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# Fluvial geomorphology and neotectonic activity based on field and GPR data, Katrol hill range, Kachchh, Western India

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**Abstract**

The largely rocky and rugged landscape of the Katrol hill range, composed of Mesozoic rocks and structurally controlled occurrences of Quaternary sediments, is delimited to the north by north-facing range front scarps of the seismically active E–W trending Katrol Hill Fault (KHF). The landscape and drainage characteristics of the Katrol hill range are documented together with ground penetrating radar (GPR) investigations along the KHF to delineate its nature for understanding neotectonic activity in the contemporary tectonic setting. The overall geomorphology is controlled by the south oriented tilt block structure of the range, indicated by its pronounced influence on the morphology and drainage network. The drainage comprises north-flowing and south-flowing rivers with the drainage divide located close to the northern edge of the range, which also marks the highest topographic elevations. The narrow zone between the crest line and the drainage divide has been identified as the zone of gorges, where gorges and deeply incised fluvial valleys have been formed within Quaternary sediments by the various north-flowing streams. 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.

Based on the geomorphic and stratigraphic evidence, three major phases of Quaternary tectonic uplift in the Katrol hill range are inferred. The oldest pre-miliolite phase (middle Pleistocene) was followed by a prominent phase of fluvial incision with formation of gorges during early Holocene, and then by the last one during late Holocene, continuing at present. Uplift of the range occurred in well-marked phases during the Quaternary in response to differential uplift along the KHF under an overall compressive stress regime. GPR investigations at selected sites show that the KHF is a steep south-dipping reverse fault near the surface, which becomes vertical at depth. This suggests neotectonic reactivation of the KHF under a compressive stress regime, responsible for active southward tilting of the Katrol hill range.


## 1. Introduction

Landscapes of seismically active areas are dominated by structural and tectonic influences. The various geomorphic features and drainage in such areas provide evidence of neotectonic activity in response to movement along faults (Ouchi, 1985; Schumm et al., 2000). The planimetric geometry of fluvial network, in particular, is an important indicator of the morphostructural framework (Beneduce et al., 2004). Impact of vertical movements along faults and their timing can be delineated from fluvial geomorphic features and tectonic landforms (Rockwell et al., 1984; Wells et al., 1998; Ascione and Romano, 1999; Li et al., 2001). Determining these is important, as faults with a long geological history in millions of years may also be responsible for their recent dynamic state (Coltorti et al., 1996). The present study provides evidence of neotectonic activity based on a detailed geomorphological study of the Katrol hill range supplemented by ground penetrating radar (GPR) studies for delineating the characteristics of the main causative fault, the Katrol Hill Fault (KHF), located in the seismically active Kachchh region.

The seismically active Kachchh palaeo-rift is located in the western continental margin of India (Fig. 1). The E–W trending Kachchh rift was formed during the late Triassic and became fully marine in the middle Jurassic (Biswas, 1987). The basin was filled by ~4000 m thick Mesozoic

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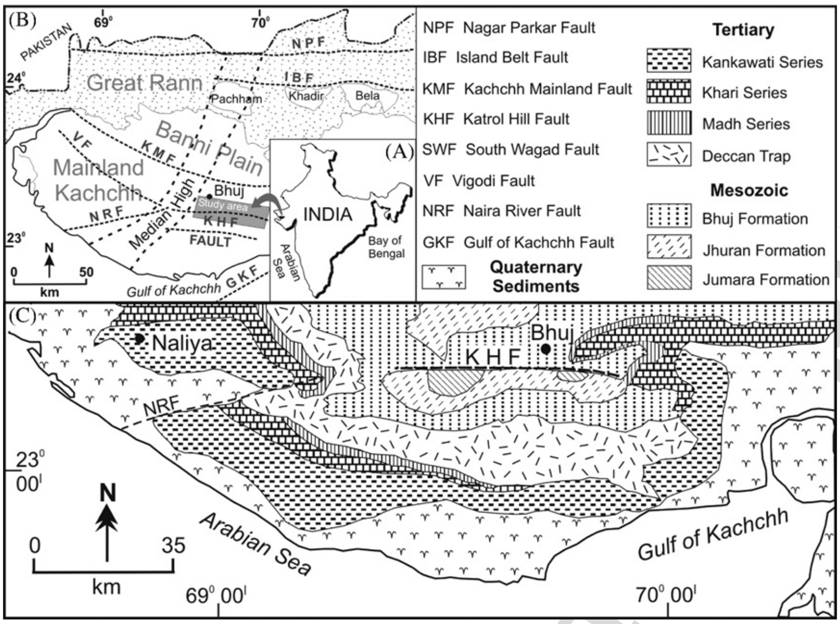


Fig. 1. (A) Location map. (B) Map of Kachchh basin showing the various faults (after Biswas and Khattri, 2002). (C) Geological map of the southern part of the mainland Kachchh (after Biswas and Deshpande, 1970).

sediments (Biswas, 1977) and inverted at the end of the Cretaceous period (Biswas and Khattri, 2002). Since then, a large part of the basin continued to suffer intermittent uplift along various E–W trending basin-bounding and intrabasinal faults (Fig. 1B), thereby maintaining first order structural control on the topography (Biswas, 1974). Several medium to high magnitude earthquakes in the last 300 years indicate active coseismic deformation of the basin under an overall compressive stress regime (Biswas and Khattri, 2002). In view of the seismically active nature of the area, there is a need for generating data on the impact of structure on landscape and drainage configuration. It is also essential to delineate evidence of tectonic activity during Quaternary times and interpret them in terms of movement along faults. The present study has been carried out along these lines and is intended to serve as a stepping stone for further seismotectonic and palaeoseismic studies in the region.

The Katrol hill range is located in the central part of Mainland Kachchh (Fig. 1B and C). The range is characterized by highly rugged rocky landscape with a series of E–W trending north-facing scarps at its northern margin that mark the seismically active KHF. The salient fluvial geomorphic features of the Katrol hill range and the Quaternary deposits are described and interpreted in terms of neotectonic activity along the KHF. GPR has been employed at selected sites to determine the shallow subsurface nature of the KHF to understand neotectonic activity within the contemporary tectonic setting and stress regime.

## 2. Geology and structural regime

Most of Mainland Kachchh is occupied by Mesozoic rocks which represent continuous deposition from Bathonian to Santonian (Biswas, 1977). The Mesozoic sequence has been classified into the Jhurio, Jumara, Jhuran and Bhuj formations (Biswas, 1977). The Jhurio Formation forms the base of the exposed Mesozoic succession and is characterized by limestones and shales deposited in littoral to infra-littoral environments. The overlying Jumara Formation is largely argillaceous owing to the dominating lithology of gypsiferous shales and alternating beds of limestones and occasional sandstones.

The Jhuran Formation is characterized by alternating beds of sandstones and shales. The top of the Mesosoic sequence is marked by a thick non-marine (fluvio-deltaic) Bhuj Formation comprised dominantly of sandstones. The Katrol hill range, also referred to as the Central Highland, is located to the south of KHF and exposes rocks belonging to the Jumara, Jhuran and Bhuj formations (Fig. 1C). The E–W trending KHF is a major range bounding fault that divides the Mainland Kachchh into northern and southern parts. Geomorphologically, the KHF is expressed as an E–W trending line of north-facing scarps separating the rocky plain comprising sandstones of the Bhuj Formation to the north and the rugged terrain of Katrol hill range, made up of highly deformed Mesozoic rocks older than the Bhuj Formation (Fig. 1C). The KHF, therefore, marks a sharp lithotectonic contact between the Bhuj Formation and older Mesozoic formations (Fig. 1C), including the Jhuran and Jumara formations that form a narrow zone of domal structures along the KHF. To the south, the various Mesozoic formations dip southwards and are overlain by Palaeocene trappean basaltic flows, Tertiary rocks and Quaternary sediments extending up to the coastline of Gulf of Kachchh (Fig. 1C). Apart from the dominating E–W structural trend represented by the KHF and related faults, several NNE-SSW and NNW-SSE

