CHAPTER 3

GEOMORPHOLOGICAL CHARACTERISTICS OF FAULT SCARPS

The evolution or development of landform is a complex process as multiple factors interact each other to produce a landform of a region. Fault scarps are landforms which are originally formed by faulting activity however, the modification of scarp can be influenced by the geomorphic processes (Nash, 1980). They are geomorphologically important landforms that record details of progressive fault exposure and development in an area or landscape through time (Akçar et al., 2012; Benedetti et al., 2002; Schlagenhauf et al., 2010; Cowie et al., 2017; Mechernich et al., 2018; Goodall et al., 2021). Investigation on such geomorphic records can provide basic data necessary to understand the role of tectonics over a few years to millions of years (Steward and Hancock,1988; Keller and Pinter, 2002; Nash, 2013). The objective of this chapter is to evaluate and describe the morphological characteristics of the scarps along the KMF, which is subjected to a detailed investigation in this work.

FAULT SCARP

'Scarp' is a geomorphologically significant landform with well-developed slope face (Esterbrook,1999). Scarps occur in geologically different settings and environments in the earth surface. The fault scarps are landforms formed by vertical displacements along the Earth crust during a faulting event (Nash, 2013). The fault scarps can be classified into two broad categories- bedrock and alluvial fault scarp (Nash, 1980). The alluvial fault scarps are those developed commonly in unconsolidated sediments. The bedrock fault scarp, a variety of fault scarp formed in resistant rock, generally exposes actual fault plane (Steward and Hancock,1988). The bedrock scarp being more resistant to the action of surface processes such as denudation and erosion they stay resistant to degradation, while those formed in soft sediments are more prone to erosion and modification by geological agents (Nash, 2013). Investigation on these landforms can reveal the amount of displacement and timing of past earthquakes over a long-term basis (Steward and Hancock,1988). Nash (2013) defined fault scarps as a linear topographic feature or landform resulting from the displacement along a dip slip or strike slip or oblique slip fault. Therefore, relief observed in the topographic feature can be equal or less than the culminative offset or throw generated during the faulting event. The geomorphic processes operating on the scarp also varies from one another (Nash, 1980). Here, the bedrock scarps being more resistant to geomorphic processes, the erosion is limited by availability of material for transport. Therefore, those formed in bedrock stands for a few hundred thousand years without much degradation. However, the alluvial scarps are characterised by the availability of material for erosion but limited by the availability of geomorphic surface processes to transport the material. Therefore, the bedrock scarp can be entitled as a production limited scarp, while alluvial scarps fall in the category of transportation limited scarps (Nash, 1980). There are numerous studies on alluvial fault scarp due to the relative ease in modelling and representation of surface processes controlling the changes in scarp morphology (Nash, 1987, Colman and Watson, 1983). Despite numerous studies on alluvial scarp, bedrock scarp related studies are less attempted because of its control nature and physical resistance to changes over time (Tucker et al., 2011).

The fault scarp once developed may degrade, retreat or recline as it ages (Nash, 2013). Dealing with scarp related studies one should be familiar with these terms. The term ‘scarp degradation’ is applied to changes in the morphology of the scarp by geomorphic processes operating in the surface (Nash, 2013). The term ‘degradation’ in a scarp in simple sense implies to the erosion of these topographic feature with ages. Other related terms used while dealing the evolution of scarp or related topography includes scarp recline and scarp retreat. Both these terms are used to explain the scarp behaviour or pattern of erosion with time. The ‘scarp recline’ generally refers to the scarp decrease in the slope angle of a scarp as it degrades (Nash, 2013). On the other hand, the latter term ‘scarp retreat’ refers to the backward parallel or lateral movement of the scarp as it degrades. The bedrock scarp generally degrades by retreat. There are many examples in the world where the fault scarps have retreated many kilometres back from the fault that produced it. Example for the same is well displayed in the Basin and Range province of the western US (Nash, 2013). Here, the fault scarp was formed in bedrock as a result of normal faulting, however erosion caused the former surface to retreat several kilometres from the fault.

Steep vertical to subvertical scarps are typical eye-catching geomorphic features of the fault systems in the Kachchh basin. These scarps of the basin were usually categorised as resequent faultline scarp by Biswas (1993), who made extensive studies in the area. The scarps associated with the principal fault system of the basin are eroded and retreated from the fault line. The morphology and amount of retreat of the scarps also vary from one another. The varied pattern of degradation is related to history of fault development and variation in the fault zone architecture (Steward and Hancock, 1988). These qualities of the landform make it as an important tectonic feature to reconstruct the long-term tectonic evolution of the fault and the basin. Similar studies concerning the reconstruction of long-term tectonic evolution of fault scarps are a potential topic in the major rift systems of the world.

To understand the morphological characteristics of scarps along KMF, profiles were extracted from 30 m SRTM (Shuttle Radar Topography Mission) supplemented by field observations and geological mapping (incorporating lithologies and KMF). Multiple independent profiles of the scarp were constructed to understand the strike variation height and general morphology of the scarp. Multiple profiles are essential, when the DEM used is of low resolution. This profiling method was adapted to minimise the noise, vertical uncertainties in the data. Dome-wise morphological characters were computed to examine the scarp characteristics and development owing to the active tectonic movements along the individual domes along KMF. A dome-wise comparison will also yield more information on the scarp modification on the individual segments of KMF. Additional SWATH profiles were constructed for the scarps to get a more clear picture of the variation in the morphological parameters. The SWATH profiles were constructed using SWATH PROFILER add-in in the ArcGIS software.

SCARP MORPHOLOGY

Eastern KMF

Along the KMF, scarp is well exposed in the eastern and western side of the KMF. In the eastern side of KMF good exposure of the scarp is seen developed between the Nirona and the Devisar villages. The major dome/anticlines in the sector includes Jhurio dome, Habo dome, Kas Hill dome, Lotia dam dome, Jhuran anticline, Khirsara dome and the Devisar dome (Biswas, 1993). The highly discontinuous landform strikes parallel to the KMF and forms a geomorphic expression for the KMF (Fig. 3.1).

Devisar Dome

The Devisar dome forms the part of Kas hill anticline located in the eastern KMF (Biswas, 1993) (Fig. 3.1). The northern limb of the dome exposes north facing scarp close to the KMF. The expose scarp ranges in height from 15 to 29 m, with an average height of 22 m. The scarp is commonly formed on carbonaceous sandstone of the Bhuj Formation

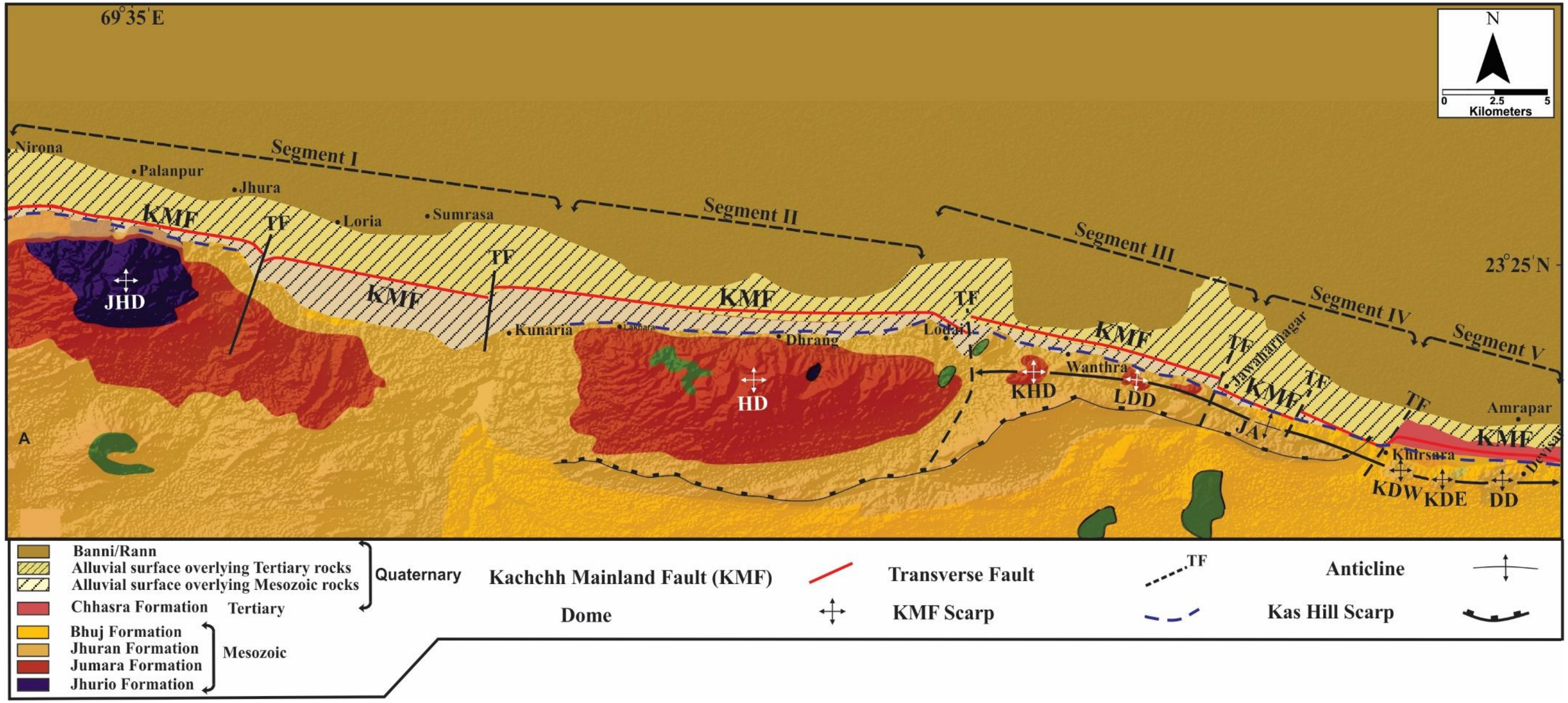

Figure 3.1 Geological map of the study area draped over the Digital Elevation Model (source: https://earthexplorer.usgs.gov and Biswas & Khattri, 2002). Major contrast in the lithologies and physiography of segments in the eastern KMF are highlighted in the map. Note that the KMF passing between the rugged topography of NHR and flat Banni plain to the north. The narrow belt of Quaternary sediments between the KMFS and Banni plain is demarcated. The KMF is concealed under thick pile of colluvio-fluvial and alluvial sediments in the eastern Kachchh. DD: Devisar dome, KDE: Khirsara dome east, KDW: Khirsara dome west, JA: Jhuran anticline, LDD: Lotia dam dome, KHD: Kas hill dome, HD: Habo dome, JHD: Jhurio dome.

(Fig. 3.2). The scarp on the Bhuj Formation is highly discontinues and eroded. The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.3). The KMF is 400-500 m from the scarp face. This suggests that the scarp has retreated on an average of 415 m from the faultline. The scarp face is moderately steep. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief is developed at the center of Devisar dome. The relief of scarp decreases to a minimum at the tip of the dome, where the scarp is dissected by streams originating from the NHRFZ. The scarp along KMF ends further east of the Devisar dome. As such, Devisar scarp represents the furthest exposed outcrop of the KMF scarp in the eastern end. At several localities, a thin veneer of colluvial sediments aprons at the base of the scarp. The presence of such colluvial deposits indicates that the unconsolidated sediments produced from the scarp face. Therefore, it can concluded that the present visible bedrock scarp has developed from a combination of erosional exhumation of the fault plane under episodic tectonic uplifts of the region.

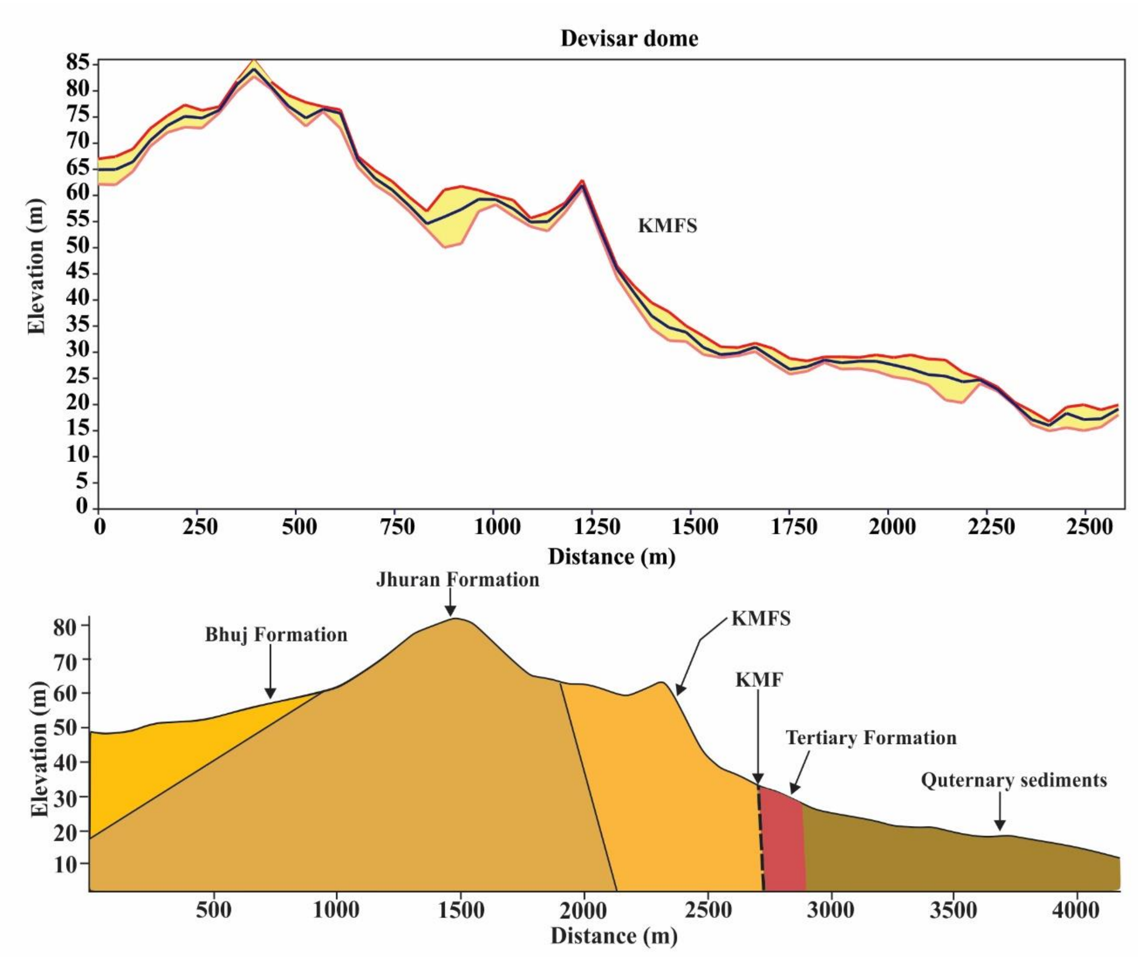

Figure 3.2 Swath profile and cross section profile of Devisar dome. Colour scheme is as per geological map in Fig. 3.1.

