Bedrock gorges in the central mainland Kachchh: Implications for landscape evolution

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Kachchh possesses a fault-controlled first-order topography and several geomorphic features indicative of active tectonics. Though coseismic neotectonic activity is believed to be the major factor in the evolution of the landscape, detailed documentation and analysis of vital landscape features like drainage characteristics, bedrock gorges and terraces are lacking. The present study is a site-specific documentation of gorges developed in the central part of the mainland Kachchh. We analyzed and interpreted four gorges occurring on either side of Katrol Hill Fault (KHF). The Khari river gorge is endowed with six levels of bedrock terraces, some of which are studded with large potholes and flutings. Since no active development of potholes is observed along the rivers in the present day hyper-arid conditions, we infer an obvious linkage of gorges to the humid phases, which provided high energy runoff for the formation of gorges and distinct bedrock terraces and associated erosional features. Development of gorges within the miliolites and incision in the fluvial deposits to the south of the KHF indicates that the gorges were formed during Early Holocene. However, ubiquitous occurrence of gorges along the streams to the south of KHF, the uniformly N40°E trend of the gorges, their close association with transverse faults and the short length of the exceptionally well developed Khari river gorge in the low-relief rocky plain to the north of KHF suggests an important role of neotectonic movements.

1. Introduction

Bedrock gorges are spectacular geomorphic features that result from high-intensity fluvial erosion. These are characterized by minimal alluvial sediment storage and are typically formed when sediment transport capacity exceeds sediment supply over a long term (Howard *et al* 1994). Bedrock incision processes like plucking, abrasion and cavitation may also lead to fluting and potholing of massive jointed and unjointed rocks (Whipple *et al* 2000). Bedrock channel systems have been found useful for understanding landscape evolution because they reflect boundary conditions, such as fluctuations in base level and/or land level, climate change and tectonics across landscapes (Whipple *et al* 2000). Climate, lithology and rock uplift are identified as the critical parameters governing the formation of bedrock gorges (Whipple *et al* 2000). However, coupled tectono-geomorphic models often suggest that high strain rates are spatially associated with high erosion rates (Burbank *et al* 1996). In this paper, we describe the geomorphologic characteristics of the bedrock gorges developed along lower as well as higher order stream channels in the vicinity of the Katrol Hill Fault (KHF) in Kachchh (figure 1).

2. General geologic setting

Kachchh is a pericratonic palaeo-rift graben which is currently experiencing active co-seismic deformation (Biswas and Khattri 2002). Major geomorphologic characteristics of the Kachchh basin

Keywords. Bedrock gorges; rocky terraces; potholes; tectonic uplift; landscape evolution; Kachchh.