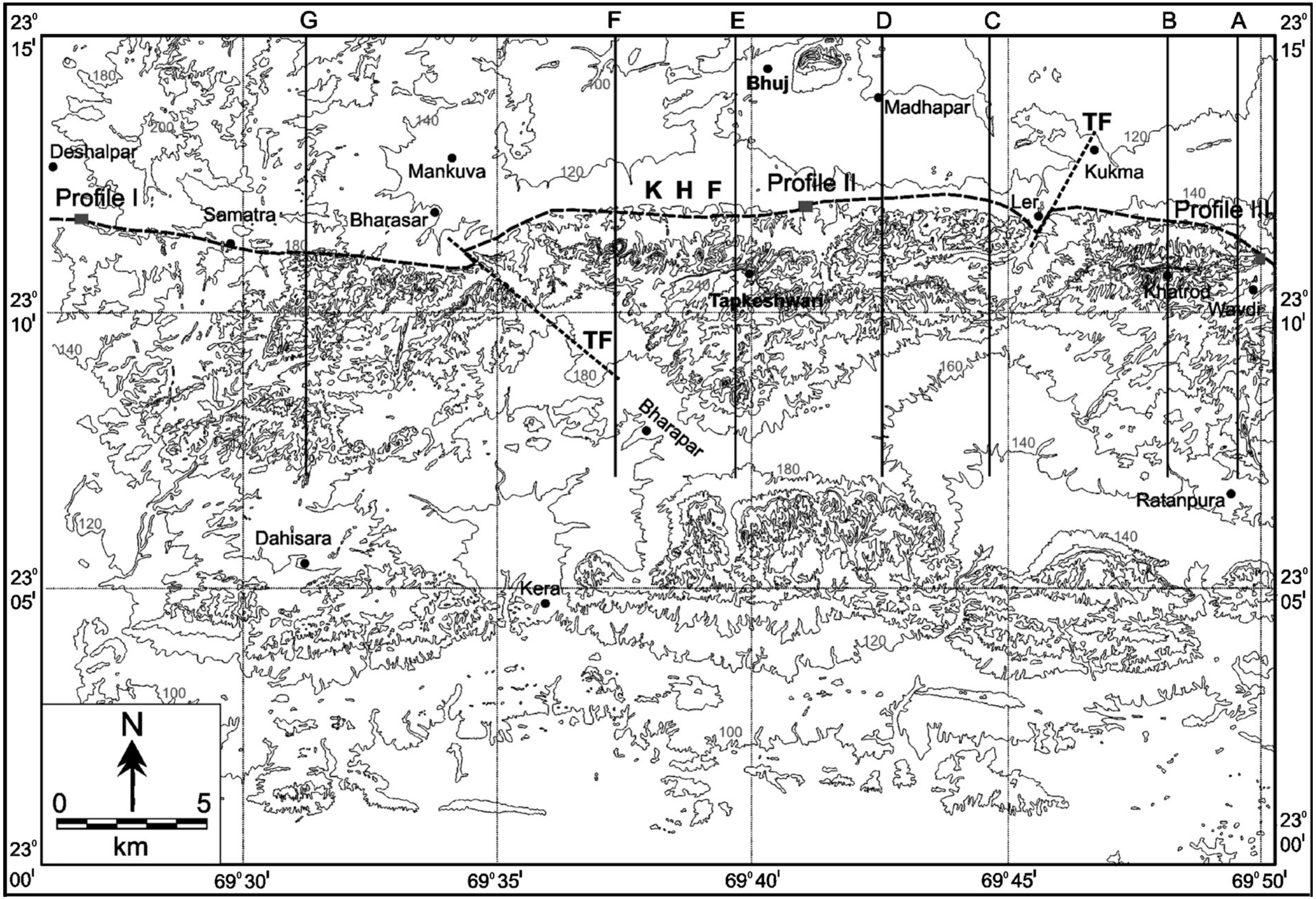


Fig. 2. Contour map of southern mainland Kachchh prepared from Survey of India topographical maps on 1:50,000 scale. Note the rugged topography of the Katrol hill range, sharp geomorphic contrast with the rocky plain to the north and the progressive decrease of ruggedness in topography and elevation towards south. Lines A–G show the alignment of topographic sections in Fig. 5A. Location of GPR profiles is also shown.

trending transverse faults also affect the Katrol hill range (Thakkar et al., 1999; Maurya et al., 2003a).

The presence of a narrow zone of domal structures to the south of KHF is a significant feature of the Katrol hill range. Prominent domes are located at Khatrod, Ler, Gangeshwar and south of Bharasar (Thakkar et al., 1999). The northern limbs of the domes occurring to the south are truncated by the KHF. The southern limbs of the domes are gently inclined, as little as 5–10° towards south, but the northern limb is steeply dipping towards the north or vertical. Some of these domes contain several N–S dykes and plugs with occasional sills in their central part (Biswas, 1987). The sandstones of Bhuj Formation to the north of the KHF show broad open E–W trending anticlinal and synclinal folds.

## 3. Tectonic geomorphology

The rugged landscape of the Katrol hill range (Fig. 2) shows evidence of the dominating control of neotectonic activity in its geomorphic development. The range abruptly rises above the rocky plain to the north. The most impressive aspect of the area is the north facing E–W trending line of range front scarps that mark the geomorphic expression of the KHF. The overall youthful topography of the Katrol hill range and the range front scarps indicate dominance of tectonic activity over erosional processes (Thakkar et al., 1999). The role of tectonic activity along the KHF in landscape shaping of the southern mainland Kachchh is indicated by the development of cyclic planation surfaces (Biswas, 1974). Five such surfaces have been recognized: Upper Cretaceous surface, Early Tertiary surface, Mid-Tertiary surface, Late Tertiary surface and Early Quaternary surface. These surfaces correlate with unconformities in the stratigraphic sequence and indicate periods of tectonic events causing breaks in sedimentation and initiation of erosional cycles (Biswas, 1974). Within the Katrol hill range, the various planation surfaces show southward tilting, suggesting episodic unidirectional movements along the KHF during the Cenozoic (Biswas, 1974). The rocky plain to the north of the KHF is identified as the Early Quaternary surface.

Southward tilt of the planation surfaces and southward dips of the Mesozoic and Tertiary rocks (Biswas, 1974) indicate that the southern Mainland Kachchh represents a large tilt block, delimited by the KHF to the north and the Gulf of Kachchh Fault to the south (Maurya et al., 2003b). The larger tilt block is sliced into two smaller blocks by another major E–W trending fault, whose geomorphic expression is similar to that of the KHF (Figs. 6A and B). This north-facing and E–W trending escarpment forms the southern limit of the highly rugged topography of the Katrol hill range (Maurya et al., 2003b).

The Katrol hill range shows a general decrease in topographic ruggedness towards the south (Fig. 3). The highest summits of this range lie close to the northern edge, which is in conformity with the narrow zone of positive structural relief along the KHF. The peaks along the crest line of range front scarps have average heights ranging from 250 to 300 m, the highest being the Khatrod peak with an elevation of 349 m a.s.l. located to the east. The elevations progressively decrease towards the south. The crest line is marked by impressive north-facing scarps (Figs. 2 and 3) with steep slopes that show characters typical of fault-generated mountain front scarps. This E–W trending scarp line follows the KHF, whose actual fault line occurs to the north (Maurya et al., 2005). In some portions, several 20–30 m high scarplets occur between the major scarp line and the fault line of KHF. These escarpments are the remnants of the retreating free face. The presence of the crest line close to the KHF and gradual reduction in the ruggedness of the topography towards south conform to the tilt block structure of the Katrol hill range.

The KHF exerts a major influence on the drainage network of the area. The drainage of Katrol hill range consists of north flowing and south flowing rivers (Fig. 4).

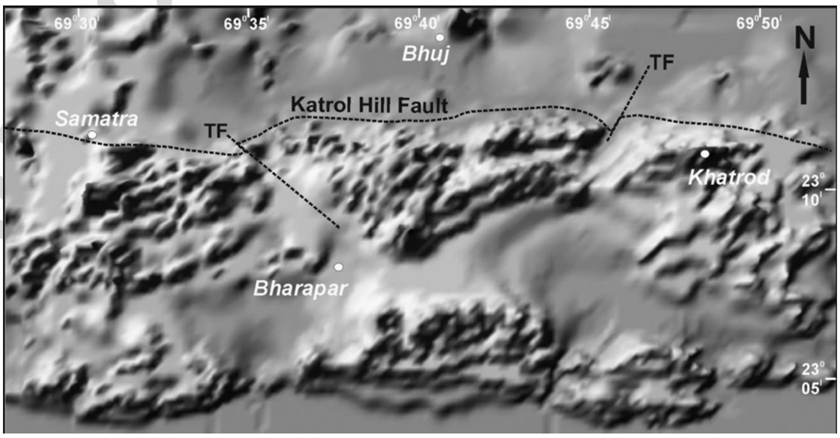


Fig. 3. Shaded relief map showing the rugged topography of Katrol hill range. The positions of the Katrol Hill Fault (KHF) and the other faults are marked using GPR data and field mapping. Note geomorphic contrast between the rocky plain to the north of the KHF and the rugged topography to the south of the fault. Also seen are the E–W trending back valleys.