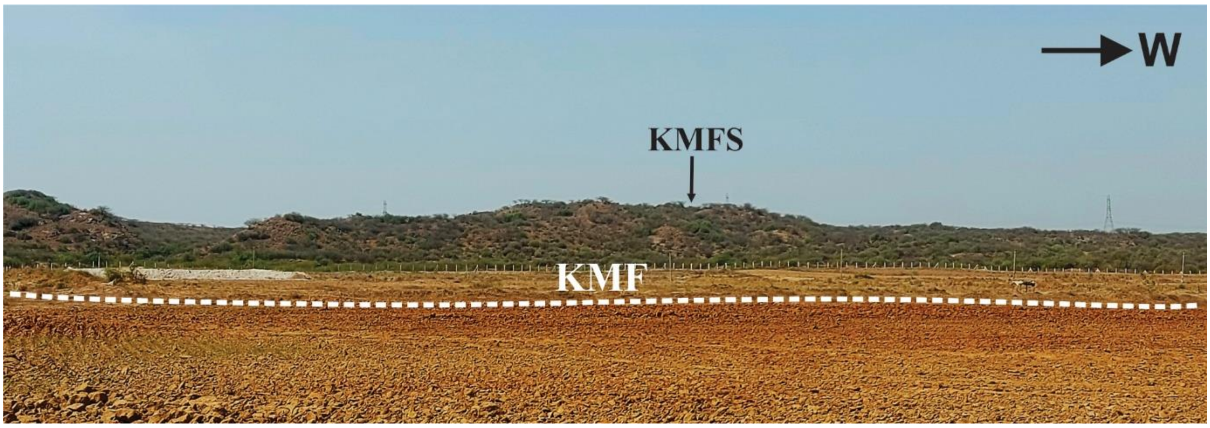

Figure 3.3 Southward view of north facing KMFS near the Devisar dome. Note that the scarp is not coincident with the KMF.

Khirsara Dome

The Khirsara dome is generally classified as Khirsara dome west and Khirsara dome east (Biswas, 1993, Fig. 3.1). The domes are located western of the Devisar dome (Fig. 3.1). The expose scarp range in height from 5 to 17 m, with an average of 11 m. The scarp is commonly formed on Bhuj Formation (Fig. 3.4). The scarp is generally highly broken and eroded. The scarp in the Khirsara dome is degraded higher than one observed in the previous dome. The scarp does not consistently coincide with the active fault trace. The KMF is 660-810 m from the scarp face. This suggests that the scarp has retreated on an average of 743 m from the faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. The maximum relief of the scarp is developed in the Khirsara dome west. At the same time, the scarp developed in the Khirsara dome east have a comparatively lower relief. The relief of scarp decreases to a minimum at the saddle zone between the domes, where the scarp is dissected by streams originating from NHRFZ. Thin veneer of colluvium aprons base of the scarp at several localities.

Jhuran Anticline

The Jhuran anticline is an anticline within the mega structure of the Kas Hill anticline (Biswas, 1993) (Fig. 3.1). The exposed scarp within the anticline ranges in height from 6 to 54 m, with an average height of 30 m. The scarp outcrops in the Bhuj and Jhuran Formations in the dome. Similar to the previous cases, here also the scarp is broken and highly eroded. The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.5).

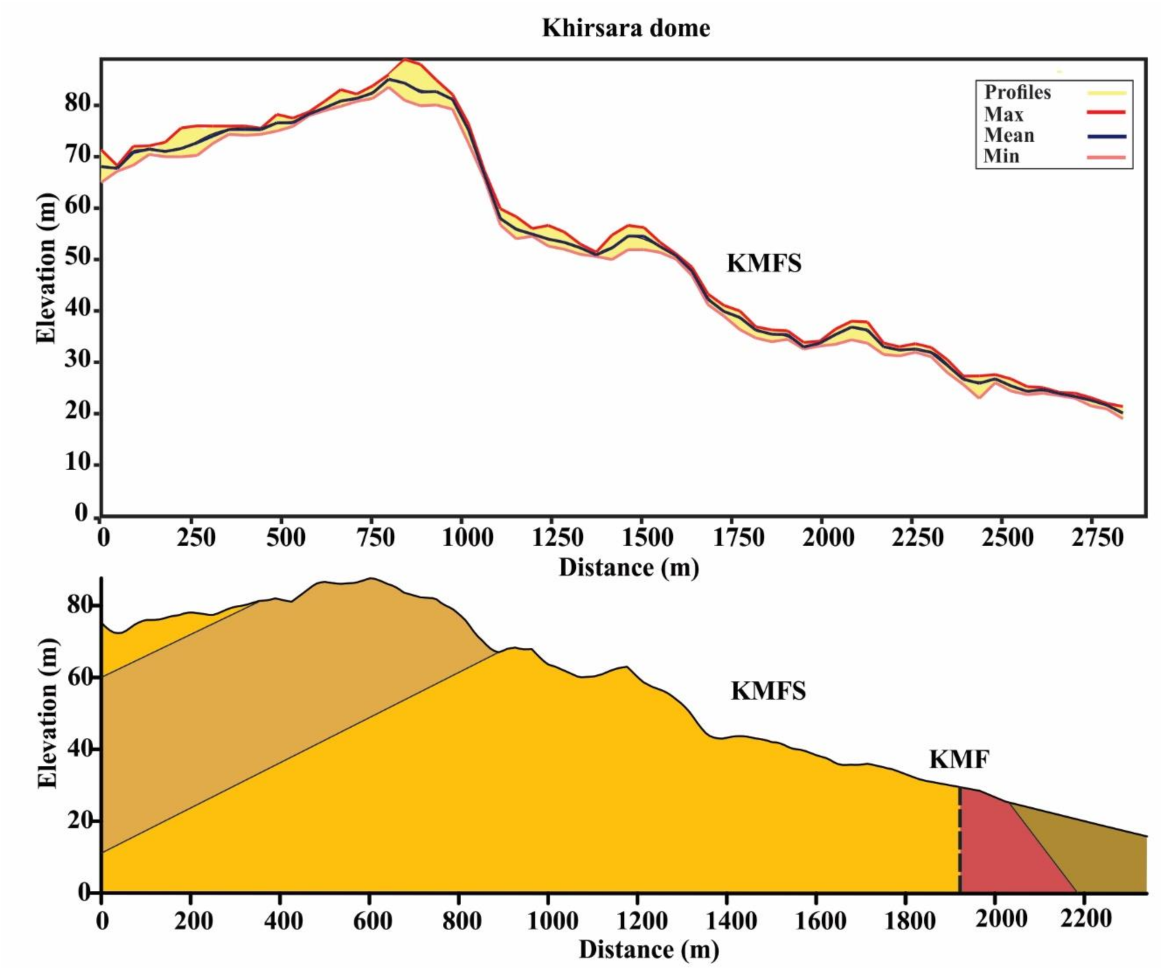

Figure 3.4 Swath profile and cross section profile of Khirsara dome. Colour scheme is as per geological map in Fig. 3.1.

However, the eastern tip of the dome exposes a well-developed outcrop of the fault scarp. Here, the scarp is coincident with the fault plane (Fig. 3.6). The scarp has a slope that is close to vertical (scarp slope angle-85^{0}), and it has preserved faulting features such as striations. This scarp outcrops in the western tip of the Jhuran anticline close to the Khirsara village, and therefore named as Khirsara scarp in the present study. In the other portions of the dome, the scarp does not consistently coincide with the active fault trace. The KMF is 0-740 m from the scarp face. This suggest that the scarp has retreated on an average of 740 m from the faultline. The maximum retreat of the scarp is seen at the center of the anticline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief is developed at the western side and at the center of dome. At several localities,

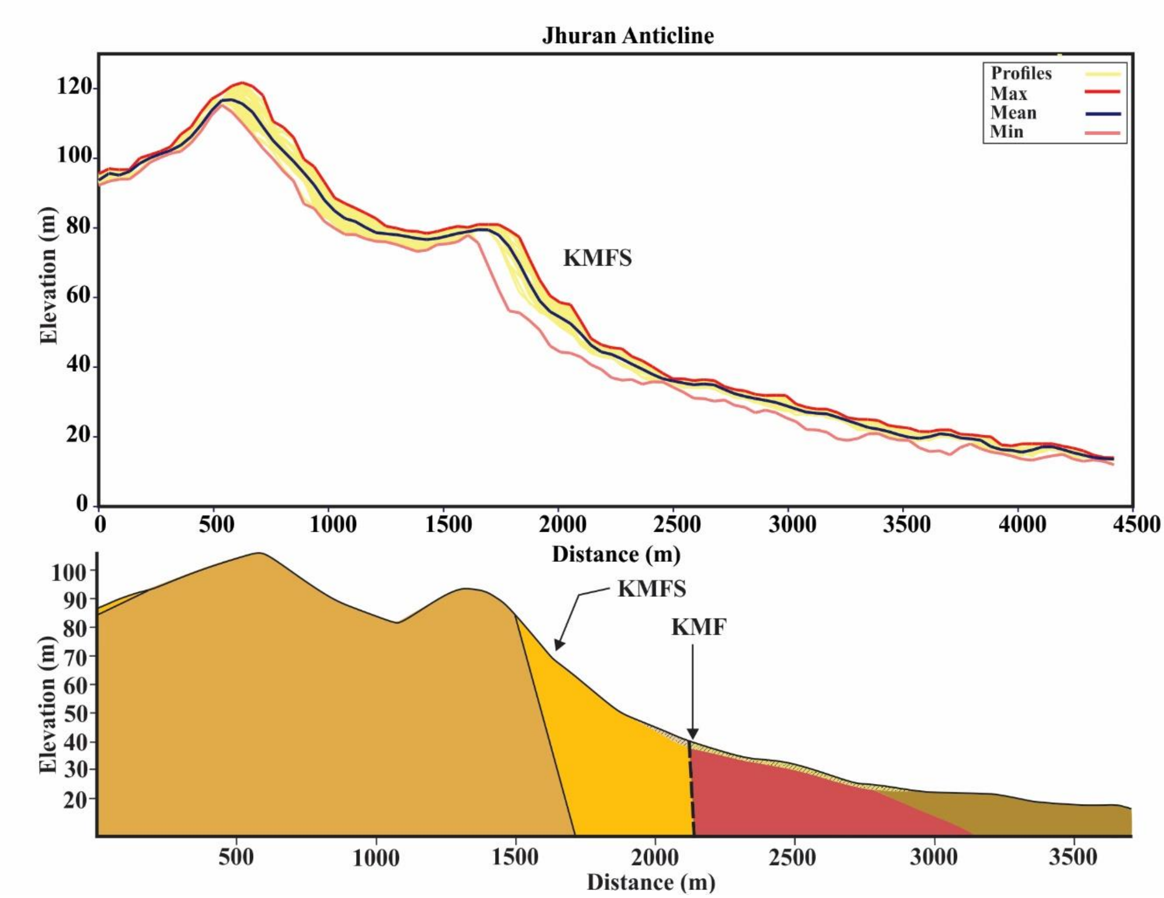

Figure 3.5 Swath profile and cross section profile of Jhuran anticline. Colour scheme is as per geological map in Fig. 3.1.

Figure 3.6 Photograph shows KMFS near the eastern side of the Jhuran anticline. Here the scarp preserves remanent of the original fault plane.

colluvium aprons base of the scarp. The colluvio- fluvial deposits are also seen along the incised cliffs of hillslope channels on the downstream side of the scarp. The presence of such colluvio-fluvial deposits indicates that the unconsolidated sediments produced from the scarp face is removed downslope by debris flow/run off and deposited at the channel valleys. The thickness of colluvium is higher in the center and western side of the dome. Furthermore, the overall colluvial thickness is significantly higher than the previous domes. Therefore, with exception of the eastern tip of the dome, it can be concluded that visible bedrock scarp throughout the domes have been significantly eroded.

Lotia Dam Dome

The Lotia Dam dome is located in the western part of the Jhuran anticline. The scarp exposed in the dome ranges in height from 50 to 69 m. The average scarp height along the Lotia Dam dome is 59m. The scarp is commonly formed on Jhuran and Jumara Formations. The scarp base is covered by aeolian miliolite at several locations (Fig. 3.7). The scarp is highly broken and highly eroded. The bedrock scarp does not consistently coincide with the active fault trace. The KMF is 100-550 m from the scarp face (Fig. 3.8). This suggests that the scarp has retreated on an average of 421 m from the faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief of is developed at the center of the dome. The relief of the scarp decreases to a minimum at the tip of the dome, where the scarp is dissected by streams originating from NHRFZ. At several localities, thick colluvial deposit covers at the base of the scarp. The colluvio-fluvial deposits are also seen along the incised valley faces of the hillslope channels on the downstream side of the scarp.

