

CHAPTER 3

CONTROLS ON LANDSCAPE CONFIGURATION

The landscape configuration of Kachchh is shown to be primarily controlled by the E-W trending major faults in the basin (Biswas, 1974; 1993; Maurya et al., 2017). These include the KMF, SWF, GF and IBF. These faults bound the uplifts on the upthrown side with the downthrown block received Neogene sediments with thin cover of Quaternary sediments (Biswas, 1993; Maurya et al., 2017). A major characteristics of the above mentioned uplift bounding faults is that they show a fault parallel hill ranges developed over flexures comprising domes and anticlines (Biswas, 1993). The fault-line is accompanied by NHRFZ in the upthrown block. The rugged hilly topography is controlled by a linear chain of flexures from east to west, viz., Devisar anticline, Wantra dome, Habo dome, Jhurio dome, Keera dome, Nara/Manjal dome, Jumara dome, Jara dome, Mundhan anticline, Ghuneri dome, Karanpur dome and Lakhpat anticline and others (Biswas, 1993). The NHRFZ and the seismically active KMF have been investigated in details in its eastern half. Various geomorphic indicators of active tectonics like drainage anomalies, fault scarp, river terraces and fault associated Quaternary deposits from the eastern part have been investigated (Chowksey et al., 2011a, 2011b; Maurya et al., 2017a). However, similar studies have not been carried out so far from the western part of the NHRFZ. In general, the western part of the NHRFZ has relatively lower relief and is largely devoid of Quaternary deposits.

FIELD BASED MORPHOTECTONIC ANALYSIS

The present study area in the western part of the Mainland Kachchh uplift exposes domes and anticlines along the KMF. From east to west, these are the Manjal dome, Jumara dome, Jara dome, Mundhan anticline, Ghuneri dome, Karanpur dome and the Lakhpat anticline. The rugged topography of the NHRFZ along the KMF in the study area is attributed to multiple tectonic movements involving uplift of the above mentioned structures along the KMF. The topography of the NHRFZ is controlled by the structural configuration of the domes and anticlines. The rugged nature and elevation is maximum in the Manjal dome in the east which progressively decreases towards west.

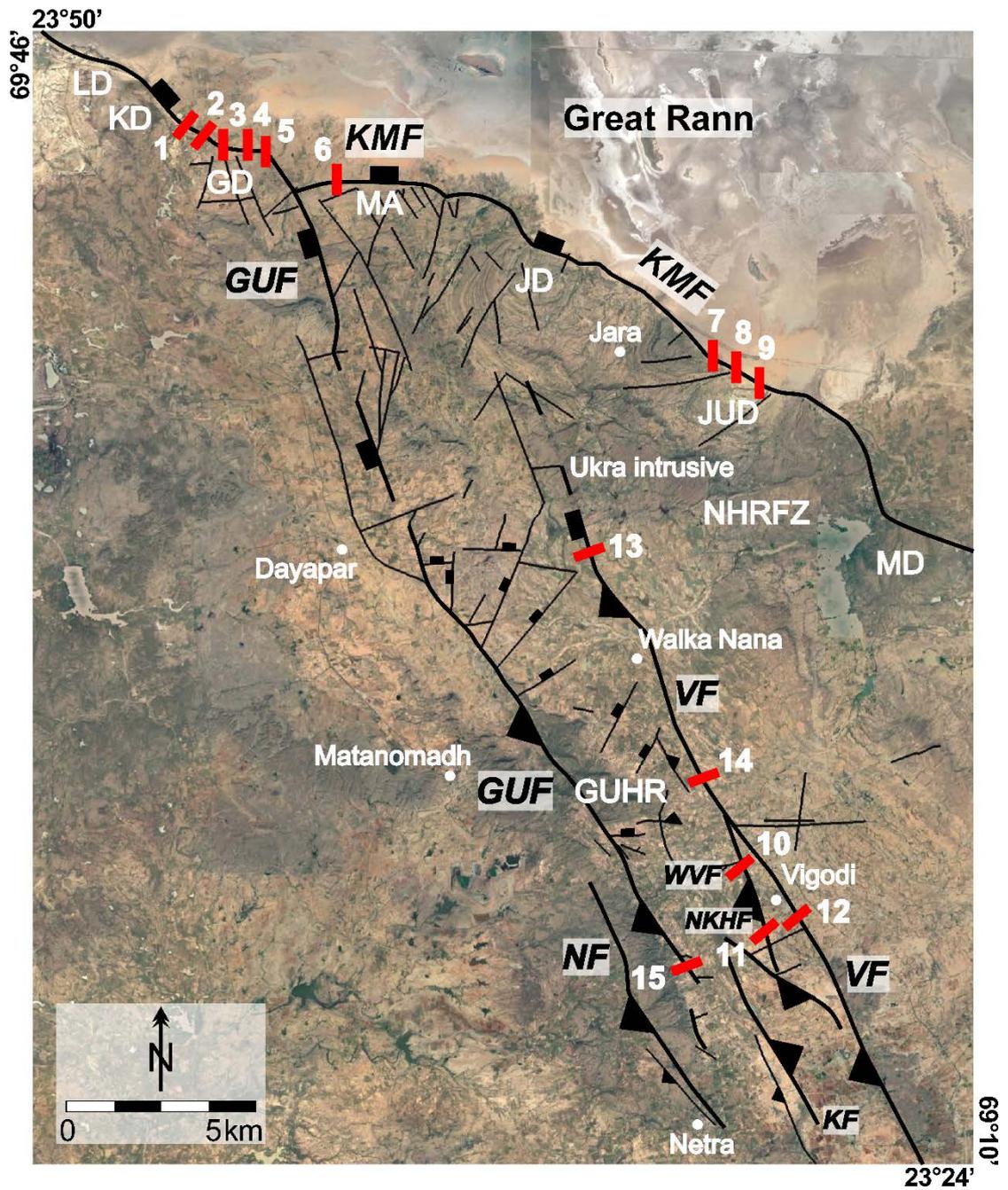


Fig. 3.1. Annotated Google Earth Pro image. The red bars indicate the location of GPR survey sites. Sites 1 to 9 are located along the KMF. Sites 10 to 15 are located in the Vigodi-Gugriana-Khirasra-Netra Fault System (VGKNFS). VF: Vigodi Fault, WVF: West Vigodi Fault, GUF: Gugriana Fault, KF: Khirasra Fault, NKHF: North Khirasra Fault, NF: Netra Fault, KMF: Kachchh Mainland Fault, NHRFZ: Northern Hill Range Fault Zone, GUHR: Gugriana Hill Range, LD: Lakhpat dome, KD: Karanpur dome, GD: Ghuneri dome, MA: Mundhan Anticline, JD: Jara Dome, JUD: Jumara Dome and MD: Manjal Dome. The northern downthrown block of the KMF is occupied by the Great Rann surface.

To the south of KMF, an intra-uplift fault system, the VGKNFS exercises a major influence on the landscape of the area away from the KMF. The fault system trends parallel to the KMF, however, the structural characteristics are different suggesting variable nature of the stresses at the northern margin of the uplift and the intra-uplift areas (Shaikh et al., 2020). The various morphotectonic units based on extensive field studies, critical evaluation and interpretation of topographic profiles are described below.

The area is divisible into following morpho-tectonic units.

- Northern Hill Range Fault Zone – NW-SE trend
- Gugriana Hill Range – NW-SE trend
- Central Rocky Plain – NW-SE trend
- Great Rann

As shown above, the morphotectonic units show a strong correlation with the NW-SE geological and structural regional trend. In general, the area exhibits a highly uneven erosional topography over the Mesozoic Formations.

NORTHERN HILL RANGE FAULT ZONE (NHRFZ)

The northern margin of the Kachchh mainland uplift is marked by an E-W trending structurally controlled hill range called the NHRFZ that is bounded by the KMF 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 asymmetrical domes and anticlines of various sizes. The chain of various structures from the west comprises the Karanpur dome, Ghuneri dome, Mundhan anticline, Jara dome, Jumara dome, Nara dome, Keera dome, Jhura dome, Habo dome, Wantra dome and Devisar anticline 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 and represent deposition in rift environment (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 show gentle dips. The following description described the major structure features impacting the overall landscape of the study area. The geomorphologic expression of these structures and their impact on the landscape

shaping are shown in the accompanying photographs. The E-striking, ~1.6 km long, linear, elongated Lakhpat dome is located on the westernmost extremity of the KMF in the NHRFZ (Biswas, 1993). The northern end of the Lakhpat dome is truncated by the KMF (Figs. 3.2a, b). The Lakhpat dome, situated on the upthrown block of the KMF, exposes steep to gentle northerward dipping Mesozoic Ferruginous sandstones. Narrow strips of Tertiary limestone can be observed in the fault zone. The northern downthrown block occupies the Quaternary sediments belonging to tidal flats of the Kori creek.



