# CHAPTER - 7

# ACTIVE FAULTING ALONG THE KATROL HILL FAULT

Offsetting of Quaternary deposits is the most direct evidence for suggesting reactivation of a fault. The tectonic and geomorphic setting of the KHF with a thin cover of Quaternary sediments is ideal for preservation of such evidence. Detailed field studies were carried out in the Khari River basin, the largest river arising from the Katrol Hill Range and flowing towards the north, crossing the KHF (Figure 7.1). Detailed mapping of the Quaternary deposits, especially those overlapping the KHF fault zone was done so as to locate offsetting in these deposits as a consequence of reactivation of KHF (Figure 7.1).

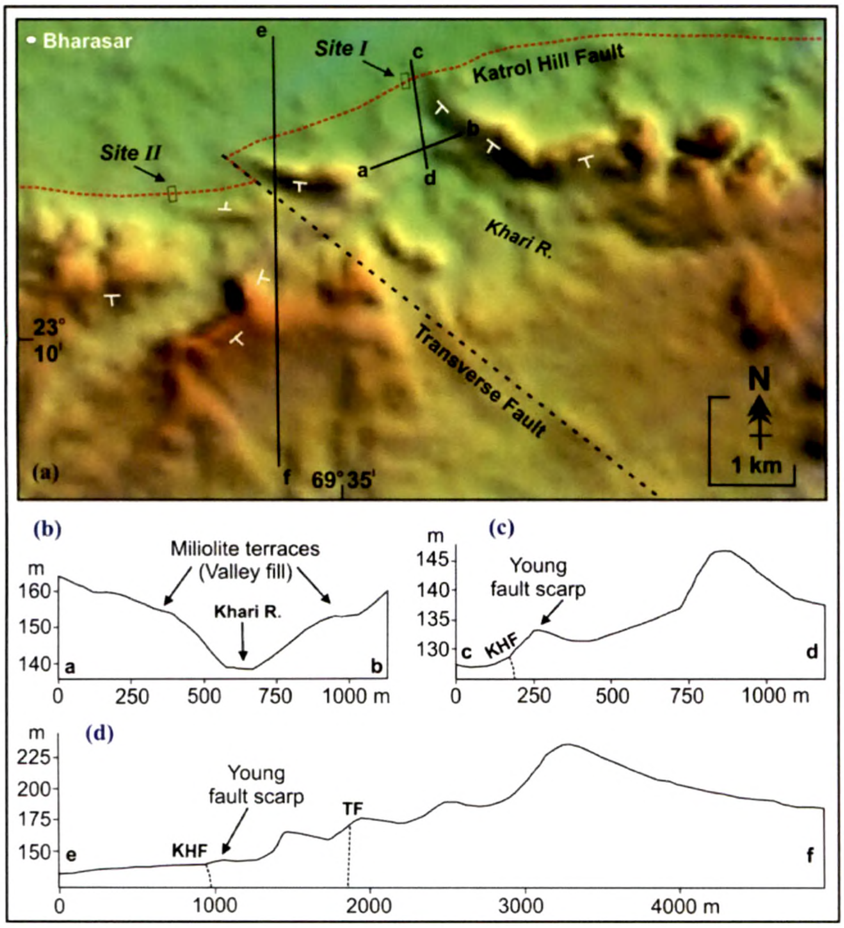


**Figure 7.1** (a) SRTM image of the area to the south of Bharasar showing the geomorphic and structural setup in the upper reach of Khari basin (Source-http://srtm.csi.cgiar.org). Note the variations in the dip of the strata due to doming of the older Mesozoic Formations. The location of the fault is based on present study. (b) Topographic section across the Khari River parallel to line a-b, showing 10-15 m high paired terraces of the valley fill miliolite. (c) Topographic section across the KHF. Note 5-6 m high young scarp to the south of KHF and geomorphological contrast across the fault. (d) Topographic section showing rugged topography of the Katrol Hill Range and position of the KHF and transverse fault.

The Khari River shows significant amount of incision. Paired river terraces and hanging fluvial valleys have formed (Figures 7.1, 7.2) within the vicinity of the KHF in the Khari River basin (Patidar et al., 2007, 2008). The offsetting and deformation of Quaternary deposits is observed in the Khari River basin. Field documentation and mapping of neotectonic indicators is carried out to understand the relation and nature of the KHF with younger deposits.