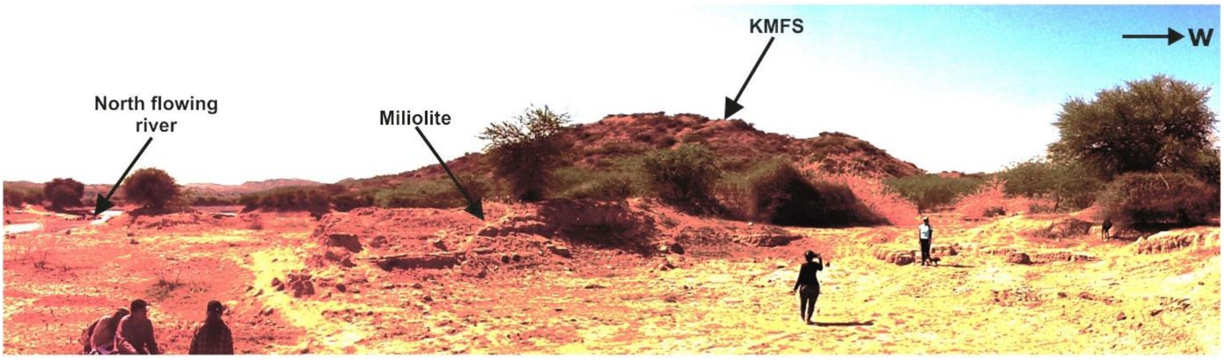

Figure 3.7 Photograph shows the KMFS exposure near the eastern side of the Lotia Dam dome. The scarp at the location is formed in the Jumara Formation. The base of the scarp is characterised by aeolian miliolite deposits.

The presence of such colluvio-fluvial deposits indicates that the unconsolidated sediments produced from the scarp face is removed downslope by debris flow/run off and deposited

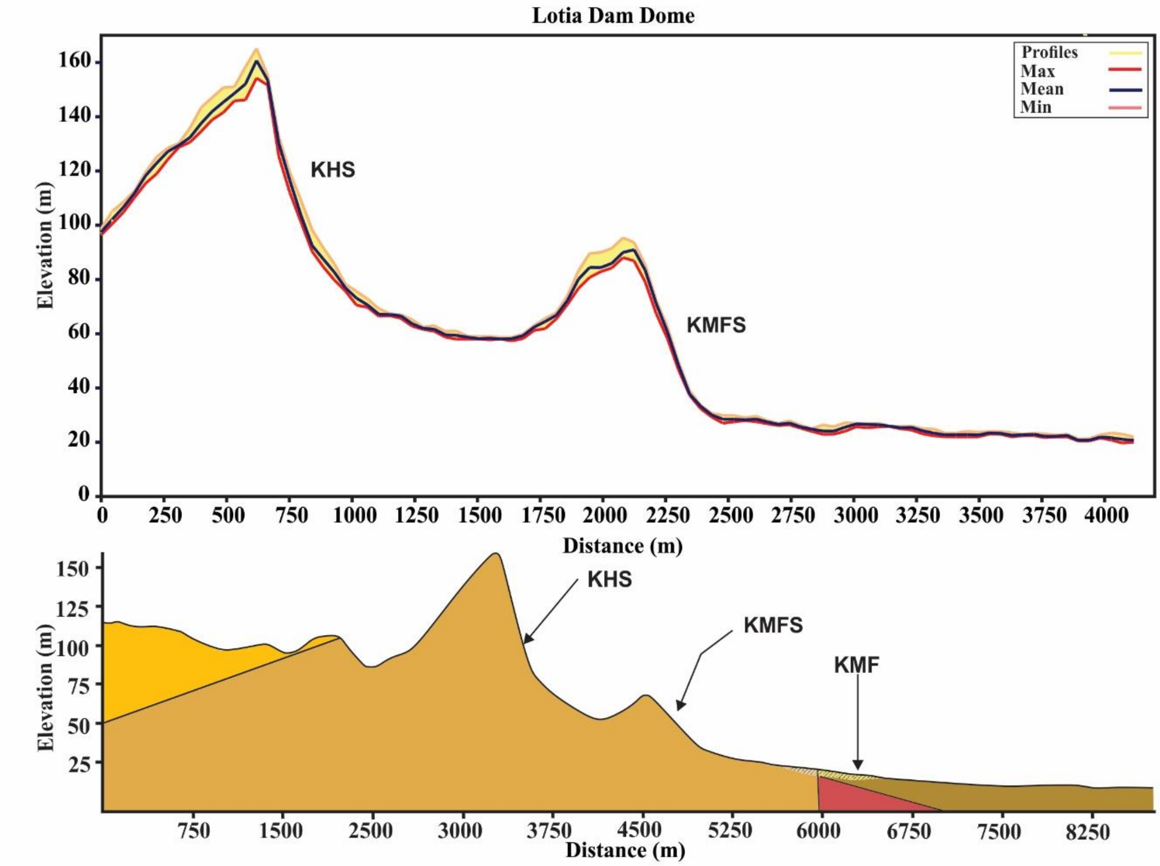

Figure 3.8 Swath profile and cross section profile of Lotia Dam dome. Colour scheme is as per geological map in Fig. 3.1.

within the channels. Thickness of the colluvio-fluvial deposits are comparatively higher than the previously mentioned Jhuran anticline.

Kas Hill Dome

The Kas Hill dome is located west of the Lotia Dam dome. The expose scarp of the Kas Hill dome varies in height between 41 to 66 m, with an average height of 53 m. The scarp is commonly formed on Jhuran and Jumara Formations, which is highly broken and eroded. As in the previous cases, here also, the bedrock scarp does not consistently coincide with the active fault trace (Fig 3.9). The KMF is located 132-1160 m from the scarp face. This suggests that the scarp has retreated on an average of 626 m from the faultline. The scarp is eroded and retreated more when compared to the previous dome, the Lotia Dam dome. The center and western tip of the scarp is highly eroded and retreated from the faultline when compared to the eastern tip of the dome. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ.

Maximum relief is developed at the center and western tip of the dome. The relief of scarp decreases to a minimum at the eastern tip of the dome. At several localities, veneer of colluvium aprons base of the scarp. The colluvio-fluvial deposits are also seen along the incised valleys of hillslope channels on the downstream side of the scarp. The presence of such colluvio-fluvial deposits indicates that the unconsolidated sediments produced from the scarp face is removed downslope by debris flow/run off and deposited at the channel valleys. The Kas Hill Scarp in the background becomes the prominent scarp on in the dome. Considering the morphological characteristics of the KMFS it can be concluded that the present visible bedrock scarp has developed from a combination of erosional exhumation of the fault plane and episodic tectonic uplifts of the region.

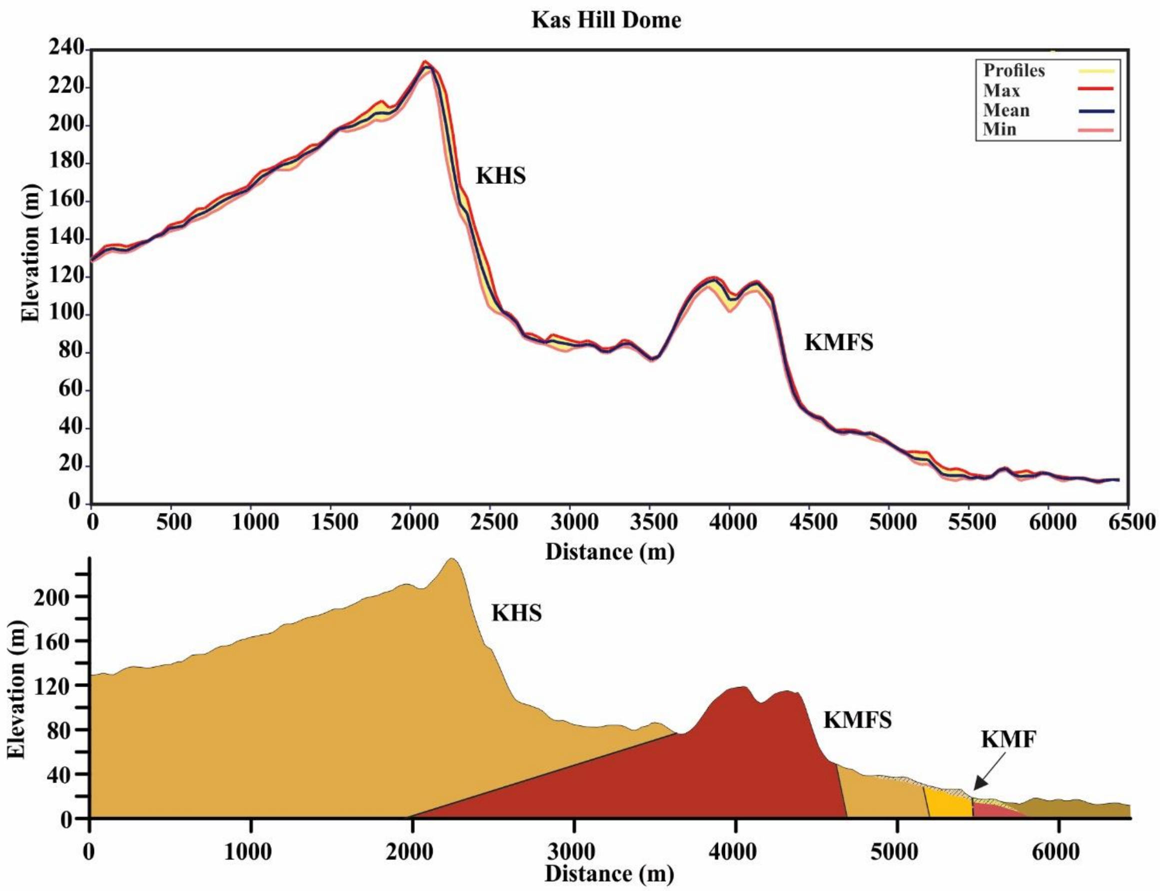

Figure 3.9 Swath profile and cross section profile of Kas Hill dome. Colour scheme is as per geological map in Fig. 3.1.

Habo Dome

The expose scarp range in height from 28 to 151 m, with average height of 89m (Fig. 3.10). The scarp is formed on Jhuran Formation and Jumara Formation. The scarp is highly broken and eroded. The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.10). The KMF is located 820-1423 m from the scarp face. The scarp has retreated on an average of 1120 m from the faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief of 151 m is developed at the center of Habo dome (Fig 3.11 a). The relief of scarp decreases to a minimum from the centre of the dome, where the scarp is dissected by streams originating from NHRFZ. Apart from these characteristics the Habo dome has well developed faceted spur or triangular facet (Fig. 3.11 b).

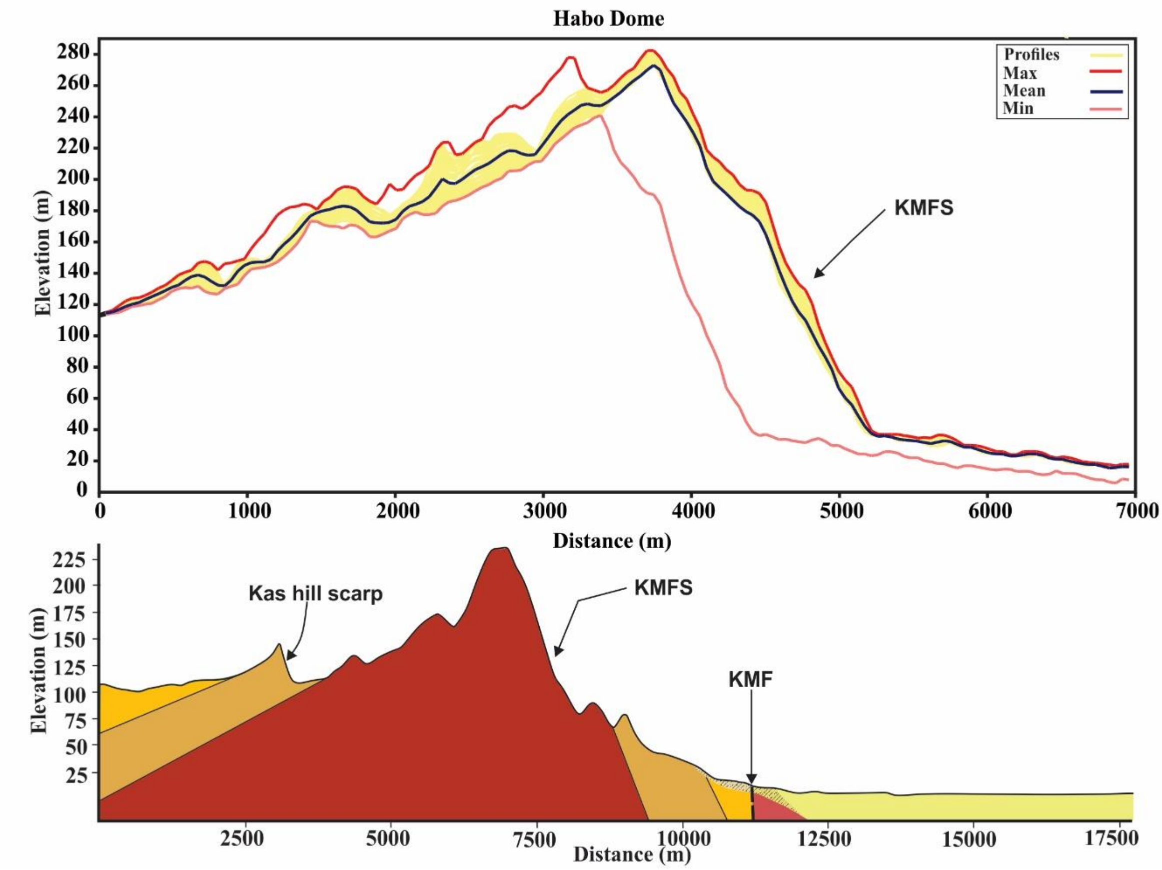

Figure 3.10 Swath profile and cross section profile of Habo dome. Colour scheme is as per geological map in Fig. 3.1.