J. Earth Syst. Sci. **115**, No. 2, April 2006, pp. 249–256

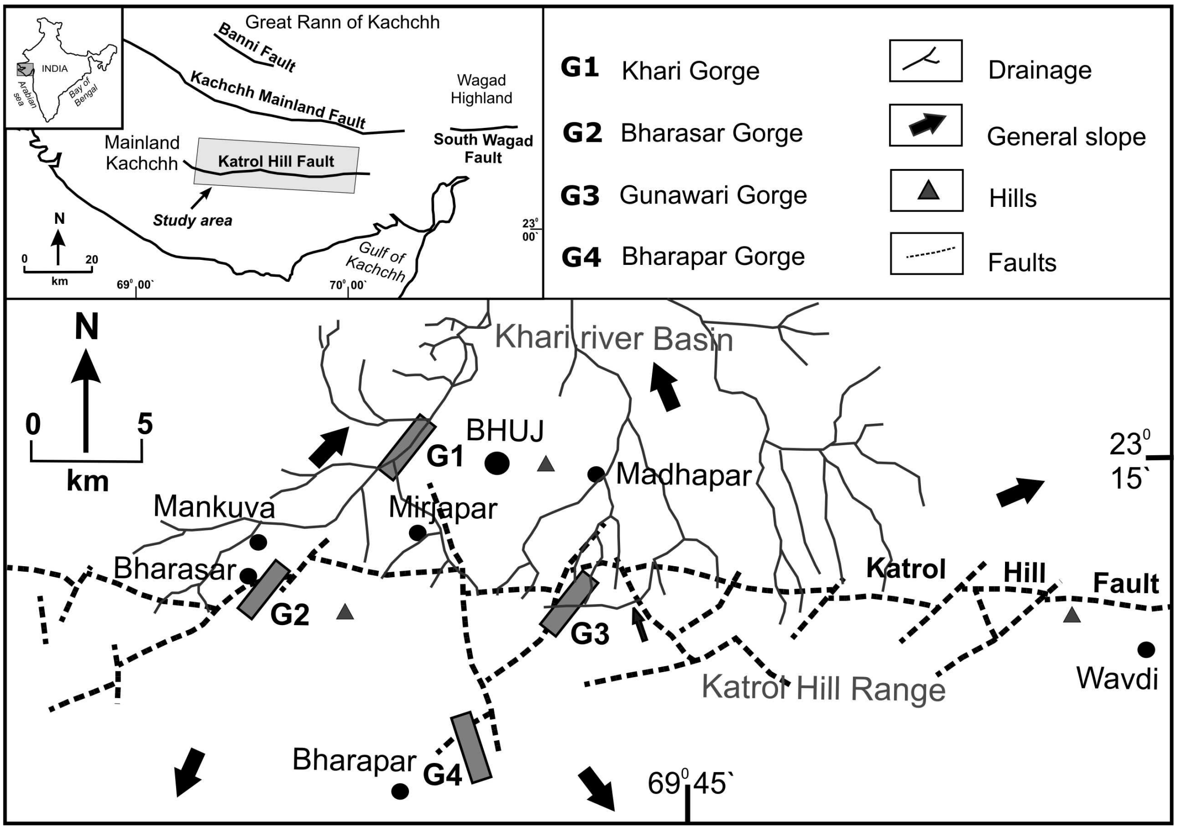

Figure 1. Map of the study area showing the location of gorges studied, the Khari drainage basin, prominent physiographic divisions, major tectonic lineaments and general slope direction.

include a fault-controlled first-order topography, uplifted Quaternary and pre-Quaternary planation surfaces, youthful fault scarps and a structurally controlled drainage network that exhibits incised rocky valleys and gorges (Biswas 1974; Thakkar *et al* 1999). The study area exposes Middle Jurassic to Cretaceous sedimentary rocks with the Katrol Hill Fault (KHF) marking a distinct structural contact between the Bhuj Formation (Late Cretaceous) to the north and the Jumara and Jhuran Formations (Middle Jurassic to Early Cretaceous) to the south (Biswas and Deshpande 1970). Quaternary deposits fill the structural valleys within the Katrol hill range, cover rocky pediments in the foothills, and occur as alluvial and colluvial fans to the north of the Katrol Hill Fault (Thakkar *et al* 1999). Sandy biomicrites known as Miliolite Limestone of the Middle Pleistocene age overlie the colluvial and alluvial deposits and are older than the fluvial sand bars exposed within the Katrol hill range (Thakkar *et al* 1999). The Katrol Hill Fault (KHF) and the Kachchh Mainland Fault (KMF) trending E–W show right-lateral and left-lateral shifts at places along transverse faults (Biswas and Deshpande 1970; Maurya *et al* 2003). Close examination of structural features shows that the transverse faults have been active since the Late Pleistocene (Thakkar *et al* 1999; Maurya *et al* 2003).