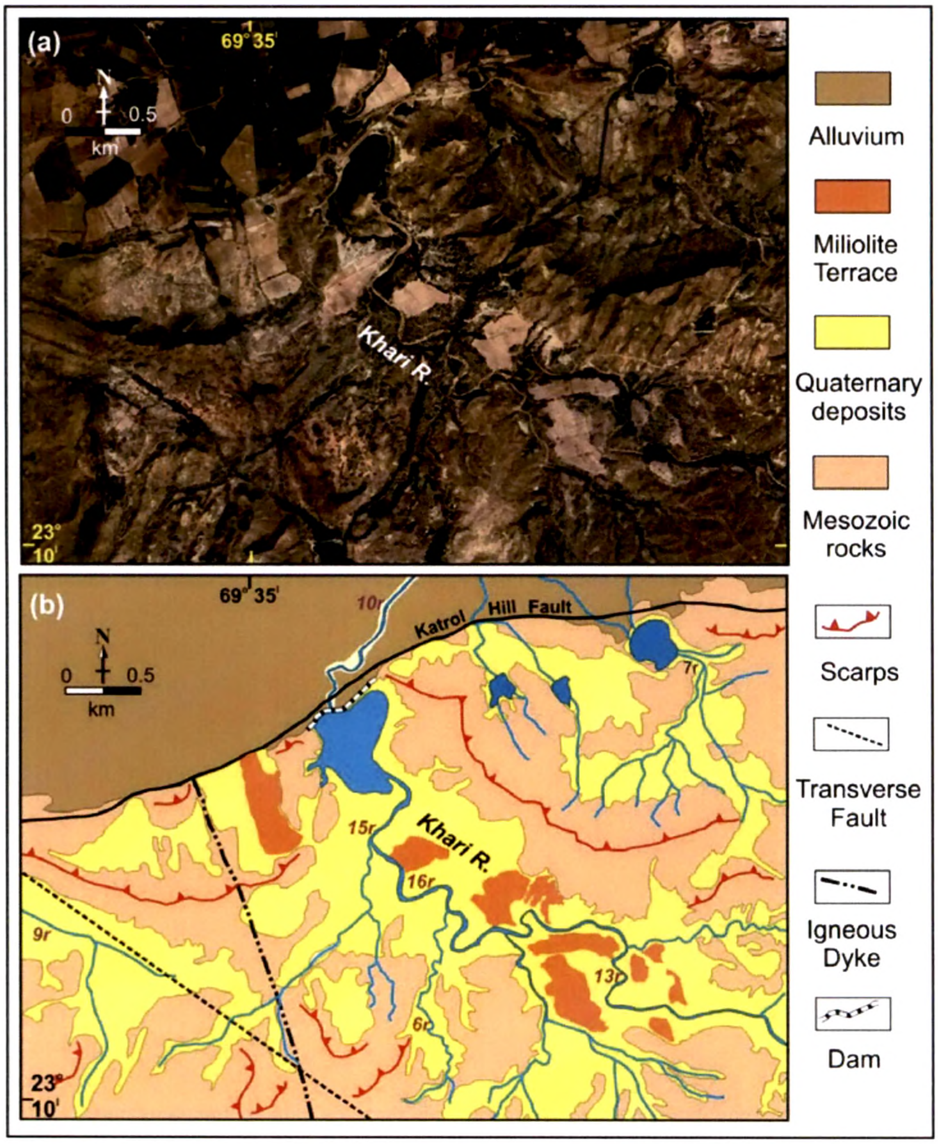


**Figure 7.2** (a) Satellite image showing sharp geomorphic contrast across the KHF and highly sinuous nature of the Khari River. (b) Geological map of a part of Katrol Hill Range showing paired miliolite terraces incised by Khari River, scarps, KHF, transverse fault and dyke.

## EVIDENCE OF ACTIVE FAULTING

### Site I:-

This site is located along the Khari River just north of the scarpline (Figure 7.1). Here the Quaternary sediments are seen overlying the Mesozoic rocks. The KHF passes across the Khari River at this site and trends in NE–SW direction (Figure 7.1). The fault, exposed on the river floor, marks the lithotectonic contact between the Bhuj Formation to the north and shales of the Jhuran Formation to the south (Figure 7.2). The cliff section exhibits Mesozoic rocks overlain by 7 m thick Quaternary sediments (Figure 7.3). The overlying Quaternary sediments show offsetting along two faults (F1 and F2) with associated micro faults.

Unit A comprises the oldest Quaternary deposits of bouldery colluvium, which is displaced by 7 m along the SE-dipping KHF. The bouldery fragments of shale and sandstone of pre-Bhuj Formation having 40-50 cm diameter at the base of unit A show unconformable contact with the underlying south-dipping Mesozoic rocks. Total thickness of this unit is about 4 m and the size of unsorted boulders is found to gradually reduce towards the surface. The gravelly clasts of unit A are oriented along a steep-dipping fault plane prior to offset by the gentle SE-dipping KHF. The top of unit A in the SE block is at ~9 m, while the same occurs at ~2 m in the NE block (Figure 7.3), which gives a total vertical offset of ~7 m within the Quaternary sediments overlapping the KHF (Patidar et al., 2008). The base of unit A is not exposed on the foot wall to the north. Thin, discontinuous, clast-rich layers are also seen in unit A. This unit correlates with the basal colluvium found to occur below the miliolites all along the KHF and is inferred to be of middle Pleistocene age.

The overlying unit B comprises mostly sands with layers of gravelly sand. The thickness of unit B is 0.5 m in the hanging wall, which abruptly increases up to 2 m in the foot wall. Unit B shows offsetting along both the faults. Thin layers of fine gravel sandwiched within this unit also show deformation and offsetting by minor faults (Figure 7.3). In the foot wall, a thick layer of 0.75–1 m of coarse homogenous fluvial sands, designated as unit C, rests over unit B. This unit is missing in the hanging wall. Overlying unit C is a 1.5–1.7 m thick, well-lithified, miliolitic sand deposit named as unit D. The higher degree of compaction of this unit can be attributed to the presence of carbonate content. The continuity of unit D is also missing in the hanging wall. The composite sediment package comprising units B-D lithologically correlates with