Faceted spur is geomorphic feature observed in areas effected by active extensions, for example, the Basin and Range, Baikal rift and Aegean region (Wallace, 1978; San' kov et al., 2000; Meyer et al., 2002). Presence of well-developed triangular facet indicates long-term influence of tectonics and fluvial incision of the landscape. The triangular facets are more prominent in the center and disappears at the tip of the dome (Fig 3.11 b). The facet morphologies are more triangular in shape suggesting strong fluvial incision in correspondence with tectonic uplift. At several localities, thick colluvium covers at the base of the scarp. The colluvio-fluvial deposits are also seen along the incised cliffs of hillslope channels on the downstream side of the scarp. The thickness of the colluvium is several times higher than the previous domes. The presence of such colluvio-fluvial deposits indicates that the unconsolidated sediments produced from the scarp face is removed downslope by debris flow/run off and deposited at the channel valleys.

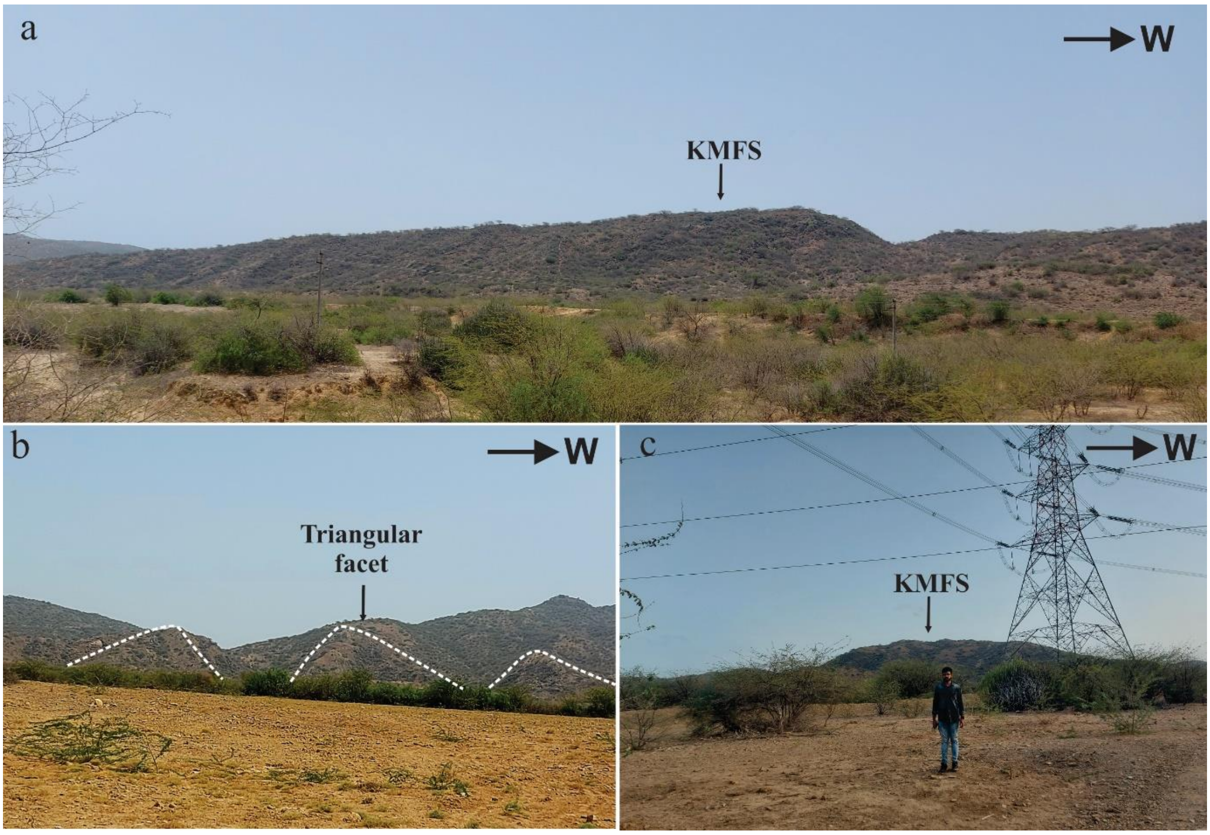

Figure 3.11 (a) Photograph shows the KMFS exposed in the Habo dome. Here the scarp is generally exposed in the Jumara and Jhuran Formations. (b) A view of triangular facet exposed at the center of the Habo dome. (c) Southward view of the KMFS exposed at the Jhurio dome.

Jhurio Dome

The Jhurio dome is located further west of the Habo dome. The domes are separated by a wide interdomal saddle. The available literature suggests that highest stratigraphic offset along the KMF is at the vicinity of the Jhurio dome (Biswas, 1993). The expose scarp height in the dome ranges between 25 to 94 m, with an average height of 50m. The scarp is commonly formed on Jhuran Formation and Jumara Formation. The scarp is highly broken and highly eroded. Further, the bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.12). The KMF is 232-967 m from the scarp face. This suggest that the scarp has retreated on an average of 647 m with respect to the original faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief is developed at the center of the dome (Fig. 3.11 c). Presence of feebly developed triangular facet indicates long-term influence of tectonics and fluvial incision in the landscape. Similar to the Habo dome, the facets are more prominent at the center and disappears to the tips. The facet morphologies are rounded to triangular shape in the Jhurio dome suggesting strongly incised scarp.

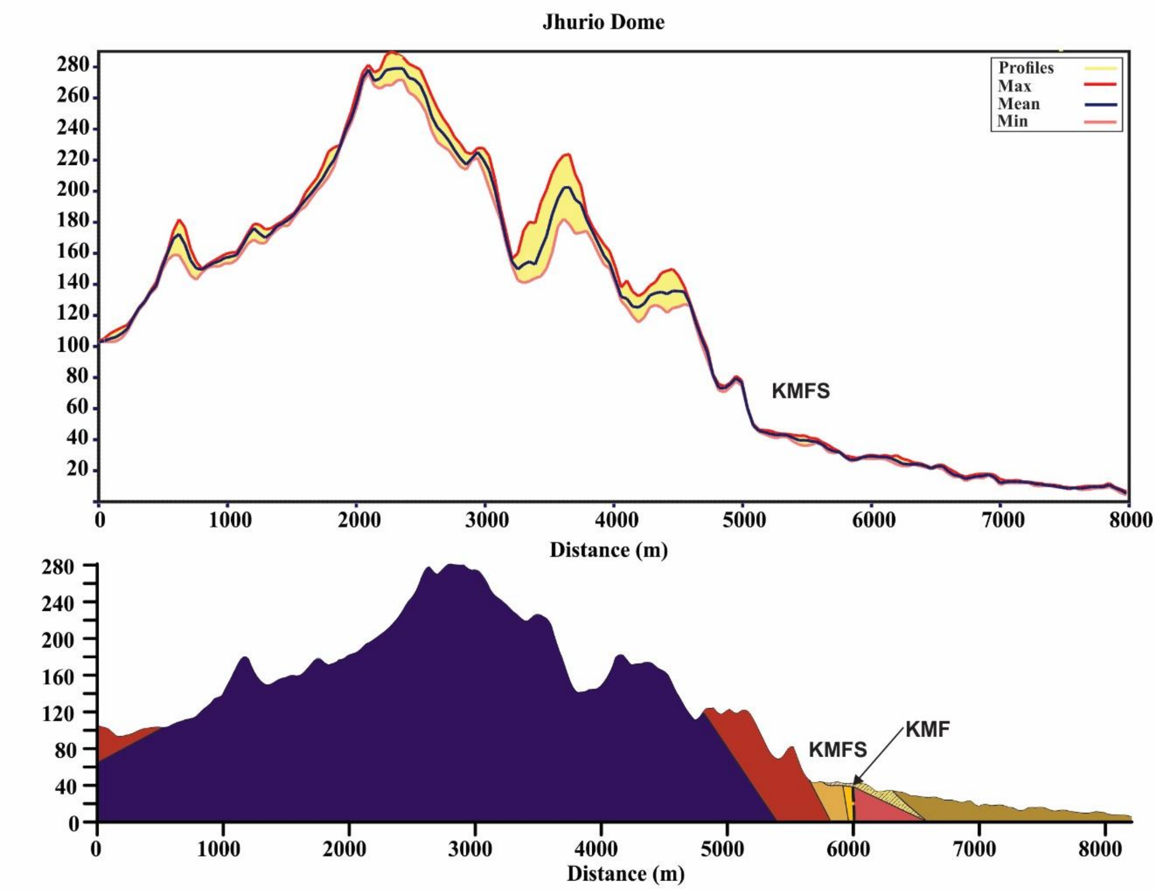

Figure 3.12 Swath profile and cross section profile of Jhurio dome. Colour scheme is as per geological map in Fig. 3.1.

The relief of scarp decreases to a minimum at the tip of the dome, where the scarp is dissected by streams originating from NHRFZ. At several localities, thick colluvium aprons at the base of the scarp. The colluvio-fluvial deposits are also seen along the incised cliffs of hillslope channels on the downstream side of the scarp. The thickness of the colluvio-fluvial deposits is comparable with that of the Habo dome. The presence of such colluvio-fluvial deposits indicates that the unconsolidated sediments produced from the scarp face is removed downslope by debris flow/run off and deposited at the channel valleys.

Western KMF

A good exposure of the scarp is seen in the stretch between the Nara dome to the Lakhpat anticline in the western KMF (Fig. 3.13). The scarps are highly discontinuous compared to the eastern counterpart. The domes and the anticlines in the western portion of the KMF are in structurally lower levels than the domes and anticlines in the eastern

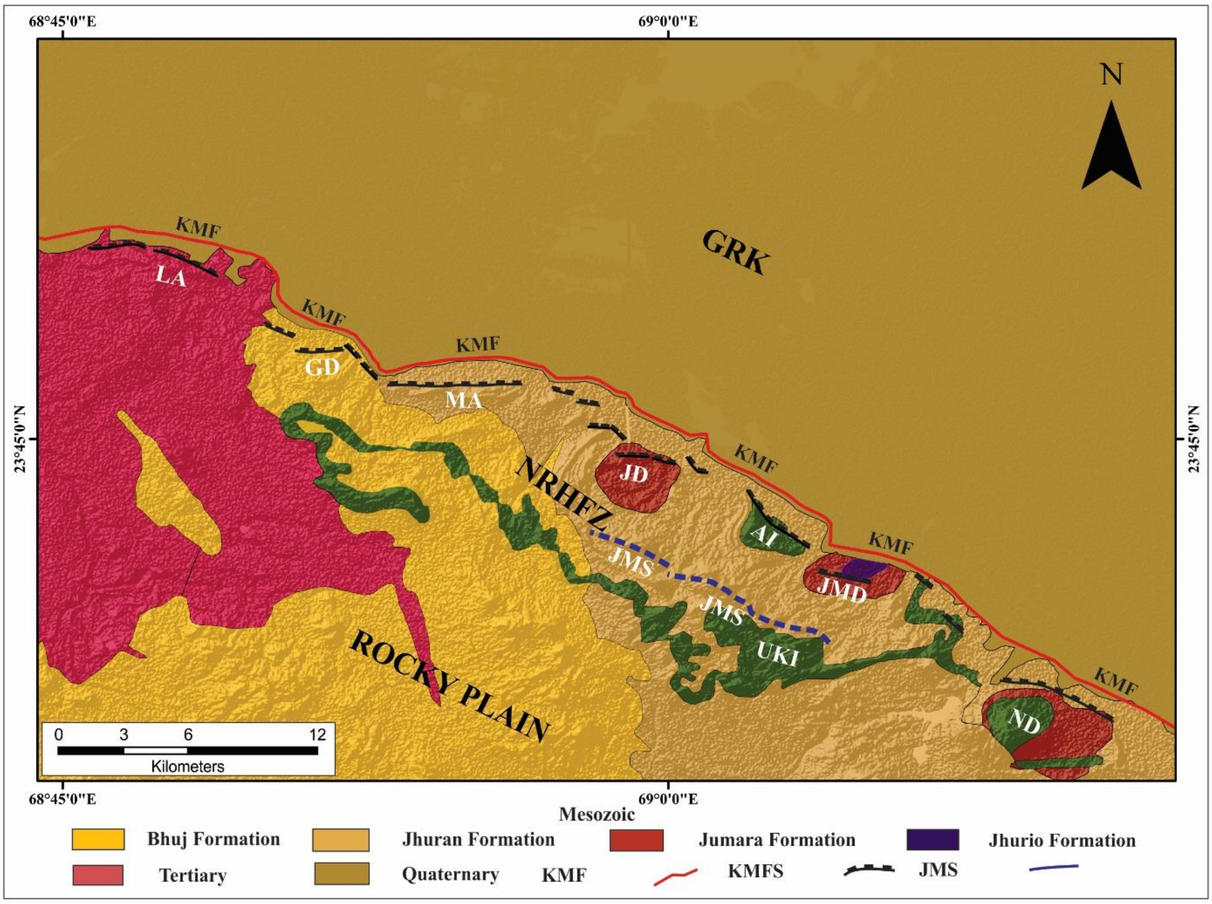

Figure 3.13 Geological map of the study area draped over the Digital Elevation Model (source: https://earthexplorer.usgs.gov and Biswas & Khattri, 2002). Major lithologies and physiography of segments in the eastern KMF are highlighted in the map. Note that the KMFS becomes highly discontinuous along the western KMF. JMS forms a continuous and prominent feature striking parallel to the KMFS and KMF. Here, ND: Nara dome; JMD: Jumara dome; AI: Amedi intrusive; UKI: Ukra intrusive; JD: Jara dome; MA: Mundhan anticline; GD: Ghuneri dome; LA: Lakpat anticline; JMS: Jaramara Scarp; GRK: Great Rann of Kachchh.

part (Biswas, 1993). The structurally lower level of the anticlines and domes along the KMF points to intense erosion during its evolutionary phases. The intense erosion in the region has a major influence in the scarp morphology and nature as well. The characteristics of the scarps along the major domes of the western KMF are described below.

