CHAPTER - 4

QUATERNARY STRATIGRAPHY

Studies on Quaternary sediments are of great importance in delineating landscape evolution. The Quaternary sediments overlapping the fault zones provide important clues for reconstructing the neotectonic history. These sediments help in understanding the role of neotectonic movements in geologically ancient landscapes like Mainland Kachchh.. In such areas it is important to combine geomorphological studies with Quaternary stratigraphy as it can lead to identification of neotectonic events responsible for the evolution of landscape. In the present study considerable emphasis was placed on the mapping of the various Quaternary deposits occurring in the study area. Though the study area mostly comprises rocky landscape developed over Mesozoic rocks. The distribution and nature of Quaternary sediments was found to provide important evidence for neotectonic activity. Quaternary deposits occur both within the Katrol Hill Range and to the north of the scarps overlapping the KHF. Though the deposits show patchy occurrences, a welldefined sequence of depositional phases can be recognized. A lithostratigraphic frame work of the Quaternary sediments occurring within the Katrol Hill Range and those overlapping the KHF zone, has been worked out. This has been combined with geomorphologic data to delineate major phases of Quaternary tectonic activity. The Quaternary sediments consist of bouldery colluvial deposits in front of the range front scarps, valley fill miliolites and alluvial deposits of late Pleistocene age within the back valleys and scarp-derived colluvium forming the youngest deposit. This chapter describes the mode of occurrence and stratigraphic framework of the Quaternary deposits of the Katrol Hill Range and their significance in terms of neotectonic activity along the KHF.

MODE OF OCCURRENCE

The Katrol Hill Range in general exhibits a rugged mountainous landscape that exposes well lithified rocks of Mesozoic age (Figure 4.1a, b). Even the courses of the various river valleys resemble bedrock rivers for most part of their courses as they are largely free of unconsolidated alluvial deposits. However, 15-20 m thick Quaternary deposits do occur within the Katrol Hill Range especially along the back valley reaches of the Gunawari and the Khari River (Figures 4.1c, 4.2) while to the north of the range front scarps, the deposits are patchy and mostly concentrated around the north flowing river valleys (Figure 4.3). The distribution and occurrence of