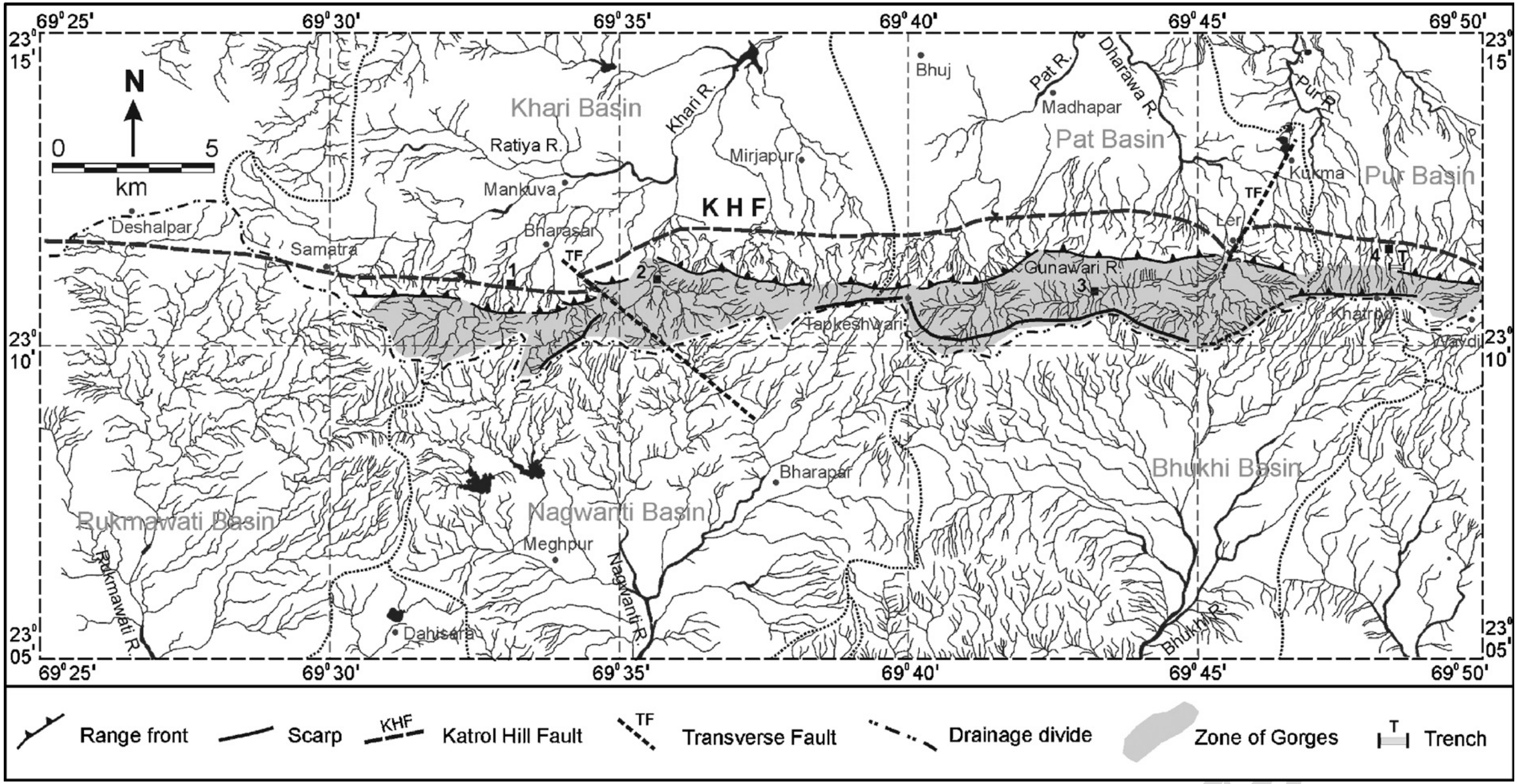


Fig. 4. Map showing drainage network of the Katrol hill range. Note the E–W trending range front scarps, drainage divide between the north-flowing and south-flowing rivers and the zone of gorges between them. 1–4 mark the locations of the lithologs shown in Fig. 9B. Location of the trench in Fig. 12 is also shown.

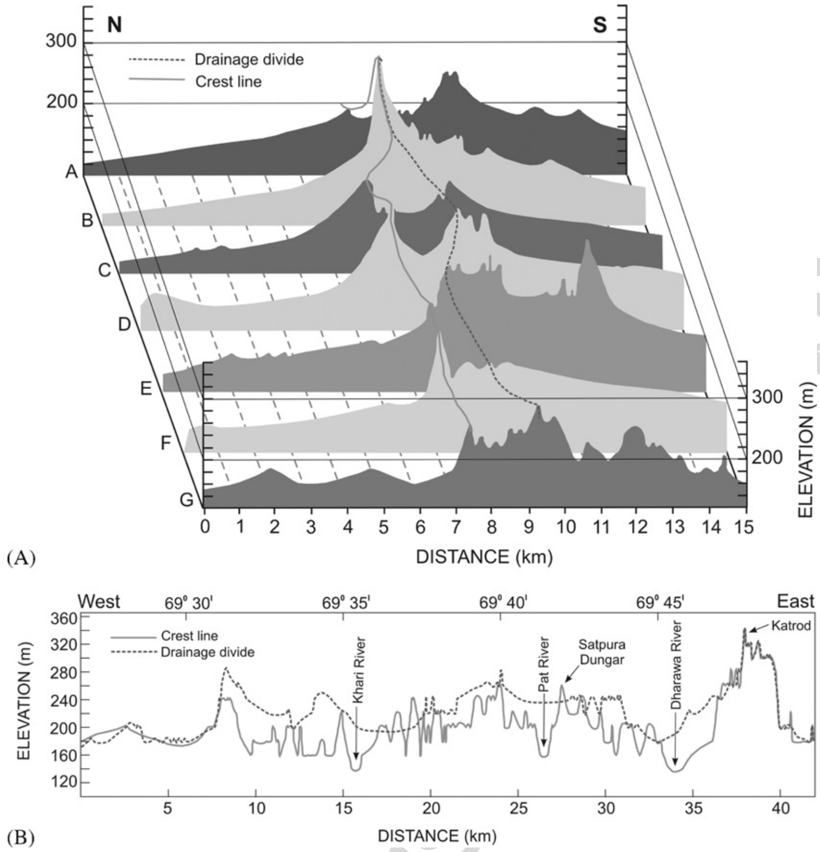


Fig. 5. (A) Topographic sections along N–S direction showing crest line of the range front scarps and the drainage divide. Location of section lines is shown in Fig. 2. (B) Topographic section along the crest line of the range front scarps and the drainage divide.

The scarp line shows three major breaches that have been formed by the northward flowing Khari River, Pat River and Gunawari River (Fig. 4). The free faces of the scarps show northward inclinations ranging from 50° to sub-vertical. The free face is characterized by longitudinal rills and notches formed by surface runoff flowing over the crest of the scarp. A sharp discontinuity of slope is seen in the lower part of the free face where it joins the debris slope. The crest forms the original upper surface above the free face. The crests of the KHF scarps show different degrees of rounding, a reflection of the removal of free face by erosion. The debris slope below the free face show northward slopes ranging from 15° to 35°. Morphology of scarps may be controlled by erosion or deposition (Wallace, 1977). Evidence for erosional control on the morphology of KHF scarps includes gullying of the scarp face, rounding of the crests, concentration of coarse debris at the base, at places covered by miliolites, absence of fine-grained alluvial deposits gullying by various streams further away from the scarps.

## 4. Drainage characteristics

The Katrol hill range shows a very dense network of streams (Fig. 4), despite the hyperarid climate of the region. All the rivers are ephemeral and consistent flow of water is rarely observed even during the monsoon period. The present drainage appears to be in an erosional phase, indicated by the deeply incised courses exposing pre-Quaternary rocks with very scattered occurrences of recent channel deposits.

The drainage of Katrol hill range has been classified into north-flowing and south-flowing networks. The Pur, Pat and Khari are the major north-flowing rivers that arise from the northern part of the Katrol hill range (Fig. 4). The streams originating from the northern slopes drain into the Banni plain. The south-flowing rivers drain a major part of the Katrol hill range (Fig. 4) and flow along the tectonic slopes to meet the Gulf of Kachchh. The Rukmavati, the Nagwanti, the Phot and the Bhukhi are the major consequent rivers flowing towards the south (Fig. 4).

The various rivers follow deeply incised courses with several entrenched meanders. The drainage divide is located to the south of the range front and occurs close to the crest line (Fig. 4). In the eastern part, around Khatrod, the drainage divide follows the crest line of the range front (Figs. 4 and 5A and B). The close spacing of the range front crest line and the drainage divide testifies to the overwhelming influence of neotectonic activity along the KHF and the resultant active southward tilting of the Katrol hill range on the drainage network. The tilting is essentially attributed to the uplift of the block in the north due to differential movement along the E–W trending KHF.

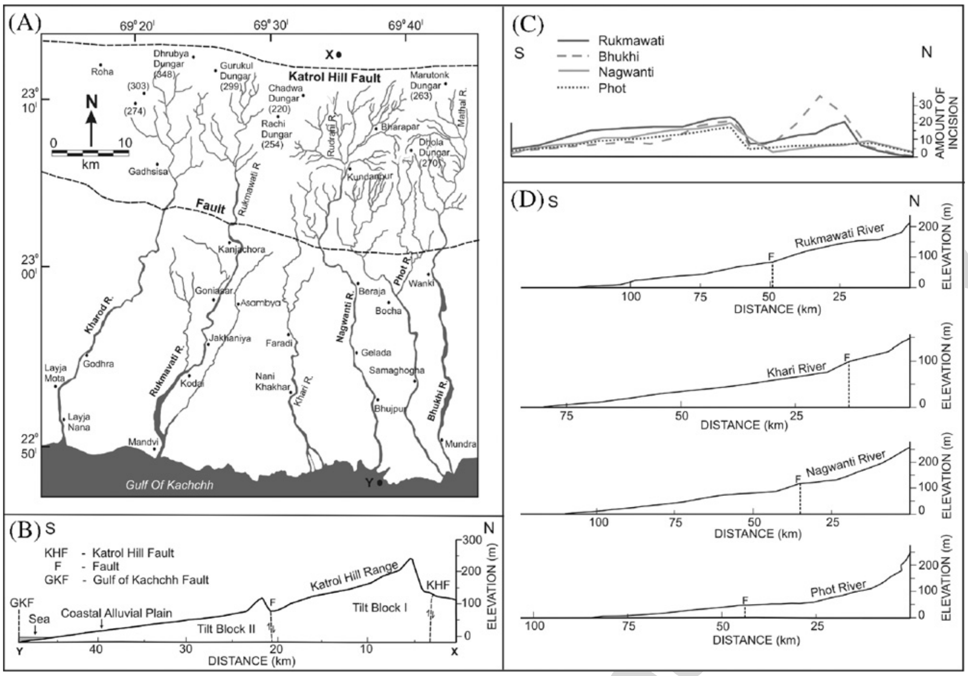


Fig. 6. (A) Map showing the major south-flowing rivers of the Katrol hill range and the two E–W trending faults. (B) Topographic section along the $X$–$Y$ (shown in 6A). Note the close correspondence of the general topography with the two fault bound tilt blocks. The attitude of the KHF is marked on the basis of GPR data. (C) Graphical representation of the depth of incision by major south-flowing drainage showing control of active tilting on fluvial incision. (D) Longitudinal profiles of the south-flowing rivers.

