pleistocene resulted in the deposit of colluvium at the base of the scarp. The episodic nature of the activity along the KMF during Late Pleistocene resulted in the formation of alternate sedimentary units of colluvio-fluvial and fluvial deposits. Moreover, the drainages of the eastern sector were depositional with shallow and braided fluvial characteristics. Drainages of western sector were of more erosional character, which led to further deepening of Jara River gorge and other drainages in the sector (Fig 8.3 d). The erosional character of the rivers in the western part of the sector led to poor preservation of the colluvium generated from the scarp face.

Holocene: Uplift induced erosion of footwall block and the scarps continued. This led to further degradation and retreat of the scarps along KMF. The Holocene sea level rise led to the deposition of marine sediments in the zone of KMF and at the scarp base in the western KMF (Kumar et al., 2021). Fluvial incision and gorge formation by rivers continued to adjust with the tectonic pulses along KMF. This resulted in deepening of the Jara River gorge (Fig. 8.3 e). The headward propagation and erosion by scarp deriving rivers caused further retreat of the scarp to the present position.