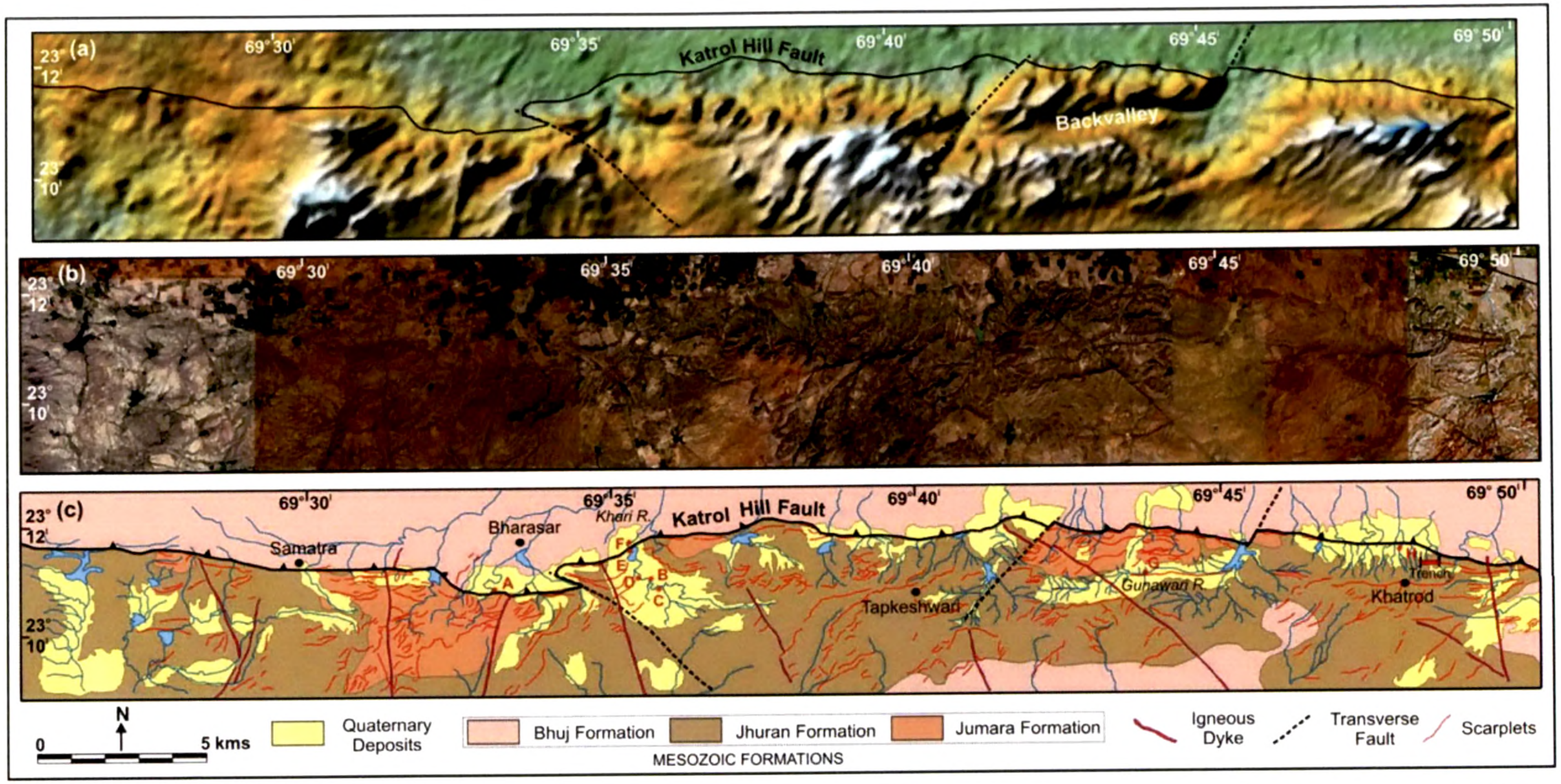

Figure 4.1 (a) Digital elevation model of the Katrol Hill Range showing sharp geomorphic contrast across the KHF (Patidar et al., 2008). (b) Satellite image of the Katrol Hill Range illustrating the geomorphology and structural set up (source-www.googleearth.com). (c) Geological map of the Katrol Hill Range prepared by field mapping and satellite image interpretation. Note the KHF marking the lithotectonic contact between the Bhuj Formation in the north and the older Mesozoic rocks in the south and the distribution of Quaternary deposits. Location of the lithologs in Figure 4.4 and the trench in Figure 4.10 is also shown.

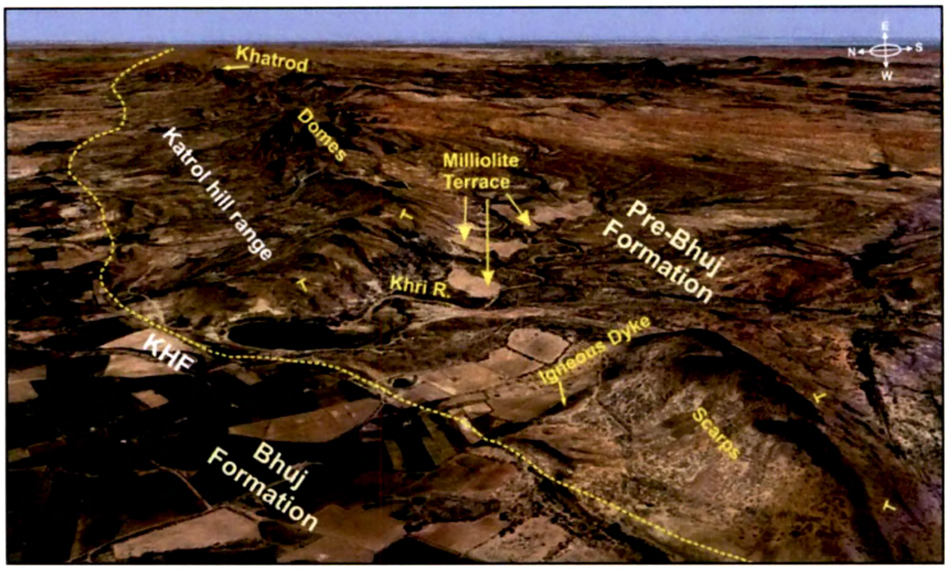

Figure 4.2 Three dimensional view of Katrol Hill Range showing the scarp line and gently dipping southern flanks of the domes (source- www.googleearth.com). Terraces surfaces developed over valley fill miliolite along Khari River are shown.

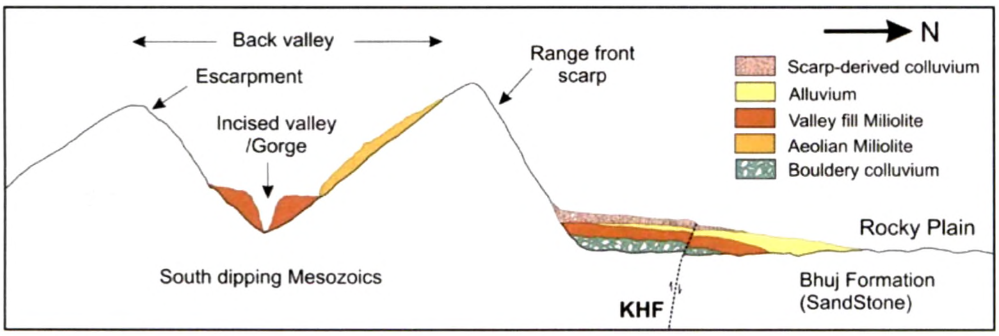

Figure 4.3 Schematic N-S section showing the generalized mode of occurrence and stratigraphic set up of the Quaternary deposits in the Katrol Hill Range. Nature of the KHF and offset in Quaternary sediments is as per the data in chapter 6 and 7.

these deposits is strongly controlled by the structural setup and show several evidence of neotectonic activity (Patidar et al., 2008). The sediments were studied along the incised cliff sections along the various north-flowing streams including those arising in the back valleys and those arising from the range front scarps. The various sediments were laterally traced along the river valleys to work out their stratigraphic relationships. Vertical lithologs of the exposed Quaternary sediment column were also prepared and are shown in Figure 4.4. Shallow trenches were also excavated to understand the nature of youngest Quaternary sediments. A detailed stratigraphy of the Quaternary deposits is difficult to work out owing to their patchy occurrences. A general order of superposition of the various kinds of Quaternary deposits along Katrol Hill Range is proposed based on their stratigraphic relationships. The Quaternary deposits occur in the form of colluvial deposits, aeolian and valley fill miliolites, fine grained alluvium (mainly silts) and scarp-derived colluvium (Figure 4.4). These deposits have been found useful for identifying phases of neotectonic activity along KHF.

