NEOTECTONIC SETTING

The northern margin of the Kachchh mainland uplift is marked by a E-W trending structurally controlled hill range called Northern Hill Range that is bounded by the Kachchh Mainland Fault on its northern side. The range extends from Lakhpat in the west to the area around Devisar in the east. The hill range displays a rugged mountainous topography developed in the Mesozoic rocks which form discrete domes of various sizes. The chain of various domal structures comprises the Mundhan dome, Ghuneri dome, Nara dome, Keera dome, Jhura dome, Habo dome, Wantra dome, Devisar dome in addition to several smaller domes (Biswas, 1987; 1993). The domes expose rocks belonging to the Jhurio, Jumara, Jhuran and Bhuj formations that range in age from middle Jurassic to late Cretaceous (Biswas 1987). The formations comprise well compacted and hard sedimentary rocks of various lithologies like sandstones, shales and limestones. The domes are asymmetric in the sense that the northern limb of the domes is steeper as a consequence of the tectonic movements along the KMF that truncates the northern margin of the hill range, while the southern limbs shows gentle dips. The Jhura dome is the largest followed by the Habo dome in terms of the area covered. The domal hills are separated by inter-domal saddles through which major drainages flow northward and disappear in the Banni plain. To the east of Devisar the hill range goes down below the Samakhiali-Lakadia plain.

The present study area is confined to the eastern part of the E-W trending Northern Hill range stretching from the Nirona in the west to Devisar in the east. The present detailed field and GPR based study was concentrated in the eastern part, as it shows a widespread and intense aftershock activity since the 2001 Bhuj earthquake (Mandal and Chadha, 2008). During the present course of study various geomorphic indicators of active tectonics like drainage anomalies, fault scarp, river terraces and fault associated Quaternary deposits were studied in details to delineate the neotectonic setting and neotectonic influences in the landscape development of the KMF zone. In this chapter, salient tectonically generated geomorphic anomalies are described to delineate the spatial variation in the landscape along the KMF zone.
PART-B Kachchh Mainland Fault (KMF)

MORPHOTECTONIC SEGMENTS

The Kachchh Mainland Fault (KMF) is the largest intra-basinal fault of the Kachchh basin that bounds the Mainland uplift in the north beyond which lies the flat expanse of the Banni-Great Rann basin. The fault trends WNW-ESE in the western part while it trends E-W in the eastern part. The fault is known to have suffered several phases of tectonic activity during the Cenozoic (Biswa, 1974; 1987; 1993) and has been found responsible for the several earthquakes in historic times including the 2001 Bhuj earthquake, 1956 Anjar earthquake and the 1819 Allahbund earthquake as well (Chung and Gao, 1995; Bilham, 1998; Biswas and Khatri, 2002). However, Quaternary tectonic evolution of the KMF is not yet precisely understood.

Apart from the north facing scarps marking the KMF, several transverse faults are traceable within the Mesozoic rocks and are evidenced by offset fault scarps of the KMF, beheaded/deflected or offset drainage, sags, shutter ridges and pressure ridges (Maurya et al. 2003a). A significant feature observed is that almost all major transverse faults displacing the KMF and truncating the domes are occupied by a high-order river channel debouching into the Banni plain (Maurya et al. 2003a). For example, the Nirona river, Kaila river, the Pur river and the Kaswali river in the study area flow along the inter-domal transverse fault zones.

The KMF is not a continuous fault, but is laterally displaced by several NNE-SSW to NNW-SSE trending transverse faults (Biswa, 1993). These faults have also been periodically reactivated along with the KMF during the post-rift tectonic evolution of the Mainland Kachchh (Biswa, 1993; Maurya et al. 2003a). Based on the tectonic framework that includes the existence of several transverse faults (Biswa, 1993; Maurya et al. 2003a) and the corresponding geomorphic set up, the KMF zone in the study area is divided into five morphotectonic segments from west to east (Fig. 3.1a). The segment-I is located between Nirona and Pur rivers, segment-II lies between Kunaria and Lodai, segment-III includes the area between Lodai and Jawaharnagar, segment-IV comprises the KMF zone between Jawaharnagar and Khirsara and segment-V is located between Khisara and the area to the east of Devisar. Further east the scarp dies out and the area comprises an almost flat but gently undulating and northward sloping topography that merges with the Samakhiali-Lakadia plain further east. As a result of the field and GPR based studies carried out in the present study, the eastward extension of propagation of KMF is
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established. The lateral extension of the KMF has been extended by ~20 kms as a result of the present investigations. The extended part of the KMF delineated has been identified as the Segment-VI and named as the Amrapar-Sikra segment.