3. Drainage characteristics

In mainland Kachchh, the Katrol Hill Range forms the main drainage divide between the north-flowing and south-flowing drainage. The north-facing scarps of the Katrol Hill Range mark the Katrol Hill Fault (KHF), an active intrabasinal fault of the Kachchh basin. The north-flowing drainage originates within the mountainous terrain of the Katrol Hill Range and subsequently flows across the KHF, the rocky plain, the northern hill range and the Kachchh Mainland Fault (KMF) before dying out in the Banni–Rann plains. Within the Katrol Hill Range almost all streams display bedrock gorges of varying dimensions. However, in the rocky plain to the north of the KHF, which is identified as part of an Early Quaternary planation surface developed all over Kachchh, the rivers show incised bedrock channels with occasional development of deep narrow gorges with multiple levels of rocky terraces and isolated pockets of alluvial deposits. As the region is located in the hyper-arid belt in western India, the present climate is characterized by prolonged periods of drought with occasional precipitation. The rivers show ephemeral character and runoff lasts only for a few days when erosion is the dominating fluvial process. Lack of deposition is further evidenced by the rocky valleys and absence of channel alluvium along most of the river courses. However, successive erosional episodes are preserved along the bedrock channels in the form of gorges, rocky terraces or straths at various levels. We investigated four gorges formed along north and south flowing rivers originating from the Katrol Hill Range (figure 1) with a view to understand their significance in the evolution of the landscape. Of these, three are located to the south of KHF within the Katrol Hill Range while one (the Khari river gorge) is located in the rocky plain to the north of KHF. This is interestingly the most well-developed gorge with multiple rocky terraces. We have compared various parameters of all the four gorges, explaining in detail the Khari river gorge (G1 in figure 1). The Katrol Hill Fault and the associated transverse faults being tectonically active, an attempt has been made to look for possible linkages between gorge formation and neotectonic activity along various faults.

4. The Khari river gorge

The Khari river rises from the Katrol Hill Range and flows northward along a 10–15 m deep incised channel developed on a highly pitted and rocky landscape identified as an Early Quaternary erosional surface formed over Late Cretaceous sandstones belonging to the Bhuj Formation (figure 1). About 4 km west of Bhuj on the Bhuj–Kodki road, the river exhibits a locally developed deep gorge ($\sim$400 m long) with bedrock terraces in the Cretaceous sandstones and a palaeochannel filled with alluvial deposits (figure 2a, b). A basic dyke runs along the N100° trend across the channel confining a pond to the downstream side of the gorge. Also seen is a prominent vertical normal fault trending N50° (figure 2a). Since the level of the deepest part of the Khari gorge and the pond in the downstream is relatively lower than the average height of the valley floor, the flow of the water is reversed at the downstream end of the pond. A similar tectonic pond is also observed at the upstream end of the gorge, bounded by two normal faults across the gorge (figure 2a). Several transverse and E–W faults with both normal and reverse movements have been mapped on two scattered and eroded hillocks located north of the gorge (figure 2a). Though the channel of Khari river remains dry for most of the year, the gorge-reach is permanently filled with stagnant subsurface water that seeps up along the various structural features mentioned above. This is also evidenced by the fact that the water in the gorge does not vanish even after several consecutive years of drought.

The general trend of the gorge is N40° E (figure 2a) and is about 21 m deep. The vertical gorge walls are $\sim$15 m deep, which confine an extremely narrow channel (1.5–4 m wide). The narrow gorge is followed upwards by a succession of paired rocky terraces of varying morphologic characteristics (figure 2a, b), some of which are studded with numerous large potholes and prominent directional erosional structures like flutes and longitudinal ridges and grooves. A total of six bedrock terraces have been mapped at the gorge site, each of which exhibits characteristic morphologic features, especially in terms of the size of potholes. The total number of potholes and flutings with their average size and orientation on each bedrock terrace are given in table 1. The uppermost strath has been identified as T_1, while the lowermost with the smallest surface area as T_6 along the gorge. T_1 and T_2 are distinct planar surfaces with typical terrace morphology occurring at 21.3 m and 18.6 m respectively. These terrace surfaces are weathered and do not show definite erosional fluvial forms as observed in other terraces. The T_1 terrace exhibits several joints parallel to the direction of the gorge. The T_2 terrace is wide in the middle part, which narrows down and bifurcates towards the upstream direction on both sides of the gorge (figure 2a). The T_3 is the most prominent and widest terrace, which is characterized by the occurrence of many potholes and flutings (figure 3a, b). Most of the potholes and flutings are concentrated on the northern side of the T_3 terrace, while a meagre number of these are seen on the other bank. It is observed that the T_3 on either sides of the gorge slopes 2° in the downstream direction. Several large potholes and flutings occur on this terrace. The potholes have an average diameter of 45 cm and an average depth of 75 cm. The flutings show a general NE trend that is consistent with the present day flow direction.