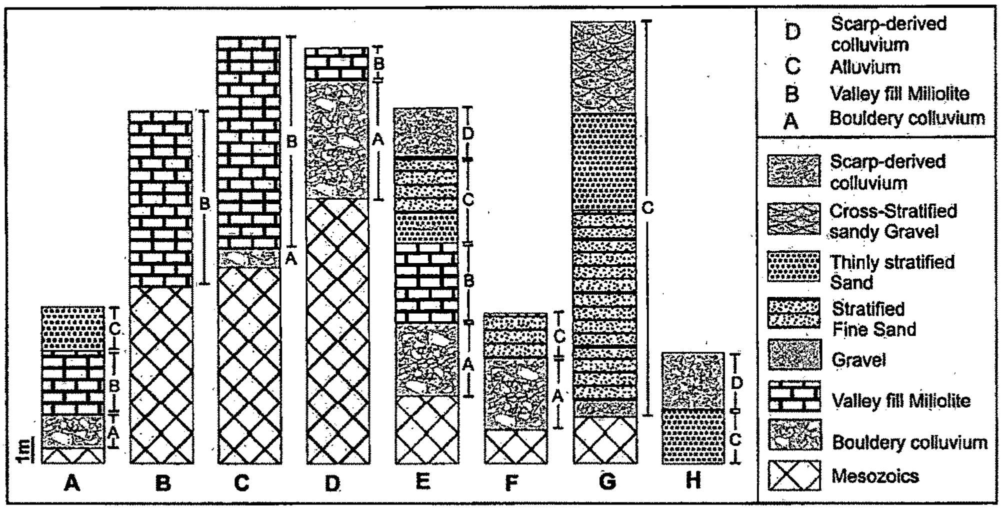

Figure 4.4 Representative lithologs of exposed Quaternary sequences along the Katrol Hill Range. Locations of the exposed cliff sections (A-H) are shown in Figure 4.1.

LITHOSTRATIGRAPHY OF QUATERNARY DEPOSITS

The sequence of the Quaternary deposits starts with the bouldery colluvium, aeolian miliolite, valley-fill miliolite, alluvium and scarp-derived colluvium (Figure 4.3, Table 4.1). These Quaternary deposits are incised by various northflowing Rivers. The bouldery colluvium contains large fragments of shale and sandstone and is overlain by miliolites along the Katrol Hill Range. The miliolite deposits of the area are separated into two categories. The older miliolites occur on hill slopes which comprise well lithified, fine-grained miliolitic sand and are of aeolian origin (Figure 4.3). They also occur as obstacle dunes and occupy topographic depressions and hollows in the slopes of high hills and ridges. The valley-fill miliolite occurs along incised cliffs (Figure 4.3) and shows stratification with pebble-to-cobble size clasts of Mesozoic rocks, suggesting the role of fluvial activity in their deposition (Figure 4.4).

Valley-fill miliolites are also found in the backvalleys created within the Katrol Hill Range between the crestline and drainage divides. Since they are derived from carbonate-rich sand from miliolite rocks, these deposits show varying degrees of compaction. The fine-grained alluvial deposits are found to overlie the miliolites and occur in patches within the Katrol Hill Range along various river valleys (Figure 4.4). The scarp-derived colluvium is the youngest Quaternary deposit of the area and is found at the base of the range front scarp. The deposit shows a maximum thickness of 2-3 m along various north-flowing Rivers. 230Th/234U ages of the miliolites occurring in the Katrol Hill Range vary from 130 to 30 ka, suggesting late Pleistocene age for these deposits (Baskaran et al., 1989; Chakraborti et al., 1993; Somayajulu, 1993). Based on the stratigraphic relationship of other Quaternary deposits with miliolites, a general stratigraphic framework has been worked out (Table 4.1).

Table 4.1 Table showing Stratigraphy of the Quaternary deposits along Katrol Hill Range (Patidar et al., 2008).

QUATERNARY DEPOSITS	LITHOLOGY	OCCURENCE	GEOLOGICAL TIME
Scarp-derived colluvium	Angular to sub-angular pebbles and cobbles embedded in sandy to gravlelly matrix	At the base of range front scarp	Late Holocene
Alluvial deposits	Fine sands, silts and clays	Sporadically along the various north-flowing streams	Middle Holocene
Valley-fill Miliolite	Sandy sheet of miliolite with boulders and pebbles	Extensively deposited along the river valleys	Late Pleistocene
Aeolian Miliolites	Well-shorted fine grain sand with carbonate rich send	At higher elevations along the southerly directed slopes of the hill range and at the base of the north-facing range front scarps	
Bouldery Colluvial deposits	Boulder-size fragments of shales and sandstones	At the base of range front scarps	Middle Pleistocene

Significant amount of incision of exposed Quaternary sequences by young-order streams within the vicinity of the KHF indicates post depositional upliftment of the area.

Bouldery Colluvium

Colluvial deposits show scattered occurrences at the base of range front scarps, which are indicative of their degradation. These deposits form the base of the exposed Quaternary sequences and are found to thin out within a few hundred meters to a couple of kilometers towards north. Colluvial deposits prominently occur around Wavdi, Khatrod and SW of Bharasar where they are found to be sandwiched between