Nara Dome

KMFS is less exposed between the domes of Nara and Jhurio. However, a notable exposure of the KMFS is seen at the Nara dome. Here, the expose scarp ranges in height between 10 to 66m. The scarp is commonly formed on sandstone of Jhuran Formation. The scarp on the Jhuran Formation is highly broken and highly eroded. The bedrock scarp does not consistently coincide with the active fault trace. The KMF is 400-500 m from the scarp face. This suggests that the scarp has retreated on an average of 415 m from the faultline. The scarp relief is not constant along the length of the scarp (Fig. 3.14). The area of exposure

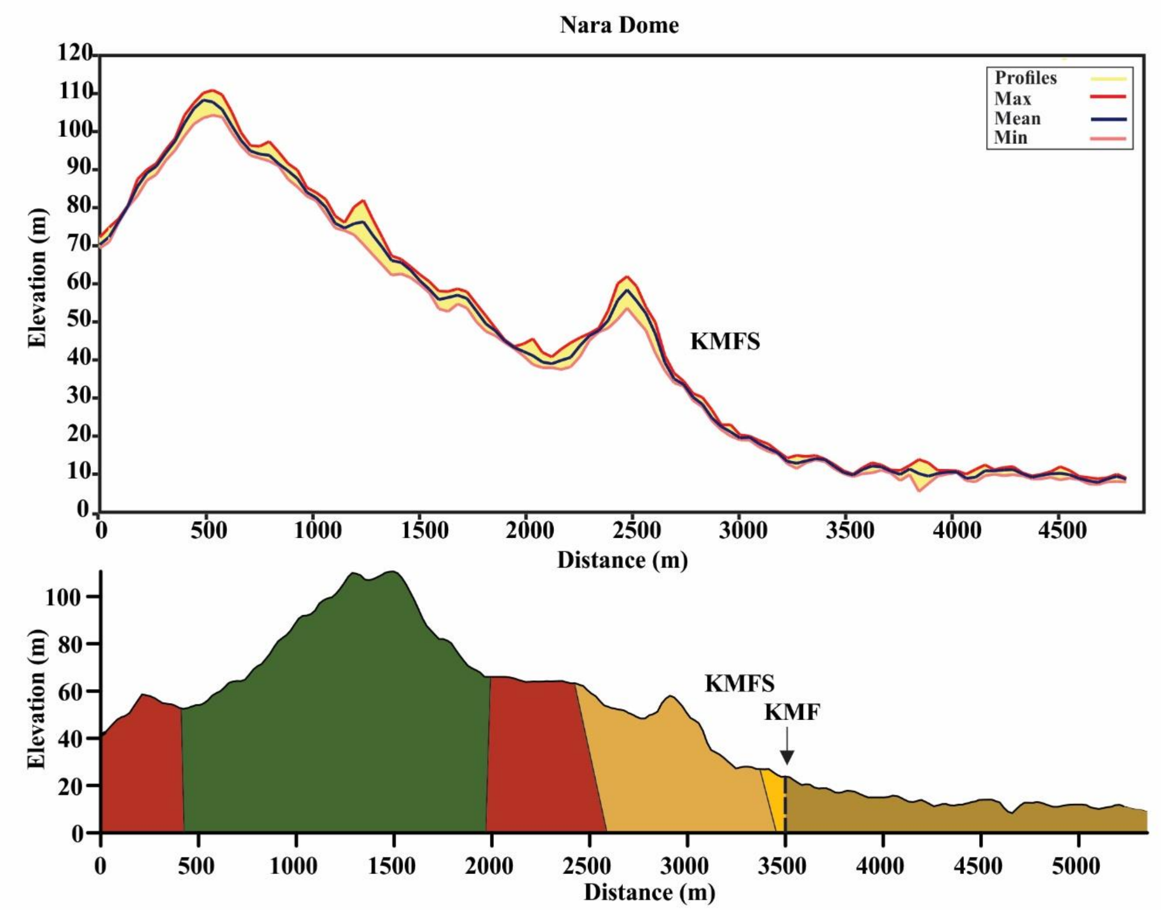

Figure 3.14 Swath profile and cross section profile of Nara dome. Colour scheme is as per geological map in Fig 3.13.

decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief is noticed at the center of Nara dome. The relief of scarp decreases to a minimum at the eastern and western tip of the dome, where the scarp is dissected by streams originating from NHRFZ. At several localities, veneer of colluvium aprons base of the scarp. However, the thickness of colluvio-fluvial deposit are very less compared with the domes in eastern KMF. The thick Holocene sediments of the Rann surface extends upto the base of the scarp.

Jumara Dome

The Jumara dome is characterised by 'D' shaped nature (Biswas, 1993). The center of the dome exposes Jhurio Formation; the oldest Mesozoic Formation (Fig. 3.15). The stratigraphic offset along the dome is comparable to the Jhurio dome in the eastern KMF (Biswas, 1993). The scarp exposes in the dome varies in height between 13 m to 30 m. The

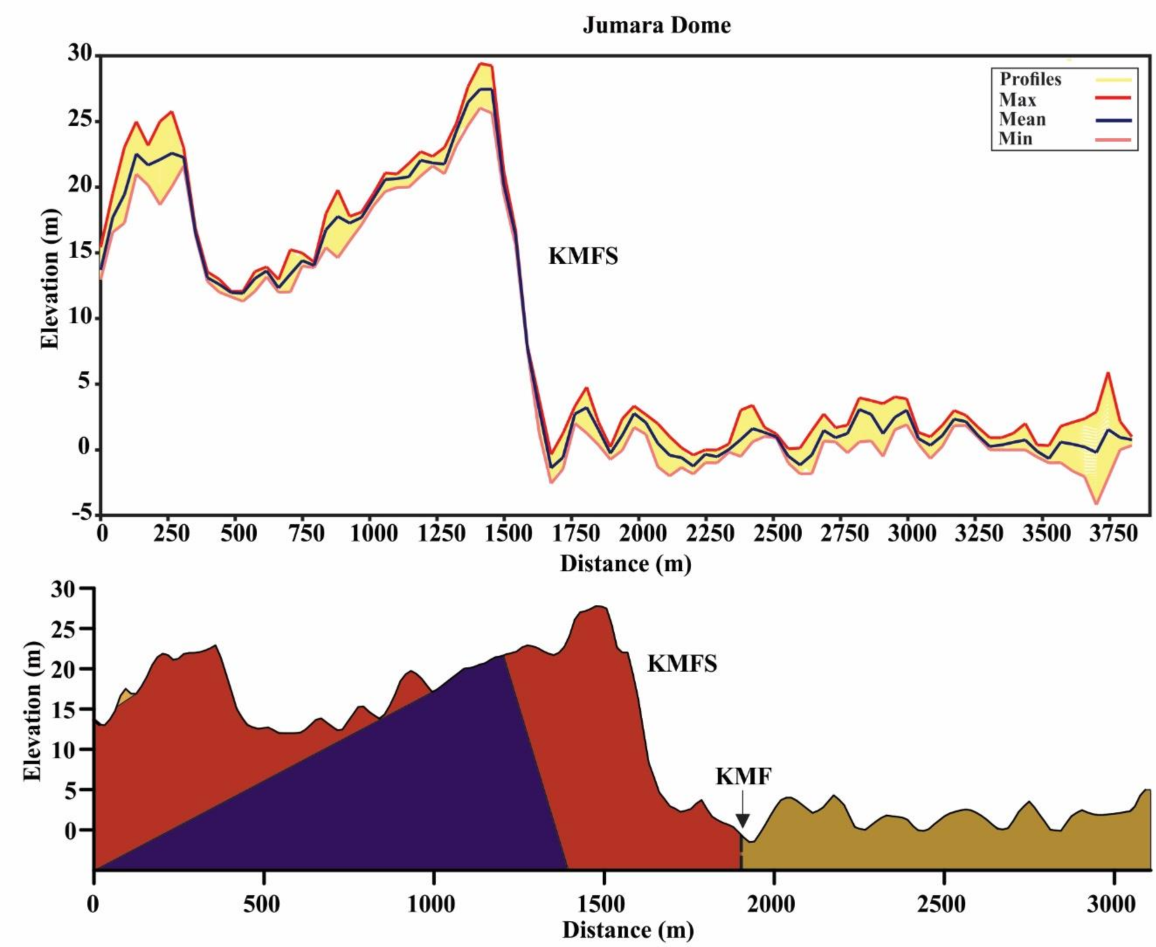

Figure 3.15 Swath profile and cross section profile of Jumara dome. Colour scheme is as per geological map in Fig. 3.13.

scarp is commonly formed on Jumara Formation. The scarp on the Jumara Formation is highly broken and highly eroded (Fig 3.16 a & b). The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.15). The KMF is located 351-426 m from the scarp face. This suggests that the scarp has retreated on an average of 388 m from the faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ.

Maximum relief is developed at the center of the Jumara dome. At several localities, veneer of colluvium aprons base of the scarp. The colluvio-fluvial deposits is negligible along the incised cliffs of hillslope channels on the downstream side of the scarp. The base of the scarp is overlained by thick Rann sediments. Between the Nara and Jumara dome KMFS is seen developed in the Ukra instrusive. One of the well-developed exposures of KMFS in Ukra intrusive could be seen at the Amedi village. The village is located between the Jumara and the Jara dome. The scarp in the Amedi village is characterised by several small north flowing channels. The channels have done intense erosion characterised by incised channel in the scarp face.

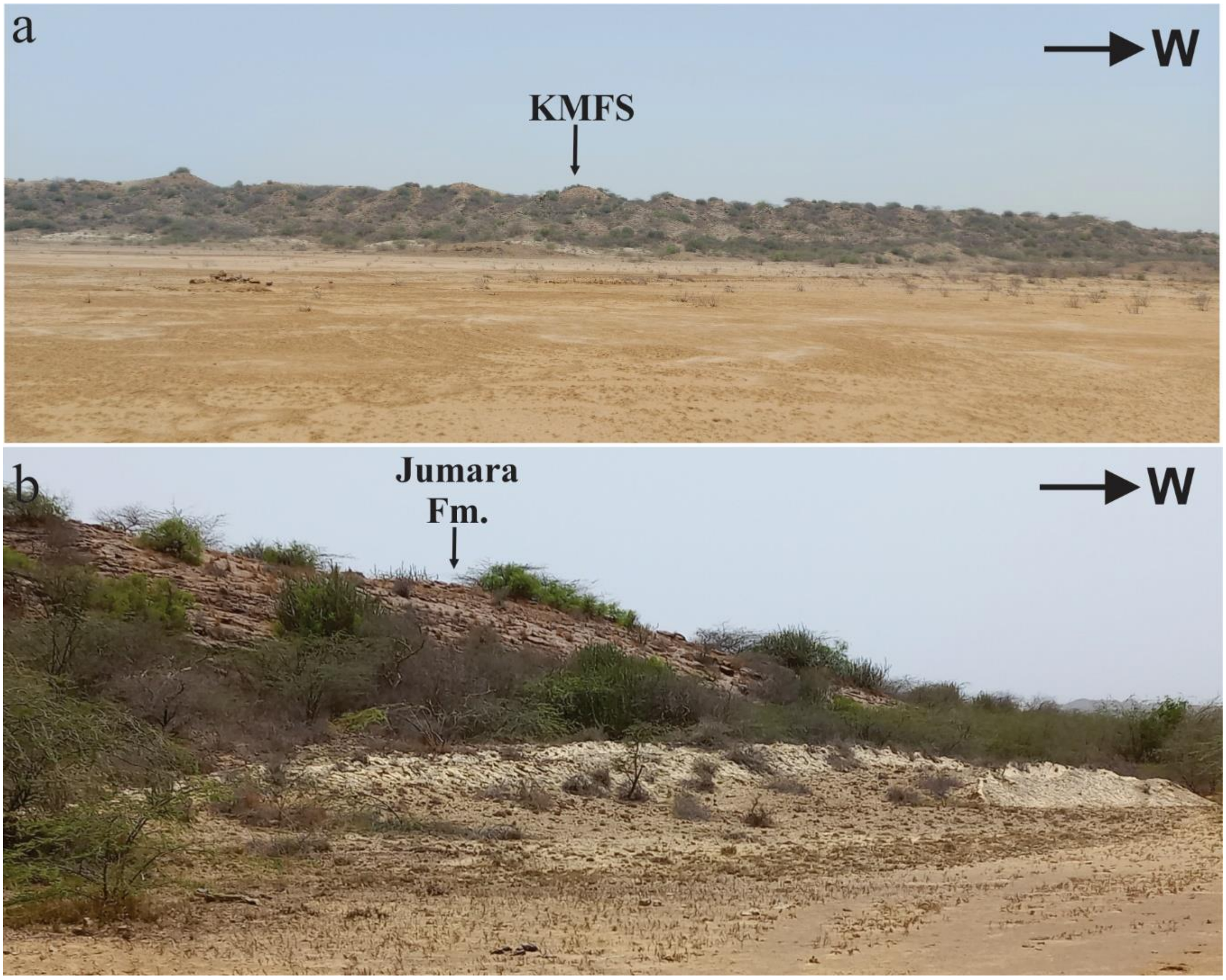

Figure 3.16 (a) Field photograph showing the KMFS near the Jumara dome. (b) A close view of the KMFS at the center of the Jumara dome. Here the scarp is formed in the Jumara Formation.

Jara Dome

The Jara dome is located further west of the Jumara dome. The scarp exposed at the dome ranges in height between 12 m to 26 m. The scarp is commonly formed on Jhuran and Jumara Formations. The scarp is highly broken and highly eroded. The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.17). The KMF is 383-523 m from the scarp face. The scarp has retreated on an average of 436 m from the faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief is developed at the east and west tip of Jara dome. The relief of scarp decreases to a minimum at the centre of the dome, where the scarp is dissected by streams originating from NHRFZ.