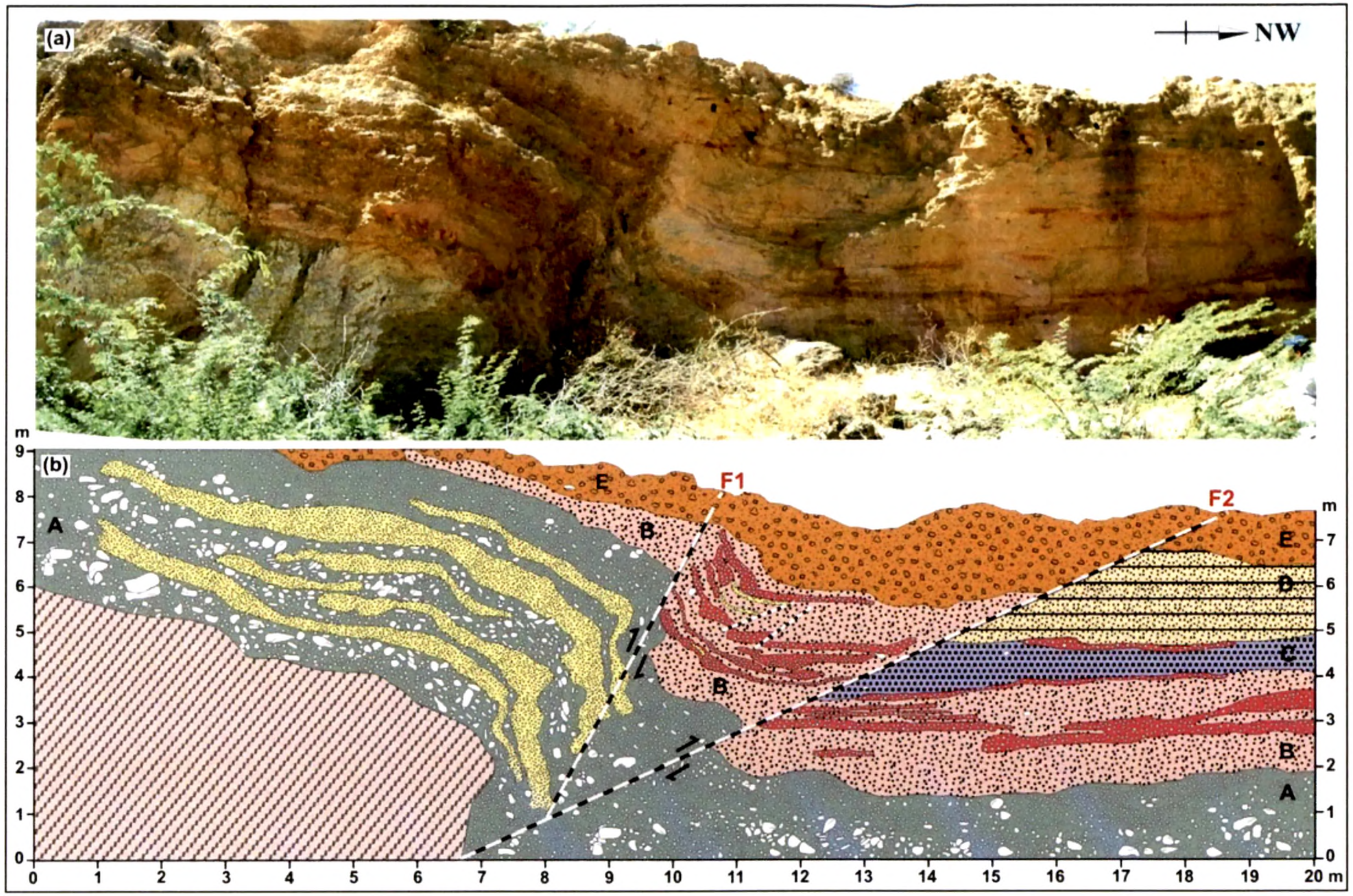


**Figure 7.3** (a) Exposed cliff section along the Khari River to the SE of the Bharasar showing offsetting in the Quaternary sediments along KHF. (b) Overlay of the cliff section showing the lithology and deformation in the fault zone and the splaying nature of KHF in Quaternary deposits. A- bouldery colluvium, B- gravelly sand, C- coarse sand, D- stratified miliolitic sand, E- scarp derived colluvium.

valley fill miliolite dating back to late Pleistocene. The overlying alluvium is absent in the exposed section. The topmost layer of the section is 1.25-1.5 m thick and is named as unit E. A thin apron of unit E consisting of angular and unsorted debris correlates with the scarp-derived colluvium of late Holocene age (Table 4.1) described by Patidar et al. (2007). This unit continues from the hanging wall to the foot wall and shows offset along F2 only (Figure 7.3).

The various units described above show erosional bases. However, the major erosional contacts are between units A and B, as well as between D and E. These mark major phases of erosion, which serve to categorize the total observed offset into discrete events of faulting (Figure 7.4). Accordingly, three events or phases of reactivation of the KHF have been delineated. The first event post-dates the deposition of unit A (Event 1), which led to the formation of the steeper fault (F1) as a consequence of upward propagation of the KHF, followed by the development of erosional surface over it. This was followed by deposition of fluvial sediments comprising units B, C and D, with minor breaks in sedimentation. The second event occurred after the deposition of unit D (Event 2), which was again followed by erosion (Figure 7.4). During this event, the second fault with gentler dip (F2) was formed. However, the offset related to this event was recorded along both faults. The wedge formed between the two faults resulted in the preservation of a major part of unit B, which also shows several sympathetic minor faults. The overlying units C and D and major part of unit B were not observed in the hanging wall due to post-faulting erosional activity. Over this erosional surface, unit E which comprises scarp-derived colluvium was deposited (Figure 7.4). The offset observed in this unit along both faults forms the third event of faulting (Event 3).