Fig. 3.2. (a) E-W striking Mesozoic sandstone exposed in the form of a narrow ridge on the northern limb of the west striking Lakhpat nose. The KMF is buried north of the exposed Mesozoic sandstone. (b) North dipping Mesozoic ferruginous sandstone exposed west of the stream flowing between Lakhpat nose and Karanpur dome. (c and f) Partially bleached NNW striking fault gouge marking the position of the KMF exposed NE of the Karanpur dome. (d) At the eastern fringe of Karanpur dome, the Mesozoic-Tertiary lithotectonic contact (attitude: N140° strike, N50° dip direction and 85° dip) highlights the position of the KMF. (e) Close-view of tilted fluvial miliolite deposits capping the Mesozoic-Tertiary lithotectonic contact. (g), (h), (i), Eocene nummulitic limestone beds (attitude: N285-310° strike, N15-40° dip direction and 85-88° dip) exposed at the northwestern flank of Ghuneri dome. (j) Nearly vertical Tertiary limestone beds (attitude: N85° and N88° strike, N175° and N178° dip direction, 88° and 85° dip) exposed north of NE limb of Ghuneri dome. Ride exposing ferruginous Mesozoic sandstone can be observed at the far side of the photograph. (k) Overturned flexure observed on the northern flank of the Ghuneri dome as the NW-striking ferruginous sandstone beds (attitude: N120° and N123° strike, N210° and N213° dip direction, 78° and 65° dip) are inverted and dip steeply towards the south. (l) Nearly vertical Mesozoic sandstone beds (attitude: N297° strike, N27° dip direction and 87° dip) exposed in the KMF damage zone at the eastern flank of the Ghuneri dome. (m) South dipping fault with unknown slip-sense exposed east of Mundhan anticline (attitude: N70° strike, N160° dip direction and 45° dip). (n) East dipping Mesozoic sandstone (attitude: N330-30° strike, N60-120° dip direction and 24-34° dip), exposed east of Mundhan anticline. The KMF is further north of this location. (o) East striking nearly vertical Jhuran sandstone (attitude: N276° and N275° strike, N6° and N5° dip direction, 86° and 88° dip) jutting from the Great Rann surface. (p) NE-striking faulted dyke (attitude: N55° strike, N145° dip direction and 43° dip) exposed to the north of Jumara scarp. (q) Northern limb of the Manjal dome exposing ~50 m high and ~3.5 km long KMF scarp. The KMF is further north of the scarp buried below Rann surface. (r) Northern limb of the Manjal dome intruded by ~NW dipping igneous rocks. The inferred position of the KMF is highlighted by black dashed line in Figs. a-d, g and h.

SE of the Lakhpat dome, finely powered and partially bleached fault gouge marks the position of the KMF where Mesozoic sandstone are exposed on SW side and Tertiary limestones are exposed on NE side (Figs. 3.2c, f). Northern side of the Lakhpat anticline is bounded by the KMF where the Tertiary rocks have been moved down. In the fault zone, strips and wedges of Tertiary rocks are observed in between the parallel fault strands, which delimit the fault damage zone. According to Biswas (1993), the association of Lakhpat anticline with KMF and other subsidiary faults clearly indicates that it has been produced by the uplifts along these faults. The northern side of the Lakhpat dome is truncated by the KMF. E-W trending, ~3 km long, linear, elongated Lakhpat dome, situated on the upthrown block of the KMF,

exposes the rocks of steep northerly dipping (write attitude) Eocene limestones. The northern downthrown block occupies the Quaternary sediments belonging to tidal flats of the Kori creek. Miliolite deposits in front of Lakhpat dome are also exposed and are in contact with the Eocene limestones in the downthrown block (Biswas, 1993). The KMF strikes NW near Lakhpat anticline. From the north of Lakhpat to the saddle area between Mundhan anticline and Jara dome, the fault is well-exposed, having patchy occurrence. A series of transverse faults at the margins of the domal structures have played an important role in progressive southward offset and minor changes in strike of the KMF further eastward as seen near Ghuneri, Sahera, Mundhan, Jumara and and Nara.

The oval-shaped Karanpur dome is located towards the SE of the Lakhpat dome (Biswas, 1993). Its western and southern ends are delimited by faults (Biswas, 1993). At places, thin miliolite sediment cover can be observed. The NNW-striking KMF is located on the NE side of the Karanpur dome, which is buried below 3–5 m thick fluviably reworked miliolite deposits (Fig. 3.2d). NNW-striking and steeply dipping beds of Eocene limestone are in contact with the ferruginous sandstone, which highlights the flexure zone. The exposure is capped by ~2 m thick titled fluviably reworked miliolite deposits (Fig. 3.2e). This is the only exposure in the study area where the KMF acting as the lithotectonic contact capped by Quaternary deposits. ~2–4° titling of miliolite deposits to NE side is attributed to the neotectonically active nature of the KMF (Figs. 3.2d and e). The titled Quaternary miliolite deposits capping the KMF may represent instantaneous/co-seismic response of off-fault tectonic deformation along the KMF (McCalpin, 2009). Towards the east of Karanpur dome, the KMF zone is marked by nearly vertical, indistinct fault gouge zone (Fig. 3.2g). N115° striking Thin stripes of almost vertical Eocene limestones jutting from the flat soil surface between the Lakhpat and Ghuneri dome suddenly end up against the steep Mesozoic Ferruginous sandstones, which distinctly marks the location of the KMF (Fig. 3.2h).

The ferruginous sandstone, ironstone bands at few places and patchy occurrence of shale belonging to the lower member of Bhuj Formation are exposed in the rhythmic fashion showing swerving strike of beds in the Ghuneri dome. The KMF is well-exposed in the vicinity of the Ghuneri dome, serving as the litho-tectonic contact between ferruginous Mesozoic sandstone and Tertiary limestone. The vertical to sub-vertical KMF cuts the steep northern flank of Ghuneri dome tangentially (Biswas, 1993). To the north of western flank of Ghuneri dome, the KMF damage

zone is characterized by E- to ENE-striking, near-vertical beds of Eocene nummulitic limestone resting against the steeply dipping Mesozoic ferruginous sandstone (Fig. 3.2i). However, the secondary slip planes described by Biswas (1993) could not be located, striding the strips of Eocene, Miocene and Pliocene rocks. Biswas (1993) also noted the presence of fault-breccia or hard, ferruginous quartzites in the contact zone of Mesozoic and Tertiary rocks. On the eastern flank of Ghuneri dome, the E-striking nearly vertical Tertiary massive limestone beds (Fig. 3.2j) are in lithotectonic contact with the Mesozoic ferruginous sandstone in the south (Fig. 3.2l). The Tertiary limestone beds are inverted and dip steeply (85-88°) southwards, as also noted by Biswas (1993) (Fig. 3.2j). NW-striking nearly vertical Mesozoic sandstones exposed at the eastern flank of the Ghuneri dome marks the presence of KMF damage zone (Fig. 3.2l). Overturned flexure has also been observed on the northern flank of the Ghuneri dome as the NE-striking ferruginous sandstone beds are inverted and dip steeply towards SW (Fig. 3.2k).

Biswas (1993) has described three structural closures of the E-W trending, elliptical in shape, elongated, Mundhan anticline – Sahera dome on the east, largest dome in the middle and Mundhan dome on the west. The asymmetric anticline has been affected by numerous NW-SE, NE-SW, ENW-WSW trending transverse faults that show oblique-slip movement and displace the E-W trending parallel to sub-parallel linear ridges composed of rocks of Jhuran Formation as can be seen in satellite view. Of them, the NW-SE trending faults are more prominent. The longest of them is NW-SE trending fault, extends for ~9 km which meets the KMF near the western flank of the Mundhan anticline (Biswas, 1993). On their northern extremity, all the secondary, transverse faults terminate in the vicinity of the KMF while they extend southward beyond the confines of the Mundhan anticline and disappear below younger beds.

In the inter-domal saddle region between the Mundhan anticline to the west and Jara dome to the east, there is another intrusive body forming a small hill, composed mostly of dolerites (Biswas, 1993). This intrusive body is exposed in the Kachchh mainland fault damage zone and is described by Biswas (1993) as Mundhan stock as it shows steep, discordant contacts with the Jhuran sandstone. To the north of this intrusive body, alluvial piedmont surface is located. The KMF abruptly truncates the intrusive body towards its northern margin. The trace of the KMF can be located as almost vertical dipping Jhuran sandstone beds are exposed to the north of the Mundhan stock.

The Jara and Jumara domes show the most complicated morphotectonic set up that comprises low but highly eroded hilly topography between the KMF scarp to the north and the Jaramara scarp to the south. It comprises a structurally controlled topography developed over the Jumara and Jara domes. The elevation ranges from 30 m to 60 m and slopes towards the north. In general, the morphotectonic unit comprises low hills and valleys with contrasting lithologies of competent beds forming circular ridges confirming to the domal structure. The unit is drained by structurally controlled rivers with deeply incised bedrock channels.

The Jara and Jumara domes have suffered maximum uplift along the KMF as suggested by the dissection to deeper stratigraphic levels (Biswas, 1993). As a consequence, these two dome are the only ones that expose the oldest Mesozoic formations i.e. the Jhurio and Jumara formations. Geomorphologically, also the landscape developed over the two domes varies from the other domes in NHR in terms of scarp development, ruggedness, spectacular landforms and drainage characteristics. In view of this, the morphotectonics of the Jara and Jumara domes is described separately in the following paragraphs.