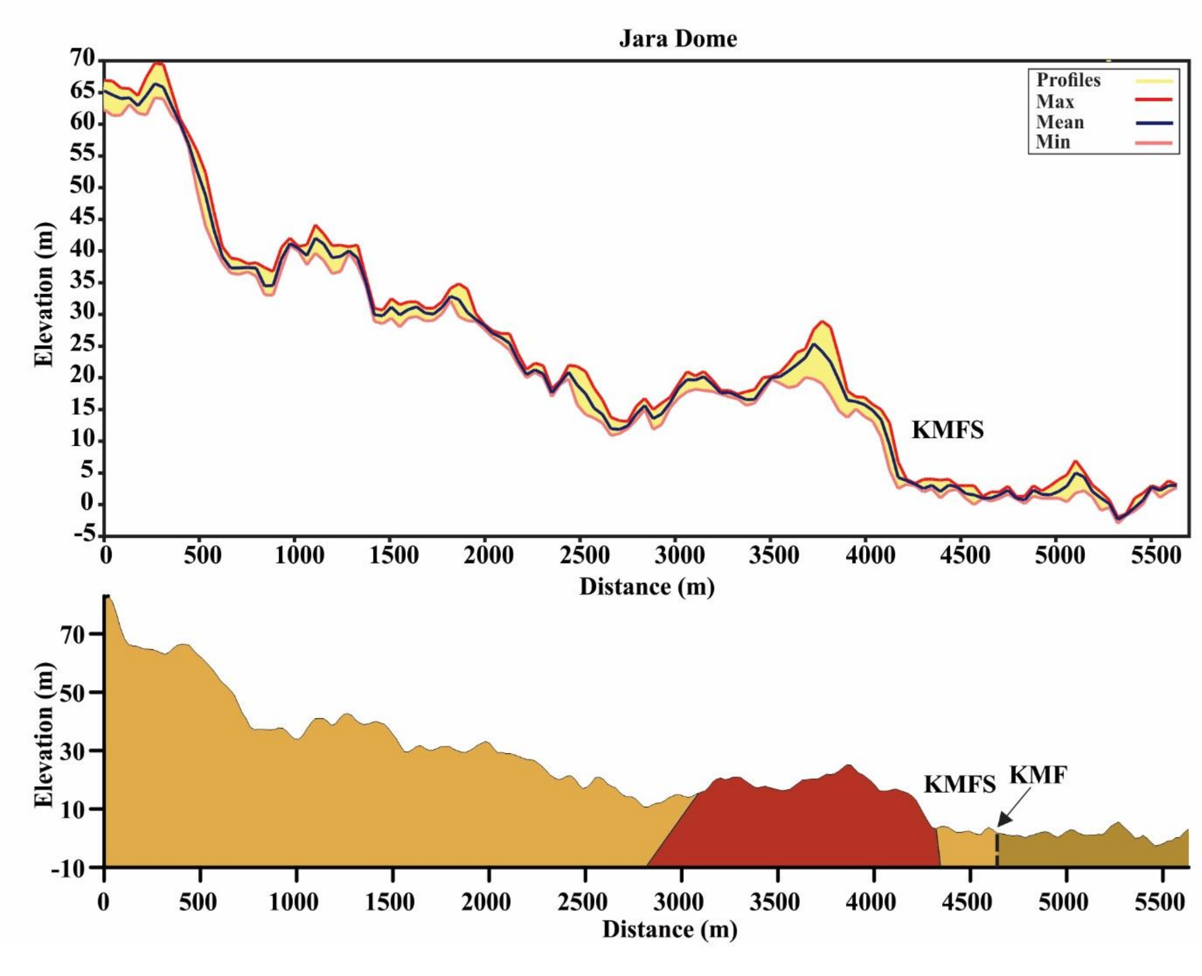

Figure 3.17 Swath profile and cross section profile of Jara dome. Colour scheme is as per geological map in Fig. 3.13.

At several localities, a veneer of colluvium aprons base of the scarp. The exposure of the KMFS is also seen in the interdomal saddle between the Jara dome and Mundhan anticline.

Mundhan Anticline

The expose scarp range in height from 7 to 37 m, with average height of 20m. The scarp is commonly formed on Bhuj Formation and Jhuran Formation. The scarp is highly broken and eroded. The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.18). The KMF is located 80-257m from the scarp face. Maximum relief that the scarp has retreated on an average of 168 m from the faultline. The scarp developed at the center of the anticline are retreated more in comparison with the tip of the anticline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases is developed at center of the anticline. At several localities, veneer of colluvium aprons base of the scarp. The colluvio-fluvial deposits are negligible along the incised cliffs of hillslope channels on the downstream side of the scarp.

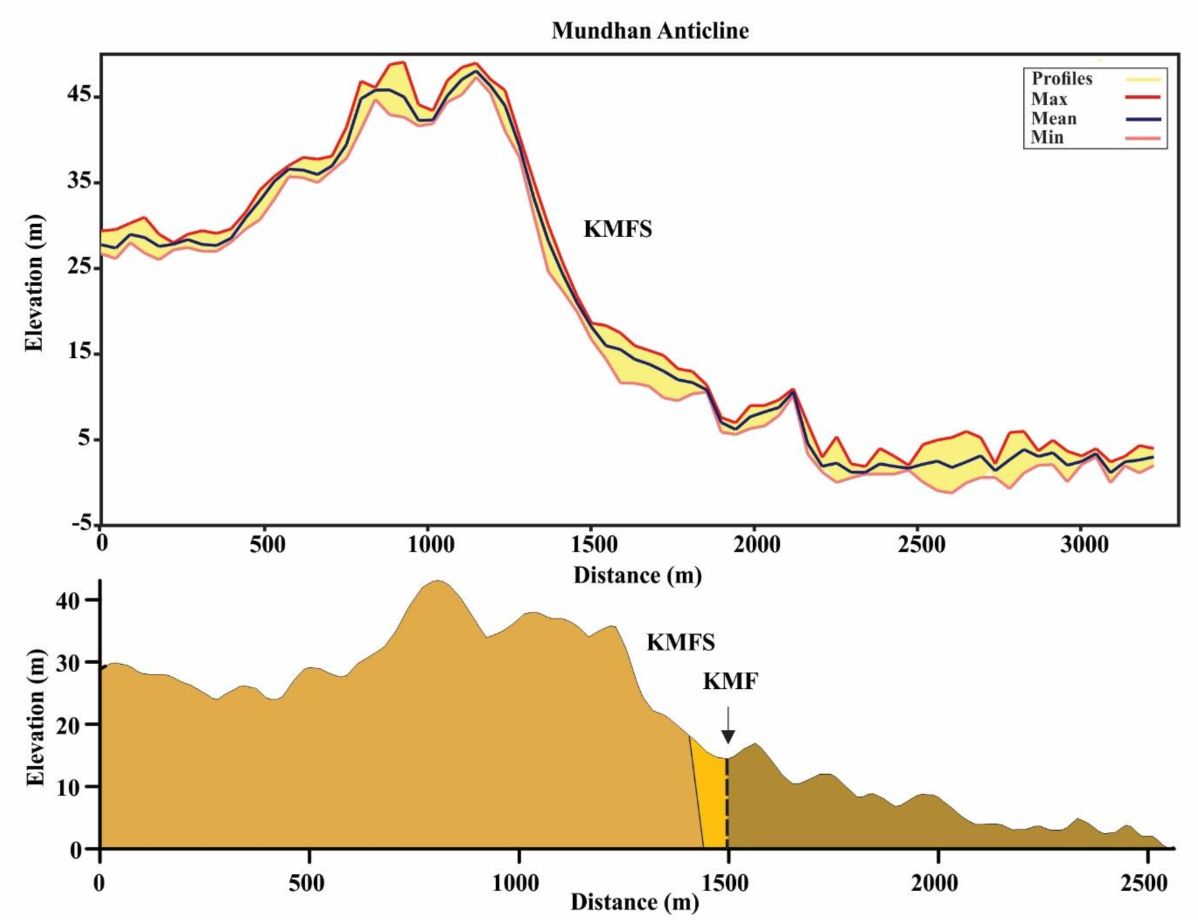

Figure 3.18 Swath profile and cross section profile of Mundhan anticline. Colour scheme is as per geological map in Fig. 3.13.

Ghuneri Dome

The expose scarp ranges in height from 10 to 16 m. The scarp is commonly formed on the sandstone of Bhuj Formation. The scarp on the Bhuj Formation is highly broken and highly eroded. The bedrock scarp does not consistently coincide with the active fault trace along the dome (Fig. 3.19). The KMF is located 40 m -161 m from the scarp face and on an average the scarp has retreated 100 m from the faultline. The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Maximum relief is developed at the eastern and western sides of the dome. The relief of scarp decreases to a minimum at the centre of the dome. At several localities, veneer of colluvial sediments apron the base of the scarp. The colluvio-fluvial deposits are also seen along the incised cliffs of hillslope channels on the downstream side of the scarp.

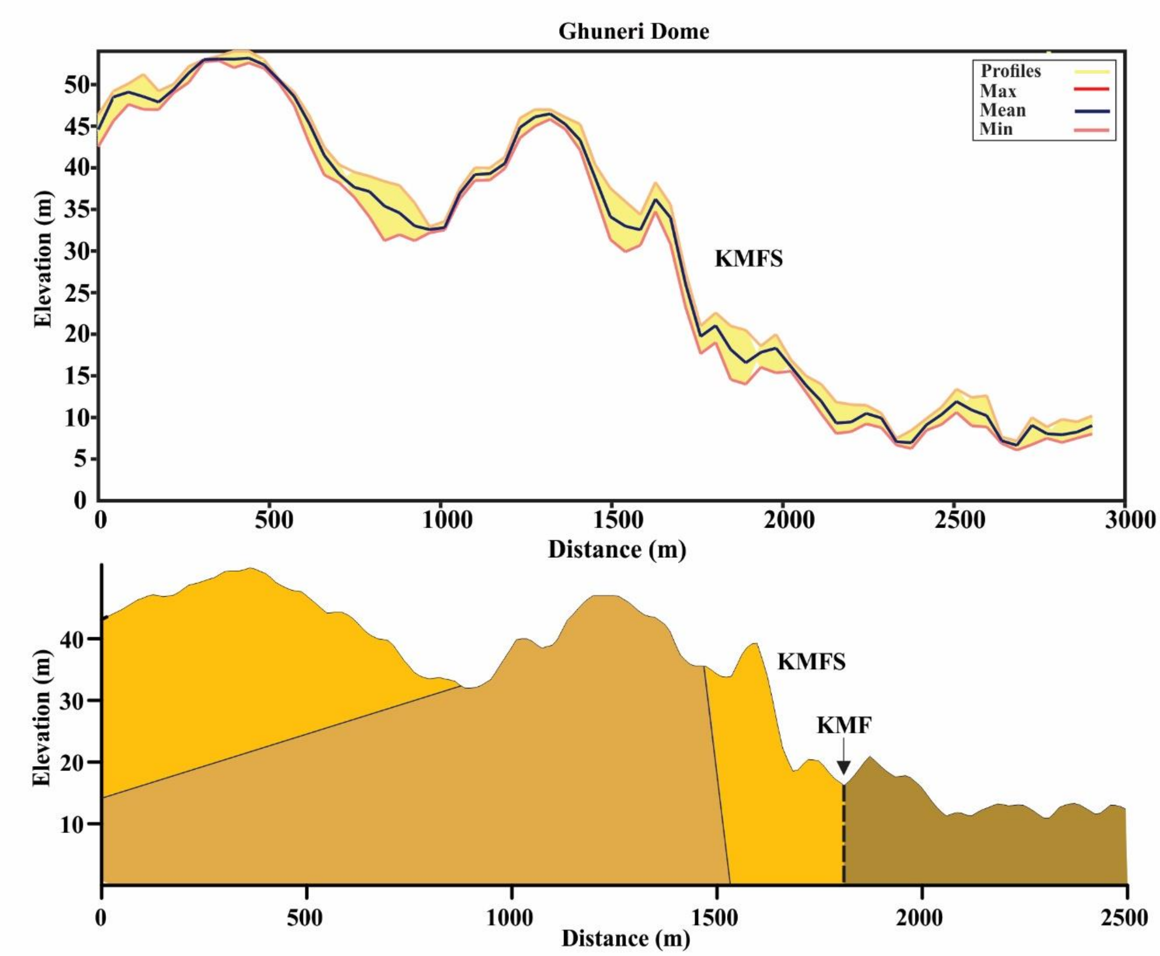

Figure 3.19 Swath profile and cross-section profile of Ghuneri dome. Colour scheme is as per geological map in Fig. 3.13.

However, the thickness of the colluvio-fluvial deposits are negligible when compared to the deposit in the eastern KMF.

Lakhpat Anticline

The Lakhpat anticline marks the western most extend of the NHRFZ. The exposed scarp in the anticline ranges in height between 5 to 15 m. The scarp is commonly formed on carbonaceous sandstone of Bhuj Formation (Fig. 3.20).