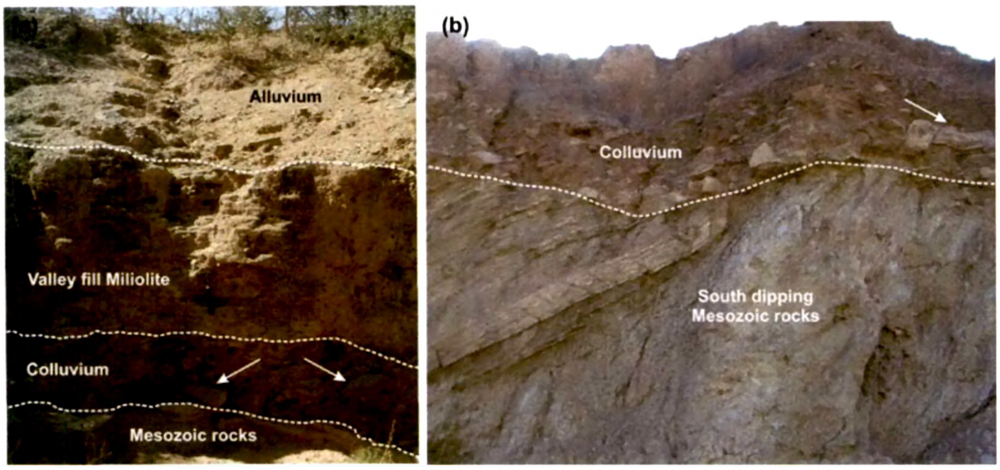

Figure 4.5 (a) Cliff section along a lower order stream located to the north of scarp line near Bharasar. Note the stratigraphic succession of the various Quaternary sediments overlying the Mesozoic sandstones. (b) Bouldery colluvium unconformably overlying the south dipping Mesozoic rocks in Khari River. Arrows point to large clasts.

the Mesozoic rocks and fluvial miliolites (Figure 4.5). These are incised by several streams that originate from the scarps and flow northward. The deposits comprise large angular subrounded boulders, cobbles and pebbles with small amount of finer sediments filling up the voids. Lithologically, the colluvium is dominantly made up of fragments of shales, thin bedded sandstones and siltstones indicating that they have been derived mainly from the formations located to the south of the KHF. The colluvial deposits are at places mantled by miliolite deposits (Figure 4.5a, b). Since no clasts of miliolites are found and the fact that it is always found to occur below valley fill miliolite, this bouldery colluvium can be attributed to a pre-miliolite phase of neotectonic activity (Patidar et al., 2007, 2008). As the miliolites have been found to represent a late Pleistocene phase of deposition, we infer a middle Pleistocene age for the colluvial deposits along the KHF has been inferred.

Aeolian and Valley-fill Miliolite

The miliolites form the most extensively occurring Quaternary sediments in the area. The constituent rock is a medium to coarse grained clastic limestone with a higher lithic content (Baskaran et al., 1989). These are described as originally carbonate rich sediments blown by wind from coastal areas and deposited as scattered obstacle dunes along the rocky slopes and hollows of the Katrol Hill Range (Biswas, 1971). Although, aeolian transport has been invoked for some of the occurrences of these deposits, the horizontally stratified sheet deposits containing cobble and pebbles, point to fluvial deposition. The wind blown miliolite deposits occupy the higher elevations along the southerly directed slopes of the hill range (Figure 4.3). Similarly a few isolated pockets of aeolian miliolites are encountered at the base of the north facing range front scarps where they appear to have accumulated in the shallow troughs between the scarps and the fault line. All these occurrences are found to be located away from the present day river valleys.

The aeolian miliolites were subsequently reworked by fluvial action evidenced by cobbles, pebbles and boulders of Mesozoic rocks (Figure 4.6) which we refer here to as valley fill miliolites as they are found to occur along the various river valleys. Most of the back valleys are found to be filled up by valley fill miliolites while the aeolian miliolites occur on upper part of the valley slopes (Figures 4.3, 4.4). The valley fill miliolites (fluvial) show a distinct episode of fluvial aggradation and the incised channels and gorges formed within them. At places these sediments provide vital information about the faulting and have great neotectonic significance (Patidar et al., 2007, 2008).

The valley fill (fluvial) miliolites preferentially occur within the back valleys along the narrow E-W zone of gorges delimited by the crest line of the scarps and the drainage divide to the south (Figure 4.7). The valley fill miliolites occur along the river valleys and show several evidence of fluvial activity, which include well stratified nature, presence of gravel rich layers, fluvial sedimentary structures like small scour and fill, cross bedding and large clasts of Mesozoic rocks. The valley fill miliolites show a gently sloping terraced surface which in contrast to the aeolian miliolites which show typical morphology of obstacle dunes with a distinct internal

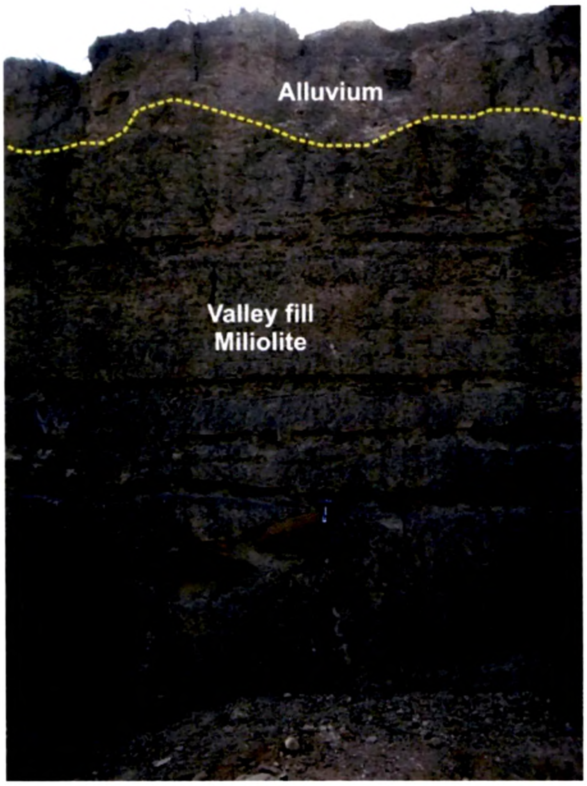

Figure 4.6 Incision in valley fill miliolite in the upper reaches of the Khari River showing large clasts of Mesozoic rocks.

large scale aeolian cross bedding and uniformly fine grain size. These deposits are found to be generally consisting of well stratified sheets and are exposed along the vertical cliff faces of the various north flowing streams. Some of the deep gorges along the back valley reaches of the north flowing rivers have been found within the miliolites. The back valley reaches of the Gunawari and Khari Rivers are found to be fully filled by valley fill miliolites (Patidar et al., 2007, 2008). The formation of 10-15 m deep narrow incised valleys and intermittent gorges in the valley fill miliolites is significant as it suggests uplift of the range due to neotectonic activity along the KHF (Figures 4.7, 4.8). A few gorges begin within the Mesozoic rocks and thereafter continue within the miliolite deposits.

