CHAPTER 9

DISCUSSION

FAULT SYSTEMS

The E-W striking Kachchh Rift Basin (KRB) at the western continental margin of Indian plate is located in the northern part of Gujarat state, India. KRB has undergone polyphase deformation owing to changing stress-field since Late Triassic. The Kachchh palaeo-rift graben at the western continental margin of India is currently undergoing active coseismic deformation in response to the periodic release of N-S oriented compressive stresses along the E-W trending intra-basinal faults. The seismically active Kachchh Mainland Fault (KMF) is the largest intra-basinal fault that is characterized by a narrow zone comprising a chain of domes and anticlines forming the rugged hilly topography of the Northern Hill Range Fault Zone (NHRFZ) in the upthrown block. The NW striking VGKNFS, which formed during the basin rift phase, is traceable for ~80 km with a fault zone width of ~10 km. It is located south of the E-W striking NHRFZ at western part of the KRB (Biswas, 1993). The VGKNFS acts as an intra-uplift fault system as it is located within the Kachchh mainland and thus, it can be differentiated from the uplift-bounding fault systems of the KRB, e.g., the KMF.

Kachchh Mainland Fault (KMF)- Uplift bounding fault

The shallow subsurface geophysical investigations, assisted by structural and tectono-geomorphic observations were performed along the western part of the seismically active KMF. The KMF is the largest intra-basinal fault characterized by a narrow flexure zone called NHRFZ comprising of a series of asymmetrical domes and anticlines in the upthrown block. The fault strike changes from NNW-SSE to E-W from Lakhpat in the west to Jumara dome in the east. The shift in the strike is due to oblique-slip motion along various transverse faults that end up against the KMF flexure zone. Inversion tectonics plays a crucial role throughout the western part of the NW- to NNW-striking KMF.

The shallow subsurface geophysical investigation was adopted by using Ground Penetrating Radar (GPR) to image and locate the subsurface position and to comprehend the sub-seismic geometry of KMF buried beneath shallow Quaternary sediments. The subsurface Interface Radar-20 (SIR-20) GPR system of GSSI Inc., USA along with 200MHz, 80MHz and 35MHz frequency antennas were used to reliably map the fault-line. The KMF with normal/reverse dip-slip with associated deformed sedimentary and tectonic signatures in the western part of the KRB serves as test site for GPR survey.

The long-term terrain rejuvenation presumably covers and hides any surface expression of deformation in the damage zone of the KMF. GPR data reveal significant off-the-main-fault deformation and complex structures, which are not at all apparent in surficial observations and satellite imageries. GPR data exhibit structural architecture dominated by multiple synthetic/antithetic slip planes/tension gashes, along with the presence of the KMF. In the deformation zone of KMF, along the main fault strand, the stratigraphic framework becomes more complicated, including colluvial wedges, small-scale horst and graben structures. Across the KMF, there is a sharp change in the amplitude response of radar facies due to change in lithology. Reflector offset is also there in few cases. The KMF is inferred to be north/south-dipping normal/reverse/vertical fault, hence altering its attitude in places due to the influence of NW-/NE-striking transverse faults with oblique-slip motion. Colluvial wedges in the GPR sections are documented, which are the reliable structural markers of discrete Quaternary faulting events along the KMF. The GPR data along with the field evidence viz. fault zone deformational features – fault gouge, almost vertical dip nature of the competent lithology in the fault zone, shearing effect of the lithology has been considered useful in locating the position of the KMF and inferring its sub-seismic fault geometry. Faulted alluvial and colluvial Quaternary sediments are documented from GPR data. The various field evidence suggest the western part of the KMF to be neotectonically active in the ongoing compressive stress regime. This study supports the assertion that extensive shallow subsurface imaging is required for accurate determination of KMF position, geometry and slip-sense and also, to ascertain the characteristics of the fault deformation zone.

Conceptual model of colluvial wedge formation along KMF

The study area offers a prime example of colluvial wedge formation and development of other brittle deformation structures in the KMF zone. Fig. 9.1 depicts the sequence of schematic cross-sections showing the evolution of colluvial wedge and associated Quaternary deposits in Cenozoic times.

In the KRB, Paleocene, post-Paleocene, post-Miocene and Early Quaternary are the major periods of tectonic motion (Biswas, 1993).