A terrace 1.8 m lower than the T_3 is observed to be more pitted and highly eroded than the earlier terraces and is termed as T_4. Coalescing of potholes has resulted into mushroom shaped rocky projections on this terrace and the dimension of potholes is much larger than those seen on terrace T_3. The average diameter and depth of the potholes occurring on terrace T_4 are 55 cm and 85 cm respectively. Terrace T_5 occurs 4.2 m below the T_4 and shows still larger potholes with an average diameter of 160 cm and depth 110 cm. At the upstream end of the gorge, the water flows at the level of T_4 and falls down T_5 terrace creating rapids for a distance of about 50 m before merging with the gorge water level, which is $\sim$9 m lower than the identified T_5

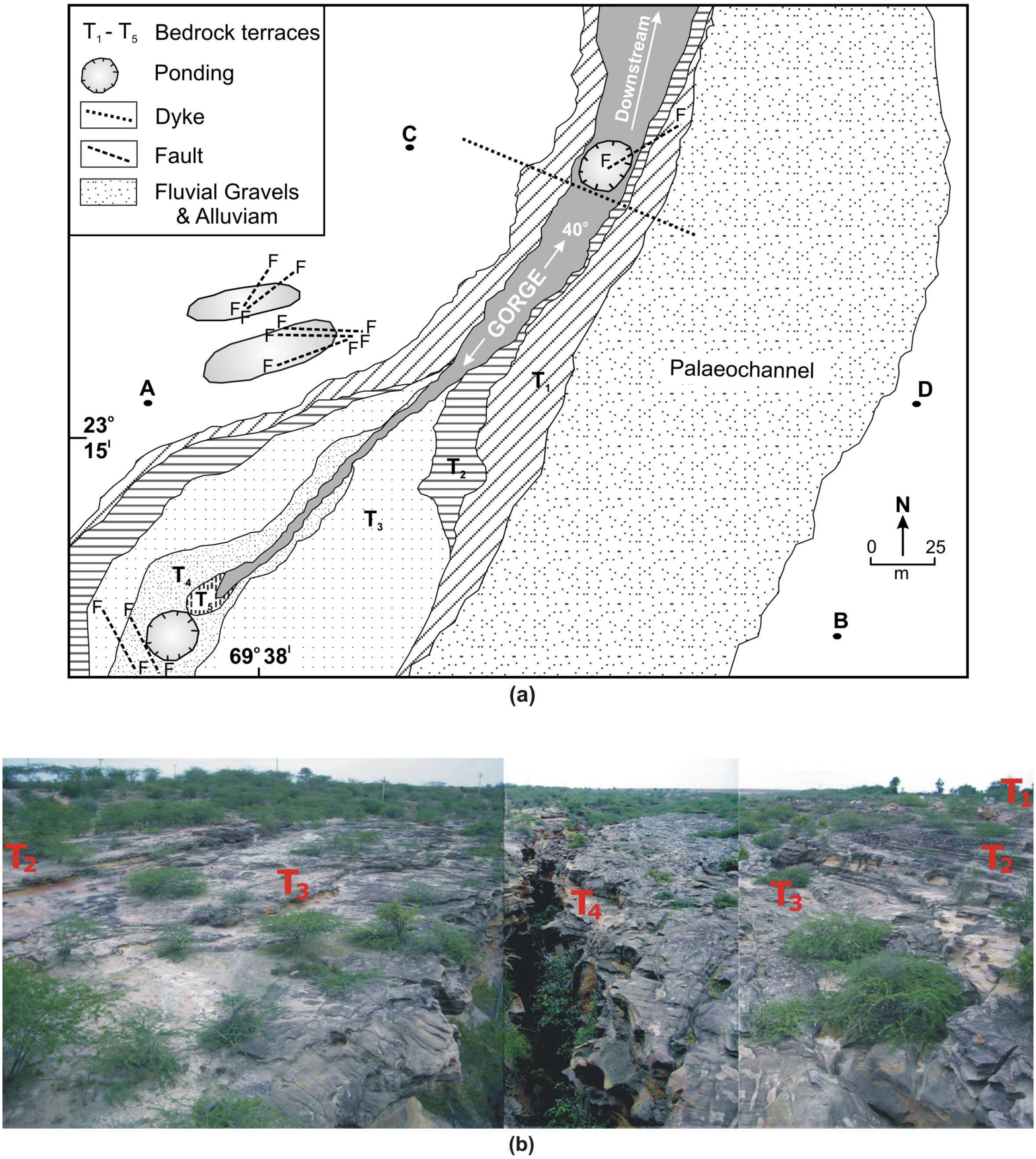

Figure 2. **(a)** Morphotectonic map of Khari gorge site showing bedrock terraces T_1 to T_5 and the palaeochannel. T_6 is the lowest terrace within the gorge having negligible aerial dimension. Ponds bounded by faults at both ends of the gorge are marked by circles. A–B and C–D are section lines of figure 4. **(b)** A panoramic view of Khari gorge, 4 km west of Bhuj. Note the rocky terraces on both sides of the gorge.

surface. The largest potholes observed and averaging 225 cm in diameter with average depth of 225 cm (table 1) occur at the levels between average water table and the T_5 surface. These largest potholes are limited to the upstream margin of the gorge and their elevations gradually merge with the bottom of the gorge. This indicates a phase of intense downcutting that resulted in the formation of a deep narrow gorge. Further downstream, the gorge walls are vertical and smooth except for the continuous horizontal indentations controlled by stratification planes. However, the varying nature, distribution and abundance of these features on different terraces suggest episodic nature and varying