The thickness of the valley fill miliolites abruptly decreases to 2-5 m to the north of the fault line which indicates that most of the miliolite material remained trapped in

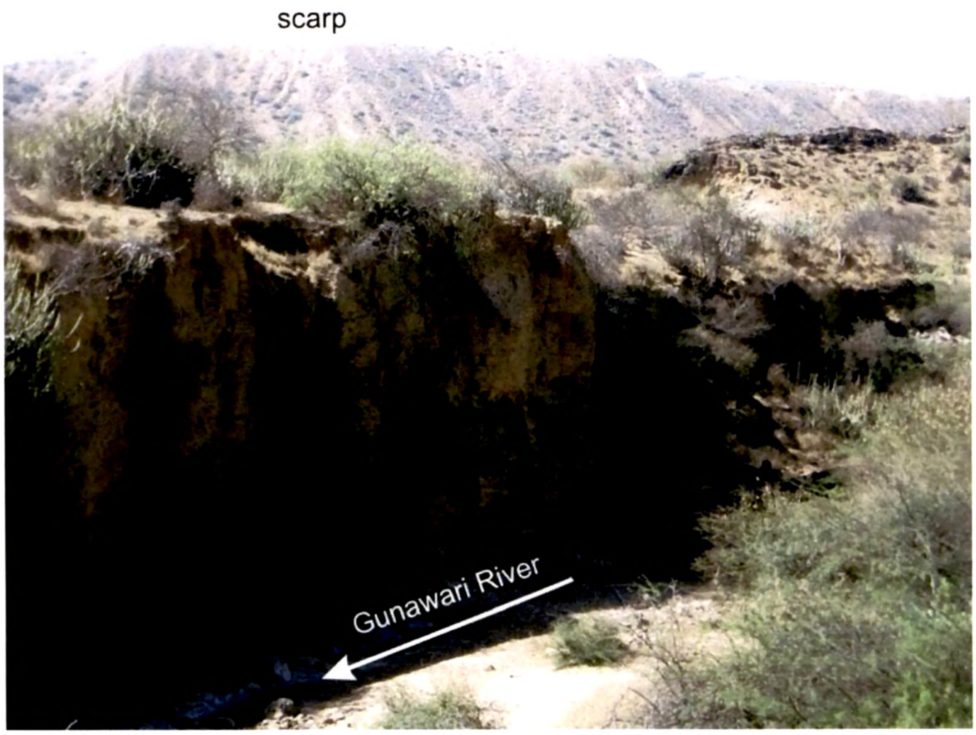

Figure 4.7 South facing view of the cliff section of Gunawari River in its back valley reach showing incision in valley fill miliolite deposits. In the background is a E-W trending cuesta scarp.

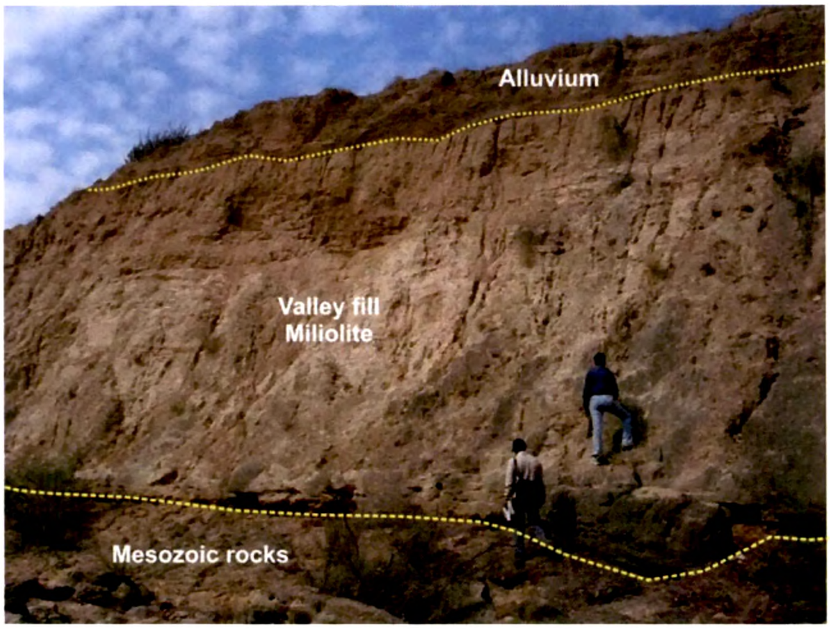

Figure 4.8 Incised cliff of thick valley fill miliolite overlain by alluvium in Gunawari River to the south of Ganganath Mahadev temple. Mesozoic rocks occurring at the base are also incised.

the back valleys (Figure 4.3) while only a very small part of the total volume of miliolite was carried across the KHF by the north flowing rivers. However, it is to the north of the range front scarps that the stratigraphic relationship of valley fill miliolites with other Quaternary deposits becomes clear. $^{230}Th/^{234}U$ ages of the Kachchh miliolites range from about 30 ka to 130 ka (Baskaran et al., 1989; Chakraborti et al., 1993; Somayajulu, 1993). The miliolites themselves occupy deep narrow valleys carved out within the Mesozoic rocks suggesting a pre-miliolite phase of neotectonic uplift. This is in agreement with the pre-miliolite phase of neotectonic activity along the KHF indicated by the bouldery colluvial deposits underlying miliolites to the north of the scarps.