### 4.1. South-flowing drainage

The south-flowing drainage occupies a major part of the Katrol hill range (Fig. 4). Though these channels are deeply incised, the gorges are generally rare. The various streams display rocky channels with steep gradients and general absence of alluvium. The various streams comprise the source area of the Bhukhi, Phot, Nagwanti and Rukmavati basins (Figs. 4 and 6A). A remarkable correlation between the depth of river incision by south- flowing rivers and the two tilt blocks is observed (Fig. 6B and C). This is brought out well by the change in the depth of incision observed in the rivers. A marked decrease in the depth of incision is noted as these rivers flow southwards in the direction of the tilt (Fig. 6C). An abrupt increase in incision is seen as the rivers cut through the second tilt block, which is followed by a decrease in the degree of incision in the direction of tilt. The long profiles of these rivers also show distinct control by the tilt blocks (Fig. 6D). This suggests that active tilting of the blocks due to differential uplift along the E–W trending faults has controlled the degree of incision along the south-flowing rivers (Fig. 6B–D). The south-flowing rivers incise through a narrow coastal alluvial plain consisting of Late Quaternary deposits before debouching in the sea (Maurya et al., 2003b, c).

### 4.2. North-flowing drainage

The north-flowing drainage of the Katrol hill range comprises the Khari, Pat and Pur rivers and their dense network of tributary streams (Fig. 4). The Pat and Pur rivers join the Khari River further north of Bhuj. These incise through the rocky plain to the north of KHF and disappear in the Banni plain.

These rivers flow on the Early Quaternary land surface (Biswas, 1974) implying they have evolved late in geological history. The western half of the northern margin of the Katrol hill range is drained by the Khari River and its tributaries. The source region of the north flowing drainage lies in the extremity narrow linear zone along the crest line of the range front. Though the source region of the north-flowing drainage is small, the number of streams is extremely high (Fig. 4). A majority of the first order streams originate on the north-facing escarpment of the mountain front (Fig. 4). In comparison, the number of streams originating and draining the back valleys behind the range front is extremely small (Fig. 4).

The back valleys have a general E–W trend controlled by the strike of various formations. The Gunawari River in the western part follows such an E–W trending back valley behind the range front before it pierces through the scarp line near Ler village and proceeds further north (Fig. 4). The Gunawari valley also marks the area where the separation distance between the crest line and the drainage divide is the largest. The drainage divide runs along a major E–W trending cuesta scarp located to the south of the range front (Fig. 4).

The majority of the north-flowing lower order streams originate along the north-facing escarpment of the mountain front scarps. These streams originate as rills or

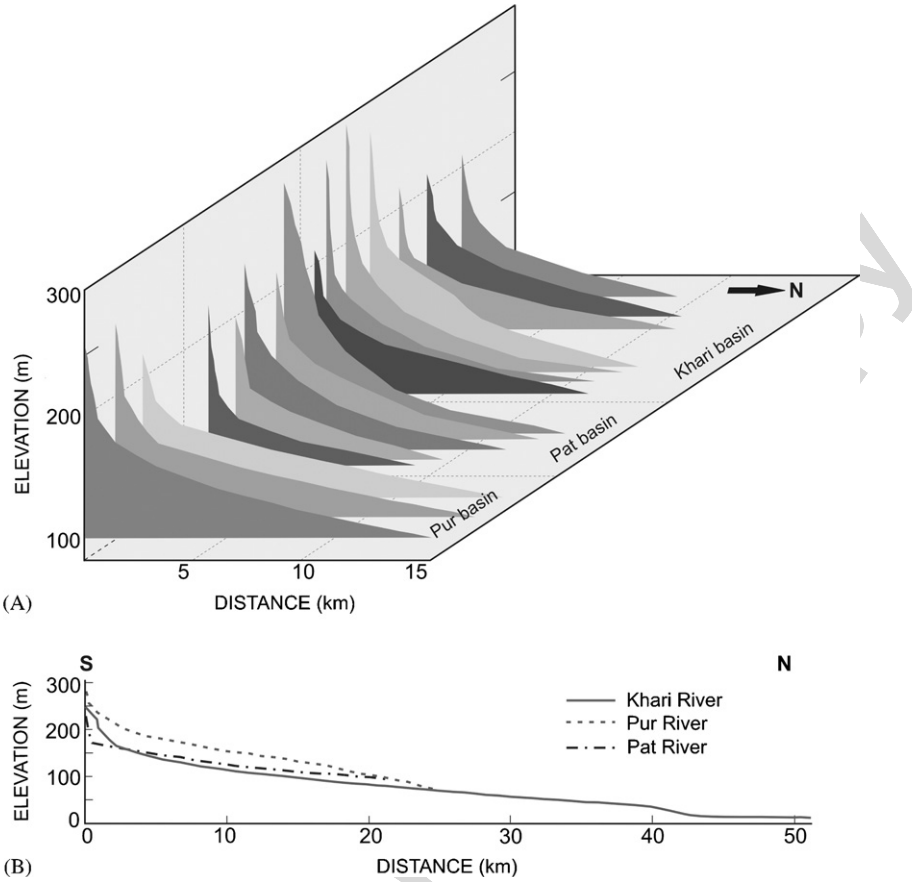


Fig. 7. (A) Longitudinal profiles of selected north-flowing lower order streams arising from the scarp faces. The upper part of the profiles corresponds to the free face of the scarps. (B) Longitudinal profiles of the north-flowing Khari, Pat and Pur rivers originating in the back valleys.

gullies on the scarp face that are transformed to incising streams at the base of the scarps. These streams are characterized by highly sinuous courses before they join with higher order streams. The longitudinal profiles of selected lower order streams arising from the scarp faces show distinct vertical profiles in the upper parts, which corresponds to the steep face of the scarps (Fig. 7). These profiles are in contrast to those of the streams originating in the back valleys, which are gentler but nevertheless show steep gradients (Fig. 7A and B).

A major feature of the north-flowing rivers is their deeply incised courses with intermittent gorges within the Katrol hill range. This is an E–W trending zone of gorges located between the crest line and drainage divide (Figs. 4 and 5A and B). Several gorges of varying dimensions occur within the zone between the crestline of the scarps and the drainage divide (Fig. 4). This zone of gorges is located near the KHF and correlates with the most rugged part of the Katrol hill range. Gorges at several places are associated with minor intra-range faults (Thakkar et al., 2006). Within the hill range, the Gunawari River flows along a general E–W trending back valley forming a 10–15 m deep narrow incised valley with several prominent gorge reaches. The incised valley walls and gorge walls expose Mesozoic rocks, Quaternary miliolites and fine-grained alluvial deposits.

Similarly, the Khari River in its proximal reach flows through a E–W trending back valley incising through Quaternary miliolite deposits and underlying Mesozoic rocks. Several of its lower tributaries in this reach show 10–20 m deep gorges, and one has formed a fluvial hanging valley. This first order tributary exhibits an extremely narrow ~7 m deep channel within the Quaternary miliolite deposits, located about ~8 m above the valley floor of the trunk stream (Fig. 8A). Several streams located in the area between the scarp line and the drainage divide show extremely narrow gorges with more or less similar geomorphic settings, with 10–20 m deep incision. The incised gorges within the structurally controlled back valleys testify to tectonic uplift in recent times. The presence of gorges near the KHF points to the role of neotectonic uplift of the range.