From Nirona in Segment-I to Khirsara in Segment-IV, the KMF zone is characterised by thick Quaternary sediments which have buried the KMF below them. The sediments comprise coarse grained colluvio-fluvial to finer grained alluvial sands and silts which are described in details in the next chapter. In the Segment-V (Khirsara-Devisar segment), the alluvial cover is negligible. The Quaternary sediments forms a thin blanket of structureless and unconsolidated alluvial sands and fine gravels averaging 1-2 m in thickness covering the Mesozoic and Tertiary rocks. Major Quaternary aggradation phases evident in other segment are absent though the drainages appear to be of similar characteristics. The general topography of the hill range is also relatively lower (Fig. 3.1) but remains rugged as evidenced by the deeply incised river courses in the bedrock.

The morphotectonic segmentation of the KMF was found necessary to compare the stratigraphic development of the Quaternary sediments in relation to neotectonic activity along various parts of the KMF zone in the study area. The present study indicates that the KMF is not a single continuous fault. Its continuity is broken by several transverse faults which indeed have resulted in several individual segments of KMF. The behaviour of each individual segment is different from the other. Variations within the geomorphic parameters of individual segments are result of differential uplift of the various segments.

FLUVIAL GEOMORPHOLOGY

The drainage configuration in seismically active areas is mainly governed by structural set up. The KMF zone is traversed by several north flowing streams originating in the hilly terrain of the Northern Hill Range (Fig 3.1b). Major rivers of the area flow in the inter-domal depressions, which are fed by streams arising from the gentle southern limbs of the domes. The domal hills are characterized by typical radial drainage patterns (Fig. 3.1b). The north flowing rivers arising in the domal hills, form narrow, deep valleys and gorges within the Mesozoic rocks and follows incised channels to the north of the scarp line.
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*Figure 3.1 (a) DEM of the eastern part of the Northern Hill Range. Note the close correspondence between the individual structures and the physiography. Also seen is the sharp physiographic contrast provided by the north facing scarps at the northern margin of the range and the flat terrain of the Banni plain which tends to die out at the eastern margin. The morphotectonic segments (I-VI) as delineated in the present study are also shown. Note that the KMF has no geomorphic expression in the segment-VI. (b) Generalised geomorphological map of the Northern Hill Range and the KMF zone. The KMF zone is marked by a narrow belt of Quaternary sediments between the scarps and the Banni plain. The domes show typical radial drainage patterns conforming to the structure. Also shown are the numerous small streams that arise from the scarp region and flow northward traversing the Quaternary sediment cover. All drainages disappear in the Banni plain. 1-15 marks the locations of the lithologs of the exposed Quaternary sediments described in the next chapter.*
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It is observed that most of the rivers display tight entrenched meanders as they cross the KMF scarp. This phenomenon is on account of the adjustment by the rivers to a sudden change in the gradient induced by neotectonic activity along the KMF. Significantly, the incision is found to rapidly decrease towards north as the streams die out as they reach the Banni plain. This decreasing trend in the incision confirms the tilting of the Quaternary surface due to the rejuvenation of the KMF.

Variation in the concavity of north flowing streams profile is seen in the various morphotectonic segments of KMF (Fig. 3.2). Longitudinal profiles of the streams in the Nirona-Jhura segment, Kunaria-Lodai and Jawaharnagar-Khirsara segments shows steep concavity in the upstream part and are relatively gentler in the lower reaches in comparison to the other easternmost segments. The experimental studies by (Snow and Slingerlands, 1990) reveal that when a river is experiencing uplift in a tilted manner where maximum uplift is towards the upstream side will results in greater erosion at the upstream direction than at downstream end to maintain the equilibrium profile. Thus, this variation can be directly related to the differential uplift within the different morphotectonic segments of KMF.

Figure 3.2 Longitudinal river profiles of north flowing streams in various segments of KMF zone. The steepness of the profiles is observed to consistently reduce from segment-I to segment-V.
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THE KMF SCARP

The steep north facing scarps demarcating the northern limit of the Northern Hill Range marks the geomorphic expression of the KMF. The imposing north facing scarp comprises steep north dipping Mesozoic rocks having a trend E-W to ESE-WNW marks a prominent geomorphic expression of the KMF (Fig. 3.1a). Overall, the KMF zone displays the characteristics of a dynamic range front environment that is evident from the steep fault scarp, incised valleys, entrenched meanders, northward sloping alluvial surfaces and predominantly coarse grained colluvio-fluvial deposits.

The topographic profile drawn over the crest of the Northern hill suggests that the Jhura dome has the highest elevation followed by Habo dome which decreases further eastward (Fig. 3.3a). The elevations are the cumulative effect of uplift of the range along the KMF in post-Mesozoic time. Variations in the elevations of the domes are a reflection of the variable magnitude of uplift along the length of the KMF. This suggests that the Jhura dome has undergone maximum uplift which progressively decreases eastward.

