CHAPTER 5
MORPHOTECTONICS

5. MORPHOTECTONICS

5.1 INTRODUCTION

'*Morphotectonics*' is a commonly used term to study all aspects of the relationship between geological structure and landforms (Hills, 1956). The term 'morphotectonics' applied to more specific usage is dealt herein as tectonic geomorphology or structural geomorphology. The subject not only deals with macro-scale features and long term geological spans but also concerns with more recent and detailed effects of tectonic processes (Embleton, 1987). The term 'Neotectonics' or 'Active tectonics' is coined to reflect geologically recent deformation, though; there is considerable amount of disagreement as to the time scales to which these terms refer. In this study, both terms have been used to describe the tectonic activity mainly during Quaternary period. The study of relationship between neotectonics and geomorphology involves delineation of the role of recent and continuing crustal instability and the use of morphological evidences in conjunction with other geological data to identify locations and styles of tectonic deformations.

In recent years, tectonic geomorphology has been an important tool to study recent crustal deformations. It is even more relevant in the areas such as the present one where the information is lacking in terms of *in situ* stress measurements and other geophysical data by which an idea about the recent crustal instability can be obtained. Also, such kind of studies are of potential value to seismic risk assessment and therefore getting growing attention. Different methods and approaches of modern tectonic geomorphology are used to solve the problems related to neotectonics and the landform genesis at different scales.

To start with, a brief review of the work done in this field in recent years that would highlight the role of tectonic geomorphology in understanding recent crustal deformations is given. Although, the importance of geomorphology in the study of neotectonics was felt right in early 20th century detailed studies on neotectonics in the light of geomorphology developed from late sixties upto late eighties. Most of the work done in this regard is concerned with individual calculations of different drainage parameters emerging out of the longitudinal profiles and the parameters related to the mountain fronts, some have also tried to study the drainage and Mountain front interaction in relation with neotectonics. As has been stated by different workers (e.g. Ziony and Yerks, 1985), the first order indicators of continued tectonic activity are the occurrence of earthquakes. Thus, in the light of the high seismic activity, the Kachchh region provides an avenue to study features developed on account of active tectonism.

Several examples from different areas show that drainage is of utmost importance from the point of view of recognising the recent deformation because of its sensitivity to any change caused by the tectonic activity. Bull and MacFadden (1977) took into account the rate of entrenchment to explain the uplifts to the north and south of Garlock fault, southern California. Similarly, using the stream profile anomalies Seeber and Gorintz (1987) explained the differences in uplift conditions in different parts of Himalayas. Many other workers explain how different drainage related parameters could be used as effective tools to recognise influence of tectonic activity. For example Maclean (1985), Mayer (1985), Krzyszkowski and Stachura (1998), Krzyszkowski et al, (1995), Merritts and Vincent, (1989) and Huang (1993) attributed differences in valley morphology and long profiles to differential uplifts.

Recently McKeown et al, (1988), Merritts and Vincent (1989) and Rhea (1993) used relatively new drainage parameters such as PHI (Pseudo Hypsometric Integral), *SFD*

(Sinuosity Fractal Dimension) and GI (Gradient Index) to show differential uplifts. Other than drainage, Wells et al. (1988) analysed *mountain fronts* bounded on one side by a fault in detail. They show that how quantification of mountain fronts and *faceting* help in recognising the most recent activity along a fault zone. Bull and MacFadden (1977), Bull (1978) and Krzyszkowski (1995) also carried out similar studies.

For the present purpose the author has studied different facets of geomorphology including fluvial geomorphology, mountain front sinuosity and alluvial fans to analyse the influence of tectonic activity.

5.2 FLUVIAL GEOMORPHOLOGY

Analysis of drainage related geomorphic parameters is of foremost importance because alluvial channels are considered to be very sensitive to neotectonic processes (Burnett and Schumm, 1983; Ouchi, 1985) and these adjust to vertical deformation or base level change by channel modification, specifically by incising, aggrading or modifying its sinuosity.

The landscape of Central Kachchh Mainland comprises two prominent fault related ridges (i.e. the Katrol Hill Range (KHR) and the Sanosra Dungar Range (SDR) (Fig. 5.1). KHR forms the major drainage divide, not only for the Central Kachchh Mainland but also for the whole of Kachchh Mainland region, and provides the main watershed for various north and south flowing rivers. The north flowing rivers debouch into the Great Rann-Banni depression, which on crossing over the Kachchh Mainland Fault have deposited semi-conical shaped alluvial fans (this aspect is discussed in a later section). The south flowing rivers originating in the KHR meet the Gulf of Kachchh and Arabian Sea and have given rise to small-coalesced fine grained deltas near their mouths.