Role of transverse faults

Each of the folded structural elements of the NHRFZ is affected by the secondary transverse faults with a variable strike and with normal/reverse/oblique slip-sense. This secondary fault network is inherited from the extensional stress regime of the KRB. Intra-domal and inter-domal faults were observed that obliquely meet or displace the KMF otherwise terminate against the KMF. It is to be noted that field exposure where the transverse faults directly meet the KMF were not found. As these transverse faults are well-exposed, there was no need to perform a GPR survey across these faults. Note that none of the intra-domal or inter-domal faults, presented in Fig. 3.3, are capped by the Quaternary sediments cover. Hence, field evidence that indicates these faults to be neotectonically active were not found. The NW-/NE-striking inter-domal faults occupy the structurally low-lying saddle region, which separates the domes with differential uplift in the NHRFZ. ~600 m WNW of Ghuneri dome, the W-striking non-striated extensional fault was encountered in Bhuj sandstone lithology (Figs. 3.3a, b). The exposure lacks the continuity of any stratigraphic marker across the fault plane and also, no slickenside kinematic indicators were observed. The hangingwall block, however, marks the local occurrence of normal drag folding, which indicates normal slip-sense of the fault. This

transverse fault is exposed in the region between the Ghuneri dome and Karanpur dome, where the KMF strike varies from NW–W. The shift in the strike of KMF may be due to the component of strike-slip movement along the W-striking transverse fault. At this site, however, no structural evidence of strike-slip movement have been reported.

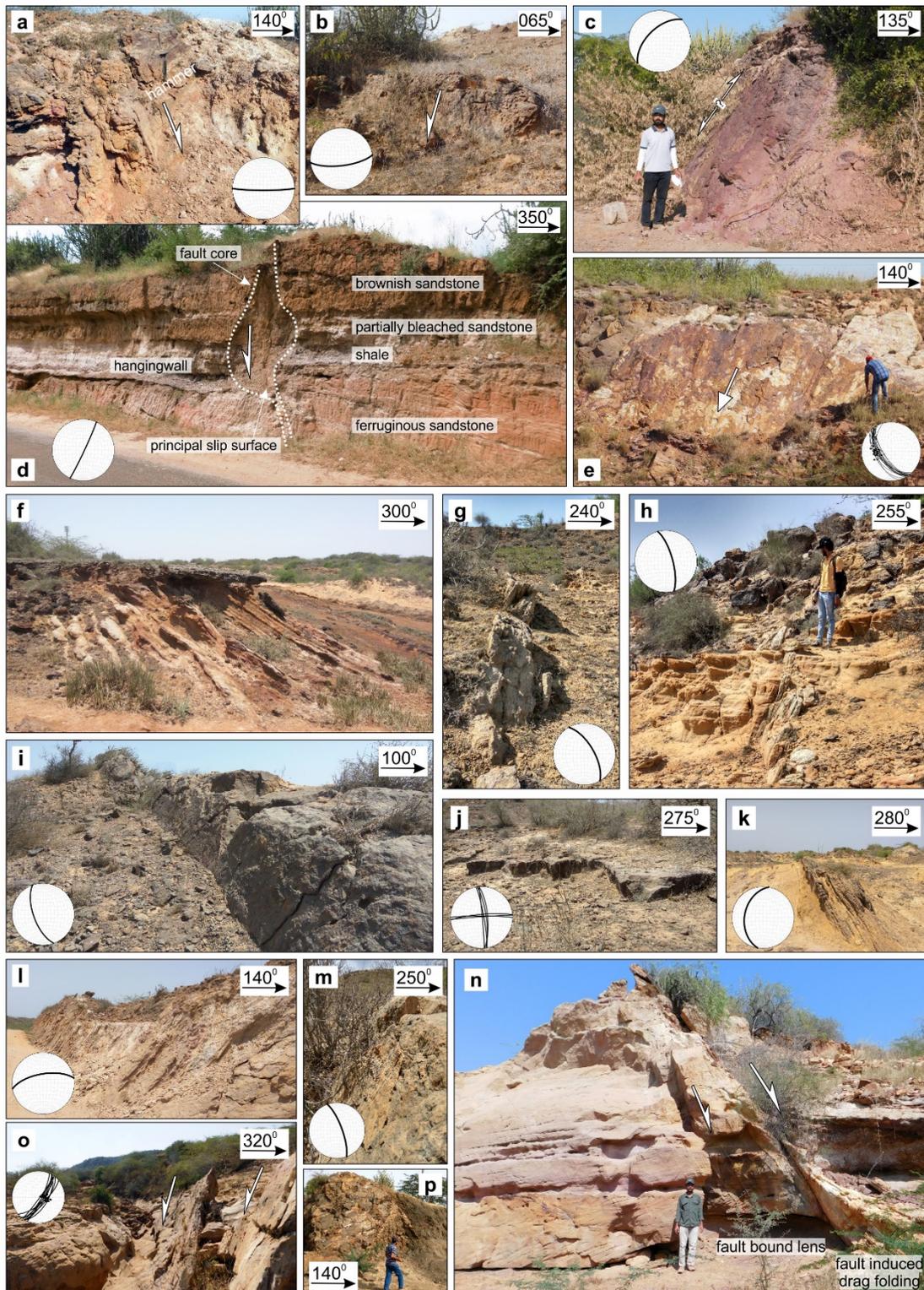


Fig. 3.3. (a) and (b) Non-striated fault with normal slip-sense exposed ~600 m WNW of Ghuneri dome (attitude: N90° and N83° strike, N180° and N173° dip direction, 85° and 72° dip). (c) Non-striated fault with unknown kinematics (attitude: N37° strike, N315° dip direction and 57° dip) exposed east of Mundhan anticline. (d) ~350 cm high outcrop exposure of the NE-striking extensional fault (attitude: N205° strike, N115° dip direction and 87° dip) exposed ~3.5 km south of Mundhan anticline. White dotted lines outline key structures. (e) NW-striking GUF with oblique slip exposed ~2 km south of western flank of Mundhan anticline. (f) Unconformity exposed within the rocks of Jhuran Formation at the western flank of the Ghuneri dome. (g, h, i, k and l) Small-scale intra-domal faults exposed in the Ghuneri dome. (g) Intra-domal cross-fault (attitude: N350° strike, N60° dip direction and N65° dip). (h) Transverse fault exposed within Bhuj sandstone (attitude N345° strike, N72° dip and N75° dip direction). (i) Transverse fault cutting across the Mesozoic strata of the Ghuneri dome (attitude: N340° strike, N65° dip and N250° dip direction). (j) The field photograph shows the presence of two sets of almost vertical joint planes in Bhuj sandstone at the southern extremity of the Ghuneri dome (Trend: N350° and N270°). The trend of one of the joint plane correlates well with the N270° trending transverse fault at the same location. Two major joint sets trending N3500 and N2700 were observed within Bhuj sandstone at the north-western fringe of the Ghuneri dome. (k) NNE trending transverse fault exposed in Bhuj sandstone at the north-western side of the Ghuneri dome (attitude: N190° strike, 40° dip and 280° dip direction). Note that the transverse fault displaces the KMF line in strike slip environment and moves it to further north in the north-western block of the transverse fault. It means that the transverse fault is younger than the KMF line. (l) E-W trending transverse fault observed in Bhuj sandstone lithology encountered at the western part of the Ghuneri dome (attitude: N80° strike, 65° dip and 350° dip direction). (m) NW-SE trending transverse fault encountered at the middle segment of the Mundhan anticline displacing the Mesozoic strata in strike slip environment (attitude: N340° strike, N75° dip and N70° dip direction). The discontinuous mound of the Mundhan anticline can be seen in the field photograph. Several such discontinuous mounds are displaced laterally due to strike-slip motion in NW-SE and NE-SW trending transverse faults in the Mundhan anticline. (n) NE striking cross-fault with normal slip exposed at the SW fringe of the Jara dome. (o) Another NE striking cross-fault with normal slip exposed at the western fringe of the Jara dome. (p) NE striking dyke exposed in the Vicinity of the Manjal dome.

Another NE-striking transverse fault with unknown slip-sense was encountered in the saddle region between the eastern flank of Ghuneri dome and western flank of Mundhan anticline (Fig. 3.3c). Its NE end terminates along the NW–W striking KMF. It may be possible that the strike-slip movement along this NE-striking fault may have induced a change in the strike of the KMF from NW–W.