The variable uplift also correlates well with the relative ruggedness of the topography and depth of incision in the various domes. Corresponding to the maximum uplift indicated, the Jhura dome shows a highly rugged topography and maximum depth of incision. As shown in the topographic profile, the Jhura dome is not only the largest in size, but it is also the most deeply dissected dome where the dissection extends up to the lowest stratigraphic level whereby the older Mesozoic formations are exposed. The Jhura dome is, in fact, the only dome in the entire Northern Hill Range where all Mesozoic formations are well exposed.

The Habo dome is the second largest dome both in terms of the size and degree of dissection. Fig. 3.3a displays the depth of dissection suffered by the Mesozoic stratigraphic formations (i.e. Jhurio, Jamara, Jhuran and Bhuj Formation) throughout the along the Northern Hill Range. The Jhurio Formation forms the oldest lithology followed by Jamara Formation, both are well exposed in the deep gorges formed by the north flowing stream in Nirona-Jhura segment and Kunaria-Lodai segment (Biswas, 1977). Towards the east the incision by the north flowing streams decreases and thus younger Jhuran and Bhuj Formations are exposed in the entrenched river sections (Biswas, 1977). East of Devisar, the hill range appears to go down below the Samakhiali –Lakadia plain and presumably extends further east in the subsurface.
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**Figure 3.3 (a)** Topographic profile drawn over the crest of the E-W trending KMF scarps. The superimposed geological formations are not representative of the lithology of the scarps. Instead, the formations shown depict the depth of dissection down to maximum stratigraphic level in the respective part of the segments. The formations are schematically plotted based on the geological description of Biswas (1977). The figure shows eastward decreasing depth of dissection thereby progressive exposing younger formations. This correlates with the prominent decreasing height of the KMF scarps in the eastward direction. **(b)** Thickness of the Quaternary sediments developed in various segments of KMF.
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The Quaternary surface profile shown in Fig. 3.3b depicts the variation in elevation of Quaternary surface lying to the north of the KMF scarps. The profiles indicate that the Quaternary surface is at the highest elevation in the Kunaria-Lodai segment followed by Nirona-Jhura segment. A sharp decrease in the elevation of Quaternary surface is seen in various eastward segments. The Quaternary surface is at the lowest elevation in the Khirsara-Devisar segment (Fig. 3.3b). The above observations regarding the variation in north flowing river incision in the Mesozoic segment along with the variation in the Quaternary surface development in different morphotectonic segments indicate the differential uplift among the various segments of KMF. Thus, transverse faults have played a dominant role in the segmentation of the KMF and possibly in the dissipation of tectonic stresses in compressional stress regime during the Quaternary.

FIELD SETTING OF THE KMF

The tectonic history of the KMF is intricately linked with the evolution of the Kachchh rift basin. The rift opened during the early Jurassic and witnessed continuous sedimentation during its rifting phase until the late Cretaceous. The KMF along with other intra-basinal faults were formed as vertical normal faults during the active rift phase (Biswas, 1987). Tectonic activity along these faults significantly influenced the pattern and facies distribution of the Mesozoic sediments (Biswas, 1977). As a consequence of the collision of the Indian plate with the Eurasian plate in the north, the rift was inverted at the end of Cretaceous (Biswas and Khattri, 2002). The changeover from extensional stress regime to compressional stress regime, resulted in the formation of intra-basinal uplifts (viz. Mainland uplift, Wagad uplift, Desalpar uplift and Island belt uplift) with corresponding structural lows due to movement along faults (Biswas and Khattri, 2002). Accumulation of the compressive stresses along the intra-basinal faults including the KMF led to the formation of a narrow flexure zone consisting of domes and anticlines on the upthrown sides of the faults (Biswas, 1987). The structural lows that include the Banni-Great Rann basin to the north of the KMF were filled up by thick transgressive marine sediments during the Neogene and Quaternary periods (Biswas, 1993). During the post-Cretaceous inversion phase, the faults bounding the uplifts were periodically reactivated thereby facilitating the deposition of Cenozoic sediments and evolution of the present day landscape (Biswas, 1987).
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The marine Neogene sediments were deformed in a narrow zone all along the KMF during the post-Neogene time under compressive stress regime. Reactivation of the KMF at this time juxtaposed the Neogene sediments against the Mesozoic rocks comprising the Northern Hill Range. The Neogene sediments were subsequently buried under the thick Quaternary sediment pile of the Banni-Great Rann basin and the neotectonically controlled colluvial and alluvial sedimentation in the KMF zone (Chowksey et al. 2011a, b).