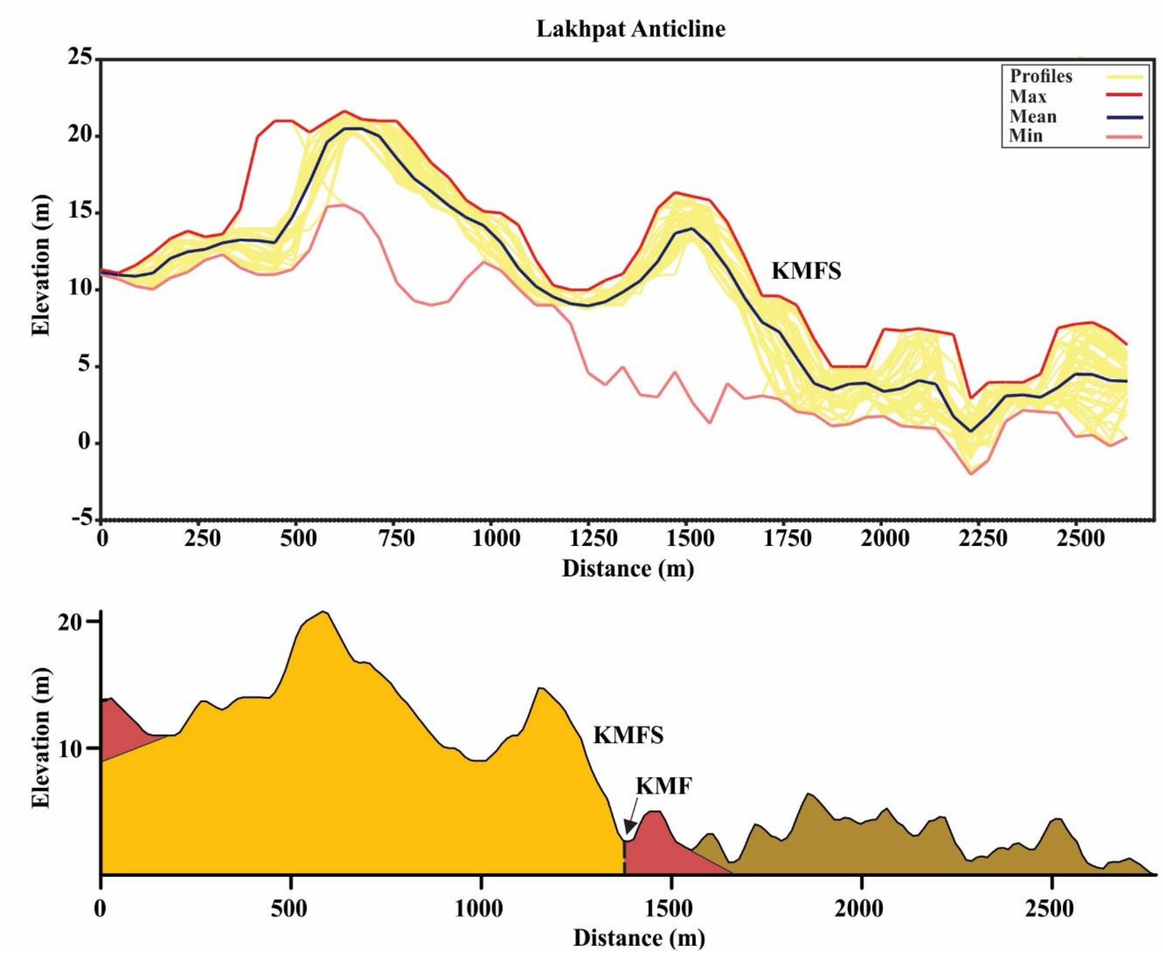

Figure 3.20 Swath profile and cross-section profile of Lakhpat dome. Colour scheme is as per geological map in Fig. 3.13.

The bedrock scarp does not consistently coincide with the active fault trace. The KMF is 60-120 m from the scarp face. On an average the scarp has retreated 60 m from the faultline. The scarp relief is not constant along the length, similar to the scarp formed in other domes. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. Beyond Lakhpat dome a well-developed exposure of the KMFS is absent.

TWIN PARALLEL SCARPS

The unique and notable feature along the KMF is the development of twin parallel scarps. The twin parallel scarps emerge as a prominent feature in the vicinity of the Jara-Jumara dome and Kas Hill anticline located at the western and eastern portion of the KMF respectively. The scarps, Jaramara Scarp (JMS) and Kas Hill Scarp (KHS) strike parallel to the KMFS in the Jara-Jumara sector and the Kas Hill sector. In the sector JMS and KHS become the prominent scarp with height higher than the KMFS. The youthful nature and appearance of the scarps gives an impression of an active fault scarp. However, a major fault other than the KMF is absent in the vicinity of JMS and the KHS. The evolution and preservation of the scarp along the KMF is not known. Furthermore, the scarps act as a secondary drainage divide for the north-flowing rivers in the region. Numerous 3rd and 4th order streams originate from the scarp face. The morphology and extend of the scarps in the respective sectors are described below.

Jaramara Scarp

The scarp ranges in height between 70 to 154 m. The KMF is located 3500-4000 m north from the scarp face. The scarp relief is not constant along the length of the scarp (Fig. 3.21 a). The area of exposure decreases markedly where the scarp is dissected by rivers originating from the Ukra intrusive. The maximum relief of 154 m is developed at the central portion of the scarp. The relief of the scarp decreases to a minimum at the eastern and western ends, where the scarp is dissected by streams originating from NHRFZ. Multiple independent profiles constructed across the strike of the scarp illustrates an average shape for the scarp (Fig. 3.21 b). The profiles suggest that the scarp face at all location have a concave up to vertical shape.

The nature of the profiles is indication of the erosional degradation of the scarp. The origin and evolution of this specific scarp in the current tectonic framework of eastern Kachchh basin appears peculiar in nature. The scarp generally trends E-W and strike parallel to KMFS in the eastern half (Fig. 3.21a, 3.22 a, b, d). Towards the catchment of Jara river the strike changes to NNE-SSW. Further west of the Jara River the scarp persists in the Jara dome for some distance and eventually fades away. In the eastern side the scarp runs parallel to the KMFS and finally dies out or merges with the Ukra intrusive. The scarp is more prominent and well developed at the interdomal saddle between the Jara and Jumara domes. The scarp is formed in the back limb of flexure and exposes mainly rigid sandstone member

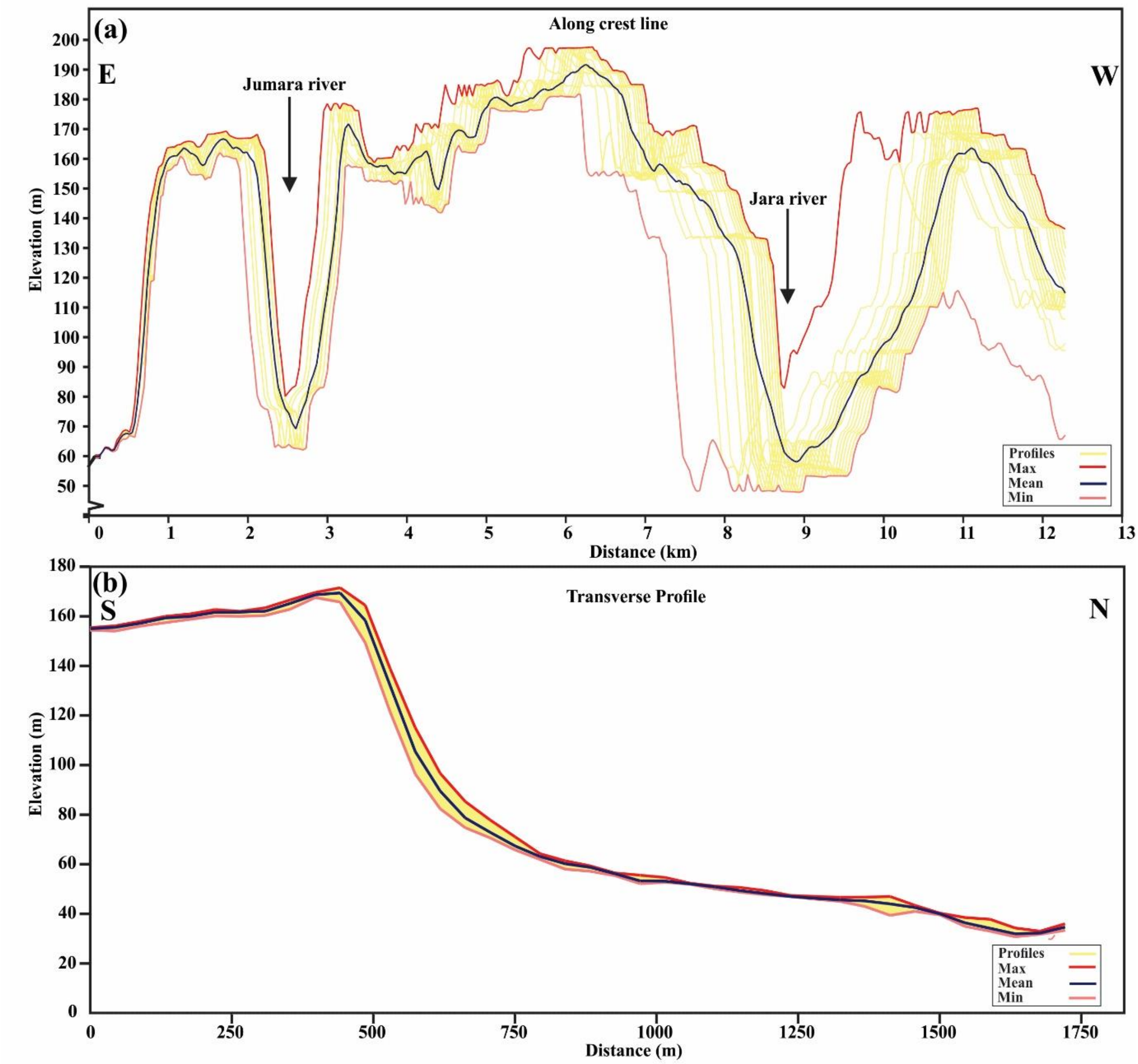

Figure 3.21 Swath profile along and across the Jaramara Scarp**.**

of the upper Jhuran Formation (Fig 3.22 c). The variability in scarp height along the strike indicates that scarp development occurred in multiple cycles of uplift and erosion. At several locations, colluvial aprons are noticed at the base of the scarp. The collapse materials at the base of the scarp range in range from big boulders to gravels. A thickness of colluvial deposits is several times lower than the eastern KMF.

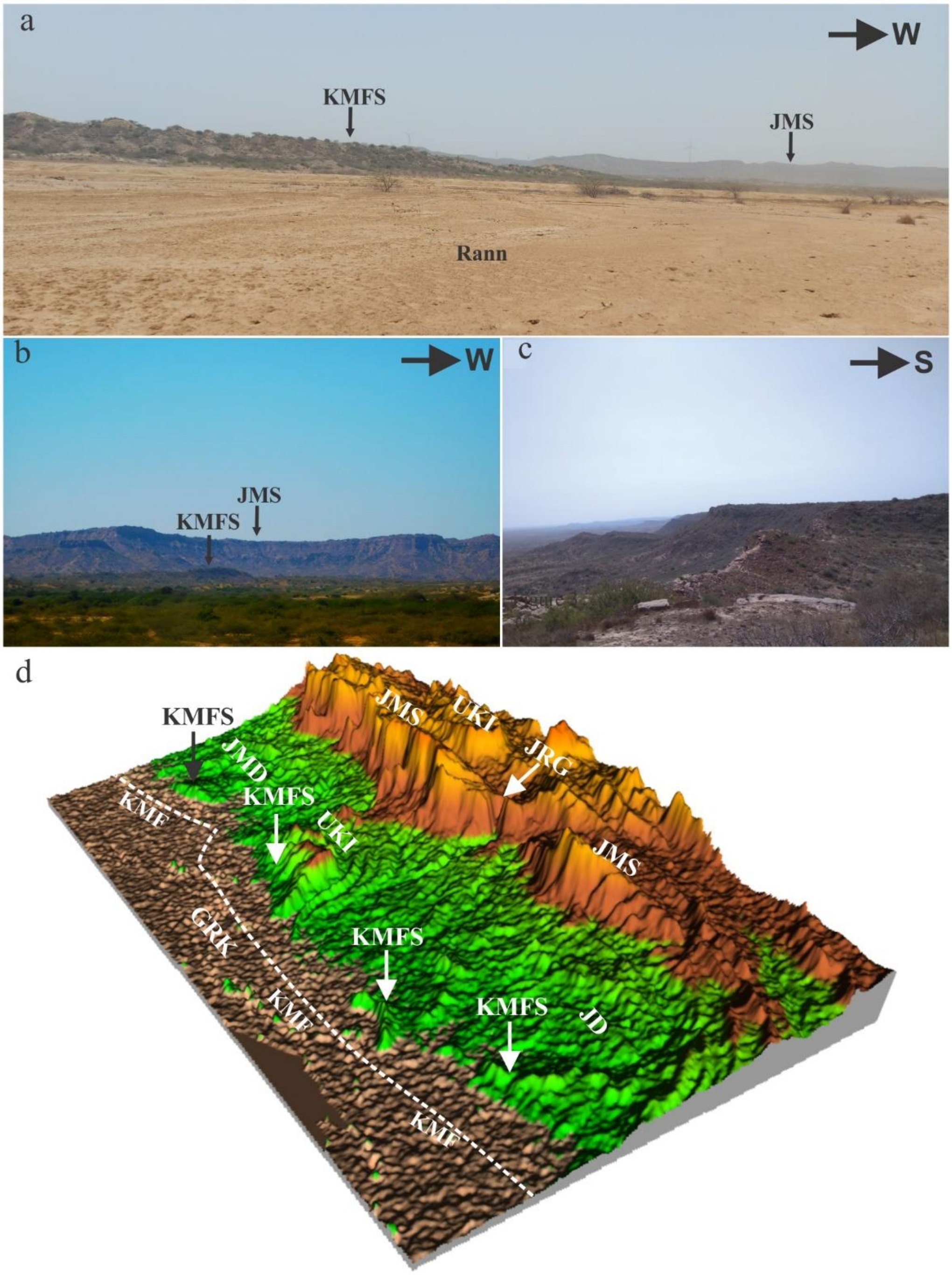

Figure 3.22 (a) Southward view of the KMFS at the western extremity of the Jumara dome. The JMS is seen in the background. The Jaramara Scarp have comparatively greater height than the KMFS (b) Southward view of the KMFS with JMS in the background. (c) Oblique view of the JMS at the central portion. (d) Digital elevation Model (DEM) depicting the major geomorphic features of Jara-Jumara sector. Note that the Jaramara Scarp becomes the prominent scarp in the sector. Here JMS: Jaramara Scarp; KMFS: Kachchh Mainland Fault Scarp; KMF: Kachchh Mainland Fault; JMD: Jumara dome; JD: Jara dome; UKI: Ukra intrusive; GRK: Great Rann of Kachchh, JRG: Jara River gorge.

Kas Hill Scarp

The expose scarp ranges in height from 80 to 190 m (Fig. 3.23 a). The bedrock scarp does not consistently coincide with the active fault trace (Fig. 3.24, 3.25 a, b). The scarp relief is not constant along the length of the scarp. The area of exposure decreases markedly where the scarp is dissected by rivers originating from the NHRFZ. The origin and evolution of this specific scarp in the current tectonic framework of eastern Kachchh basin appears peculiar in nature.