~3.5 km south of the E striking Mundhan anticline, NE-striking non-striated extensional fault is encountered in Bhuj Formation consisting of sandstone and shale

beds (Fig. 3.3d). The southern side of this NE-striking fault ends up in the NNW striking GUF. Whereas the northern end of this ~2.3 km long fault ends with another transverse fault striking NW. At the road-cut section, the fault disturbs the almost horizontal stratigraphic units at the high oblique angle (Fig. 3.3d). The stratigraphic units are composed of bleached and ferruginous varieties of sandstone and shale belonging to the Bhuj Formation. The NE-striking high-angle extensional fault has an estimated throw of ~85 cm as the hangingwall on SSE side has moved down relative to the footwall block. Based on the outcrop observation, the main structural components such as the fault core and principal slip surface are observed. The principal slip surface is well-exposed in the lowermost stratigraphic units consisting of ferruginous sandstone overlain by bleached to purplish shale layer. In the studied road-cut section exposure, the lozenge-shaped, tectonic rock body of the fault lens can be observed. This marks the limits of the concentrated shear zone and consists of highly deformed host rock material, mainly a combination of sandstone and shale. It turns instantly into undeformed host rock mass outside the width of the fault lens, indicating a narrow width of the fault damage zone. The northernmost occurrence of the NW-striking GUF crops out in Bhuj sandstone lithology, ~2 km south of the western flank of the Mundhan anticline (Fig. 3.3e). In its northernmost extremity, the GUF shows oblique-slip movement with normal dip-slip and dextral strike-slip components (Shaikh et al., 2020). Presence of such series of NW-, NE- and W-striking transverse faults in inter-domal saddle regions and their oblique-slip movement may have given rise to a step-like pattern of the KMF strike, which is ascending towards the west.

NW-striking intra-domal faults with oblique-slip kinematics are prevalent in the Ghuneri dome and Mundhan anticline located in the western part of the NHRFZ (Figs. 3.3, 3.4). ENE- to E-striking faults are few. Several W-, NW-, NNE-, NE-striking intra-domal faults were observed in the Ghuneri dome, which dies out in the vicinity of the W-striking KMF (Figs. 3.3g, h, i, k, l). As these intra-domal faults are exposed in the uniform lithology and also the faults are devoid of slickenside kinematic indicators, the slip-sense from outcrop exposures could not be inferred. There was no clear evidence of the stress regime or tectonic events responsible for the movement along these intra-domal faults. In the satellite imageries, the Ghuneri dome shows a rhythmic pattern of alternating bands of sandstone, shale and ferruginous bands. In plan view, however, the intra-domal faults are observed to displace the rhythmic bands of hard Mesozoic rocks in the strike-slip environment.

The W-striking elliptical Mundhan anticline is located E of Ghuneri dome (Biswas, 1993) (Fig. 3.4). The asymmetric anticline has been affected by numerous WSW-, NW-, NE-striking oblique-slip transverse faults and displace the W-striking parallel to sub-parallel linear ridges composed of rocks of Jhuran Formation, as can be seen in the satellite view. Of them, the NW-striking faults are more prominent. The longest of them extends for ~9 km, which meets the KMF near the western flank of the Mundhan anticline. On their northern extremity, all the secondary faults get terminated in the vicinity of the KMF while they extend southward beyond the confines of the Mundhan anticline and merge in the VGKNFS. In ground view, it appears as if the NE-striking faults are truncated by NW-striking faults forming a distinct Y-pattern (Biswas, 1993). The NW-striking fault showing oblique-slip movement, which runs in the inter-domal saddle region between the Ghuneri dome and Mundhan anticline has been responsible for the sudden change in the strike of the KMF from ~NW in the Sahera to west in the vicinity of the Mundhan anticline.

MORPHOTECTONIC ANALYSIS OF JARA AND JUMARA DOMES

The terrain over the Jara and Jumara domes is highly rugged and dissected compared to the above described other domal structures to the west. The Mesozoic sediments exposed in the two domes have been studied in great details (Jain et al., 1996, 2014; Prasad, 1998; Rai, 2003; Desai and Patel, 2008, 2009). The Jumara dome is identified as the type area of Jumara Formation (Biswas, 1977, 1993), while the Jara dome to its west also exposes an excellent sediment succession of Jumara and Jhuran Formations (Fig. 3.5). The domes are asymmetrical in the sense that their southern limb are gentler and merge with the highly rugged topography on the back slopes of the domes while their northern limbs are comparatively steeper. On the southern side of the domes marks the Ukra intrusive rocks. In the northern hill range, these asymmetrical domes are not continuous and are separated by interdomal saddle areas which are occupied by highly structurally controlled, north flowing drainages. However, no detailed geomorphological studies are available even though the neotectonically active nature of the various faults have been emphasized in the context of the overall landscape evolution of the Kachchh basin (Biswas, 1974).

The landscape of the study area is significant as it contains a steep, E-W trending precipitous Jaramara escarpment at the southern margins of the Jumara and Jara domes (Fig. 3.5). No such comparable scarp occurs along the entire stretch of the NHRFZ. The present study, dwells upon the geomorphological peculiarities which

provide evidence of uplift induced long-term erosion that resulted in the development of the present highly dissected erosional landscape including the Jaramara scarp (Shaikh et al., 2018).

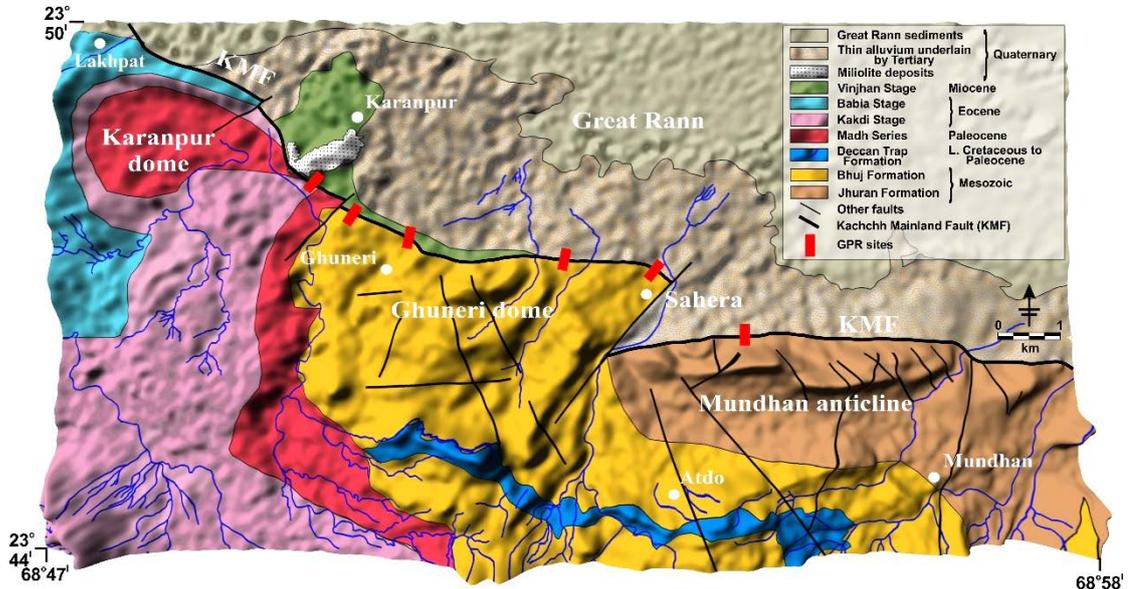


Fig. 3.4. Morphostructural map of the present study area with mapped faults and rivers superimposed over shaded relief map derived from SRTM v.3 data. Red bars denote the GPR survey sites.

Jumara dome

The Jumara dome forms the eastern part of the study area. It is a D-shaped asymmetrical dome with the straight margin marked by a north facing fault scarp of the KMF (Fig. 3.5). The scarp exposes steeply dipping beds forming the northern limb of the Jumara dome. The KMF is not exposed but its approximate position in the surface can be identified further north of the scarp on the basis of almost vertical E-W trending low outcrops of Mesozoic rocks and the abrupt termination of an NNE-SSW trending dyke extending into the Banni plain. The various lithologies of the Mesozoic rocks form circular outcrops with more competent lithologies forming circular ridges along with parallel intervening lows of comparatively softer rocks. The central part of the dome exposes the Jhurio Formation which is the oldest Mesozoic Formation (Biswas, 1977). The Jumara dome is identified as the type area of Jumara Formation which is readily identified in the field by its characteristic lithologic association of limestone, shale and golden-oolite rock forming the dominant geological formation exposed in the dome (Biswas, 1977). The Jumara Formation consists mainly of quartzose and gypseous clayey shales with hard beds of marlites (Biswas, 1977).