During each of the three faulting events, the KHF clearly appears to have displaced the then existing topographic surfaces as it propagated upwards (Figure 7.4). Based on the correlation of the offset sediments with the available stratigraphic set-up of Quaternary deposits, that Event 1 occurred sometime in late Pleistocene, while Events 2 and 3 are tentatively bracketed to early Holocene and <2 ka respectively. The deformation observed in the Quaternary sediments is the cumulative effect of repeated faulting along the two south-dipping reverse faults (F1 and F2).

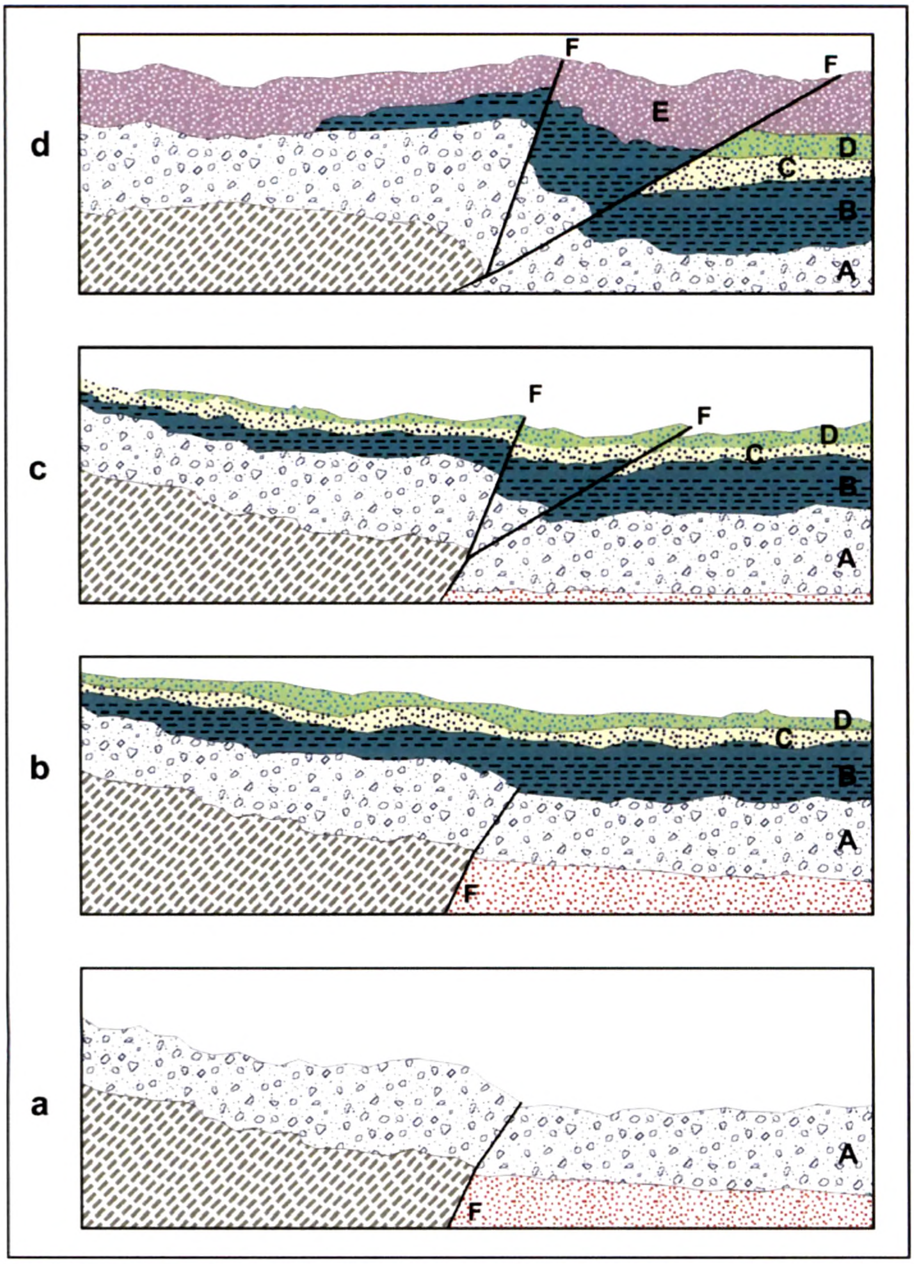


**Figure 7.4** Sketch diagram (not to scale) showing the active faulting events as observed in the exposed section shown in Figure 7.3. (a) Deposition of bouldery colluvium unconformably over the Mesozoic rocks and offsetting of the same (Event 1) due to reactivation of KHF followed by erosion. (b) Deposition of horizons B, C and D with erosional breaks. (c) Offsetting of the Quaternary sediment column due to reverse faulting along KHF (Event 2). A new fault is formed during this event of active faulting. A brief interval of erosion smoothens the topography produced by faulting. (d) Deposition of the youngest horizon E. Reverse faulting along KHF (Event 3) offsets the entire sediments cover, displacing the topography as well. Post-faulting erosion giving rise to the present topography.

**Site II:-**

This site is located to the south of Bharasar along a tributary of the Khari River (Figure 7.1). The fault plane of the KHF within the Mesozoic rocks is exposed in the channel which is stratigraphically overlain by a colluvial horizon followed by 4-5 m thick well stratified valley fill miliolites (Figure 7.5). Here the valley fill miliolites, exposed along the incised cliffs overlap the Katrol Hill Fault (KHF) and show deformation (Figure 7.6). The extensively deposited miliolite exhibits various generations on the basis of their texture and compaction. The valley fill miliolites show several gravelly layers which have preserved evidence of tectonic deformation.

