FAULT SCARP MORPHOLOGY AND SCARP DEVELOPMENT ALONG KACHCHH MAINLAND FAULT, WESTERN INDIA

Executive Summary
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EXECUTIVE SUMMARY

INTRODUCTION

The Kachchh basin in the western continental margin of India is a pericratonic rift formed at the trailing end of the Indian plate. The basin is currently undergoing largescale coseismic deformation as indicated by the large magnitude earthquakes that occurred in last 200 years. Landscape development in a seismically active terrain is primarily controlled by tectonically active faults. A systematic study on landscape and other fault generated geomorphic features helps in understanding the tectonic evolution of the fault zone in such regions. The landscape changes associated with such deformation are less outlined on a long-term perspective in the Kachchh Rift basin (KRB). Though, enough information is available on the formation and origin of the basin, there are several issues which are uninvestigated that can help to reconstruct and differentiate the tectonic evolution during the Quaternary and pre-Quaternary time span. The kinematics and rejuvenation of Kachchh Mainland Fault (KMF), as well as the subsequent development and retreat of associated fault scarp in the Kachchh rift basin, were important concerns that remained unresolved. In this study, the fault scarp development along the Kachchh Mainland Fault (KMF) was investigated. The current research will help in understanding the geomorphic evolution of fault scarp and long-term tectonic evolution of Kachchh Mainland fault zone with special emphasis on Cenozoic period. In addition, the present study provides more specific information on the extent of fault, nature, maturity, earthquake potential of the basin. Despite the potential risk of destructive earthquakes in the Kachchh basin, very little data is available on the historical earthquakes and causative faults for the same in the basin. For this purpose, the fault generated landform, especially the fault scarps along the largest fault of the basin, Kachchh Mainland Fault (KMF) were investigated and mapped in the present work. Studies from similar settings of the world points to the fact that fault scarps can provide information about fault zone evolution over time scales which are beyond instrumental measurements or historical records.

METHODOLOGY

- Available published data on tectonic evolution, stratigraphic, structural and seismotectonic aspects of the Kachchh Rift Basin were critically studied and evaluated to understand the regional geological setting and possible influences on the landscape development along the active fault zone. The literature review on the footwall topographic evolution on major rift systems of the world helped in framing an approach for landscape evolutionary studies on the Kachchh rift basin.

- Available geological and subsurface data on KMF was critically evaluated to delineate the subsurface structural features and to infer the nature of basement configuration. This study was supplemented by detailed field investigation along KMF to generate additional data on the fault zone.
- Mapping various tectonic and geomorphic landforms along the KMF using satellite imagery and available high resolution Digital Elevation Model (DEM) and preparation of base maps for the fault zone. High resolution 1 arc Shuttle radar Topography Mission (SRTM) data and Sentinel data were used for mapping and preparation of base maps.
- The profiles were constructed perpendicular to the scarp using available high resolution digital elevation data to extrapolate/model and compare the composite scarp morphology of the various segments of the fault. The data generated from the field investigation was incorporated to generate a more accurate result.
- Multi-proxy data were generated on fault scarp lateral extent, continuity, colluvial fans, geometry of other sedimentary deposit in the vicinity, fault lines and fault traces. GIS technology and field data were used to derive quantitative attribute of the landscape.
- Morphometric analysis was carried out on selected rivers originating from Northern Hill Range Flexure zone (NHRFZ) and those rivers deriving from scarp face to decipher the major controlling factors on the landscape and its influence in geomorphic modification as well as degradation of the fault scarps. Long profiles of the rivers are constructed using elevation-distance data obtained from the Survey of India toposheet and data gathered from the field.
- The exposed Quaternary sediments were studied in detail with a view to understand the genetic aspects of the landforms and stratigraphic evolution. Both, the fluvial and colluvial sediments were investigated during the course of the study to understand slope process that led to the evolution of present landform.
- Chronological data of undegraded scarp surfaces and other tectonic landforms in the vicinity of the KMF were generated using ^{10}Be cosmogenic surface exposure technique to establish the age and phases of tectonic reactivation along the KMF.