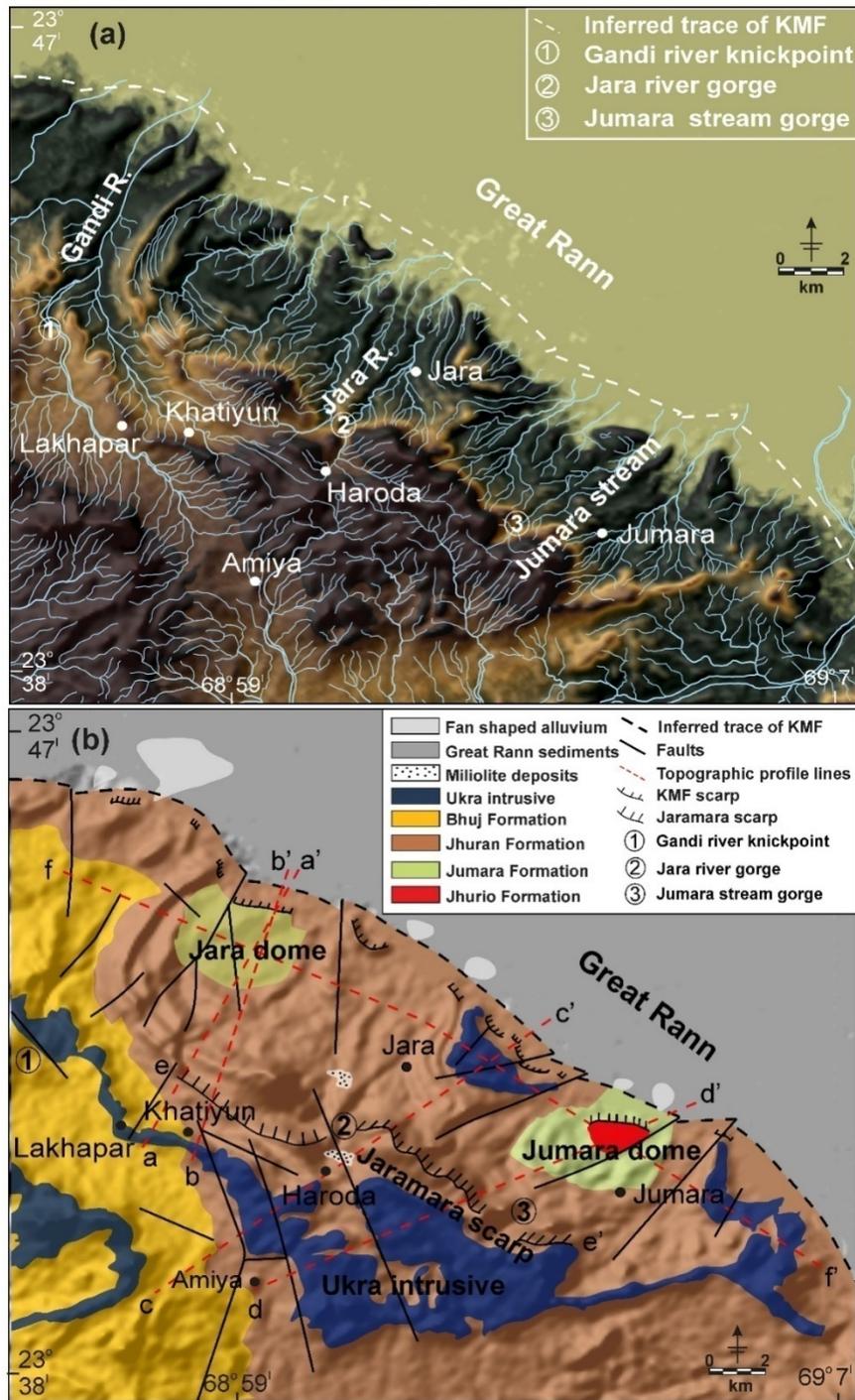


Fig. 3.5. (a) Drainage map of the study area superimposed over DEM. Note the radial drainage pattern over the Jumara and Jara domes. Also, note the southward flowing drainages arising from the Ukra intrusive (in dark colour) and the Gandi river encircling the southwestern and western fringe of the Jara dome. (b) Geological map with faults superimposed over the DEM of the study area. Note the highly rugged structurally controlled topography, the Jaramara scarp and the Ukra intrusive on the back slope of the scarp.

The sandstones are hard, pale, brown, grey or greenish coloured, cross-laminated and oscillation ripple marks (Biswas, 1977). The overlying Jhuran

Formation occurs along the fringes of the dome and the precipitous north facing Jaramara scarp marking the southern limit of the Jumara dome. Besides, another small dyke along an NE-SW radial fault in the southern part, no other dyke is seen in Jumara dome (Biswas, 1977).

Jara dome

The Jara dome exposes rocks of Jumara Formation in the core portion of Jara dome and shows a low but highly rugged rocky topography (Fig. 3.6). The exposed sequence is represented by shales with marlite bands and sandstones (Biswas, 1993). The Jhuran Formation is the most extensively exposed formation in the dome. The lower part of the Jhuran Formation is fine-grained and comprises gypseous shales, carbonaceous shales with haematitic nodules and alternating with sandstone beds (Biswas, 1993). The various lithologies are well exposed in the deeply incised cliffs of the Jara river and other rivers. At places, the Mesozoic strata are overlain by fluviially reworked Quaternary miliolite deposits. This part of the formation forms a low dissected but rugged topography of the Jara dome. The upper part of the Jhuran Formation is predominantly consisting of hard sandstone beds (Biswas, 1993), which are well exposed in the precipitous north facing Jaramara scarp. The Jara dome is dissected by several intra-domal transverse faults (Fig. 3.7). In the central part of the Jara dome, a few discontinuously occurring dykes are seen to branch off from a circumscribing sill (Biswas, 1993). These dykes are parallel and trend generally E-W. They are offset by the oblique faults and are exposed within the dome only. The longest of the dyke occurs in the northern part of the dome, close to the KMF and parallel to it while another dyke occurs in the southern part of the dome (Biswas, 1993). The dykes cut across the Jumara and Jhuran Formations vertically. To the east of Jara dome exposures of KMF is not noted barring a few vertical and very steep isolate hog-backs formed of competent beds jutting out of the Rann soil. At places slicken-sided, brecciated, box-worked ferruginous quartzitic rocks, dipping at high angles are seen (Biswas, 1993).

Interdomal Saddle

This comprises a structural low between the western flank of the Jumara dome and the eastern flank of the Jara dome. Low roughly N-S striking ridges of Mesozoic strata marking the flanks of the domes occur in the saddle reach.

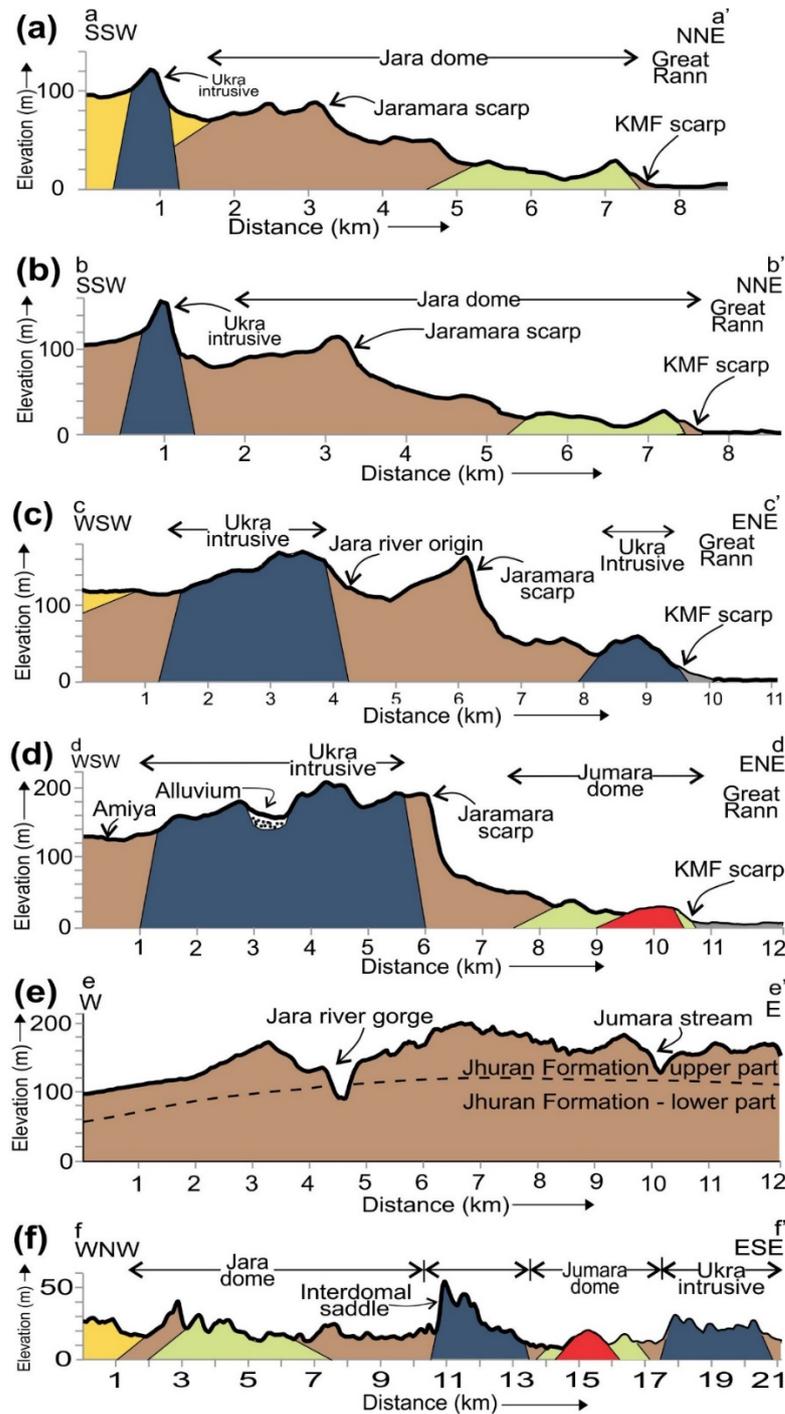


Fig. 3.6. (a) to (f) N-S oriented topographic profiles drawn over the study area from survey of India topographical maps on 1:50,000 scale. Notice the low KMF scarp, low hilly topography over the domes, the prominent expansion of the imposing Jaramara scarp and the still higher relief of the Ukra intrusive. (e) and (f) show E-W topographic profiles drawn across the study area. (e) shows topographic profile drawn over the crest of the E-W trending Jaramara scarp. Note the gradual reduction and disappearance of the scarp on either side and the deep Jara river gorge and the Jumara stream gorge superimposed over the scarp. (f) E-W topographic profile over the low hilly topography of the Jumara and Jara domes. Notice the marked lower relief as compared to the Jaramara scarp. The relatively higher relief in the interdomal saddle is because of a patch of Ukra intrusive.