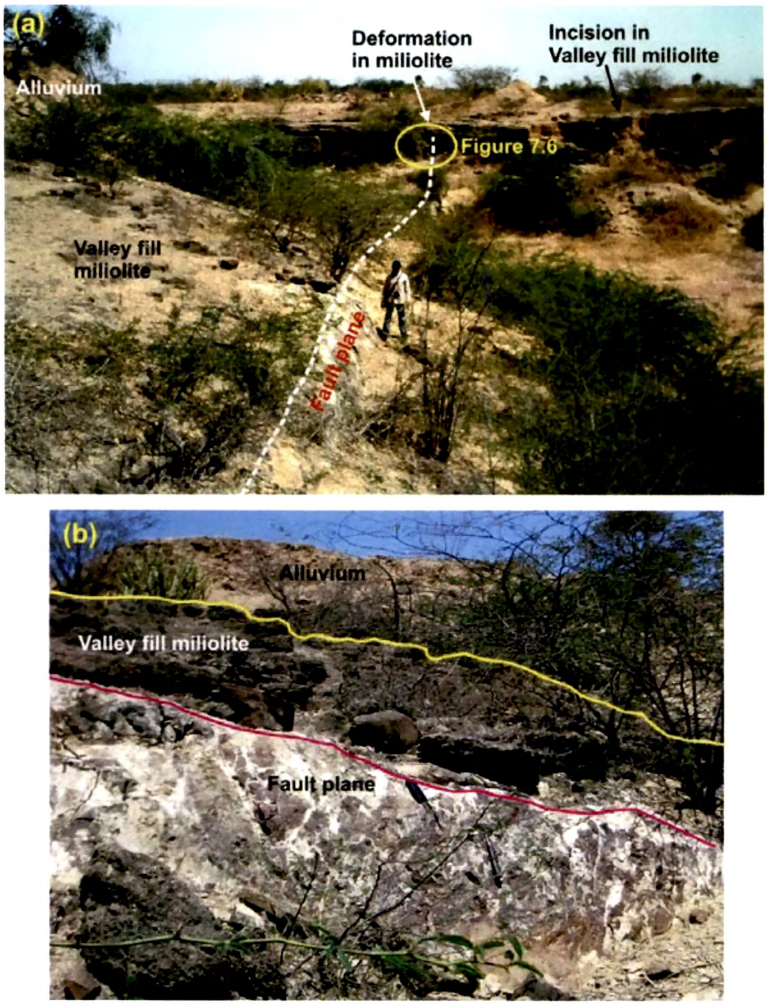


**Figure 7.5** (a) View of the KHF fault plane exposed in north flowing tributaries of Khari River to the south of Bharasar. Incision and displacement within the valley fill miliolite is shown. (b) Exposed fault plane within the channel overlain by valley fill miliolite and alluvium.

The lower unit A is stratified gravelly horizon (Figure 7.6). This unit is highly compact and extensively deposited in the valley. The overlying unit B is semi-compacted and consists of coarse sand. The offsetting of this unit is not obvious due to its erosion from the hanging wall. The fine grained well lithified miliolitic sand (unit C) rests over the unit B. This unit is relatively more compact and represents the top part of the valley fill miliolite. Unit D is a 50-60 cm thick scarp derived colluvium that shows erosional base. The offsetting is readily visible in the gravelly layers than the finer sediments which are distinguishable mainly on the basis of their degree of compaction.

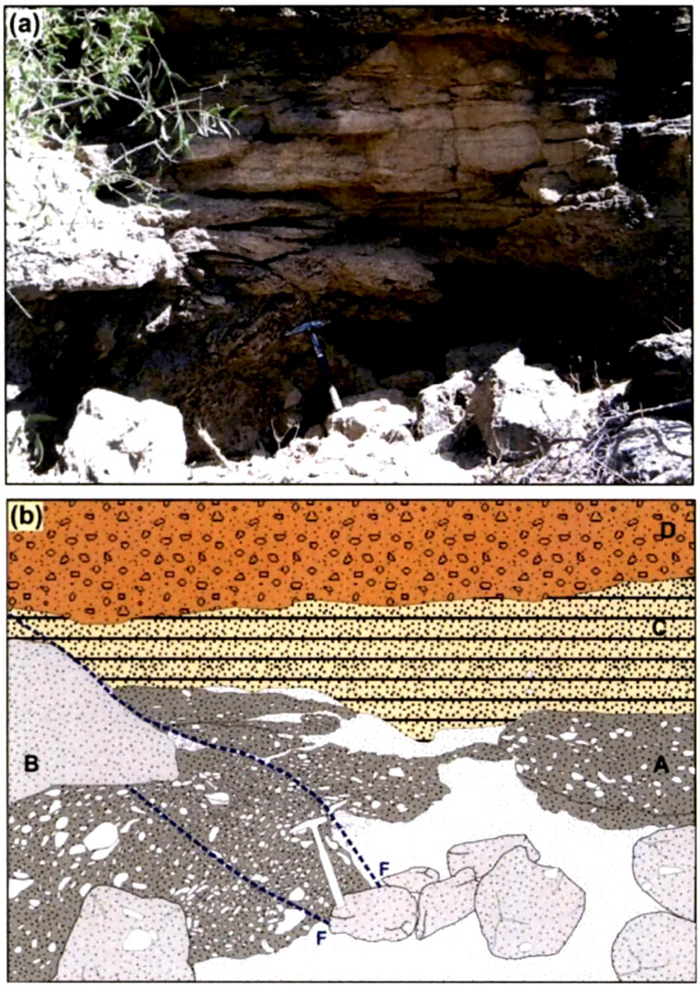


**Figure 7.6** (a) Close view of the deformation in the valley fill miliolite rock due to movement along the KHF. Note the truncation of the clasts along the fault plane. The field position of this image is shown in Figure 7.5a. (b) Overlay highlighting the layers within miliolite based on their texture pattern and compaction. A- bouldery clast rich miliolite, B- miliolitic sand C- lithified miliolitic sand, D- scarp derived colluvium.