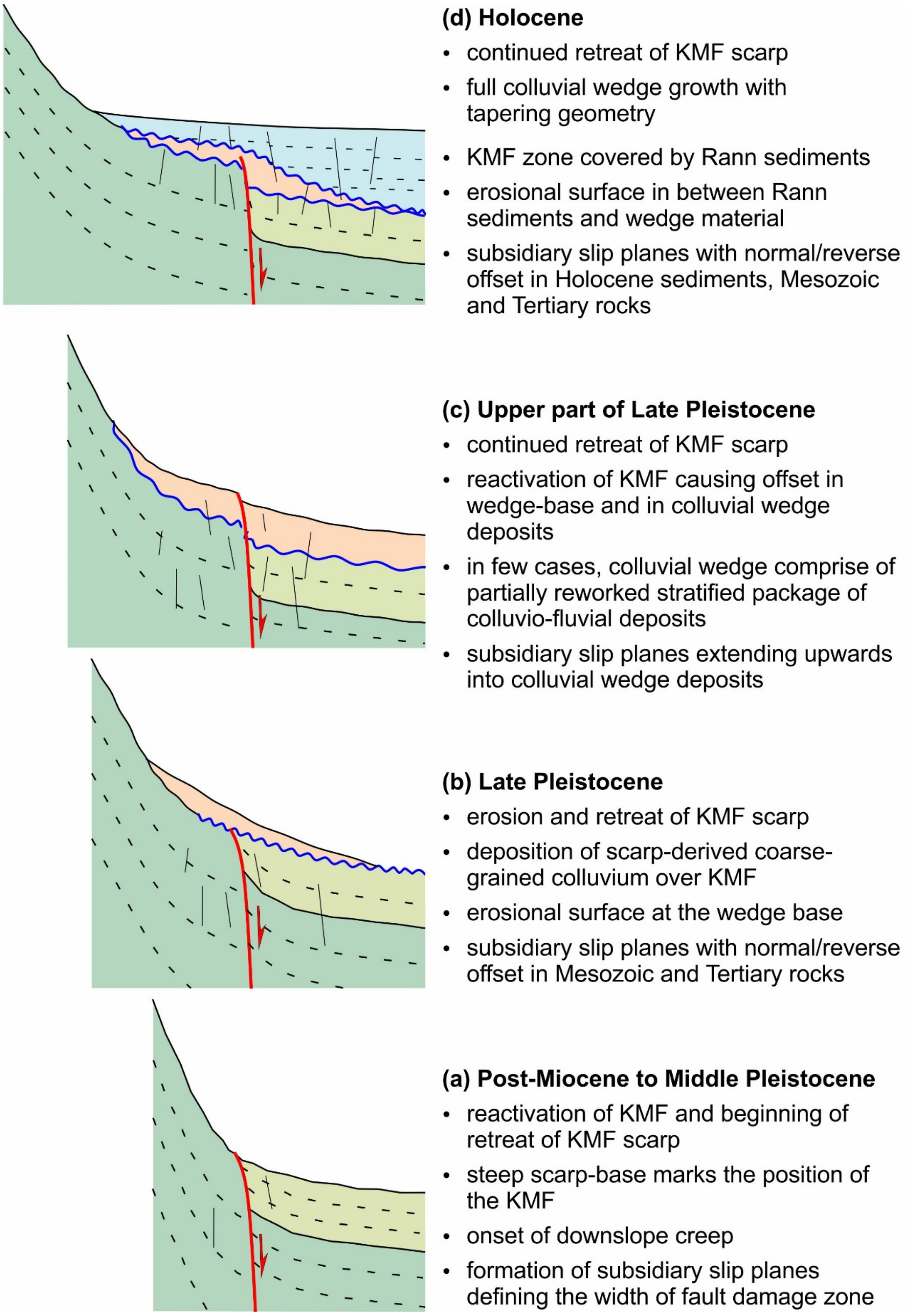

Fig. 9.1. Schematic cross-sections (not to scale) showing major stages of tectonic evolution of the Kachchh Mainland Fault (KMF) damage zone since Post-Miocene. Thickness of colluvial wedge is highly exaggerated. (a) Post-Miocene to Middle Pleistocene: reactivation of the KMF leading to deformation of Miocene marine sediments along the KMF. This time interval spans a long period of non-deposition and erosion of the pre-existing KMF scarp, which is comparable to the similar conditions in the Kachchh Mainland Uplift (KMU). Multiple phases of reactivation of the KMF during this period is indicated by uplift and southward tilting of Post-Miocene and Early Quaternary erosional surfaces in the KMU. (b) Late Pleistocene: Erosion and retreat of paleo-KMF scarp. Deposition of coarse-grained sediments (colluvium) over the KMF, generated from degradation of the pre-existing KMF scarp. A thin colluvial wedge is formed by the colluvium fill over the KMF. Thickness of colluvial sediments shown is highly exaggerated. The sediments were deposited along a thin zone along the KMF forming wedge shape. The deposits may have been partially reworked as seen in the previously described analogous deposits exposed in the eastern part of the KMF zone. The phase of depositional wedge-shaped colluvial sediments was followed by erosion leading to formation of erosional surface over it. (c) Upper part of Late Pleistocene: Offset of wedge shaped colluvial deposits due to reactivation of KMF. The scarp produced due to offsetting was flattened through erosion. (d) Holocene: Submergence of KMF zone by shallow sea leading to deposition of saline sediments of the Great Rann. Marginal marine conditions prevailed until the last ~2000 years BP leaving a flat saline surface of the Great Rann abutting against the scarps.