Table 1. *Data on potholes and erosional grooves developed on various bedrock terraces of the Khari river gorge.*

Sequence of terrace	Height from valley floor (m)	Terrace height (m)	No. of potholes	Diameter of potholes (cm)			Depth of potholes (cm)			Number of groove marks of the length 50–300 cm	
				Min	Max	Avg	Min	Max	Avg	Number	Orientation
T_1	21.3	2.7	00	–	–	–	–	–	–	00	–
T_2	18.6	1.5	00	–	–	–	–	–	–	00	–
T_3	17.1	2.1	27	10	70	40	5	150	75	45	40°
T_4	15.0	1.8	15	10	100	55	20	150	85	13	40°
T_5	13.2	4.2	06	70	250	160	50	170	110	00	–
T_6	9.0	9.0	05	150	300	225	150	300	225	00	–

Figure 3. **(a)** Close view of a large pothole on T_3 bedrock terrace. **(b)** Flutings with marked orientation on the T_3 terrace.

intensity of the fluvial processes involved in the formation of the large erosional features.

A palaeochannel filled with alluvium was mapped between 50 and 200 m SE of the Khari gorge (figure 2a). The palaeochannel exhibits 2 m thick fluvial gravels that are overlain by 1.5 to 2 m thick finer alluvial deposits. The thickness of these increases to the SE of the gorge, where the bedrock occurs at 7.5 m depth (confirmed from the bore and open dug well data). Data collected from well sections confirm the bedrock depth and also reveal a palaeo-valley profile (figure 4). Cross sections prepared across the gorge and palaeochannel indicate a northward sloping bedrock valley floor over which palaeochannel sediments were deposited.