Alluvial deposits

Fine grained channelized alluvium occurs sporadically along the various north flowing streams within the Katrol Hill Range. These form 8-15 m high cliffs along the river banks. These deposits are stratigraphically younger than the miliolites as at places they are found to occur in the deep fluvial valleys formed within the miliolites (Figures 4.3 and 4.4). At few locations they are found to overlie the Mesosoic rocks which are also incised (Patidar et al., 2007). Within the Katrol Hill Range, these deposits mostly comprise fine to coarse sands with layers of cross stratified gravels (Figure 4.9). In Gunawari River near Marutonk Dungar, and near Bhata Talav these deposits show faulted contact with the pre-Quaternary rocks (Thakkar et al., 1999). These faults trend either NNW-SSE or NNE-SSW. To the north of the range front scarps form wide patches that are used for agricultural purposes. Here the alluvium is seen to overlie the fluvial miliolites. The geomorphic setting and stratigraphic relationship of the alluvium with the valley fill miliolites point to a brief post-miliolite phase of fluvial deposition during the upper part of late Pleistocene. The miliolites together with the alluvium represent late Pleistocene aggradation phase as indicated by the chronologic data on the miliolite deposits (Patidar et al., 2007, 2008). The miliolites provide an important stratigraphic evidence for reconstructing the geomorphic evolution of the Katrol Hill Range. The fact that the various streams show development of narrow incised valleys and gorges within valley fill miliolites provides an important evidence of post-late Pleistocene tectonic uplift of the Katrol Hill Range. Considering the age range of the miliolites from 30-130 ka (Baskaran et al., 1989; Somayajulu, 1993), it is inferred that this phase of tectonic uplift occurred during the early Holocene.

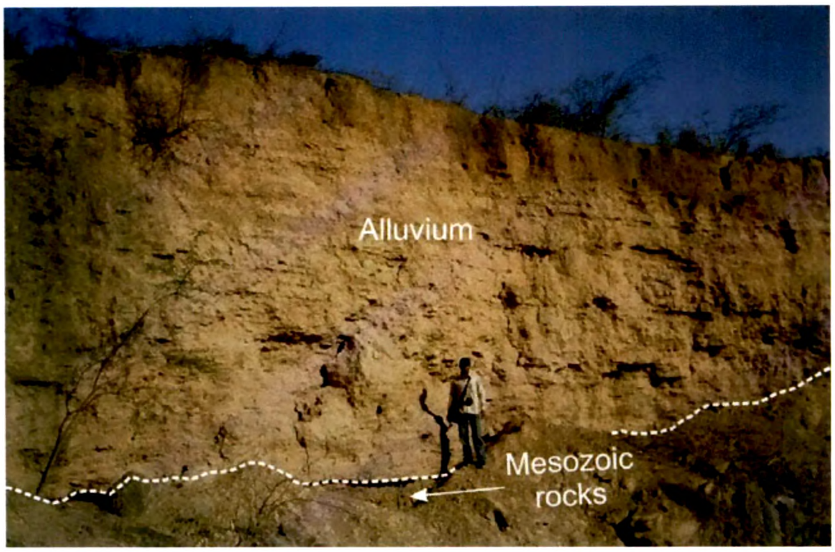

Figure 4.9 Incised cliff exposing fine grained alluvium that unconformably overlies the Mesozoic shales seen at the base along a lower order tributary of the Khari River.

Scarp-derived colluvium

The scarp-derived colluvium is the youngest of the Quaternary deposits in the study area. The deposit occurs as discontinuous gravelly apron over the older Quaternary deposits (Figures 4.3, 4.4). At places it overlies the fine alluvium whereas at other places it rests directly over the valley fill (fluvial) miliolites (Patidar et al., 2007). The deposits comprise debris as well as wash facies. In general the debris facies consists dominantly of clasts with subordinate matrix while the wash facies comprise dominantly sandy matrix with dispersed clasts and occasional nested clasts. Overall, the wash facies dominates the debris facies. These deposits indicate a significant neotectonic event along the KHF. A maximum of 2-3 m thickness is exposed along the various north flowing streams. The deposits exhibits varying degree of compaction from semi-consolidated to unconsolidated, the compacted units showing carbonate derived from the underlying miliolites. The vertical and the lateral nature of these deposits have been studied by excavating a E-W trending shallow trench (1.6 m deep and 55 m long) to east of the Khatrod scarp (Patidar et al., 2007). The trench revealed the vertical and lateral relationship of the various depositional units within the colluvium (Figure 4.10). Overall, the deposit showed crude stratification with small pockets of well bedded sediment. The trench sediments also indicate that depositional pockets tended to shift laterally during the sedimentation as evidenced by the variation of thickest parts of the individual sediment packages (Figure 4.10).

Based on lithologic characters, four major units were identified. The basal unit (Unit-I) was poorly exposed in the trench and showed the highest degree of compaction. The compaction may be attributed to the carbonate derived from the miliolites which stratigraphically underlie the scarp-derived colluvium. Compositionally, the unit consists of dominantly coarse sand with occasional large clasts. The overlying Unit-II shows maximum thickness and also maximum heterogeneity in terms of internal lithological variations and geometry (Figure 4.10). The unit is semi-compacted and comprises gravelly layers with sheet geometry with isolated and coalescing lensoid bodies of silty sand (Figure 4.10). The lateral thickening and thinning of the gravelly and sandy layers suggest shifting centre of depositional activity towards east and west. This conforms with the general setting of the sediments whereby the colluvium derived from the scarps was reworked by north flowing streams which may have migrated laterally giving rise to complicated geometry of the deposit.