The Late Cretaceous was the first phase of tectonic disruption when the Mesozoic sediments were faulted and folded (Biswas, 1993). This was followed by the inversion phase of the KRB in relation to NNE–NE oriented compressive stresses caused by the collision of the Indian plate with Eurasian plate (Shaikh et al., 2019, 2020). Several later periods of moderate tectonic activity preceded the main tectonic period of the Late Cretaceous, of which, Post-Miocene unidirectional displacement is the most important (Biswas, 1993). Shaikh et al. (2019) demonstrated the role of long-term landscape evolution in response to uplift-induced structurally controlled erosion along the western part of the KMF.

During post-Miocene to Middle Pleistocene time, the various ~W striking uplift-bounding faults of the KRB, including the KMF, were reactivated (Fig. 9.1a). The faulted contact between the Mesozoic rocks and Miocene sediments defining the patchy surface trace of the KMF indicates the post-Miocene uplift of the NHRFZ (Biswas, 1993; Chowksey et al., 2011a, 2011b; Maurya et al., 2017a; Shaikh et al., 2019). Multiple phases of reactivation of the KMF during this period is indicated by uplift and southward tilting of Post-Miocene and Early Quaternary erosional surfaces in the KMU. The aeolian miliolite deposited in the backslope of the NHRFZ, which was followed by a partial fluvial reworking of the miliolites in Late Pleistocene (Shaikh et al., 2019). This time interval spans a long period of non-deposition and erosion of the pre-existing KMF scarp owing to the hyper-arid climatic regime. The erosion, induced by fluvial and other geomorphic processes, of the softer lithologies exposed on the northern face of the asymmetrical domes of the NHRFZ resulted in further southward retreat and upliftment of the paleo-KMF scarp. This led to the onset of downslope creep of colluvial sediments. The generated Quaternary colluvial material was subsequently transported northward and deposited on to the downthrown block. Thus, the steep north dipping deformed Mesozoic rocks exposed at the scarp face in the NHRFZ served as the provenance for colluvial material generation. Note that the Quaternary colluvial deposits are confined exclusively in the KMF damage zone, north of the KMF scarp in the Great Rann sub-basin.

The erosion and retreat of paleo-KMF scarp continued during Late Pleistocene time. Periodic tectonic movement along the KMF triggered tectonic uplift of the NHRFZ, which caused to achieve the present height of the KMF scarp. The continuous deposition of coarse-grained colluvial sediments over the KMF, generated from degradation of the pre-existing KMF scarp, led to the formation of a thin colluvial wedge (Fig. 9.1b). Note that the wedge-shaped deposits are confined to the KMF damage zone only. There is no scope of lateral extension of colluvial wedge further northward in the Great Rann. Though there is a lack of published information of the presence of colluvial wedges in the fault damage zone, their formation in the seismically active terrain like KRB is obvious. The trapped Quaternary colluvial sediments in front of the KMF scarp, covering the present-day KMF indicate an influence of episodic neotectonic activity in the generation and deposition of the scarp-derived colluvial deposits. The deposits may have been partially reworked as seen in the previously described analogous deposits exposed in the eastern part of the KMF zone (Chowksey et al., 2011). The phase of depositional wedge-shaped colluvial sediments was followed by erosion leading to formation of erosional surface over it.

The offset of the earlier formed wedge-shaped colluvial deposits took place due to continued reactivation of the KMF during the end phase of Late Pleistocene (Fig. 9.1c). The Quaternary scarp produced due to offsetting was flattened through erosion. The continued erosion and retreat of the paleo-KMF scarp during Late Quaternary time led to the deposition of scarp-derived stratified partially reworked colluvio-fluvial deposits over the KMF. The later scarp-derived material acted as a filling up over the colluvial wedges.