The gravelly clasts of horizontally stratified layers of unit A abruptly truncate along a plane shown in Figure 7.6, which is an upward extension of KHF. Stratigraphically, the units B and C of site II are correlatable with units C and D of the site I (Figures 7.3, 7.6). This suggests that the deformation observed at site II can be attributed to the tectonic events delineated at site I.

**Site III:-**

This site is located about one kilometer east of Gangnath Mahadev temple. Here, extensive deposits of aeolian miliolites is found to occur in front of the range front scarps (Figure 7.7). A gentle northward slope is developed over the deposits. The aeolian character of the deposit is evidenced by the large scale dunal cross bedding and uniformly fine grained nature (Figure 7.7). The faultline of the KHF is


**Figure 7.7** (a) View of the aeolian miliolite outcrop in front (north) of the scarp line. Vertical faces of the miliolite deposits are due to mining activity. (b) Close view of the mined vertical face showing typical aeolian cross bedding. (c) Vertically dipping strata of miliolite deposits due to post miliolite neotectonic reactivation of the KHF located in the subsurface.

concealed below the miliolite deposits. No stream or ŕiver flows through these deposits. However, since the miliolite is mined for local use, low vertical faces are available for observing the sedimentary character of the deposits. The deposit is large undisturbed except in the narrow E-W treding zone that is a couple of meters wide and shows high degree of deformation. The miliolite srata show vertical dips along this deformed zone (Figure 7.7). The deformed zone is laterally traceable throughout the outcrop. The wind blown miliolite sediments appear to have been deposited in a shallow depression in front of the scarps effectively burying the KHF below them. Subsequent faulting along the KHF deformed the miliolite strata as seen by the vertical dips. The narrow zone showing vertically dipping miliolites mark the surface trace of the KHF at this site. The deformation is attributed to the post-miliolite reactivation of the KHF.

## GPR PROFILING

Subsurface studies of deformed Quaternary sequences are vital to appreciate the recent behaviour of the fault. The use of GPR has been established to demarcate the shallow geometry of the fault plane/zone, which is otherwise difficult to understand. Successful results of GPR mapping along KHF have been shown in previous chapter. To further strengthen the field observations at, Site I and Site II described in this chapter. Subsurface studies here carried out across the KHF using GPR. The preliminary aim was to identify subsurface geometry of the KHF and its upward propagation in Quaternary sediments and associated deformation pattern. Different methods of data collection were adopted with a combination of data acquisition parameters to acquire precise subsurface image of the area.

### GPR survey at Site I

This is one of the best GPR site selected after the geomorphological mapping of the area (Figure 7.1). The area exhibits extensive deposition of valley fill miliolite overlying the colluvium, which is incised by 8-10 m by north flowing forth order tributaries of Khari River. The amount of incision of youngest Quaternary deposits by seasonal rivers indicates rapid upliftment of the area due to recent tectonic movements along KHF (Patidar et al., 2008). As discussed in chapters 3 and 4 that the area to the south of Bharasar village shows prominent geomorphic expressions for neotectonic