North of the KHF in the rocky plain comprising sandstones, the various north-flowing rivers consistently show 10–20 m deep incised channels along their courses. Though no typical gorges are observed in this area, the incised bedrock channels suggest tectonic uplift of the block located to the north of the KHF. However, a locally developed deep and extremely narrow gorge is observed NW of Bhuj along the Khari River (Fig. 8B and C). The general trend of the gorge is N 40° E and is about 21 m

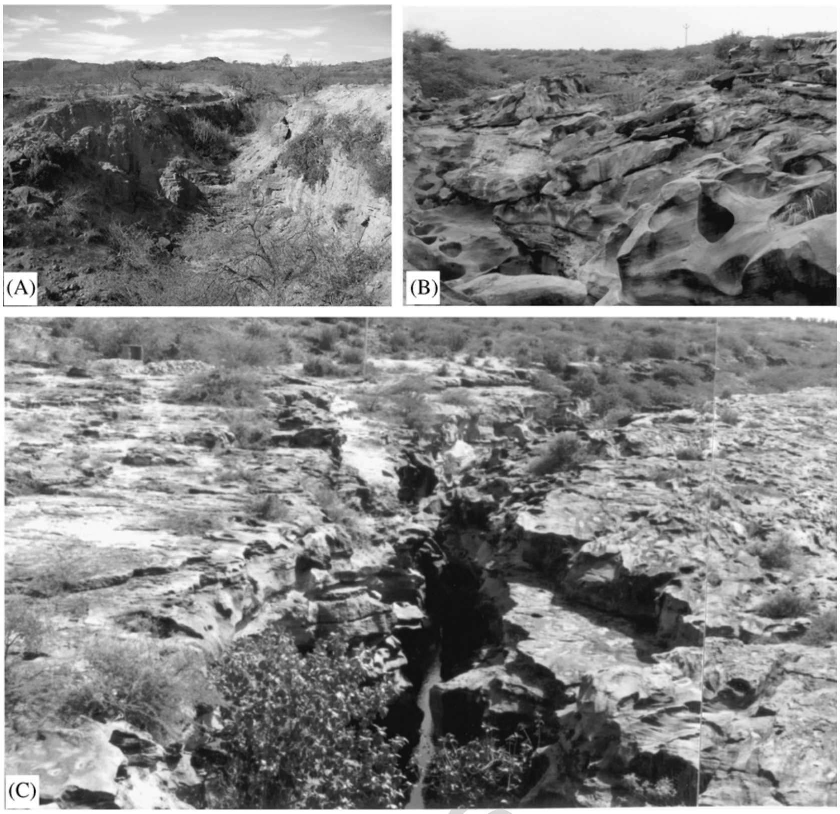


Fig. 8. (A) View of the hanging tributary valley formed within valley fill miliolites located in the back valley reach of the Khari River. (B) View of the extensively potholed surface along the gorge in the Khari River indicating intensive fluvial erosion. (C) Upstream view of the locally developed narrow gorge of the Khari River developed on the rocky plain near Bhuj.

deep. The vertical gorge walls are ~15 m deep, which confine an extremely narrow channel (1.5–4 m wide). The gorge reach is studded with numerous large potholes (Fig. 8B) and prominent directional erosional structures including flutes and longitudinal ridges and grooves. The flutings show a general NE trend that is consistent with the present flow direction. The sizes of potholes range from 45–225 cm in diameter with depth of 75–250 cm. The gorge appears to have developed locally in response to tectonic movements along several faults observed in the bedrock adjacent to the gorge site (Thakkar et al., 2006). The gorge, though locally developed, provides evidence of uplift of the area along the KHF and other associated faults. The gorges and incision by the various north-flowing rivers indicate differential uplift of the blocks to the south as well as north of the KHF.

## 5. Quaternary sediments

Studies on Quaternary sediments along fault zones provide important clues for reconstructing neotectonic history. The Katrol hill range in general exhibits a barren rocky landscape that exposes well lithified rocks of Mesozoic age. Even the courses of the various river valleys appear to resemble bedrock-dominated rivers 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 rivers, whereas to the north of the range front scarps, the deposits are patchy and mostly concentrated around the north-flowing river valleys. The distribution and occurrence of these deposits are strongly controlled by the structural setup (Fig. 9A) and show evidence of neotectonic activity.

A detailed stratigraphy of the Quaternary deposits is difficult to work out owing to their patchy occurrence. However, a general order of superposition of the various kinds of Quaternary deposits is proposed based on their stratigraphic relationships (Fig. 9A). 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. Vertical lithologs of the exposed sediment column were also prepared, and representative lithologs are shown in Fig. 9B.

The Quaternary deposits occur in the form of colluvial deposits, aeolian and valley fill miliolites, fine-grained alluvium (mainly silts) and scarp-derived colluvium (Fig. 9A and B). These deposits have been found useful for identifying phases of neotectonic activity.

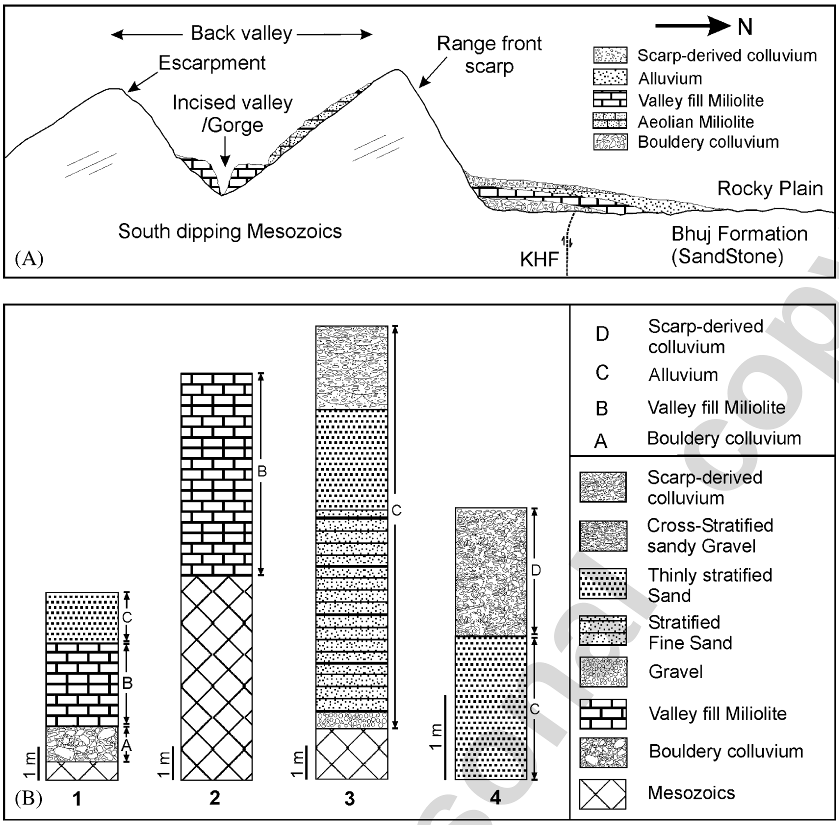


Fig. 9. (A) Schematic N–S section showing the generalized mode of occurrence and stratigraphic regime the Quaternary deposits in the Katrol hill range. (B) Representative lithologs of exposed Quaternary sediments. Location of the lithologs is shown in Fig. 4 as 1–4.

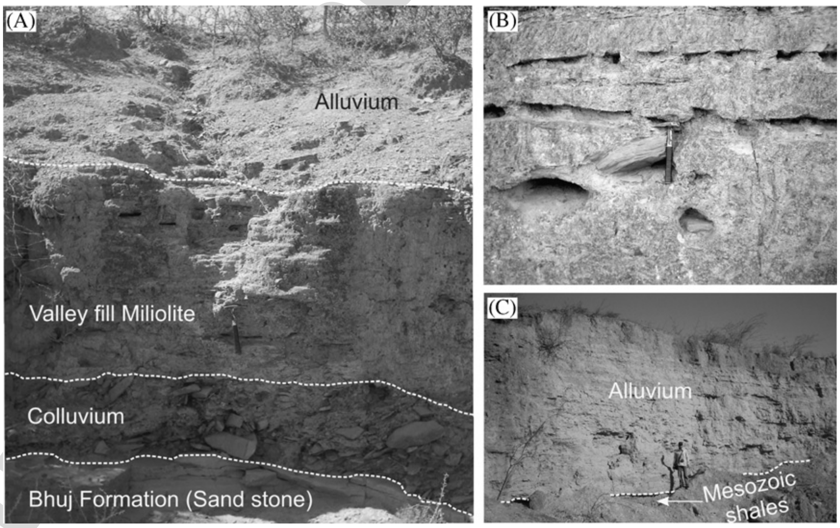


Fig. 10. (A) Cliff section along a north flowing lower order stream located to the southwest of Bharasar. Note the stratigraphic succession of the Quaternary sediments overlying the Mesozoic sandstones. (B) Detailed view of the valley fill miliolites in the upper reaches of the Khari River showing large clasts of Mesozoic rocks. (C) 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.



### *5.1. 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 ~2 km towards north. Colluvial deposits prominently occur around Wavdi, Khatrod and

SW of Bharasar, where they are found to be sandwiched between the Mesozoic rocks and fluvial miliolites (Fig. 9B and 10A). These are incised by several streams that originate from the scarps and flow northward. The deposits comprise large angular boulders, cobbles and pebbles with small amount of finer sediments filling up the voids (Fig. 10A).

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. Since no clasts of miliolites are found, and as the colluvium is always found to occur below valley fill miliolite, this bouldery colluvium can be attributed to a pre-miliolite phase of neotectonic activity. As the miliolites have been found to represent a late Pleistocene phase of deposition, a middle Pleistocene age is inferred for the colluvial deposits along the KHF.