The submergence of KMF zone by shallow sea leading to deposition of marine sediments of the Great Rann during Holocene (Kumar et al., In press). Marginal marine conditions prevailed until the last ~2000 years BP leaving a flat saline surface of the Great Rann abutting against the KMF scarp. This led to the generation of unconsolidated to partially consolidated Holocene sediments forming a top layer in the KMF zone, which are responsible for retaining the colluvial wedge shape (Fig. 9.1d).

Vigodi-Gugriana-Khirasra-Netra Fault System (VGKNFS)- Intra-uplift fault system

The kinematic framework along the NW striking intra-uplift Vigodi-Gugriana-Khirasra-Netra Fault System (VGKNFS) located at the western part of the KRB was determined during the present study. The VGKNFS consists of 0.25–50 km long, sub-parallel, striated, reactivated dip-slip faults. A total of 1150 fault-slip data consisting of fault planes and striations attitude were recorded from 66 sites (including a single site with systematic joints). Slip-sense of faults was determined by documenting kinematic indicators. Paleostress analysis was carried out using Win-Tensor, T-Tecto, FaultKin and SG2PS to compare and validate the results. The chi-square statistical analysis was undertaken to evaluate how relevant are paleostress analysis results to the present-day compressional stress field. Geophysical investigations were conducted at selected sites using GPR to understand the shallow subsurface geometry and trace the continuity of faults buried below patchy alluvial cover. 15–17 m long, 2D GPR cross-sections were recorded across faults using monostatic antenna of 200 MHz frequency. Two major deformation events – D1 and D2 are determined in the present study. The extension event D1 shows W and NW–NNW extension during Late Triassic to Late Cretaceous. It occurred during the rift phase of KRB in response of the break-up of Gondwanaland. The latest event D2 shows NNE–NE compression from Late Cretaceous up to the present. It is interpreted to have developed during post-rift inversion phase, induced by collision of the Indian plate with the Eurasian plate at ~55 Ma.

DEVELOPMENT OF EROSIONAL LANDSCAPE

The rugged youthful landscape of the area shows the cumulative effect of the long-term erosion through the Cenozoic in response to sustained uplift along the KMF and other faults. As it is obvious from the foregoing description, the KMF is the main causative fault that has impacted the formation of the asymmetrical domal structures and continued erosion over a prolonged period of time. The geomorphic diversity of the landscape is attributed to the structural complexity of the area as major morphotectonic landforms conform to the structural sub-domains, in the present case, these are the Jumara and Jara domes, the Jaramara scarp, the KMF scarp and the Ukra intrusive. The prominent and precipitous Jaramara scarp is anomalous in the sense that there is no other comparable scarp in the entire length of the NHR. The formation of the scarp is therefore intriguing but nevertheless linked to the long-term structurally controlled erosion due to tectonic uplift.

The landscape developed over the Jumara and Jara domes, which forms a part of the laterally extensive NHR is the result of the tectonic activity along the KMF during the Cenozoic. In general, the topography shows excellent correlation with the complicated structural setup of the area. The north facing scarp abutting against the Rann surface marks the physiographic exposure of the KMF. However, the actual fault line of the KMF is located further north of the scarp and is presently buried below the Rann sediments. Available structural information suggests that the KMF is vertical to a sub-vertical normal fault and has been active during Tertiary and Quaternary times (Biswas, 1993; Maurya et al., 2017). The low structurally controlled erosional rocky landscape over the Jumara and Jara domes is attributed to long-term erosion due to the uplift of NHR along the KMF. The low-level rugged topography is primarily because of the relatively softer lithologies of the Jumara Formation and the lower part of the Jhuran Formation.

The most dominating landform of the area is the vertical and almost undissected north facing Jaramara scarp. The scarp formation is primarily attributed to the hard arenaceous lithology of the upper part of Jhuran Formation. The north facing scarp is formed over the gently south-dipping strata of Jhuran Formation. The Jaramara scarp dies out beyond the confines of the Jumara and Jara scarp and no comparable scarp exists further on either side of the study area. The formation of the scarp is therefore primarily controlled by the structural complexities of Jumara and Jara domes. The prime reason for the formation and preservation of the Jaramara scarp is the Ukra intrusive on the backslope of the scarp. The intrusive extends in E-W direction and shows discordant contacts. This contrasts with the extension of the intrusive especially towards the west where it changes over to thick sills as seen in Gandi river. The existence of the precipitous Jaramara scarp is because of the presence of the large Ukra intrusive body in the discordant faulted contacts.