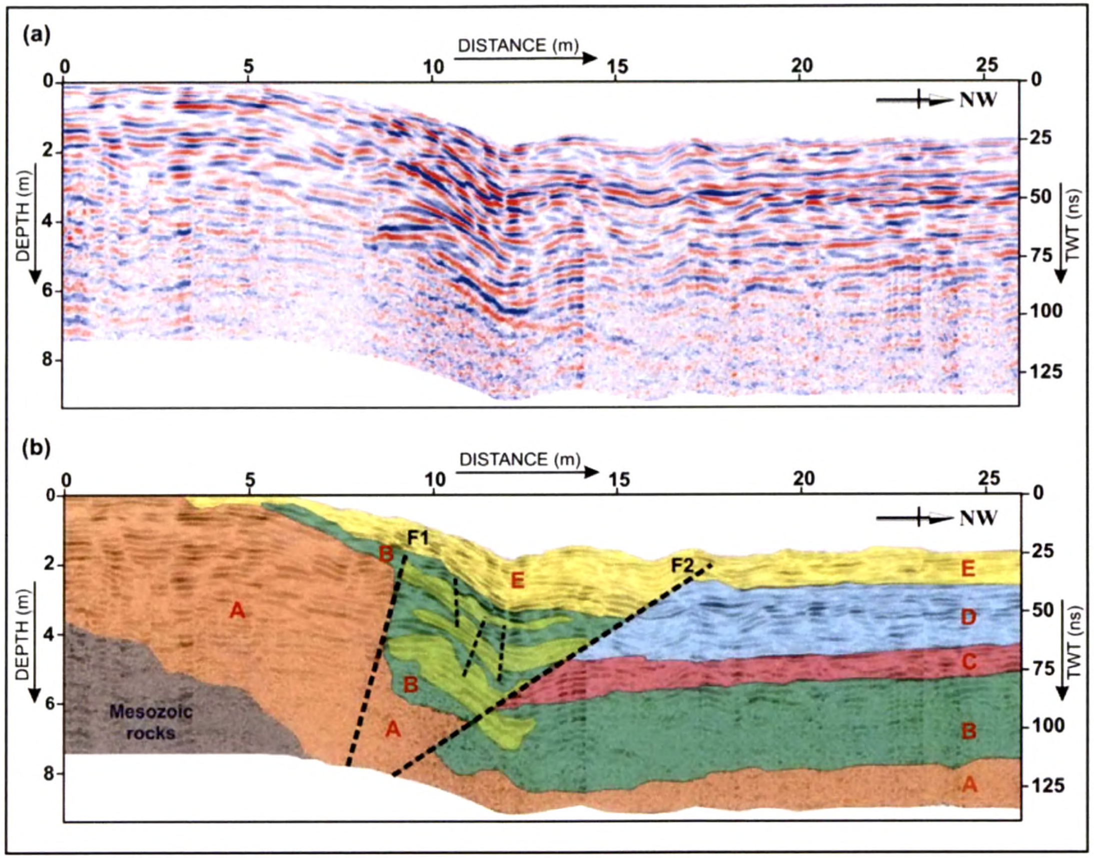


**Figure 7.8** Radar characterization of the Quaternary offset and deformation at Site I. The location of the survey site is given in Figure 7.1. (a) High resolution topographically corrected GPR profile in line scan mode raised by 200 Mhz center frequency monostatic antenna showing scattering of the signals due to SE dipping fault. (b) Overlay of the GPR profile shown in a. The units are characterized on the basis of specific reflection patterns and its correlation with the exposed cliff section. A- bouldery colluvium, B- gravelly sand, C- coarse sand, D- stratified miliolitic sand, E- scarp derived colluvium. Splaying nature of the KHF is also clear in GPR data (after Patidar et al. 2008)

upliftment along KHF. Steep north facing escarpments, entrenched meanders, gorges in miliolite, fluvial hanging valleys and paired terraces suggest rapid upliftment of the area during Quaternary period. As the Quaternary sediments apron is very thin 6-7 m in the region and the sediments are deposited in fluvial valleys, the 200 Mhz frequency of monostatic GPR antenna found adequate to penetrate the cover of clast rich Quaternary sediments. Extensive GPR surveys were carried out in this region to correlate the surface expression of faulting with subsurface discontinuities and to locate the accurate position of the KHF.

A 25 m long GPR profile raised in SE-NW direction is shown in Figure 7.8a. This profile is collected with higher number of scan/second to increase the resolution. The GPR profile is showing extensive deformation and displacement of the Quaternary sequences along a south dipping fault marked as KHF (Figure 7.8a, b). The propagation of the fault plane up to the surface is clearly seen in GPR profile. Extensive hyperbolic reflections seen in GPR profile represents to deformation along the fault plane and due to angular colluvium deposits at the middle part of the profile. The GPR data shows interesting information about the subsurface geometry of the fault plane and associated features (Figure 7.8b). At this site KHF is showing splaying nature of the fault towards surface. The fault plane is appearing as a growth fault in Quaternary deposits. The dip of the KHF is successively decreasing when it propagate upward from Mesozoic to Quaternary represent the changes in stress regime and rheology of the rocks. The GPR reflections from the upper part of the profile are correlatable with near by exposed cliff section. Interpretation of GPR data suggests vital information regarding the dip of the KHF and its upward splaying nature in young Quaternary sediments. The fault is identified as a KHF on the basis of lithotectonic contact of Bhuj and pre-Bhuj Formations exposed in the near by valley floor. The fault is marked as reverse and dipping $45^0$ due SE. The interpreted reflection patterns of the Quaternary sediments and basement Mesozoic rocks are used to interpret the other GPR profiles raised over the flat ground.

**GPR Survey at Site II**

GPR profile collected from SW of Bharasar is 45 m long in NNW-SSE direction (Figure 7.9). This site was selected after the DEM analysis and field mapping of the area (Figure 7.1). The area exhibits extensive miliolite deposits along