- Extensive field mapping supplemented by shallow sub-surface geophysical studies using Ground Penetrating Radar (GPR) was done to map the KMF precisely and calculate the amount of scarp retreat on different segments of the KMF.
- The morphostratigraphic evolution of the fault zones was reconstructed based on detailed field criteria, field relationships of the various landforms and stratigraphic data. Major tectonic events responsible for the overall geomorphic evolution of the area were also identified.
- The data generated from the field and multidisciplinary studies in the laboratory were synthesized and critically evaluated to develop a long-term evolutionary model for scarp development along KMF.

MORPHOLOGICAL CHARACTERISTICS OF SCARPS ALONG THE KMF

A fault scarp is a tectonic landform, coincident or roughly coincident with a fault plane that has dislocated the ground surface. The north facing scarps along the largest intrabasinal fault of the basin, the KMF is the highly discontinuous and considerably eroded. The morphology of the present fault scarps along the KMF do not address the geometry of the fault. The scarps along KMF have lost the original fault characteristics. The present scarp angle is an indication of the severity of denudation to which the landform has undergone over the years. The scarp is in general formed in steep northward dipping limps of the domes and anticlines. The height of the scarp is highly variable, ranging between 6 m and 190 m. The scarps along the KMF have variably retreated along the segments of the KMF. Scarps have undergone higher amount of retreat at the center of the domes than at the tips. The available evidences from the Kachchh Mainland Fault Scarp (KMFS) suggest that the amount of retreat is not fully controlled by tectonic influence. Lithology has a secondary role in the retreat of scarp along the KMF other than tectonics. Along most of the domes a single scarp is formed. However, Jara-Jumara sector in the western and eastern part of KMF shows development of additional scarp, giving a twin parallel appearance along the sectors. In these segments, the elevation of the southern scarp, the Jaramara scarp (JMS) and Kas Hill scarp (KHS) in the western and eastern part are much higher than the KMFS. Mechanism of development of twin scarp along KMF is not investigated so far. Lateral changes in fault scarp morphology are reflections of deeper level of segmentation and variation in magnitude of uplift along the individual segments of KMF. Considering the morphology and nature of the scarps along the KMF, they can be classified into (1) Residual range front normal scarp and (2) Simple range front normal scarp. Most of the scarps along the KMF fall in the category of Residual range front normal scarp. However, the scarp with preserved fault plane could be included in the category of simple range front normal scarp. To understand the long-term scarp development along KMF two domains were examined in detail. These domains were investigated due to the presence of twin parallel scarps along the KMF; which is a unique feature along the fault. The two domains are Jara-Jumara sector and Kas Hill sector in the western and eastern portion of KMF respectively.

JARA-JUMARA SECTOR-WESTERN KMF

The area is located in the western part of Kachchh and includes areas in and around the Jara and Jumara dome. The sector is divided into five tectono-structural zones- 1) Jaramara scarp (JMS), 2) Jara dome, 3) Jumara dome, 4) Inter-domal saddle zone and 5) Kachchh Mainland Fault Scarp (KMFS). The JMS forms the prominent feature of the sector with elevation several times higher than the KMFS. Formation of twin scarps in the location is peculiar. At present, KMFS lies ~350-400 m south of the subsurface trace of the KMF, whereas the JMS is located ~4000 m south of the KMFS. The sector composes mainly of Mesozoic rocks that include Jhuran, Jumara and Jhurio Formations.

Drainage characteristics

The present study emphasizes on drainages originating from the scarp face and those dissecting the scarp. Rivers show parallel to sub-parallel as the predominant drainage pattern. In addition to this, rivers show annular and radial drainage patterns at the vicinity of domes. The drainage density is very high which strongly contrasts with the hyper-arid desertic climate of the region. The major drainage divides in the sector includes- the JMS and rugged hilly topography of the Ukra intrusive. The river originating from the scarp face of the JMS is characterized by well-developed 3rd to 4th order streams. The well-developed hillslope drainages are geomorphic evidences that implies that the JMS is older in comparison with the KMFS. Major scarp deriving rivers are flowing northward in antidip direction. The anti-dip directional flow of the rivers is another geomorphic evidence suggesting that the landscape has evolved through long-term tectonically driven fluvial erosion. The morphology of the river profiles varies from concave up to convex up nature even though the broad structural pattern is same in Jara and Jumara domes. 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. The L-shaped nature of the profiles suggest that the zone of fluvial erosion is concentrated in the scarp face. Hypsometric curves of rivers show S-shaped to concave up curve indicating early to late developing stage for the landscape. 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 the 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. Moreover, the river originating from the scarp face at the central part is more in an equilibrium stage where the fluvial erosion balances the tectonic uplift. The qualities of the rivers have an important connotation on the parallel retreat and morphology of present scarp. 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 JMS. 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 compared to the upper resistant unit. The present geological setting will favour the backwearing or lateral retreat of scarp erosion than downwearing. 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.