Closer to the KMF scarp, the Mesozoic rocks in the saddle reach are capped by the hard compact rocks of the Ukra intrusive. The intrusive here forms an isolated crescent shaped outlier with a relatively higher elevation. The KMF scarp in this part is formed over the rocks of Ukra intrusive. Though a structural low, there is no drainage passing through the saddle reach due to the higher topographic level of the intrusive.



Fig. 3.7. (a) North facing panoramic view of the low hilly topography developed over the eastern margin of the Jara dome. The rocky surface in the foreground is the crest of the Jaramara scarp. (b) View of an incised cliff along a river in the low hilly topography of the Jara dome. (c) View of the exposure of a transverse fault. (d) View of the fault plane of the transverse fault. The down arrow indicates the slip direction. (e) View of another transverse fault exposed in the cliff of a tributary of the Gandhi river.

The Jaramara Scarp

This is the most spectacular landform of the area that overshadows other parts of the area by its sheer relief and prominence (Fig. 3.5). It is a broadly arcuate, E-W trending and steep north facing continuous escarpment located at the southern margins of the Jumara and Jara domes. The lower part of the scarp exposes the relatively fine-grained lower part of the Jhuran Formation consisting of alternate beds of sandstone and shales. The upper part of the scarp comprises hard thick bedded sandstones which provide the impressive aspect of a high vertical escarpment. The rocks gently dip to the south and abruptly terminate against the large Ukra intrusive. The youngest of the Mesozoic sequence, the Bhuj Formation is completely stripped off but is exposed only to the south of the Ukra intrusive.

The maximum height of the scarp is ~200 m amsl in the central part to the south of Jara village and marks an abrupt increase of elevation compared to the low relief over the domes (Figs. 3.6g, h and i). The scarp gradually slopes away on either side before dying out at beyond the confines of the Jumara and Jara domes (Fig. 3.6i). Relatively low relief scarplets are present over the back slopes of the Jaramara scarp which have formed E-W trending shallow valleys some of which are covered by thin Quaternary deposits. A prominent feature of the backslope of the Jaramara scarp is the presence of a large E-W trending intrusive body that has been described as a pluton (Biswas, 1993). The pluton, also referred to as Ukra intrusive shows rugged erosional topography over it and is bounded by E-W trending faults.

The field investigations did not reveal the presence of any fault at the base of the scarp along its entire length. The scarp is however traversed by few transverse faults that cut through the intrusive body on the back slope and extend into the low domal hills in front the scarp. The scarp, therefore, is primarily an erosional cuesta scarp developed in the gently south-dipping strata of the Jhuran Formation. The largely undissected nature of the scarp is striking (fig. 3.6i). The scarp face shows youthful nature as there is a complete absence of erosional gullies, though small streams draining through the domal hills of Jumara and Jara domes originate at the base of the scarp. Only two north-flowing streams cut through the scarp forming gorges (Fig. 3.6i). Of these, the most spectacular gorge is the Jara river gorge which is formed in the central part of the Jaramara scarp (Figs. 3.6a and b). The Jara river originates on the back slope, close to the contact of the Jhuran Formation with the Ukra intrusive body and forming a deep narrow gorge across the scarp within a short distance and flowing further north in a deeply incised bedrock valley.

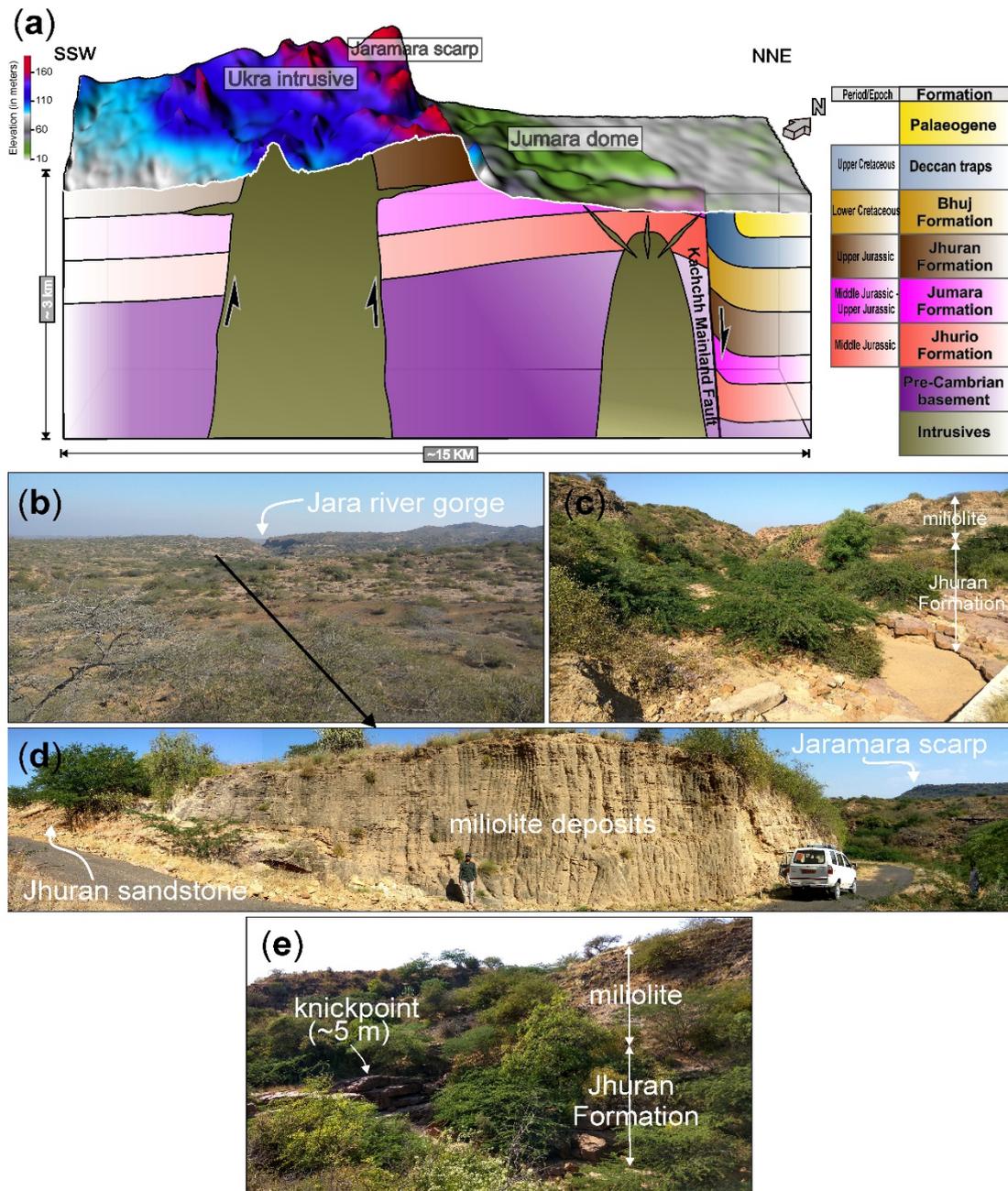


Fig. 3.8. (a) Merged DEM with N-S geological section across the Jumara dome. Note the low KMF scarp, the prominent Jaramara scarp and the rugged topography over the Ukra intrusive and its back slope. The structural section is based on Biswas (1993) with the likely downward extension of the Ukra intrusive and the subsurface interdomal intrusive. (b) North facing panoramic view of the back slope developed on the Jaramara scarp showing the Jara river gorge. (c) Downstream view of the Jara river gorge showing incision in Quaternary miliolite deposits and the underlying rocks of Jhuran Formation. (d) Photomosaic showing the miliolite deposits exposed in a road section near the gorge. The Mesozoic rocks are visible to the left side of the photo. Black arrow indicates the location of the outcrop on the back slope. (e) View of the right bank cliff of the Jara river gorge showing incision in miliolite and the underlying Jhuran Formation. Also visible is the first knickpoint at the upstream end of the gorge.

Three major knickpoints are observed within the Jara river gorge that testifies to the profound tectonic uplift induced long-term rejuvenation of the scarp (Fig. 3.6b). Neotectonic uplift is inferred as the river has formed a deep gorge within Quaternary aeolian miliolite deposits underlain by rocks of Jhuran Formation. The other river that has dissected through the scarp is the Jumara river that arises just behind the crest of the scarp and flows northward (Fig. 3.6i). The river forms a wide gorge but shallower than the one described above and flows further north through the central part of the Jumara dome (Fig. 3.6i).