Since the KMF zone is for the most part covered by the Quaternary sediments, the surface trace of the KMF is generally marked at the base of scarp. This is mainly because of the lack of subsurface data along the XMF. However, detailed field studies in the various morphotectonic segments revealed that the various north flowing streams incising through of the KMF zone show extremely patchy and poorly exposed Mesozoic and Tertiary rocks below the Quaternary sediments. In view of the consistently thick Quaternary sediments, the trace of the KMF is found to be buried in the segments I to IV. However, sporadic outcrops of the fault were identified on the basis of the observed deformation in the Mesozoic and Tertiary rocks (Fig. 3.4). The rocks were found to attain near vertical to reversed dips especially in the Mesozoic rocks.

An excellent exposure of the fault plane of the KMF was seen in a large artificially excavated pit to the SW of Jhura village (Fig. 3.4a). A sharp lithotectonic contact between the Mesozoic rocks and Tertiary rocks marked the fault plane of the KMF. The KMF is found to be a steep south dipping reverse fault at this location (Fig. 3.4a). The reverse nature of the fault was also observed in a small outcrop along a small stream to the north of Devisar (Fig. 3.4b). Here, the faulted contact of the Mesozoic and Tertiary rocks was found to dip steeply towards the south. The lithologically contrasting rocks occurring on either sides of the fault also showed similar dips. In Lotia stream, the south dipping northern limb of the flexure point to the reverse nature of the KMF (Fig. 3.4c). Significantly, all these exposures are in close vicinity of the transverse faults. This suggests that the zones of intersection of the E-W trending KMF with the transverse faults are the most stressed parts of the KMF. Fig. 3.4 shows the scanty exposures of the KMF observed in segment-I to segment-IV during the detailed field investigations carried out in the present study.
Figure 3.4 (a) View of the KMF in a large artificially dug pit to the SW of Jhura showing its reverse nature. Note the sharp lithological contact between the softer Tertiary shales on the right (north) side and the compact Mesozoic rocks to the left (south) side of the fault plane. (b) View of a small outcrop showing the reverse nature of the fault plane of the KMF along a small stream to the north of Devisar. (c) View across the Lotia stream (west of Jawaharnagar) showing the overturned (south dipping) northern limb of the flexure which points to reverse nature of the KMF (not exposed here). Cliff section shows the flat surface over Quaternary sediments overlapping the Mesozoic rocks. The KMF scarp is visible at the far end. (d) Vertically dipping sheared Mesozoic rocks to the east of Jawaharnagar indicating the surface trace of the KMF. (e) View of a small exposure of the KMF in segment-V. (f) View of the Quaternary sediments overlying the south dipping Tertiary rocks (west of Jawaharnagar).
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The present field studies, however, revealed that the KMF is ideally exposed in the Khirsara-Devisar segment (segment-V) where the Quaternary sediment cover is negligible (Fig. 3.5). In this segment, the fault plane of the KMF marks the sharp litho-tectonic contact between the Mesozoic rocks and Tertiary (Neogene) rocks (Fig. 3.5a). The fault trace is discontinuously exposed on the surface along several small incising streams flowing northward and disappearing in the Banni plain. The fault is characterized by the sharp contact between the compact sandstones of the Bhuj Formation of late Cretaceous age on the southern side and the semi-compacted Tertiary (Neogene) shales of the Chhasra Formation on the northern side (Biswas, 1993).

Figure 3.5 (a) View of a stream section to the east of Khirsara showing the KMF expressed as a steep northward dipping fault marking the sharp lithotectonic contact between the near vertical Mesozoic rocks to the south and Tertiary rocks to the north. (b) The exposed fault plane of the KMF forming a scarp. (c) View of the low incised cliffs exposing Quaternary alluvial sediments reflecting the thin sediment cover. Also visible are the Tertiary rocks in the stream bed and the scarp (shown in previous photograph) in the background. (d) Northward view of the same stream showing incision in Mesozoic rocks and the almost flat topography beyond the fault line. The person is standing exactly along fault plane of the KMF shown in a.
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Both formations show near vertical northward dips and are separated by a thin conglomeratic bed. The fault plane shows several slickensided surfaces at many places. The amount of dip of the Neogene rocks rapidly decreases away from the fault and quickly flattens out within few tens of metres before disappearing below the thin Quaternary alluvial cover. It is therefore inferred that the KMF is represented by a single fault strand near the surface marking the litho-tectonic contact between the Mesozoic and Tertiary rocks. This criteria is used for mapping the near surface trace of the KMF using GPR in other morphotectonic segments where it is buried under Quaternary sediments.