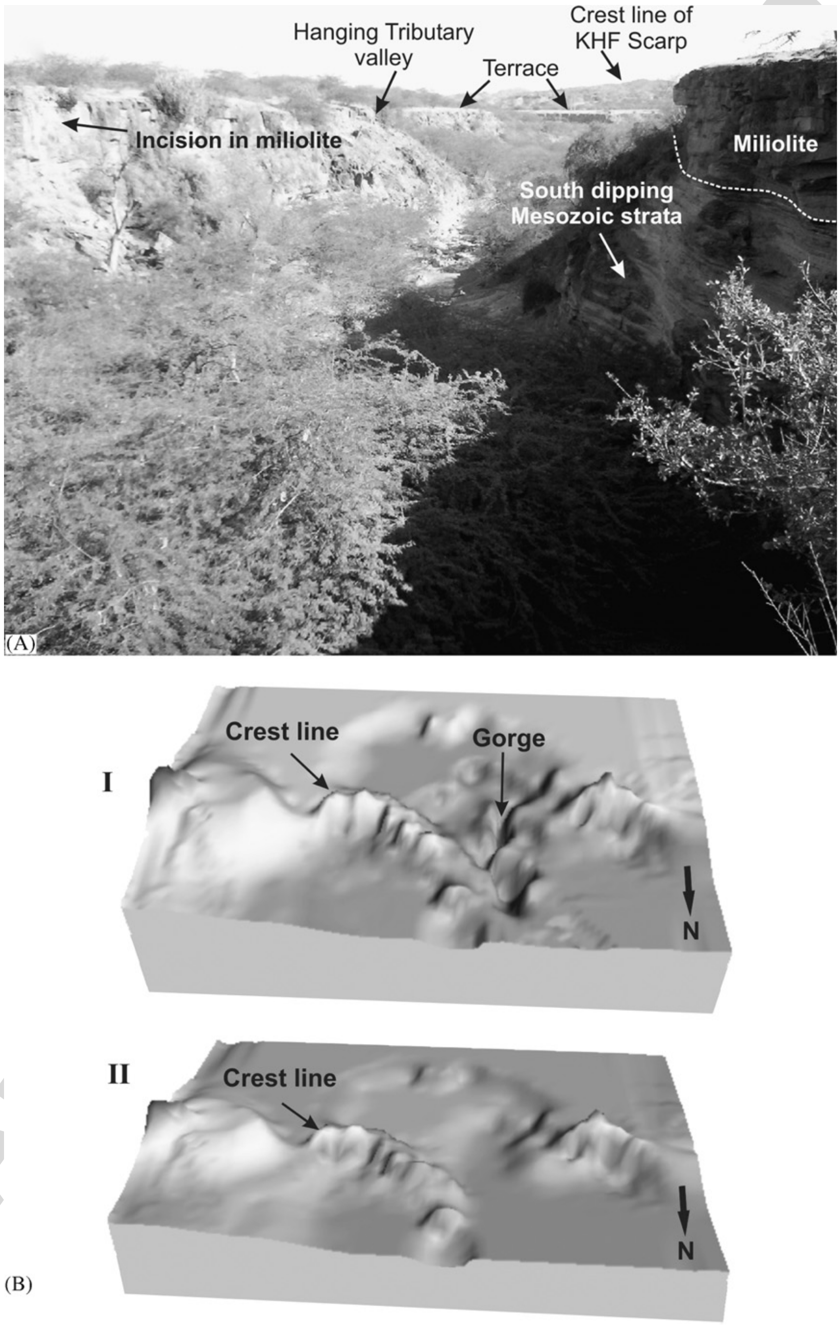


Fig. 11. (A) Northward view of a gorge developed along a back valley within the Katrol hill range by a tributary stream of the Khari River. At the far end, the crest line and terraced surface of the miliolite is seen. Location of the hanging tributary valley shown in Fig. 8A is also marked. The vertical cliffs on the left expose miliolites only while the cliff on the right side exposes south dipping Mesozoic rocks overlain by miliolites. (B) DEM showing southward view (I) of the area of the gorge shown in 8A. DEM showing rugged topography after removing the thickness of miliolite deposits (II).

### 5.2. Valley fill miliolites

The miliolites are 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 (Thakkar et al., 1999). The wind blown miliolite deposits occupy the higher elevations along the southerly directed slopes of the hill range (Fig. 9A). 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 located away from the present day river valleys.

These deposits were subsequently reworked by fluvial action indicated by cobbles, pebbles and boulders of Mesozoic rocks (Fig. 10B). These are referred to as valley fill miliolites, and occur along the various river valleys. Most of the back valleys are filled by valley fill miliolites while the aeolian miliolites occur on the upper valley slopes (Fig. 9A). However, the valley fill miliolites appear to have greater neotectonic significance. Only the valley fill miliolites were studied as they mark a distinct episode of fluvial aggradation, with incised channels and gorges formed within them.

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 (Fig. 9A). They occur along the river valleys and include well-stratified sediments, presence of gravel rich layers, fluvial sedimentary structures such as small scour and fill, cross bedding and large clasts of Mesozoic rocks. The valley fill miliolites show a gently sloping terraced surface, in contrast to the aeolian miliolites which show typical morphology of obstacle dunes with a distinct internal large scale aeolian cross bedding and uniformly fine grain size. These deposits generally consist of well-stratified sheets and are exposed along the vertical cliff faces of the various north-flowing streams.

A majority of the gorges along the back valley reaches of the north-flowing rivers are located within the miliolite zone. The back valley reaches of the Gunawari and Khari rivers are fully filled by valley fill miliolites. The formation of 10–15 m deep narrow incised valleys and intermittent gorges in the valley fill miliolites (Fig. 11A) is significant as it suggests uplift of the range due to neotectonic activity along the KHF. A few gorges begin within the Mesozoic rocks and 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 the back valleys, while only a very small part of the total volume of miliolite could be 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 (Fig. 9A). $^{230}Th/^{234}U$ ages of the Kachchh miliolites range from 30 to 130 ka (Baskaran et al., 1989; Chakrabarti et al., 1993; Somayajulu, 1993). The miliolites occupy deep narrow valleys carved out within the Mesozoic rocks (Fig. 11B) 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.

### 5.3. Alluvial deposits

Fine-grained channelized alluvium occurs sporadically along the various north-flowing streams within the Katrol hill range. These form 8 to 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. At some locations, they are found to overlie the Mesosoic rocks, which are also incised. Within the Katrol hill range, these deposits mostly comprise fine to coarse sands with layers of cross-stratified gravels (Fig. 10C). In the 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 (Fig. 10A).

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 late Pleistocene. The miliolites together with the alluvium represent a late Pleistocene aggradation phase as indicated by the chronologic data. The miliolites provide 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 (Figs. 10C and 11A) provides important evidence of post-late Pleistocene tectonic uplift of the Katrol hill range. Considering the age range of the miliolites from 30 to 130 ka (Baskaran et al., 1989; Somayajulu, 1993), this phase of tectonic uplift occurred during the early Holocene.

### 5.4. Scarp-derived colluvium

The scarp-derived colluvium is the youngest of the Quaternary deposits along the KHF (Fig. 9A and B). The

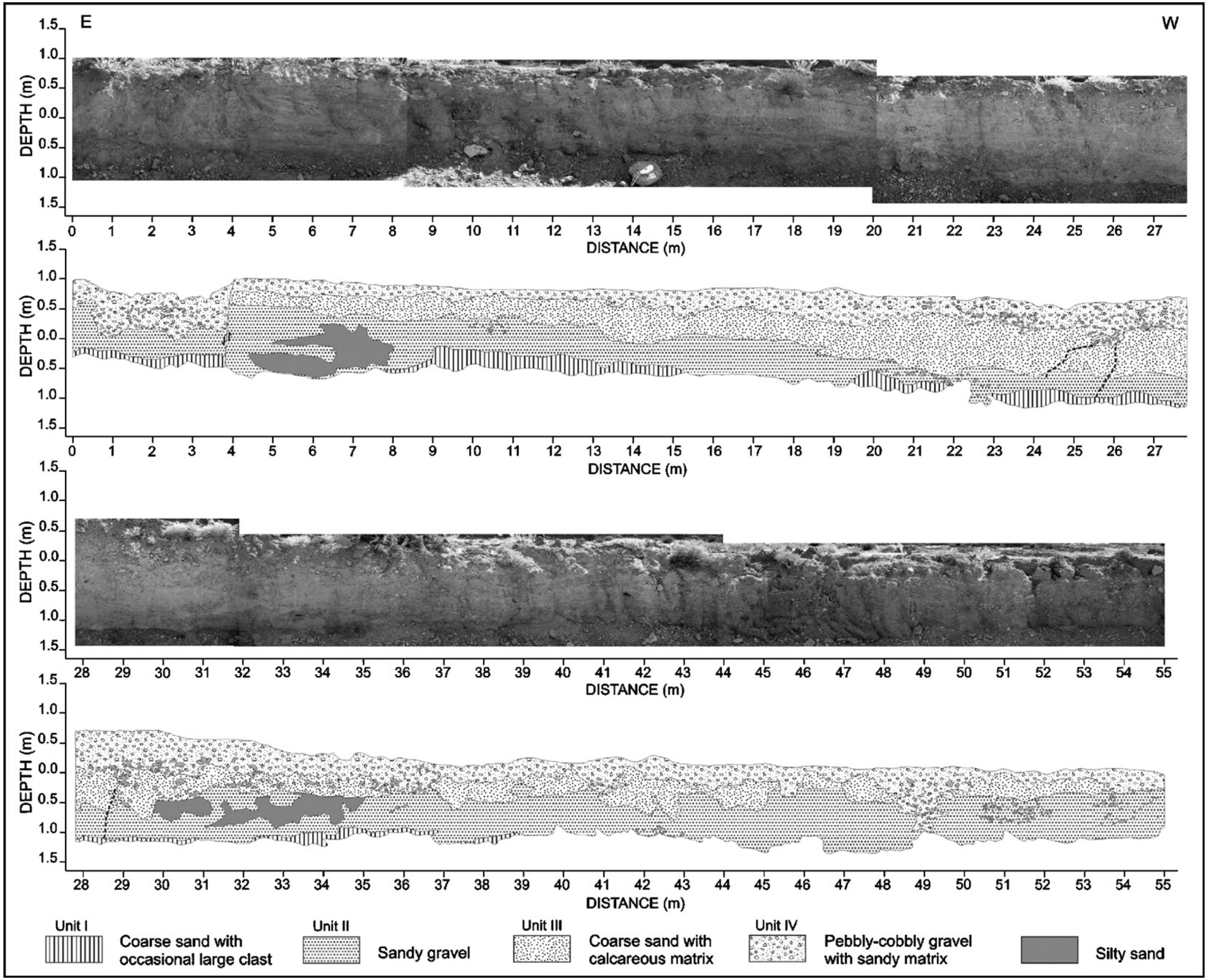


Fig. 12. Photomosaic of the E–W trending trench excavated through the scarp-derived colluvium. Note the distinctly identifiable facies and the fault at 4 m. Sand filled fissures is shown as dashed lines.