Unit-III comprises the compacted layer of coarse sand with calacareous matrix. The layer is laterally persistent and maintains its thickness almost through the entire length of the trench. The Unit-IV is the topmost and is largely unconsolidated. The unit is rich in pebble to cobble size clasts with a sandy matrix (Figure 4.10). The unit is characterized by imbricated clasts which persists even in several clast rich pockets. The most conspicuous feature of this unit is the abundance of small to medium sized narrow scours. These suggest formation of small gullies by water flowing over the surface of the underlying unit that was subsequently filled up by the reworked colluvium. A minor sub-vertical fault is observed at the eastern end of the trench. No other offsets of sediment layers were noticeable which may be attributed to the E-W trend of the trench. However, a few fissures are observed which are filled with fine sand. The scarp-derived colluvium indicates degradation of the range front scarps in response to neotectonic activity along the KHF (Patidar et al., 2007).

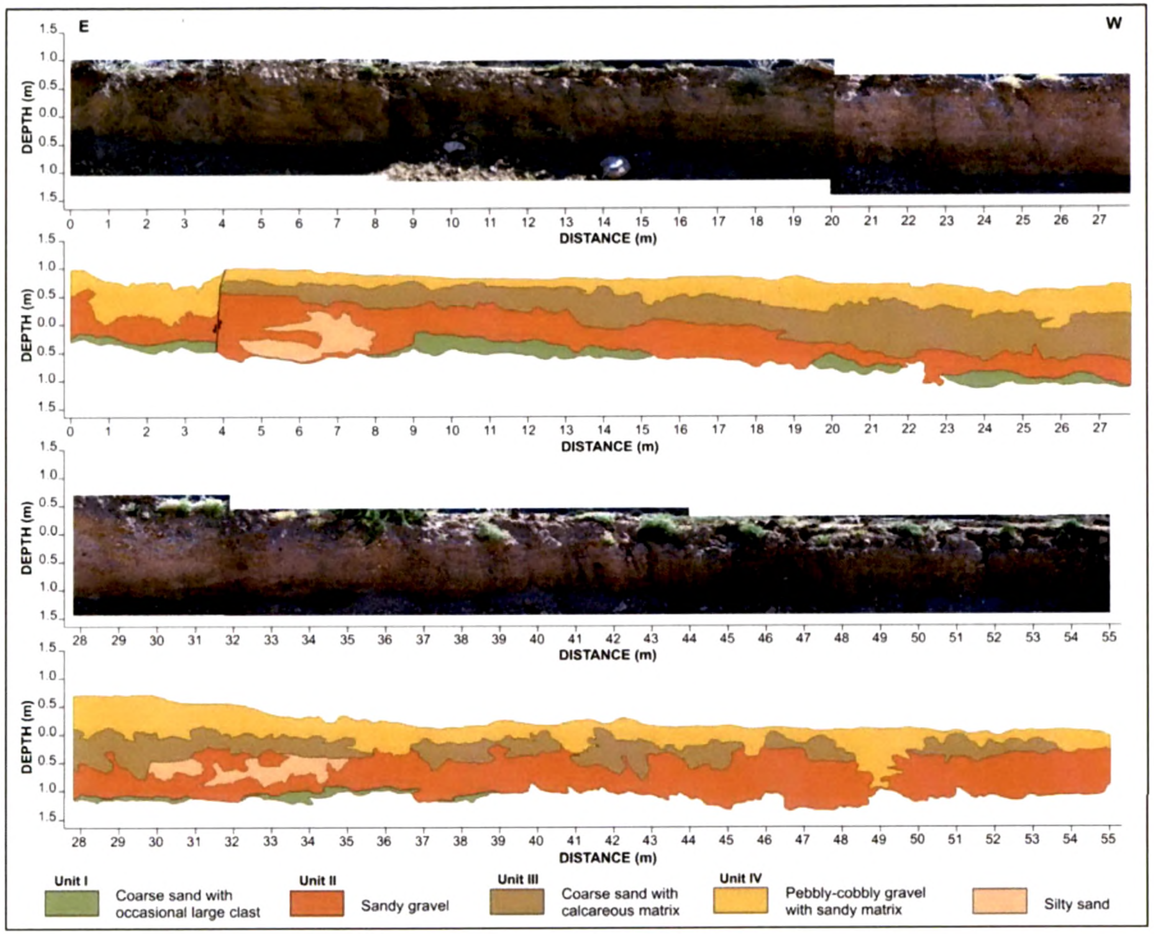

Figure 4.10 **Photomosaic of the E-W trending trench excavated near Khatrod scarp through the scarp-derived colluvium. Note the distinctly identifiable facies and a fault at 4 m.**

NEOTECTONIC ACTIVITY AS REVEALED BY STUDIES ON GEOMOPHHOLOGY AND QUATERNARY STRATIGRAPHY

The geomorphic setup and the drainage of the Katrol Hill Range provides several lines of evidence for neotectonic activity along the KHF (Figure 4.1). The E-W trending line of north facing range front scarps, the conformity of the overall landscape with the tilt block structure, the E-W trending back valleys, the sharp division of the drainage system into south-flowing and north-flowing rivers, the incised nature of the drainage, development of gorges, the mode of occurrence of Quaternary colluvial and fluvial sediments and their stratigraphic development testify to the continued uplift of the range in a tilted manner due to periodic tectonic movements along the KHF during the Quaternary period. In general, the gorges, deeply incised fluvial valleys and the large potholes along the gorge in the Khari River near Bhuj appear as a 'misfit' in the present-day hyper-arid climate of the region. Gorge-like channels occur commonly within the Katrol Hill Range while these are developed locally in the rocky plain to the north of the KHF. The occurrence of gorges in the vicinity of the KHF within the Katrol Hill Range, and the local development of a gorge along Khari River in the low relief rocky plain suggest the dominant control of tectonics on the geomorphic evolution of the area.