5. Gorges to the south of KHF

Three gorges located to the south of the KHF within the hilly terrain of Katrol Hill Range (figure 1) were studied. These occur in the vicinity of the KHF and are associated with transverse faults. A transverse-trending (N40° E) gorge (G-2) near Bharasar village (figure 1), has developed along a stream which exposes miliolites underlain by Mesozoic rocks along the valley walls. The gorge is 5 m deep at its upstream end near the transverse fault and rapidly attains a depth of 12 m within a distance of 500 m towards NE. The abrupt level difference of the valley floor, when traced on the surface coincides with an E–W trending fault, which is one of the several sympathetic faults parallel to the KHF. Further downstream the gorge attains considerable depth (∼15 m) and meets a wide valley. Within this valley fill miliolites and fluvial deposits of Late Pleistocene age (Maurya *et al* 2003) occur along an entrenched meander, the level of which is notably lower than the gorge level.

A deep, narrow gorge G-3 trending N40° E is found along the Gunawari river cutting miliolites. The Gunawari river is a second-order stream with a general E–W course in the hilly terrain of the Katrol range about 5 km south of Madhapar village (figure 1). Though the gorge does not show distinct terraces in miliolites, it is associated with a couple of transverse faults, showing surfaces with slickensides indicating left-lateral movements. The valley floor of Gunawari river shows three distinct levels, all with distinct characteristics along its channel. South of the mountain front scarps within the Katrol hill range, the river forms a very narrow gorge in miliolites and, after crossing a prominent knick point along a transverse left-lateral fault,

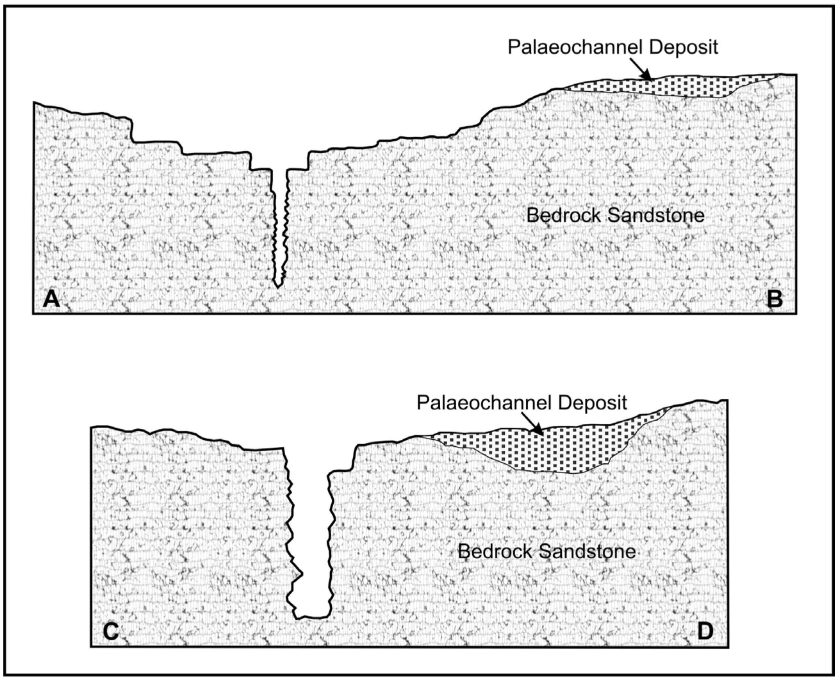

Figure 4. Cross sections across the palaeochannels. Section lines shown in figure 2(a). Note the elevated paleo-river course and thicker channel deposits near the downstream end of the gorge.

enters into a wider valley where Jurassic rocks are incised. Further downstream, in the same direction (N40° E) Late Pleistocene fluvial sand deposits are incised by 12–15 m forming vertical river cliffs (figure 5a).