deposit occurs as a discontinuous apron over the older Quaternary deposits. At places it overlies the fine alluvium whereas at other places it rests directly over the valley fill (fluvial) miliolites. The deposits comprise debris as well as wash facies. In general, the debris facies consists dominantly of clasts with subordinate matrix, whereas the wash facies is comprised of 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 lateral nature of these deposits was studied by excavating a E–W trending shallow trench (1.6 m deep and 55 m long) east of the Khatrod scarp (Fig. 12). Overall, the deposit showed crude stratification with small pockets of well-bedded sediment. The depositional pockets tended to shift laterally during the sedimentation as shown by the variation of thickest parts of the individual sediment packages.

Based on lithology, 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. 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. The unit is semicompacted and is comprised of gravelly layers with sheet geometry with isolated and coalescing lenses of silty sand (Fig. 12). The lateral thickening and thinning of the gravelly and sandy layers suggest shifting centres 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 the 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.

Unit IV is the topmost unit and is largely unconsolidated. The unit is rich in pebbles and cobbles with a sandy matrix (Fig. 12). It is characterized by imbricated clasts, persisting in several clast rich pockets. The most conspicuous feature of this unit is the abundance of small to medium sized narrow scours (Fig. 12). These suggest formation of small gullies by water flowing over the surface of the underlying unit, subsequently filled up by the reworked colluvium. A minor sub-vertical fault was 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 due to neotectonic activity along the KHF.

## 6. GPR studies along KHF

GPR is a modern geophysical technique for imaging the shallow subsurface which involves transmission of high frequency electromagnetic waves into the ground, some of which is reflected back from sediment interfaces (Davis and Annan, 1989; Jol, 1995). Propagation of radar waves in the subsurface is governed by relative permittivity and electrical conductivity which depends on lithology, textural characteristics and moisture content of the sediments (Davis and Annan, 1989). GPR has been successfully applied for investigating near surface characteristics and tectonic movement along faults (Busby and Meritt, 1999; Bano et al., 2000; Chow et al., 2001; Rashed et al., 2003; Maurya et al., 2005).

The GPR surveys were carried out at selected sites to characterize the shallow subsurface nature of the KHF to provide evidence for the type of stress conditions responsible for differential uplift along the KHF. The Subsurface Interface Radar (SIR-20) system with 200 MHz monostatic shielded antenna manufactured by Geophysical Survey Systems Inc., USA, was used. Data generation by GPR involves moving the antennas over predetermined and measured transects while the profiles are displayed and stored on laptop computer which controls the main GPR unit as well (Jol and Bristow, 2003).

Three sites were selected on the basis of field investigations. Each site was chosen after attempting several unsuccessful surveys starting from the base of the scarp, gradually moving away towards north until the fault was picked up in the profile. Several N–S oriented transacts were used for GPR studies at these sites to precisely locate the fault plane/zone and also to determine the near surface characteristics of the KHF. The GPR profiles were obtained by manually towing the antenna along measured survey lines across the fault traces inferred from geomorphic mapping. Once the fault was precisely located, repeated profiling was done until good quality data with minimal noise was obtained. The best profiles were subjected to post-survey processing using RADAN software.

### 6.1. Interpretation of GPR profiles

The GPR profile is a two-way time-antenna position image similar to a reflection seismic section (Audru et al., 2001; Salvi et al., 2003). The profiles are interpreted for delineating geological features after the raw data has been subjected to the basic processing steps recommended by Jol and Bristow (2003). The file header parameters were edited to correct the Horizontal scale and surface position adjustment. The Distance Normalization function was applied to establish constant Horizontal scale. The power spectrum was calculated to select the filter values, and the Vertical and Horizontal filters were used to remove Interference (noise) produced by extraneous objects like trees and vegetation. Automatic Gain Control (AGC) was applied to enhance the visibility of low frequency features. An average velocity of 0.12 m/ns obtained by velocity analysis was used for converting two-way travel times into depth in meters. Surface Normalization was applied to profiles that were obtained over undulating surfaces. The uppermost two near horizontal reflectors are due to the signals propagating directly from the transmitting to the receiving antenna, generally referred to as Air waves and Direct Ground waves.

GPR data has been found extremely useful for precisely locating and investigating near surface characteristics of faults in Quaternary sediments (Cai et al., 1996; Wyatt and Temples, 1996; Salvi et al., 2003; Ferry et al., 2004). Recognition of radar facies is an important step in the interpretation of GPR data. A radar facies is defined as a group of reflections or reflectors whose parameters differ from adjacent units (Bristow, 1995; Jol and Bristow, 2003; Maurya et al., 2006) and usually define lithological units, sediment packages or mappable three-dimensional sedimentary units. Reflection terminations or truncations, when used with several other radar charactristics, are significant fault indicators. Criteria commonly applied for locating faults on the GPR profiles include: abrupt termination of a group or an array of reflectors along a line; change from one radar facies to another; and change in the reflection pattern or amplitude strength of the radar signal (Meschede et al., 1997; Rashed et al., 2003; Ferry et al., 2004).

Other reflector terminations are interpreted as minor faults related to the main tectonic structure (Meschede et al., 1997). However, faults demarcating contrasting lithologies are easier to interpret as they show distinct radar facies owing to strong dielectric contrasts. Sediments produced by faulting are characterized by a diffuse radar pattern (Meschede et al., 1997). These criteria have been used to interpret the GPR profiles obtained during the present study. The salient features of the various faults studied as observed in the GPR profiles (Figs. 13–15) are described below. The location of GPR profiles is shown in Fig. 2.

### 6.2. *Profile I*

Profile I (Fig. 13A) was taken across a N–S transect south of Deshalpar. The profile was obtained on undulating ground, which was subjected to corrections during post-survey processing by applying Surface Normalisation. The profile shows a part (50 m) of the GPR data obtained by a 200 MHz along a 100 m long transect. The profile shows a zone of high amplitude reflections between 14 and 21 m that also exhibits signal scattering and truncation of reflectors.

This kind of radar pattern is typical of prominent faults, which also mark contrasts in lithology. The scattering of radar waves occurs due to a thin zone of unconsolidated deposits such as colluvium, clasts or breccia along the fault plane (Cai et al., 1996; Audru et al., 2001). Fig. 11B shows the enlarged view of the KHF. The profile also shows variable radar pattern on either side of the fault plane, which is due to differing lithology. The reflections on the northern side of the fault mark the sandstones of the Bhuj Formation while those to the south represent pre-Bhuj thin-bedded shales and limestones. As seen in the interpreted GPR profile (Fig. 13A–C), the KHF in the western part of the study area is a high angle south dipping reverse fault near the surface that becomes vertical at depth.

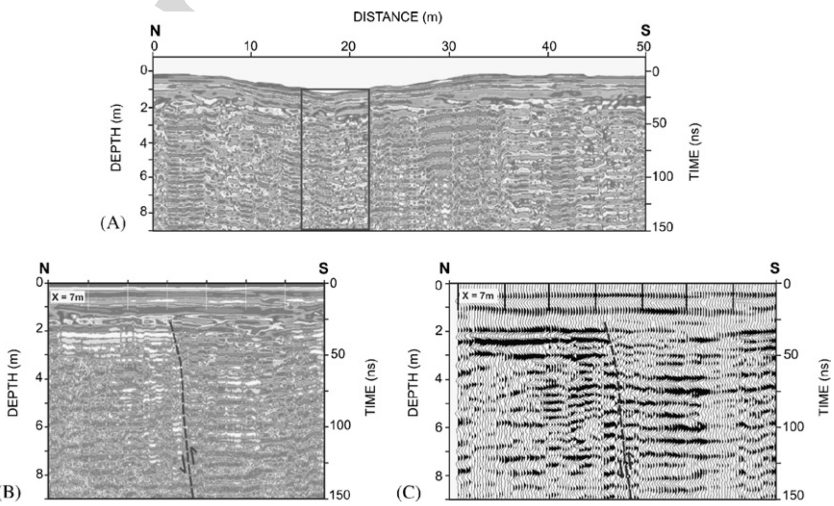


Fig. 13. (A) 200 MHz processed GPR profile obtained near Deshalpar. Enclosed area shows the location of the enlarged view shown in B and C. (B) Close up of the profile showing the fault plane of the KHF as picked up by GPR. (C) Same profile in wiggle format. Note the truncation of the reflectors along the fault plane.