GEOMORPHIC EVIDENCE OF NEOTECTONIC UPLIFT

The almost complete absence of Quaternary deposits in the study area is a strong indicator of prolonged uplift induced erosion due to tectonic activity along the KMF during the Quaternary. Continuous uplift led to constant erosion and negligible Quaternary depositional activity. All sediments generated by extensive erosion were carried away and deposited in the basin to the north of KMF which is presently identified as the Great Rann sub-basin. The Great Rann is a large E-W trending sub-basin bounded by the KMF in the south (Maurya et al., 2013). The basin preserves a huge thickness of Quaternary fluvial and shallow marine sediments (Maurya et al., 2013). The maximum thickness of the Quaternary sediments of ~300 m is found closer to the KMF and comprises shallow marine Holocene sediments at the top with fluvial sands below (Biswas, 1987; Maurya et al., 2013). The Quaternary sediments are underlain by full sequence of marine Tertiary and Mesozoic Formations (Biswas, 1987, 1993). The maximum thickness of Quaternary sediments together with the subsurface fluvial sediments was primarily facilitated by tectonic activity along the KMF. This resulted in continuous uplift of the upthrown block leading to erosion in the uplifted block and deposition of eroded sediments in the downthrown block i.e., the Great Rann sub-basin. This explains the occurrence of deeply incised bedrock channels, Jara river gorge, large knickpoints and the absence of Quaternary sediments in the Jumara and Jara domes. The role of tectonic uplift as a major factor in the formation of erosional landscape of study area is corroborated by the paleoclimatic studies from the Thar Desert which show that large scale aridity existed in the region for most part of the Quaternary Period (Dhir and Singhvi, 2012) and continues at present (Machiwal et al., 2016).

A strong component of Quaternary uplift is obvious from the one to one correspondence of structural elements with the topography, the youthfulness of the KMF scarp and the Jaramara scarp. All rivers show structurally controlled courses. Prominent control of domal structural setup on drainage configuration also points to sustained uplift that continued during Quaternary. The presence of the knickpoints, both small and large, along the rivers also suggest that the drainages are in a state of continuous rejuvenation (Figs. 3.6a–c). Longitudinal profiles of even the large rivers like the Jara river and Gandi river show large knickpoints and steep profiles (Figs. 3.6a and b). The ~25 m knickpoint in Gandi river and the Jara river gorge over the Jaramara scarp provide evidence of Quaternary tectonic activity (Figs. 3.8b–e).

The most important Quaternary deposit of the Kachchh basin identified by previous workers is miliolite (Maurya et al., 2017). The miliolite represents a broadly multi-phased sedimentation that deposited aeolian miliolitic sands in scattered depressions (Biswas, 1971). At places, the aeolian miliolite deposits are found to be fluvially reworked (Maurya et al., 2017) (Figs. 3.8c–e, 4.1a and b). U/Th dating (Baskaran et al., 1989) and OSL dating (Sharma et al., 2017) suggest several phases of aeolian deposition and fluvial reworking of miliolite sediments up to approximately 11 Ka BP. The outcrops of miliolite are relatively more in eastern Kachchh while they are rare in western Kachchh. The extensive field studies in the Jumara and Jara domes revealed very few isolated outcrops of miliolite deposits. The most significant one comprises aeolian miliolite at the head region of the Jara river gorge which indicates deposition in a depression on the backslope of the Jaramara scarp (Figs. 3.8b–e). The Jara river in its gorge reach over the Jaramara scarp shows a drop of ~60 m in a distance of ~1 km. Out of the total drop of ~60 m elevation difference in river bed profile (Fig. 3.6b), ~25 m is in the incised miliolite sediments (Figs. 3.8b–e). The deep incision in miliolite deposits is because of the post-miliolite tectonic uplift in Late Pleistocene to Holocene times.

The other significant outcrop is a small patch of reworked miliolite located on the right bank of Gandi river and adjacent to the ~25 m knickpoint (Figs. 4.1a and b). This knickpoint is the largest in the study area and is formed in the Ukra intrusive rocks (Fig. 4.1), which is the most competent lithology in the study area. On the right bank of the river at this site, a wide flat terrace surface over the fluvially reworked miliolite sand is observed (Fig. 4.1a). The slope of the terrace surface is inconformity with the SW dip of the underlying rocks that forms the southwestern fringe of the Jara dome. In contrast, the left bank exposes vertically incised cliffs that expose Ukra intrusive rocks with the ~25 m knickpoint on the downstream side (Figs. 4.1a–c). It is inferred that the ~25 m knickpoint along the Gandi river include a component of post miliolite uplift (Fig. 4.1). However, the magnitude of the uplift is not clear as no other comparable terraces are found along the Gandi river and other rivers of the study area. However, based on available chronology and the geomorphic characteristics of the two isolated outcrops in the study area, the incision of miliolite deposition in the study area is because of the tectonic uplift during terminal Pleistocene to Holocene times.