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, to understand the formation of gorge in the present tectonic settings. The gorge was sampled from a few meters above the river bed from the left bank. The exposure age of the JMS summit is 102+15ka. The exposure age suggests that the summit of the scarp exposed to cosmic rays at 102+15ka BP. The exposure age for sample collected from Jara river gorge is 1003+ 15ka. The exposure age from the western sector suggests that the Jara gorge formation initiated during the Pliocene period and the region was undergoing severe incision with elevated tectonic activity during the Early Pleistocene period. The gorge formation and uplift of JMS indicate that multiple phases of reactivation along KMF have occurred in the Late Quaternary period.

KAS HILL SECTOR-EASTERN KMF

The area 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 (KHS), 2) Kachchh Mainland Fault Scarp (KMFS), 3) Northern Hill Range (NHR), 4) Alluvial surface, 5) Banni Plain. The 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.

Drainage analysis

Rivers show parallel to sub-parallel and annular drainage pattern similar to the Jara-Jumara sector. Majority of the rivers do not show any large knickpoints, however the gradient of the river profile is very steep and channels are highly incised. The main drainage divides in the sector includes, the NHR and KHS. The rivers originating from the scarp face of KHS are also characterized by well-developed 3^{rd} to 4^{th} order streams. Here also, the major scarp deriving rivers are flowing north in antidip direction. Long profiles of major scarp originating rivers are L-shaped representing deep downcutting in the upper medial portion of the river basins. 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 represents 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. Other than tectonics the rivers are actively responding to lithological changes similar to the Jara-Jumara sector.

Quaternary sedimentation and deformation along KMF

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. The phases of colluvio-fluvial deposition in the Late Pleistocene period can be related to the episodic reactivation along the KMF and associated scarp degradation. Aeolian miliolite deposition commenced along the KMF zone during Mid Pleistocene period (130-30ka). The vertical dipping miliolite beds encountered in the vicinity of the KMF also points to the post miliolite deformation along the KMF. The

Quaternary deposition and deformation in the KMF zone put forward direct evidence for multiple phases of reactivation during the Late Quaternary period.

Cosmogenic surface exposure dating

Majority of the scarp along the KMF is degraded and retreated from the faultline. The Khirsara scarp in the eastern most segment of KMF is less effected by erosion making it a suitable location for surface exposure dating. The sandstone scarp here has faded striations visible on the surface. 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+43ka and 249+52ka respectively. The exposure ages indicate that a major reactivation and scarp formation event occurred along the KMF in the Middle Pleistocene.

LATERAL PROPAGATION OF KMF

The fluvial analysis on north flowing in the eastern KMF indicates a progressive decrease in the 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 towards the eastern segments. These evidence 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 exposure ages from the Khirasra scarp confirms the eastward propagation of KMF during the Late Quaternary time period; more precisely in the Middle Pleistocene period. The eastward propagation of the KMF resulted in dislocation of ground surface and generation of comparatively younger fault scarp along the eastern most segment of the KMF. The decrease in scarp height and amount of retreat correlates well with the progressive younging of topography towards east. 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 THE KMF

The available geological data from the basin and data generated from the present work was synthesised to propose an evolutionary model for scarp development along KMF. The evolutionary history of the scarps is as follows:

Middle Jurassic to Late Cretaceous: During rifting phase scarp with insignificant height/no scarp was formed along KMF. The excessive syn-rift sedimentation during this period shaded the scarp from developing a significant relief.

Late Cretaceous to Palaeocene: Formation of Northern Hill Range (flexure) and north facing scarp due to preferential emplacement of intrusive bodies and doming up of Mesozoic sediments. Sedimentation was low or negligible. 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.