The Quaternary sediments provide important stratigraphic evidence for delineating the major phases of neotectonic activity along the KHF. Whereas the back valleys south of the scarp line are dominantly filled with valley fill (fluvial) miliolites with patches of alluvium, the sediments to the north of the range front scarps show a scattered and restricted occurrence along the KHF zone. The oldest Quaternary deposit is unsorted colluvial debris occurring to the north of range front scarps with clast sizes ranging from pebble to boulders. By virtue of its consistent occurrence below the fluvial miliolite deposits, this colluvium is attributed to pre-milliolite reactivation of KHF, which possibly occurred during the middle Pleistocene. Incision in the miliolites provides crucial evidence for constraining the timing of formation of the present day gorges. Chronologic data available on the miliolites (Baskaran et al., 1989; Chakrabarti et al., 1993) suggest a rather prolonged time of miliolite deposition during the Late Pleistocene.

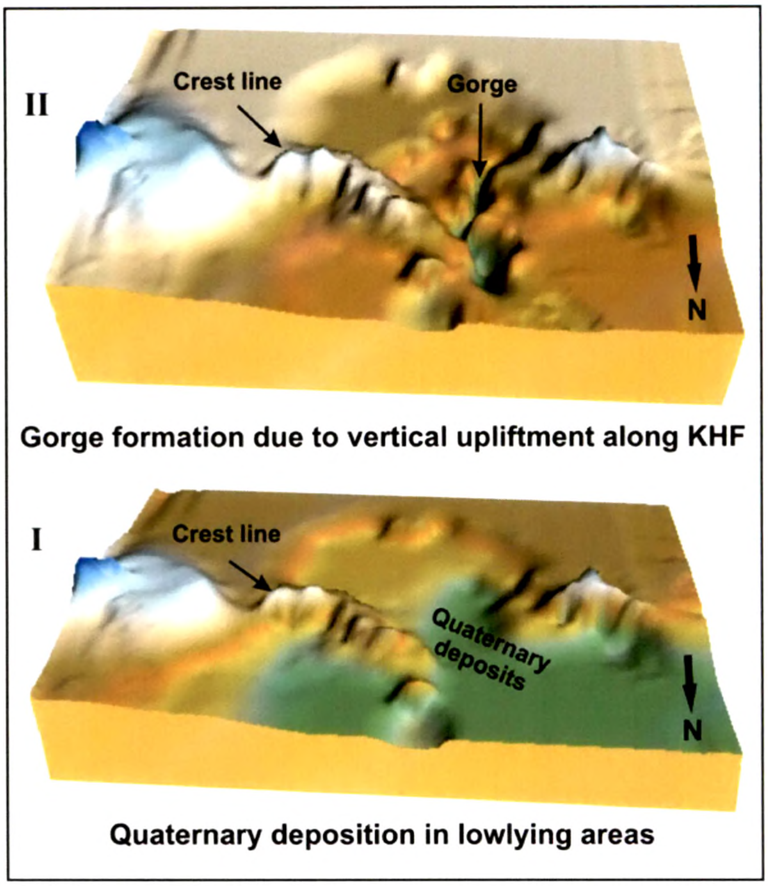

Figure 4.11 Digital Elevation Model (DEM) illustrating the conceptual model for gorge formation due to upliftment of the area. (I) Quaternary deposition prior to upliftment, (II) gorge formation due to vertical upliftment of the area along KHF.

The formation of gorges within the Katrol Hill Range, therefore possibly occurred during humid climate of the early Holocene period, which may have provided the necessary runoff for vertical erosion of the landscape. This is in conformity with the recent studies on the coastal alluvial plain located to the south of the Katrol Hill Range that have provided geomorphic and stratigraphic evidence of fluvial incision during the early Holocene in response to southward neotectonic tilting (Maurya et al., 2003b, 2008). The digital elevation model of a part of Katrol Hill Range illustrates the deposition of Quaternary sediments followed by incision due to vertical uplift of the area (Figure 4.11).

The scarp-derived colluvium is the youngest Quaternary deposit that occurs in the form of small aprons over the older sediments. The deposit varies from clast rich to matrix rich with gravel to cobble sized clasts mostly derived from the scarp faces subsequently reworked by debris and sheet wash processes. The E-W oriented trench indicates frequent lateral shifting of deposition with the top unit showing rilling and gullying. This colluvium is attributed to the youngest phase of neotectonic activity that occurred possibly during the late Holocene.

Based on the geomorphic and stratigraphic data presented here, at least three major phases of tectonic uplift of the Katrol Hill Range during the Quaternary are inferred. The oldest pre-miliolite phase (Middle Pleistocene) was followed by a prominent post-miliolite phase (Early Holocene), which resulted in fluvial incision with formation of gorges. The latest late Holocene phase continues at present. The uplift of the range in well-marked phases during Quaternary took place in response to differential uplift along the KHF under an overall compressive stress regime. The results of the present study are in conformity with seismo-tectonic studies (Biswas and Khattri, 2002), which indicate that various faults of the Kachchh basin are accumulating compressive stresses, responsible for recurrent seismic activity and differential uplift of the basin.