The fluvial landforms along the rivers of the study area show that the landscape has primarily evolved in response to sustained tectonic uplift. The structurally controlled courses, incised bedrock channels, clustering of knick points and rapids, large water falls, anomalous gorge formation and negligible Quaternary fluvial sediments along the channels point to the fact that the rivers have been in erosional mode for prolonged period of time. This is confirmed by the presence of spectacular fluvial landforms like large waterfalls in Gandi river and Makdawali river and deep gorge with multiple falls along the Jara river. Such landforms are the result of sustained tectonic uplift over long geologic time period. The present study shows that the KMF and the VGKNFS have been reactivated several time during the Cenozoic. The incision of miliolites within the Jara river gorge indicates a neotectonic component in the evolution of these spectacular fluvial landforms.

The north flowing Nara and Makdawali rivers drain a large part of the study area. The Nara river shows a large waterfall in its source area overlapping the GUF which suggests neotectonic activity along the fault. In the Central Rocky Plain, the Nara river shows a series of closely spaced knick points as it crosses the Vigodi Fault. In the Nara dome, the river shows deeply incised valley. These fluvial characteristics suggest that the river is in a state of rejuvenation which corresponded well with the fault controlled youthful landscape of the study area. The Makdawali river also shows close correlation of fluvial characteristics with the structures within the basin. The river shows prominent knick points as its flows northwards across the West Vigodi Fault and the Vigodi Fault. The river shows several other knick points attributed to the cross-faults of Vigodi Fault extending across the river. Overall, the Nara and Makdawali rivers suggest long term fluvial response to sustained tectonic uplift of the landscape along the KMF and VGKNFS.

LONG-TERM MORPHOTECTONIC EVOLUTION

The study area provides a perfect example of long-term landscape evolution in response to uplift induced structurally controlled erosion due to differential movement along faults (Chorley et al., 1973; Pazzaglia, 2003; Bishop, 2007).