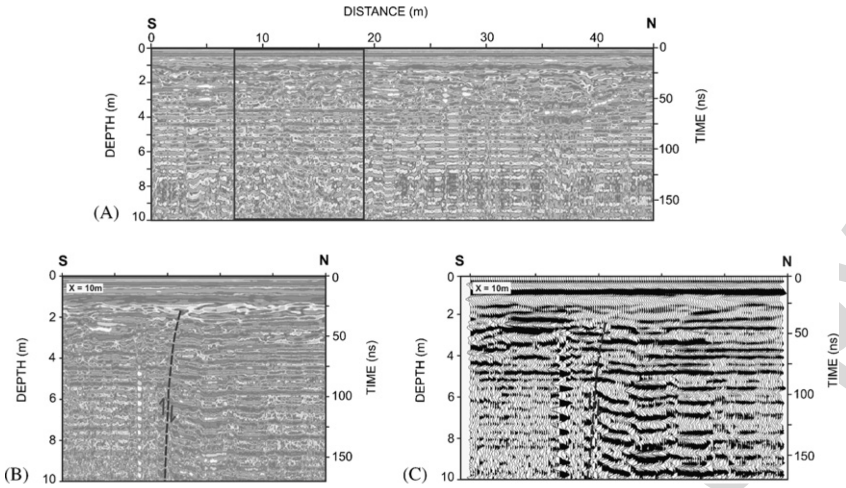


Fig. 14. (A) GPR profile obtained using 200 MHz antenna near Tapkeshwari. (B) Enlarged view of the part of the profile shown in (A) with KHF. (C) Same part of the profile in wiggle format showing the fault plane.

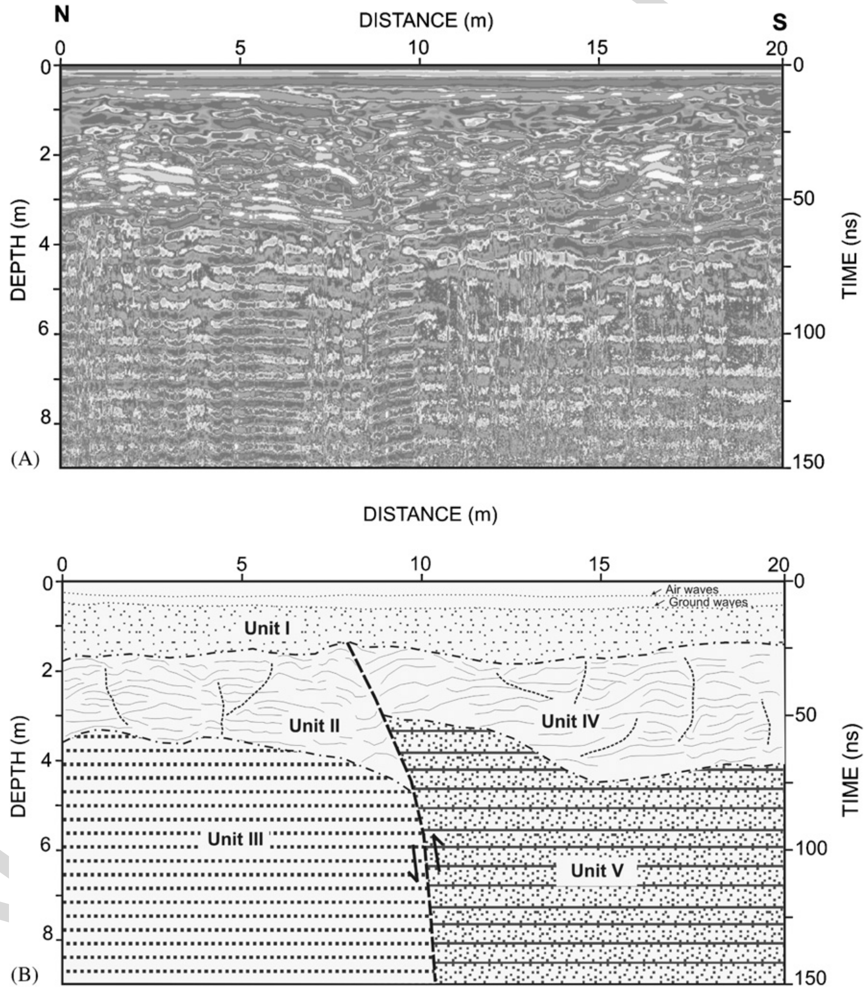


Fig. 15. (A) 200 MHz GPR profile across the KHF near Wavdi. (B) Interpreted section showing units I–V (discussed in text) marked on the basis of distinct radar signatures.

## 6.3. Profile II

The GPR transect of the profile shown in Fig. 14A is ~5 km south of Bhuj on the Bhuj-Tapkeshwari road. The profile shows GPR data along a 45 m long transect oriented NE-SW. The upper part of the profile (~5 m) exhibits prominent reflectors with high to moderate amplitude radar signals. The strength of the radar signals is, however, found to decrease with depth. The enlarged view of the interpreted fault zone (Fig. 14B and C) shows all the primary characters of tectonic elements in GPR profiles. An abrupt change in signal scattering, reflection patterns and amplitude strength is observed across the fault plane. To the NE of the fault, the profile shows repetitive truncation of reflectors along a line that marks the fault plane. The truncation of the reflectors is observed throughout the depth of the profile. The profile suggests reverse faulting along the KHF.

### 6.4. *Profile III*

This profile was obtained near Wavdi village, located at the eastern extremity of the study area. The profile is 20 m long and is oriented N–S. The entire profile shows four distinct sets of radar signals (Fig. 15A and B). The frequency spectrum, amplitude values and radar wave patterns suggest five distinct lithological units (I–V). Unit I is the thin surficial soil cover. Unit-II is the crushed and sheared sandstone, which overlies the massive sandstone below (Unit-III). To the south of the fault plane, Unit-IV also represents the sheared fine-grained rocks, below which massive rocks (Unit-V) are present.

The thinner and wavy reflectors of the Units-IV and V suggest finer grained lithology, possibly shales. In general, Units-I and III corresponding to sheared rocks show high amplitude continuous reflections from the north, show abrupt change in the dips and truncate over the fault plane. These diffused signals are the result of attenuation of the signals by weathered material. The profile shows that the KHF changes its nature from steeply dipping reverse fault in the near surface to vertical fault at deeper levels.

GPR investigations along the KHF indicate that it is a south-dipping high-angle reverse fault near the surface and vertical at depth. The fault is easily picked up by the sharp lithological contrast reflected in the profiles. The limestones and shales of the Jumara and Jhuran Formation to the south of the fault, in general, show higher intensity of deformation in comparison to sandstones of the Bhuj Formation to the north of the fault which show much less deformation.

## 7. Discussion

Neotectonic reactivation of faults is the prime factor influencing geomorphic development in seismically active regions. Critical analysis of geomorphologic characteristics and Quaternary sediments along fault zones is therefore essential for reconstructing the sequence of neotectonic events/phases. The present study, focusing on the Katrol hill range located in the seismically active Kachchh palaeo-rift, points to the dominant role of Quaternary tectonic activity along the KHF in the deposition of Quaternary sediments and the evolution of present day landscape. The KHF originated as a near vertical fault in an extensional regime during the rifting phase of the Kachchh basin (Biswas, 1987).

Subsequently, the KHF along with other E–W trending master faults have been involved in several episodes of basement involved uplift due to inversion since the Late Cretaceous (Biswas and Khattri, 2002). The KHF is, in general, recognized as an E–W trending intrabasinal fault that marks the lithotectonic contact between rocks older than the Bhuj Formation on the south and the Bhuj Formation of Late Cretaceous age to the north (Biswas and Deshpande, 1970). The GPR profiles show that the KHF is a steeply dipping reverse fault in the shallow subsurface that becomes vertical at deeper levels. The effect of neotectonic tilting of the southern block due to vertical movements along the KHF in shaping of the landscape of the Katrol hill range is implicit from the evidence documented in the present study. The general reverse nature of the fault in the shallow subsurface indicates neotectonic activity in response to accumulation of compressive stresses along the fault.

The geomorphic setup and the drainage of the Katrol hill range provide several lines of evidence for neotectonic activity along the KHF. 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.

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). The occurrence of gorges on both sides of the KHF is in conformity with the subsurface nature of the KHF delineated using GPR, which suggests that it is a south dipping near vertical reverse fault.

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 our 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.

## 8. Conclusions

The landscape and drainage of the Katrol hill range have developed in response to neotectonic uplift along the KHF. The close association of the crest line and the drainage divide, progressive reduction in the topography, and incision by south-flowing rivers suggest southward directed neotectonic tilting of the range due to movements along the KHF. The Quaternary deposits provide vital stratigraphic evidence to constrain the phases and timing of neotectonic activity. The gorges indicate pre- and post-miliolite phases of down cutting by rivers that correspond to two phases of reactivation of the KHF followed by late Holocene activity leading to deposition of scarp-derived colluvium. The GPR data indicate reactivation of KHF under compressive stress conditions.

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