Eocene-Oligocene: Compressive stress commenced in the basin. In the new stress regime, progressive relief growth in the topography and retreat of the scarp along KMF occurred. The scarps along the different segments of KMF were degraded and retreated variably. Sediments were carried to the Banni-Great Rann basin. Well entrenched channels formed in the saddle zones. The scarp became the new erosional axis of the landscape and resulted in the formation of numerous scarp derived streams.

Miocene: The prolong phases of uplift in compressive regime resulted in the formation of relatively lower elevation scarp near the faultline and retreat of older scarps (the present day KHS and JMS) further south. The Mid Miocene marine transgression inundated the Kachchh basin. Deposition of marine sediments in the downthrown block of Banni-Great Rann basin up to the KMF scarp. The presence of KMFS barred the Mid Miocene high sea from invading the inland areas. Drainage evolution continued in the footwall block.

Pliocene: Uplift induced erosion continued along KMF. Deformation of Miocene sediments due to reactivation of KMF. Uplift and erosional retreat of KMFS, JMS and KHS continued. Incising nature, enhanced scarp erosion by headward erosion by streams arising from scarps were some fluvial characteristics during the time. The Jara River gorge initiation and enhanced scarp erosion taken place in the western sector. Sediments generated were carried to the Banni-Great Rann basin.

Early and Middle Pleistocene: The continuing uplift induced erosion led to the topographic relief growth and increased retreat of KMFS, KHS and JMS along the KMF. No sedimentation in KMF zone, all sediments carried into the Banni-Great Rann basin. Fluvial incision and gorge formation by rivers continued. 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 KMF. These scarps are younger to all the existing scarps along KMF.

Late Pleistocene: Uplift induced degradation and retreat of scarps (i.e., KMFS, JMS, KHS) continued. Sedimentation in the eastern KMF. Colluvio-fluvial, fluvial, aeolian and reworked miliolite deposited in the KMF zone and infront of the scarps in eastern half. 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 deepening of Jara river gorge and other drainages in the sector. Aeolian miliolites were deposited in small pockets in the western sector.

Holocene: Uplift induced erosion of footwall block and the scarps continued. This led to further degradation and retreat of the scarps along KMF. Fluvial incision and gorge formation by rivers continued to adjust with the tectonic pulses along KMF. This resulted in the deepening of the Jara river gorge. The headward propagation and erosion by scarp deriving rivers further retreated the scarp to the present position.

CONCLUSIONS

The focus of the present study was on understanding the morphology and development of fault scarps along the Kachchh Mainland Fault in the Kachchh Rift Basin. The key objectives of the present study were achieved through critical analysis on available literature, extensive field mapping, quantitative terrain analysis with available SRTM digital elevation data, cosmogenic surface exposure dating using ^{10}Be isotope and detailed analysis of major north flowing drainages in the fault zone, with special emphasis on rivers originating from scarps. The present study provides conclusive evidence for fault reactivation and period development and modification of scarps along the KMF.

The following inferences can be drawn from the present study:

1. Scarps are highly but variably degraded along the segments of the KMF. The uneven degradation of the scarps can be directly linked to the variation in lithology and tectonic uplifts along individual segments of KMF.
2. The scarps along KMF are extensively eroded such that the scarps have lost their original fault characteristics. Thus, the scarp is designated as residual range front fault scarp in the present study. However, those with preserved fault characteristics is included in the category of simple range front normal scarp.

3. Scarp characteristics and tectonic setting of the fault zone indicate multiple phases of tectonic reactivation and scarp formation along the KMF during Cenozoic under compression stress regime.
4. Two broad phases of scarp rejuvenation linked to reactivation of KMF under compressive stress regime are inferred, pre-Miocene and post-Miocene.
5. Selective development of twin scarps in some fault segments is attributed to the periodic reactivation of the KMF and retreat.
6. The southern higher elevation scarps are essentially older retreated KMF scarps (pre-Miocene) while the present KMF scarps are shaped by post-Miocene reactivation phases of KMF.
7. Evolution of the present geomorphic setting of scarps is attributed to continued reactivation of KMF during Late Quaternary.

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