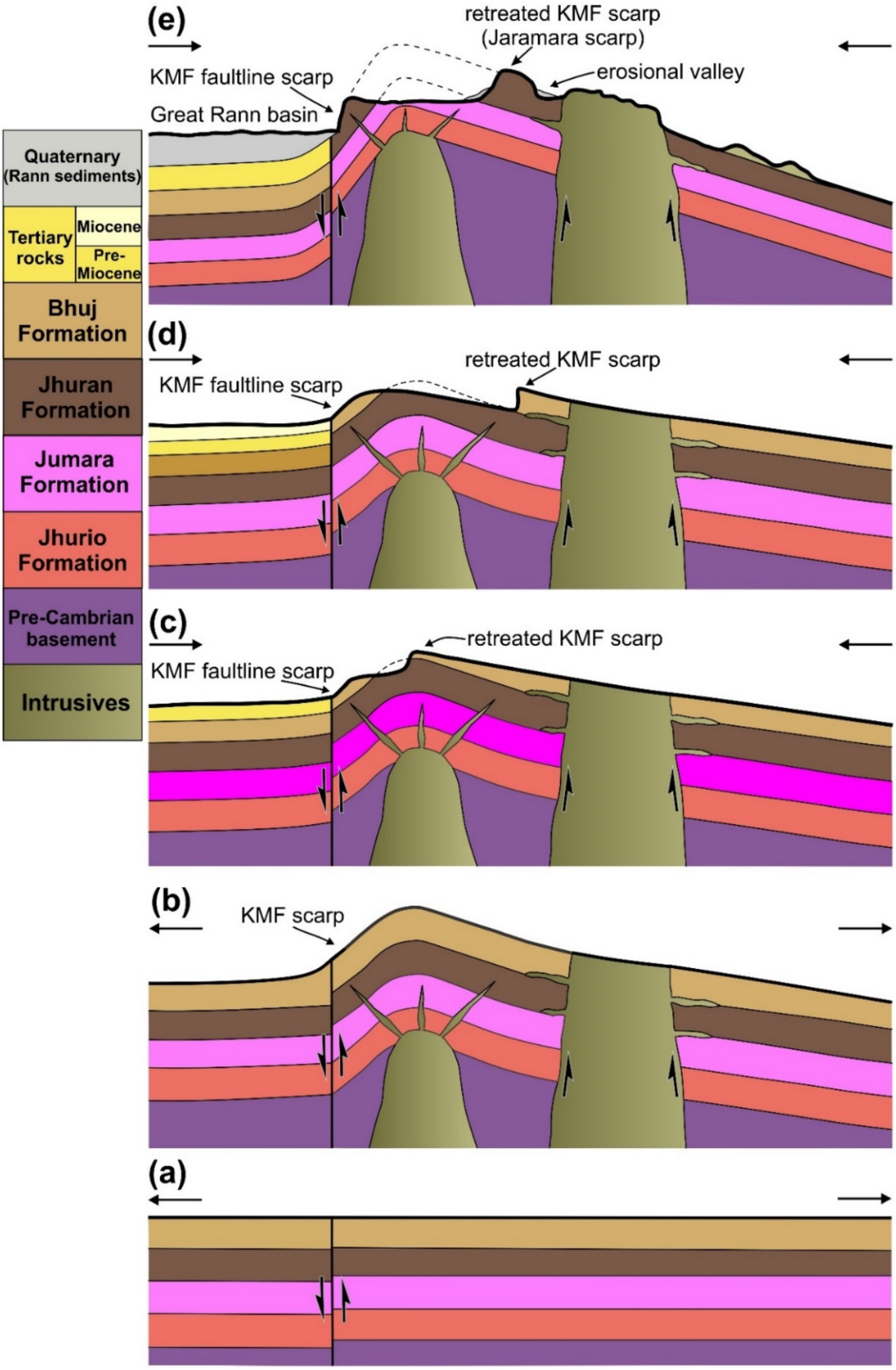

Fig. 9.2. Schematic cross-sections showing long-term landscape evolution in response to periodic tectonic uplift along the western part of the Kachchh Mainland Fault (KMF).

(a) Late Cretaceous

The Late Cretaceous was the culmination phase of Mesozoic sedimentation, which also marked the waning phase of the extensional/rifting phase of the KRB. The various E-W trending uplift-bounding faults of the KRB including the KMF were active during the rift sedimentation in Mid–Late Mesozoic time (Biswas, 1999) (Fig. 9.2a). The sedimentation was followed by an extensive phase of pre-Deccan Trap intrusive activity (Biswas and Deshpande, 1973). Maurya et al. (2017a) demonstrated the complex interaction between magmatism and faulting that led to the formation of flexure along the fault zone.

(b) Pre Deccan Trap

The pre-Deccan trap was the phase of plutonic intrusions. This led to the initiation of doming up of Mesozoic strata over the plutonic intrusion closer to KMF. The doming was facilitated by vertical movements along KMF. The domes were almost symmetrical at this time. The larger pluton (Ukra intrusive) did not cause doming as there was no large fault like KMF in close vicinity. Instead, the intrusive caused faulting along its margins facilitated by extension caused by intrusion itself. The intrusions of sills along intra-formational boundaries, the thickest concordant bodies were formed along the uppermost contact between the Jumara and Bhuj Formation. Though there is very little published information of the nature and phases of magmatic activity, a linkage between the structural pattern and evidence of pre- and post-Deccan Trap intrusive activity is obvious (Biswas and Deshpande, 1973). According to the model proposed by Maurya et al. (2017a), the pre-Deccan Trap intrusive activity along the fault zone led to the doming of the overlying Mesozoic sequence (Fig. 9.2b).

Offshoots of the intrusive flared out as dykes and sills. The Ukra intrusive, the largest of the intrusive also occurred during this time (Santonian to pre-Deccan Trap). Being a large intrusive body and its offshoots, both concordant and discordant contacts are observed. However, there is no evidence to suggest that the roots of the intrusives in the core portion of the domes and the Ukra intrusive merge downwards. The transverse faults and other secondary faults were formed at this time. The main Deccan Trap effusive activity did not affect the northern mainland as all the lava flows are confined to southern mainland Kachchh (Biswas, 1993).

(c) Post Deccan Trap to the onset of Miocene

The Inversion phase of the KRB due to the onset of compressive stresses took place between Post Deccan trap to the onset of Miocene. The domes progressively became asymmetrical as the northern limbs of the domes got steeper due to continuous faulting along KMF. The large-scale erosion occurred on the upthrown block of the KMF and in response to that, retreat in the KMF scarp happened. But the fault line scarp continued to exist throughout as uplift along the KMF continued to occur. This was followed by inversion of the basin in reference to compressive stresses induced by the collision of the Indian plate further to the north (Fig. 9.2c). The continued tectonic uplift of the NHRFZ under compression and further along the KMF is known through Tertiary and Quaternary times led to the formation of the present structurally controlled landscape (Fig. 9.2). The hyper-arid climatic regime also points to dominant role of tectonic uplift in the formation of rugged erosional landscape.