Backslope over Jaramara Scarp

This includes the south sloping surface behind the crest of the Jaramara scarp (Fig. 3.6e, f, g and h). Further south, the backslope terminates against the Ukra intrusive. The south directed slope is attributed to the southward dips of the rocks which form the outer flanks of the Jumara and Jara domes. The backslope is developed over the hard compact sandstones of Jhuran Formation which make up the upper half of the Jaramara scarp (Fig. 3.8). Few E-W trending short valleys, some with thin veneer of alluvium washed down from the surrounding slopes, are observed over the backslope which is consistent with the strike of the rocks and the Jaramara scarp. No drainages are seen on the backslopes except the Jara river which flows northward in anti-dip direction and cut across the Jaramara scarp forming a deep gorge (Fig. 3.8).

Rugged Topography over the Ukra Intrusive Body

This is a large intrusive body on the back slope of the Jaramara scarp that forms a continuous chain of hills starting from the Ukra hill located further W of the study area, extending over the backslope of the scarp before turning around to the east of the Jumara dome and terminates along the KMF scarp (Biswas, 1993). It forms prominent hilly terrain near Lakhpar, Khatiyun and Haroda (Fig. 3.9a). Overall the intrusive body is arcuate shaped and follows the strike of beds and enclosing the Ghuneri, Mundhan, Jara and Jumara domes (Biswas, 1993). A large exposure of the intrusive occurs in the saddle zone between the Jumara and Jara domes (Biswas 1993). Several dykes and sills are associated with this intrusive body. The Ukra intrusive together with associated sills and dykes is composed mostly dominantly of basalts and dolerites, occasionally porphyritic and petrographically resembles with the Deccan Trap (Biswas, 1993). The age of Ukra intrusive is from Santonian to pre-Deccan Trap

as the intrusive cuts across the youngest Mesozoic Formation, the Bhuj Formation (Portlandian to Santonian) (Biswas, 1993).

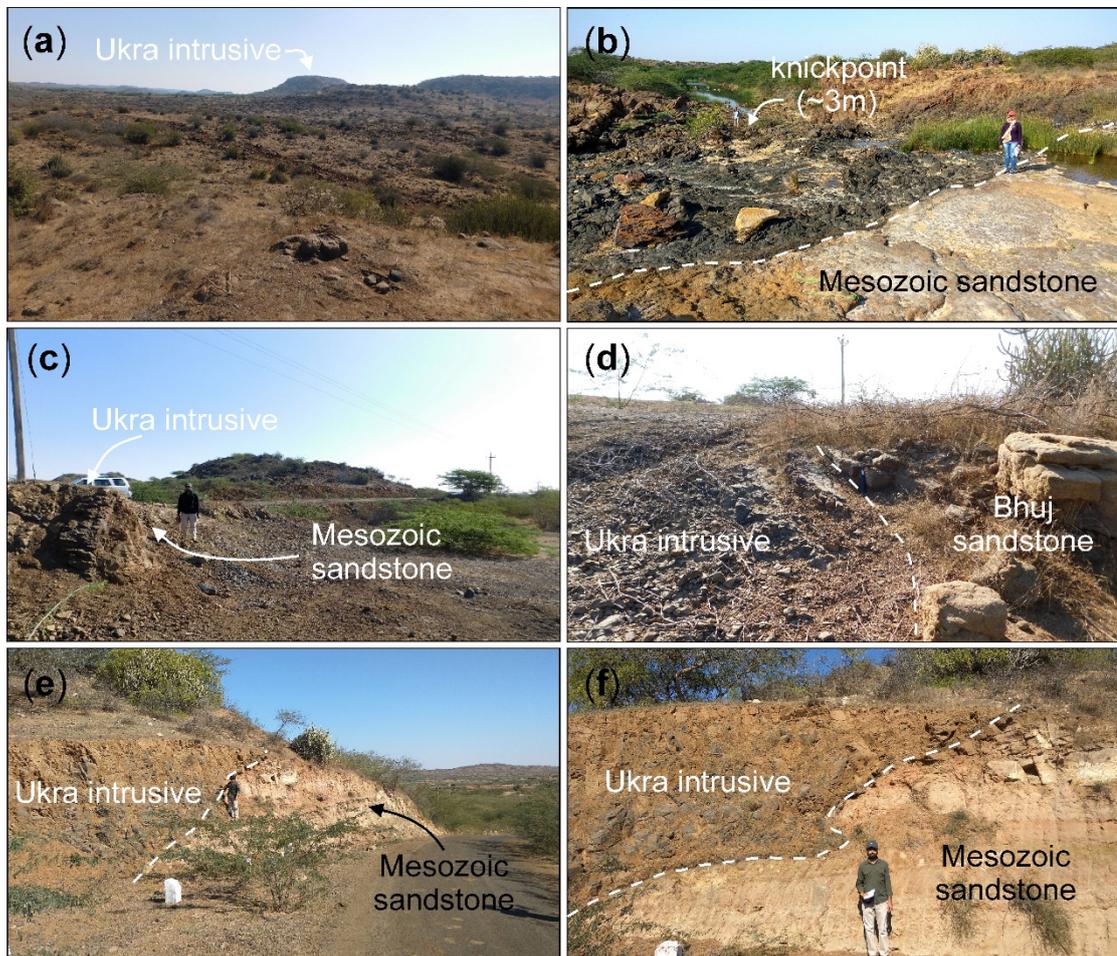


Fig. 3.9. Field photographs showing the variation in the nature of contact of the Ukra intrusive with the Mesozoic rocks. (a) View of the rugged hilly topography developed over the Ukra intrusive body to the south of Haroda. (b) Discordant contact of the Ukra intrusive in Gandi river to the north of Lakhapar. The intrusive forms a ~3 m knickpoint across the river channel at the far side of the photograph. (c) Discordant southern contact of the Ukra intrusive near Khatiyun. Notice the dyke like nature of the intrusive and the upward Mesozoic strata at the edge of the road. (d) Concordant contact of the Ukra intrusive with the overlying beds of Bhuj Formation to the west of Lakhapar. (e) Northern contact of the Ukra intrusive in a road cutting in close vicinity to the Jaramara scarp at its western end. (f) Close view of the contact shown in e. Note the general discordant nature of the intrusive as it cuts across the strata and the tendency of the intrusive to below the bedding plane.

The intrusive body shows a complicated structural setting (Fig. 3.9). To the SW of the study area, the southern margin shows a faulted contact while the northern contact is conformable as seen in the deeply incised outcrops along the Gandi river

that encircles the western margin of the Jara dome (Figs. 3.9b, c and d). The Ukra intrusive body attains its maximum width on the backslope of the Jaramara scarp. Here, both the southern and northern contacts of the intrusive are discordant and appear to mark sub-parallel vertical fault lines. Several transverse faults cut through the intrusive body and extend northwards into the Mesozoic rocks. Between Siyot and Lakhapar, the intrusive become truly a sill with both contacts concordant (Biswas, 1993). However, its northern margin here is very close to the crest of the Jaramara scarp and the contact shows the characteristics of both concordant and discordant nature (Figs. 3.9e and f). Further eastward, it is expressed as a narrow dyke before attaining the true form of a large discordant intrusive body around Haroda. Between Lakhapar and Khatiyun, the outcrop of the intrusive narrows down as it becomes a dyke (Figs. 3.9c and d) and turns sharply towards the east. Further eastward, it narrows down to form a dyke close to the waning eastern part of the Jaramara scarp before it turns around the Jumara dome in the form of a sill extending up to the KMF scarp. Though the Ukra intrusive displays widely varying relations with the surrounding Mesozoic rocks, the overall discordant nature of the igneous body is evident as it cuts across all Mesozoic Formations.

The KMF Scarp

The KMF scarp is a north facing steep scarp that delimits the rugged rocky topography of the Jumara and Jara domes. The elevation of the scarp varies from 30-50 m and abruptly rise above the flat surface of the Great Rann (Figs. 3.5e, f, g and h). The Great Rann is a vast saline terrain that emerged out of the sea during historical time (Maurya et al., 2013). The scarp therefore marks a sharp physiographic break with a rugged hilly topography over Mesozoic rocks in the southern upthrown block and the flat sandy surface comprising Holocene shallow marine sediments of the Great Rann in the northern downthrown block. The scarp-line is discontinuous and is developed over steeply dipping strata forming the northern limbs of the domes.

To the north of Jumara dome, the scarp trends in E-W direction while it is highly discontinuous in the Jara dome and trends in NW-SE direction. The change in the trend of the scarp is consistent with the varying strike of the rocks comprising the northern limb of the domes. Between, the two domes, the scarp is developed over the Ukra intrusive rocks that forms a remnant erosional patch in the interdomal structural low (Fig. 3.5j).