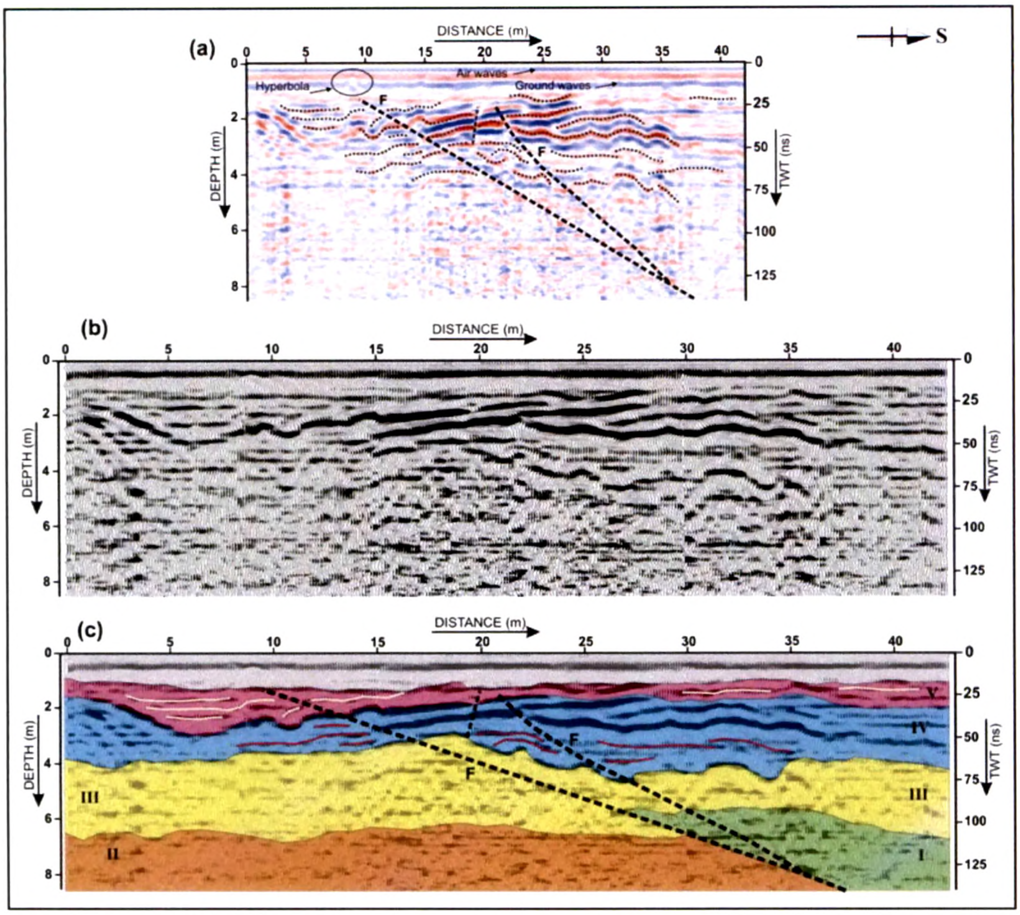


**Figure 7.9** GPR profile of site II showing subsurface nature of the Katrol Hill Fault (KHF). The location of the survey site is shown in Figure 7.1. (a) 42 m long GPR profile in linescan mode raised by 200 Mhz center frequency monostatic antenna. Truncation of the high amplitude reflections along a gentle dipping fault plane near 9 m distance can be observed. Splaying of the fault is also seen in the profile. (b) Same GPR profile in wiggle mode showing semi horizontal high amplitude reflections at the upper part of the profile where as the visibility of the reflection is not clear at the depth due to attenuation of the radar energy. (c) Overlay of the GPR profile shown in b. The units are characterized on the basis of specific reflection pattern and sedimentary sequences exposed along near by cliff sections. I- shales of Jhuran Formation, II- sandstone of Bhuj Formation, III- bouldery colluvium, IV- miliolites, V- scarp-derived colluvium.

river valleys and a dome truncating over the KHF known as Bharasar dome which is separated by NNW-SSE trending transverse fault from its eastern margin (Patidar et al., 2008). An eastward flowing second order tributary of Khari River is incising to KHF and joining to another north flowing tributary which is flowing perpendicular to the fault strike. The fault plane is preserved within the Mesozoic rocks at 4-5 m height of the present day valley floor. About 8-10 m thick valley fill miliolite and colluvium is exposed along the river banks, resting over the Mesozoic rocks. The fault plane is crossing to an eastern bank of a stream and showing extension in upper sequences of Quaternary deposits where the signatures of movements are marked in miliolites (Figure 7.5). Here, the north trending sequences of miliolites are abruptly truncate over a plane.

To find out the nature of deformation and dip of the fault plane detailed GPR survey was conducted. A 45 m long profile in N-S direction is raised over the miliolite terrace (Figure 7.9a, b, c). Most of the reflectors observed in the profile are nearly parallel. A dislocation of the reflections occurs in the center part of the profile. Although the fault displacement is not large, the discontinuity of the reflector units along the fault is obvious. The repetition of sedimentary strata of similar nature in thick miliolite deposits makes difficult to analyze the actual offsetting along the fault plane (Figure 7.9c). The reverse character of the fault can still be determined by the offsets of the reflections throughout the depth. The fault plane is dipping $50^{0}$ due south in GPR profile which is less then the fault plane exposed in Mesozoic sequences. The presence of the domes in the hanging wall of the KHF to the south, its reverse nature and reduction of the fault dip towards younger sequences suggest that reactivation of the fault in compressive stress regime.

## ACTIVE FAULTING EVENTS

Geomorphologic data, evidences of Quaternary faulting and displacement in youngest sedimentary sequences provide unequivocal evidence of neotectonic reactivation of KHF. Offset in Quaternary sediments resting exactly above the KHF fault line to the south of Bharasar, conclusively proves its upward propagation and bifurcation of master fault. The observed deformation and offset is the cumulative effect of multiple events along the KHF. The total vertical offset within the Quaternary sediments is about 7 m. Based on the stratigraphy of the various horizons, at least three events are discernible as described earlier. The events can be tentatively bracketed in geologic time based on the correlation of the affected sediments with the available stratigraphic set-up (Table 4.1). At least three events of faulting are indicated which are related to reactivation of KHF during the late Quaternary. Event 1 occurred sometime in the late Pleistocene, while Event 2 occurred during early

Holocene. Event 3 is younger than 2 ka. It is significant to note that the KHF propagated up to the surface during each of the three faulting events. Each faulting event was followed by erosion of sediments from the southern block. Studies carried out so far have suggested that the KHF is a south-dipping reverse fault. The KHF has been identified as a growth fault during the Quaternary deposition and the splaying of the main fault strand is also noticed.