The Jumara and Jara domes are characterized by the differential erosion of the lithologies induced and controlled by tectonic activity. The Quaternary deposits are confined to the north of KMF scarp in the Great Rann sub-basin which forms the downthrown block. The study of the landscape of Jumara and Jara domes shows that the two domes are possibly two intrusive controlled enclosures within the larger anticlinal flexure. The Jumara scarp forms the southern gentle limb of this large anticline in phases in the post-Deccan Trap inversion phase culminated in the present landscape (Fig. 9.2). In the initial phase, the intrusive activity occurred which included both the intra-domal and the Ukra intrusive, concordant with faulting along the KMF and transverse faults.

Down faulting along the KMF ensured that the northern limb of the NHRFZ attained far greater inclination than the southern limb. Increasing compressive stresses and continued faulting caused the northern limb to become sub-vertical to vertical. The uplifting movements led to the formation of the NHR and the initiation of large-scale erosion of the landscape. A north facing fault scarp in the steeper northern limb was produced as a consequence of faulting. The extensive tectonically controlled erosion induced by uplift led to the retreat of the KMF scarps. By Mid-Miocene, the retreated scarp was more imposing than the scarp along the fault line. This phase is considered as the initiation and the formation of the Jaramara scarp (Fig. 9.2c).

(d) Miocene – Transgression phase

The marine rocks were deposited in the downthrown block to the north of the KMF during Miocene. The erosion in the upthrown block and consequent retreat of KMF scarp continued during Miocene. The KMF scarp continued to exist during this period. The Mid-Miocene was a period of the largest transgression when the sea encroached a large part of the Kachchh basin (Biswas, 1993). However, the uplifted flexure zones and related uplifts remained exposed. The post-Miocene uplift of these zones under compression is evidenced by the faulted contact of the Mesozoic rocks and Miocene sediments that mark the surface trace of the KMF exposed in patches along its length (Biswas, 1993; Chowksey et al., 2011a, 2011b; Maurya et al., 2017a). Erosion of the study area resulted in further southward retreat of the Jaramara scarp and the upliftment of the KMF scarp to its present height (Fig. 9.2d).

(e) End of Miocene to Late Pleistocene

The post-Miocene movement along KMF under compression occurred, which caused deposition of Miocene sediments along the KMF. The continued erosion of the upthrown block (domes) lead to the further retreat of the Jaramara scarp. The erosion over domes was more due to the presence of softer lithologies forming a low hilly and structurally controlled topography. The aeolian miliolites were deposited in front of the Jaramara scarp and the deposition was going on the backslope as well followed by a partial fluvial reworking of the miliolites in Late Pleistocene. Late Pleistocene to recent uplift is indicated by the incision of miliolite on the Jara river gorge.

The Jaramara scarp attained its current position during Middle Pleistocene as evidenced by the aeolian miliolite deposited in front of the scarp and on the back slopes of the scarp (Fig. 9.2e). The miliolite deposits in the Jara river gorge striding the Jaramara scarp face are incised by ~25 m which is a reflection of the amount of uplift of the area along the KMF in the post miliolitic time. This is well supported by the ~25 m high knickpoint along the Gandi river that is formed over the Ukra intrusive. The deeply incised courses of the stream and several knickpoints and the Jara river gorge testify to the neotectonic component of uplift induced erosion of the landscape (Gallen et al., 2013).

From the foregoing discussion, it is obvious that the precipitous Jaramara scarp is the remnant of a retreated KMF scarp and currently occurs ~4 km away from the actual KMF fault line. The ~4 km distance of the Jaramara scarp from the KMF is the cumulative amount of retreat that has occurred during the Cenozoic. The scarp appears to have been preserved till present mainly because of the wide Ukra intrusive which comprises a more resistant lithology than the Mesozoic rocks. However, the preservation of the scarp is also attributed to the hard and compact arenaceous lithology of the upper part of the Jhuran Formation that makes up almost half of the scarp height. The relatively softer lithologies of the lower part of Jhuran Formation and the underlying Jumara Formation suffered more erosion and formed low dissected structurally controlled topography developed over the Jumara and Jara domes. The present KMF scarp, which is of considerably lower height than the Jaramara scarp, attained most of its present elevation due to post-Miocene uplift along the KMF.