The gorge (G-4) has developed in Cretaceous sandstones near Bharapar village south of the KHF along a transverse fault (figures 1, 5b). The southern part of the gorge trends N20° E while the northern part is oriented N40° W. Two distinct tectonic terraces are observed but none of them contains flutings and potholes. However, the gorge walls have a sinuous profile formed due to torrential flow of water (figure 5b). Though the general slope of the area is due south, the tectonic terraces slope 2° due north. We observed a significant south-dipping reverse fault parallel to the gorge that has a downthrow of 1 m towards the gorge.

All the gorges occurring to the south of the KHF exhibit a close association with the transverse faults. The exposure of transverse fault at Gunawari gorge marks a youthful scarp with left-lateral movement, while a reverse and south-dipping transverse fault near Bharapar gorge suggests neotectonic activity. Several parallel to sub-parallel transverse faults at various levels may be responsible for the development of the Bharasar gorge near the central axis of the Katrol hill range. Two abrupt level changes of the valley floor along the gorge, a sudden change in the geomorphic surface and entrenched meanders at lower reaches of the valley coincide with faults, which suggest uplift during Early Holocene. The age estimate is based on the fact that the miliolites and the other Late Pleistocene fluvial deposits are incised.

6. Implications for landscape evolution

The four gorges investigated in the present study provide vital evidence in understanding the landscape evolution of mainland Kachchh during the Quaternary. As mentioned earlier, 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. However, the Khari river gorge formed in the low-relief rocky plain is the best developed and reveals a long term history of landscape evolution. On the whole, the gorge associated rocky terraces, large potholes and other erosional structures appear as a 'misfit' in the present-day hyper-arid climate of the region. In general, the bedrock terraces with large potholes suggest a fluvial regime that was capable of high-intensity fluvial erosion. In this context, a humid climate is implied to support the high discharges and energy conditions needed to produce such landforms and features. The largest potholes occurring below T_5 at the upstream end of the gorge and related to the gorge-forming phase indicate the highest energy fluvial regime at this time. Irregularities and obstacles on bedrocks create disturbances, flow separations and local areas of increased static pressure in turbulent flows, which

Figure 5. **(a)** Cliff section of Gunawari stream showing incision in the fluvial deposits. Note the incision in the Jurassic rocks exposed in the river bed. **(b)** Narrow gorge is developed in Cretaceous sandstone near Bharapar village. The gorge follows a transverse fault known as Bharapar Fault.

reverse the direction of flow locally. The resulting eddies are transformed into vertical hydraulic vortices and the scoring of a depression begins to form potholes and flutings (Allen 1976; Lorenc and Saavedra 1980; Nemec *et al* 1982; Lorenc *et al* 1994). Fluvial erosion processes like plucking dominate wherever rocks are well jointed on a sub-metre scale (Burbank *et al* 1996) in case of bedrock erosion and development of flutings and potholes. When the rocks are massive or joint sets are widely spaced, plucking is inhibited given the prevailing channel slope and discharge conditions (Whipple *et al* 2000). Some combination of abrasion by bedload, abrasion by suspended load and cavitation is responsible for bed lowering (Whipple *et al* 2000). Under these conditions the flutes and potholes with smooth surfaces that overshadow all the topographic irregularities mark the channel bed and banks.

The geomorphic set up of the Khari gorge delineated in the present study indicates that it has evolved in two major phases. The first phase formed multiple bedrock terraces due to episodic downcutting with some amount of lateral erosion, which was accompanied by extensive fluting and potholing. The second phase predominantly involved vertical erosion leading to the development of a narrow gorge, which also formed potholes with the largest sizes at the upstream side of the gorge.

The gorges to the south of the KHF, though, equally impressive seem to reveal only the youngest events of landscape sculpting. However, incision in the miliolites constrains the timing of gorge formation. Chronologic data available on the miliolites (Baskaran *et al* 1989; Chakrabarti *et al* 1993) suggest a rather prolonged time of miliolite deposition from Middle to Late Pleistocene. The formation of gorges within the Katrol Hill Range therefore possibly occurred during humid Early Holocene period, which may have provided the necessary runoff for the formation of the gorges. Incised fluvial deposits of possible Late Pleistocene age (Thakkar *et al* 1999) also support this inference. The formation of gorges within the Katrol Hill Range thus appears to correlate with the gorge-forming phase of the Khari river gorge.