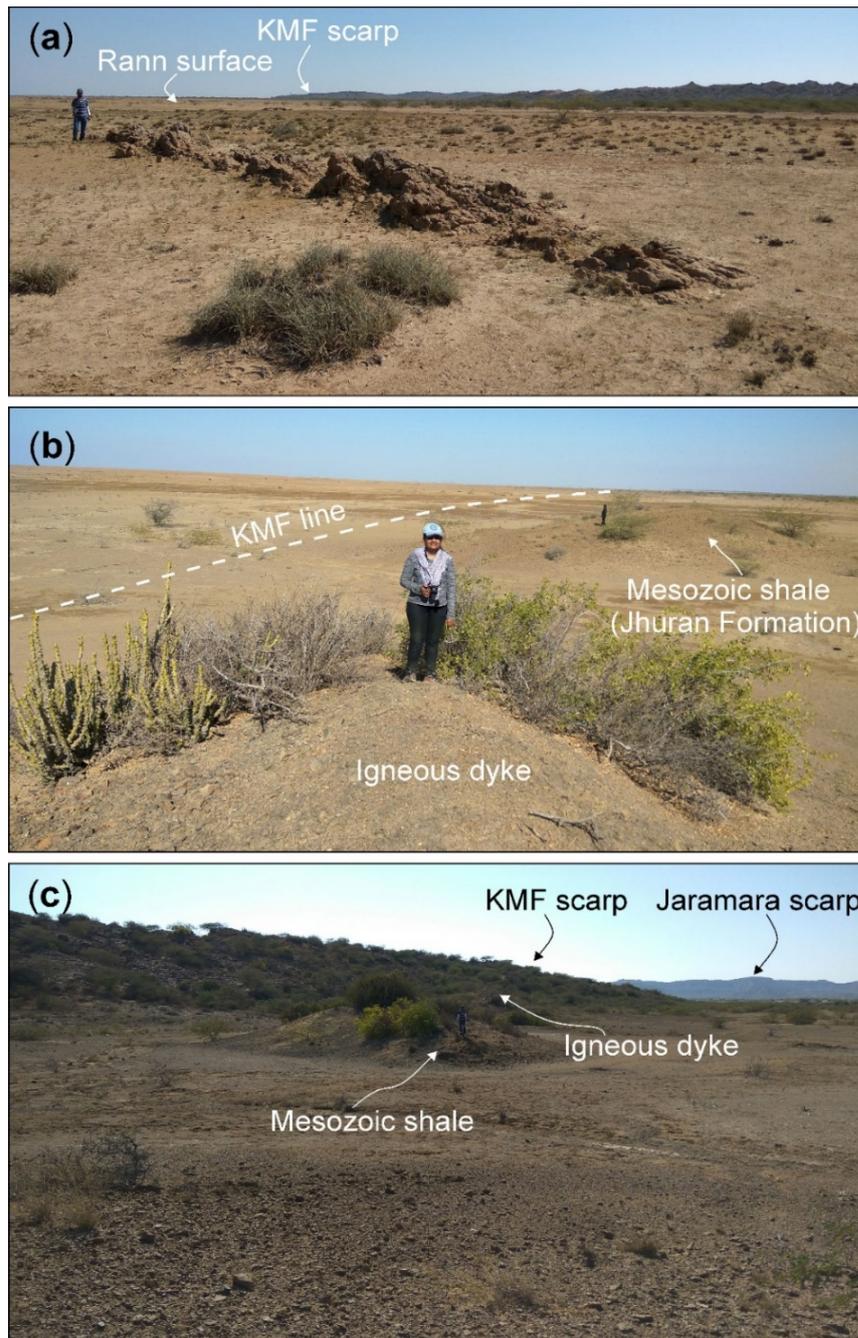


Fig. 3.10. (a) View of the northernmost exposure of the vertical beds of Jhuran Formation in the Great Rann which provides an indication of the possible location of the KMF trace in front of the scarps. The KMF scarp visible in the background is formed in the north dipping rocks of Jumara Formation. (b) Northward view of the terrain in front of the KMF scarp shown in a. In the foreground is an igneous dyke that continues from the dome and terminates abruptly where the person is standing. At the far end is a small exposure of shales belonging to Jhuran Formation. The dashed line shows the approximate trace of the KMF buried below the Great Rann sediments. (c) Southward view of the terrain shown in b. The person is standing on the dyke that continues further south into the Jumara dome. The low scarp behind the dyke exposure is the KMF scarp formed in the north dipping rocks of Jumara Formation. The Jaramara scarp is visible at the far end on the extreme right of the photo.

The present KMF scarp is therefore a retreated fault scarp with the actual fault located further north and buried under thick Quaternary sediments of the Great Rann. The approximate location of the KMF is in the subsurface further north and is indicated by competent beds jutting out of the Rann surface to the north of the scarps (Fig. 3.10a). The Great Rann sub-basin shows ~300 m thick Quaternary Sediments underlain by complete sequence of Tertiary and Mesozoic Formations (Biswas, 1987). This indicates that all the sediments generated by erosion of the upthrown block were accommodated in the adjacent Great Rann sub-basin comprising the downthrown block.

The most dominating landform of the area is the vertical and almost undissected north facing Jaramara scarp (Shaikh et al., 2018). 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 (Shaikh et al., 2018). 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 attributed to the presence of the large Ukra intrusive body on its backslope.

Gugriana Hill Range

The Gugriana Hill Range is an uplift consisting of a group of folds, has been described as a “fold-zone” because it consists of sub-parallel folds associated with a series of step faults unlike a “flexure zone” which consists of a flexure along a master-fault (Biswas, 1993). To the west of Nakhatarana, in Vigodi-Khirasra-Gugriana area, a system of step-faults has produced a zone of local uplifts (Biswas, 1993; Shaikh et al., 2020). Following a regional structural style, each uplift comprises an asymmetric anticline with a chain of domal closures along a fault on its upthrown side. This zone of folding which trends NW-SE, is sub-parallel to the western part of the northern chain of folds. It is seemingly continuous with the Charwar uplift and together they

form a central longitudinal high in the Mainland, parallel to the Northern Range (Biswas, 1993).

The folds occur within the fault wedge bounded by the main faults and their bifurcations. Khirasra brachy anticline with two subsidiary closures is the biggest structure associated with the Gugriana and Khirasra faults. The other folds associated with this fault are Walka Mota brachy anticline and a small anticline which occurs between Paneli and Kora. A series of domes of various shapes and sizes occur along the longest Vigodi fault. Of these, Vigodi brachy anticline, to the east of Khirasra fold, is the biggest. Several domes occur to its north, diminishing in size northward with the decreasing throw of the fault. This string of domes resembles on a much smaller scale, the northern chain of domes.

The structures in this fold zone are separated by faults and any complementary syncline or saddle is lacking. One and a half mile NNW of Lakhmipur a broad half dome occurs. It is bounded by the Netra fault on the north-eastern side. The Rawapar dome which is an isolated, elliptical and dome bounded by faults on all sides, occurs to the north of Rawapar. Like the folds in the other zones, these folds are also elongated parallel to the faults. The closures within the folds, produced by cross faults, give rise to higher order domes of varying shapes and sizes.

Central Rocky Plain

The Central Rocky Plain is an elongated NW-SE trending undulating plain between the NHRFZ in the north and the Gugriana Hill Range in the south. The plain is developed over the Jhuran and Bhuj formations that show gentle to sub-horizontal dips towards south. While the GUF passes through the northern margin of the Gugriana Hills, the VF passes through the centre of the rocky plain. Both faults trend in NW-SE direction and show reverse nature (Shaikh et al., 2020). For most of its length, the VF shows a narrow, NW-SE elongated ridge. In the eastern part of the rocky plain, another sub-parallel fault branches out from the VF which is known as the WVF (Biswas, 19993; Shaikh et al., 2020). Several cross-faults that offset the GUF and the VF are also found in the rocky plain. All fault lines are well exposed in the rocky plain with several slip planes with striations (Shaikh et al., 2020). The general slope of the plain is towards SE. The minor drainages originate from the NHRFZ and the Gugriana Hill Range. All drainages flow towards the rocky plain between the ranges and meet the Nara river. The Nara river flows SE in conformity with the slope before taking abrupt northward turn near Meghpar. Major part of the

rocky plain in the study area is drained by the Nara river. The eastern part of the rocky plain in the study area is drained by the north flowing Makdawali river. The fluvial characteristics of the rivers flowing through the rocky plain are described in the next chapter.

Great Rann

The Great Rann is a structural depression to the north of NHRFZ. The tectonic depression is attributed to down-faulting along the KMF (Biswas, 1993). The depression was filled up by Tertiary sediments overlain by Quaternary sediments (Biswas, 1993). The upper section of the Rann sediments comprise shallow marine sediments deposited during the Holocene (Maurya et al., 2013). The Great Rann opens up westward in to the Arabian sea near Lakhpat. Geomorphologically, the Great Rann is characterized by flat surface with imperceptible slope towards north near the KMF scarp and a general westward slope away from it. The hyper-saline surface of the Great Rann is attributed to the drying of the sea during late Holocene (Biswas, 1974). The flat surface of the Great Rann terminates against the north facing KMF scarps. The KMF is located to the north of the scarps and is buried under the Great Rann sediments except in the area around Ghuneri.