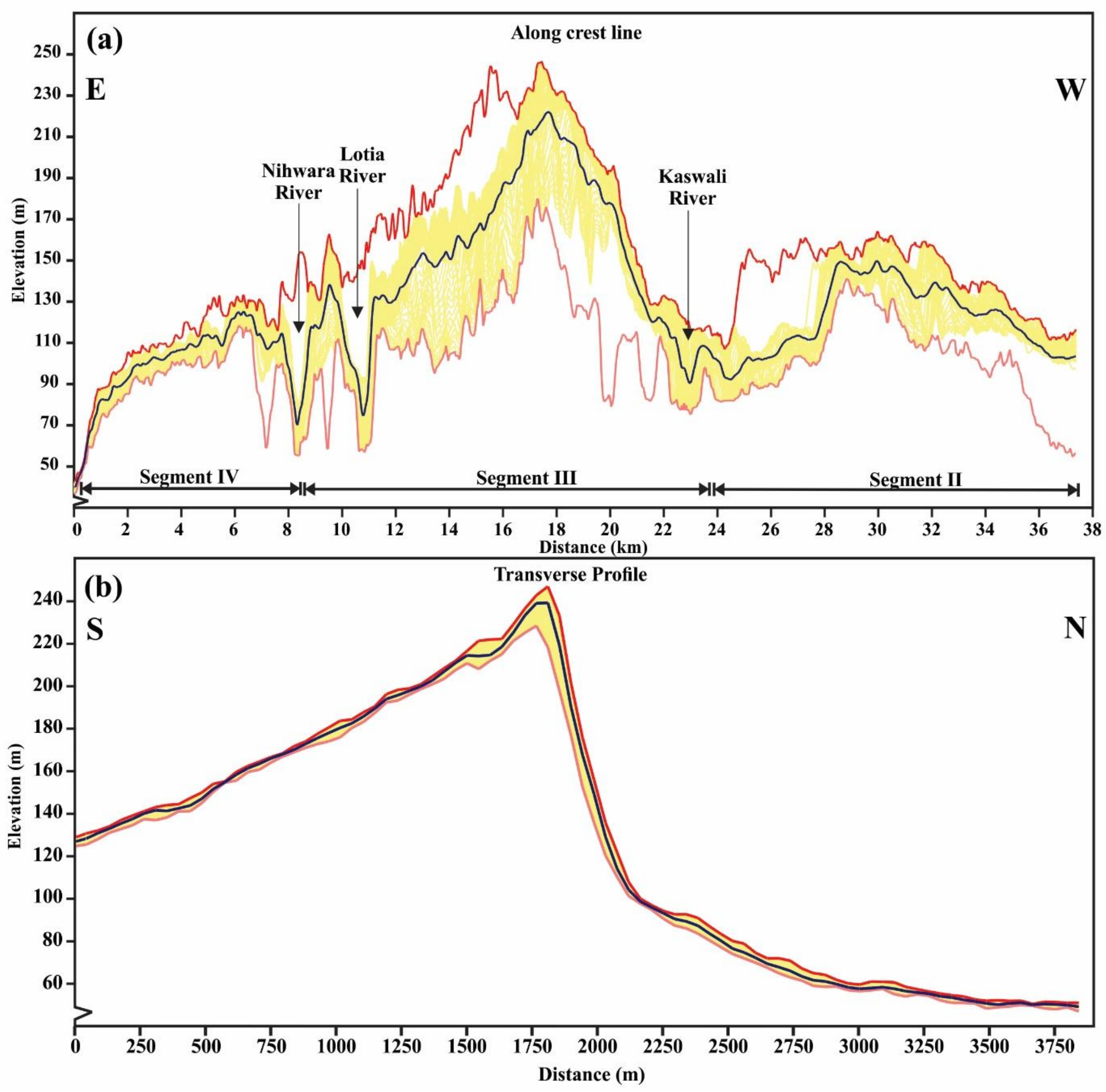

Figure 3.23 Swath profile along and across the Kas Hill Scarp**.**

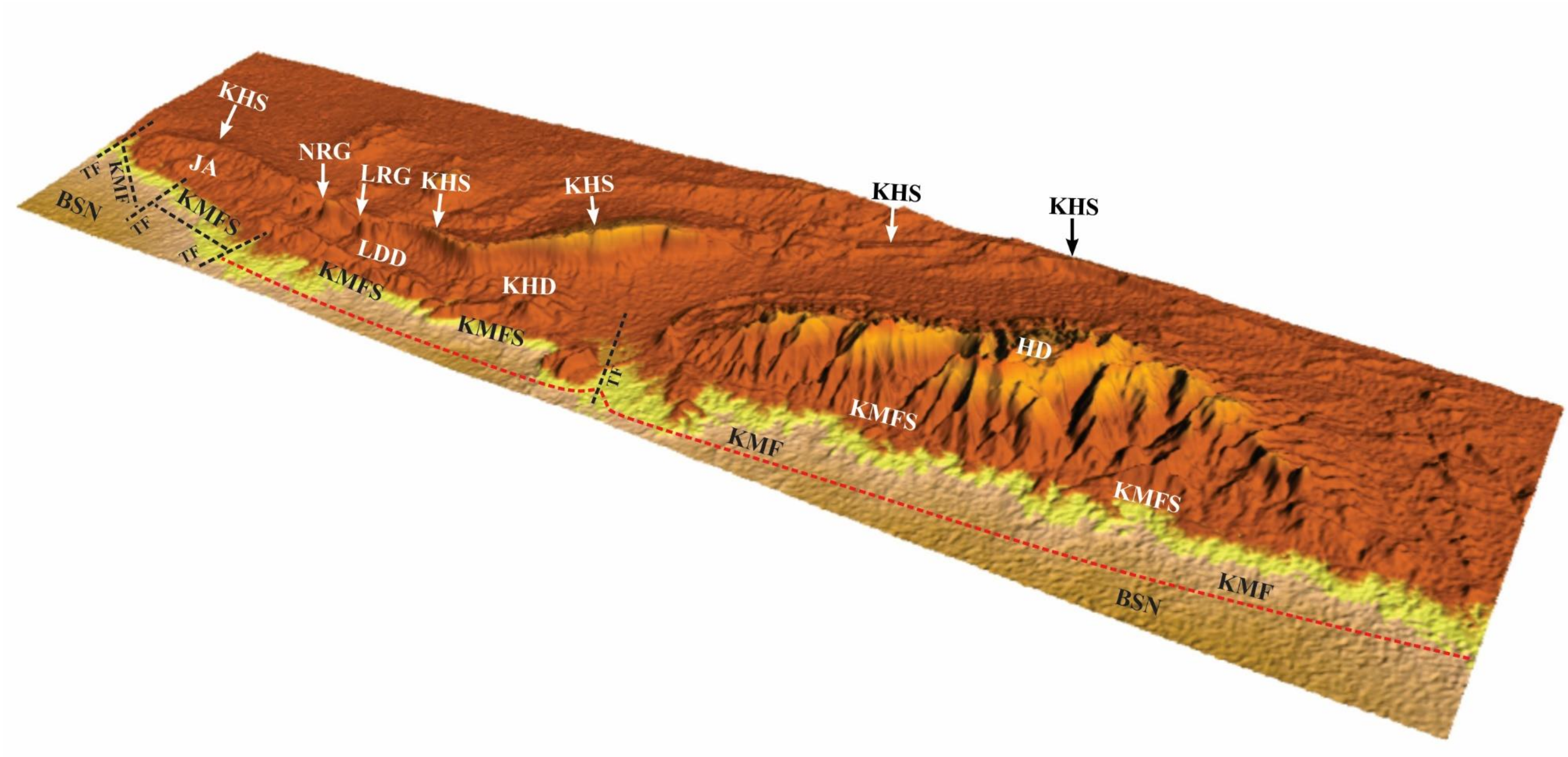

Figure 3.24 Digital elevation Model (DEM) depicting the major geomorphic features of Kas Hill sector. Note that the Kas Hill Scarp becomes the prominent scarp of the sector. Here KHS: Kas Hill Scarp; KMFS: Kachchh Mainland Fault Scarp; KMF: Kachchh Mainland Fault; JA: Jhuran anticline; LDD: Lotia dam dome; KHD: Kas Hill dome; HD: Habo dome, NRG: Nihwara River gorge, LRG: Lotia River gorge; BSN: Banni basin.

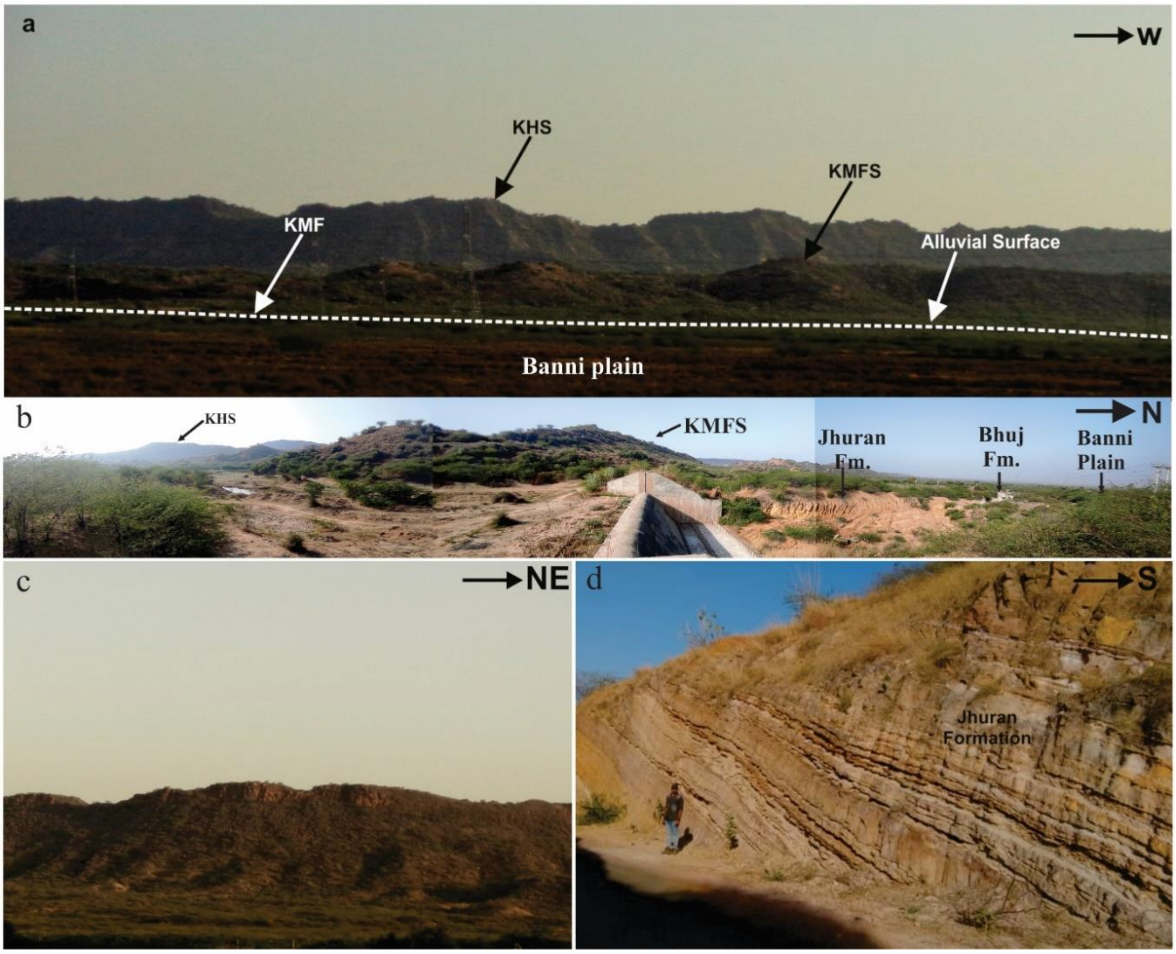

Figure 3.25 (a) Field photograph showing the KHS exposed in the segment III. Note that the KHS becomes the prominent scarp in the region with height several times higher than the KMFS. (b) Photograph showing the general geomorphic setting of the region. (c) Southward view of KHS. (d) Photograph showing a road cut section across the KHS exposing the Jhuran Formation.

The scarp becomes more prominent and gains the maximum relief of 190 m above mean sea level (amsl) in the segment III of eastern KMF (Fig. 3.23 a, 3.24). The elevation of scarp begins to decline at the segment II and IV and finally dies out (Fig. 3.24). The KHS lies approximately 2000 m away from the KMF and 1200m south to the younger KMFS. In the saddle zone, the KHS has retreated more than 4000m south to the faultline. The scarp generally trends E-W strike and parallel to KMFS in the eastern half. Towards the saddle zone (between Habo and Kas Hill anticline) the strike changes to NNE-SSW and eventually arcuate around the Habo dome and dies out further west of the dome (Fig. 3.24). In the eastern side, the scarp runs parallel to the KMFS through the segment IV and finally dies out further east of the segment IV. The scarp formed in the back limb of Kas Hill anticline exposes mainly rigid sandstone member of the upper Jhuran Formation (Fig. 3.25 d). Multiple independent profiles constructed across the scarp suggest a concave up to vertical scarp face (Fig 3.23 b). The profile shape suggest that the scarp is highly eroded (Fig. 3.25 c). Furthermore, it can be inferred that structural segmentation along the eastern KMF imposes a first-order control over the morphology and degradation of the KHS.

At several localities, thick colluvium aprons base of the scarp. The colluvio-fluvial deposits are also seen along the incised valley of hillslope channels on the downstream side of the scarp. The presence of such colluvio-fluvial deposits indicates that the unconsolidated sediments produced from the scarp face is removed downslope by debris flow/run off and deposited at the channel valleys. Therefore, it can be concluded that the present visible bedrock scarp has developed from a combination of erosional exhumation of the fault plane and episodic tectonic uplifts.