It is obvious that high-energy discharges are essential for rivers to form gorges and large potholes documented in the present study. However, the occurrence of gorges in close vicinity of the KHF within the Katrol Hill Range, local development of a spectacular gorge like the Khari gorge in the low-relief rocky plain and the close association of these with the transverse faults suggest dominant control of tectonics in determining the sites of gorge formation. All the gorges south and north of KHF are oriented towards N40° E, which is in conformity with earlier geomorphic studies that have broadly identified the Late Pleistocene-Recent as the time when transverse faults were active in central mainland Kachchh (Thakkar *et al* 1999; Maurya *et al* 2003). The occurrence of palaeochannel SE of the Khari river gorge, northward slope of the landscape north of KHF, normal and reverse dip slip faults in transverse direction indicate that the relocation of the Khari river channel after the filling up of the palaeochannels took place in response to northward tilting of the entire block north of the KHF. This is further substantiated by the elevated and tilted palaeochannel floor. Structural pondings on both ends of the Khari gorge coupled with normal and reverse faults suggest strong influence of local tectonic set up in the formation of the Khari gorge. Terraces found in the bedrock are definite evidence of the episodic rock uplift and subsequent bedrock incision.

The occurrence of gorges on both sides of the KHF is in conformity with the available information on tectonic set up of the KHF. The KHF is, in general, recognized as an E–W trending intrabasinal fault that marks the lithotectonic contact between rocks older than Bhuj Formation (Late Cretaceous) on the south and the Bhuj Formation to the north (Biswas and Deshpande 1970). An important feature of the KHF is its segmented nature as evidenced by right- and left-lateral offsets along the NE–SW to NW–SE trending transverse faults (Maurya *et al* 2003). Seismo-tectonic studies indicate that various faults of the Kachchh basin are accumulating compressive stresses along them, which is responsible for recurrent seismic activity (Biswas and Khattri 2002) and uplift of the basin. Preliminary results of a Ground Penetrating Radar (GPR) study along the KHF (Maurya *et al* 2005) suggest that the nature of the KHF in the shallow subsurface is in general a near-vertical south dipping reverse fault. We therefore, infer that the formation of gorges on both sides of the KHF took place due to neotectonic movements under an overall compressive stress regime. However, site-specific tectonic conditions controlled the distribution, orientation and the nature of gorges formed.

7. Conclusions

The study of four selected gorges located to the south and north of Katrol Hill Fault points to their development in response to neotectonically aided high intensity fluvial erosion under conditions of precipitation much higher than present. The Khari river gorge, though developed locally, reveals a long term (Early Quaternary to present) evolutionary history that can be broadly divided into two phases. The earliest phase resulted in the formation of typical bedrock terraces with extensive development of erosional features like large potholes and flutes in response to well marked periods of high intensity fluvial erosion. The second phase led to the formation of the deep narrow gorge during the wet period of Early Holocene. Incision of the miliolite and Late Pleistocene fluvial deposits along the gorges and to the south of the KHF respectively further indicate an Early Holocene (post-miliolite) age for gorge formation. Close association of the transverse faults with the gorges and the local nature of the exceptionally well developed Khari river gorge point to the control exercised by local tectonics. The study demonstrates the importance of gorges in understanding the successive stages of Quaternary landscape evolution of mainland Kachchh.

Acknowledgements

The Department of Science and Technology (DST) is gratefully acknowledged for providing financial assistance to MGT. Critical reviews by two anonymous reviewers and Dr. H C Sheth have been helpful in improving the quality of the paper.

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MS received 20 June 2005; revised 25 August 2005; accepted 19 October 2005