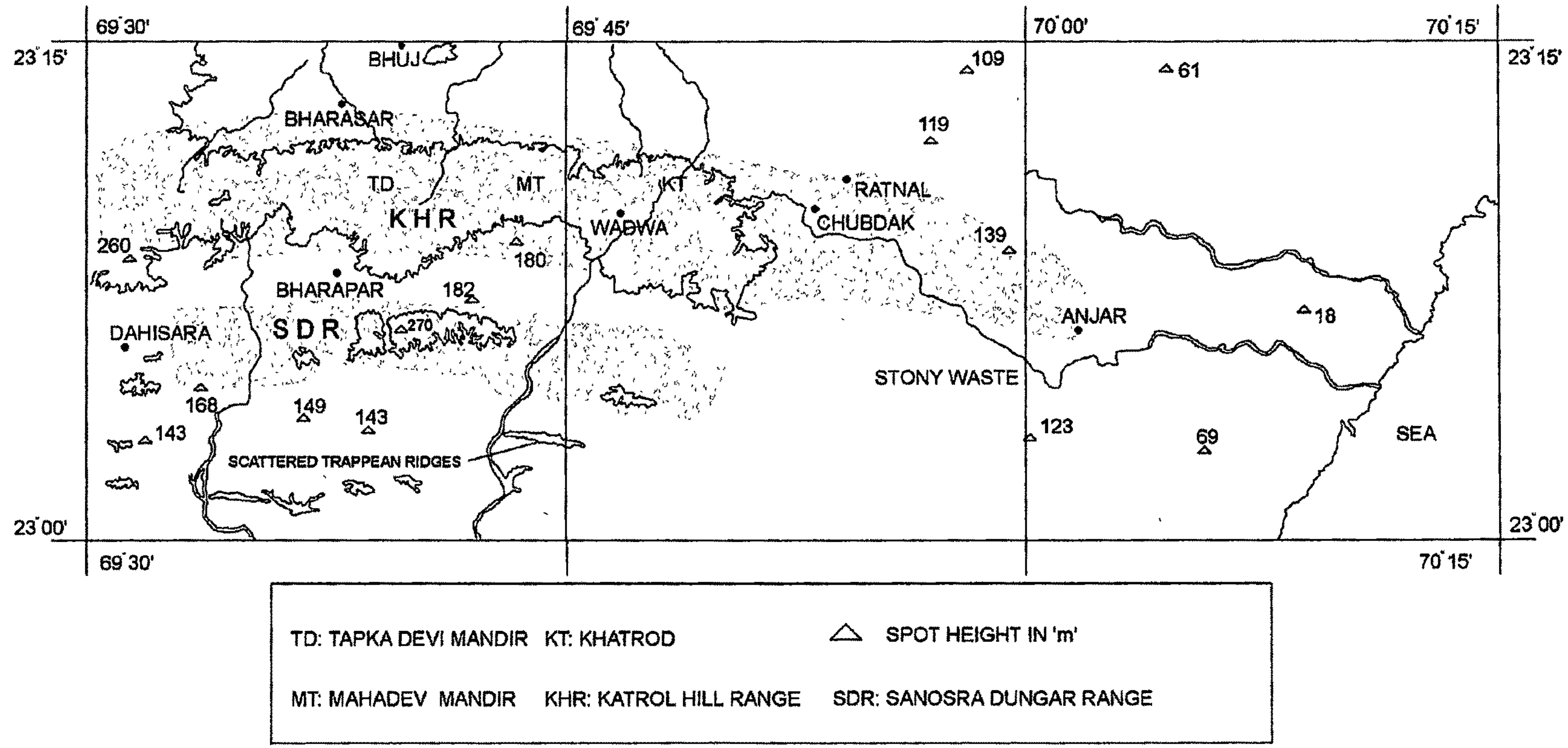


Fig 5.1 Generalised Geomorphic map of Central Kachchh Mainland showing two prominent hill ranges (i.e. Katrol Hill Range (KHR) and Sanosra Dungar Range (SDR)

The overall drainage network (Fig 5.2) of Central Kachchh Mainland and morphology of the channels such as their unusual straight courses, sudden deflections, sudden narrowing and broadening of channel width strongly point to a dominant structural control over them. This is also ideally reflected in the drainage of the study area. As is said earlier, the area is marked by the two major faults related ridges (KHR and SDR), these are envisaged to have formed on account of the slip propagation on already existing normal faults after the onset of compressional regime. The KHR rises to altitudes over 300m and is an asymmetric anticlinal flexure. The ridge axis is almost E-W trending with some local variations. The drainage pattern of this area reveals its structure and the drainage divide along the ridge crest marks a boundary between the steeper northern flank (escarpment) and a gentler southern one. The consequent streams flow perpendicular to the drainage divide. Similar is the case with Sanosra Dungar Range where the northern flank of the ridge is steeper, which further merge with the peneplained area south of KHR (Fig. 5.1). At several places in both of these ranges there is the presence of radial drainage. This ideally reflects the presence of domal structures flanking the faults. The radial pattern at places is seen to have been modified by the longitudinal drainage flowing parallel to strike of the ridge. There are several examples in the area where such morphology is observed. Although, for the sake of detailing the description the individual fault blocks are dealt as individual ridges, all of these are parts of the same system of faults. The above-mentioned explanation largely constitutes the western part of the study area where the drainage density is maximum. The eastern part of the area too, exhibits its characteristic drainage pattern. This part largely constitutes Tertiary and Quaternary deposits and hence no much variation in drainage pattern is seen on a larger scale. However, the unusual straight courses, sudden deflections and higher degree of incision point to the influence of recent tectonic movements on their morphologies.

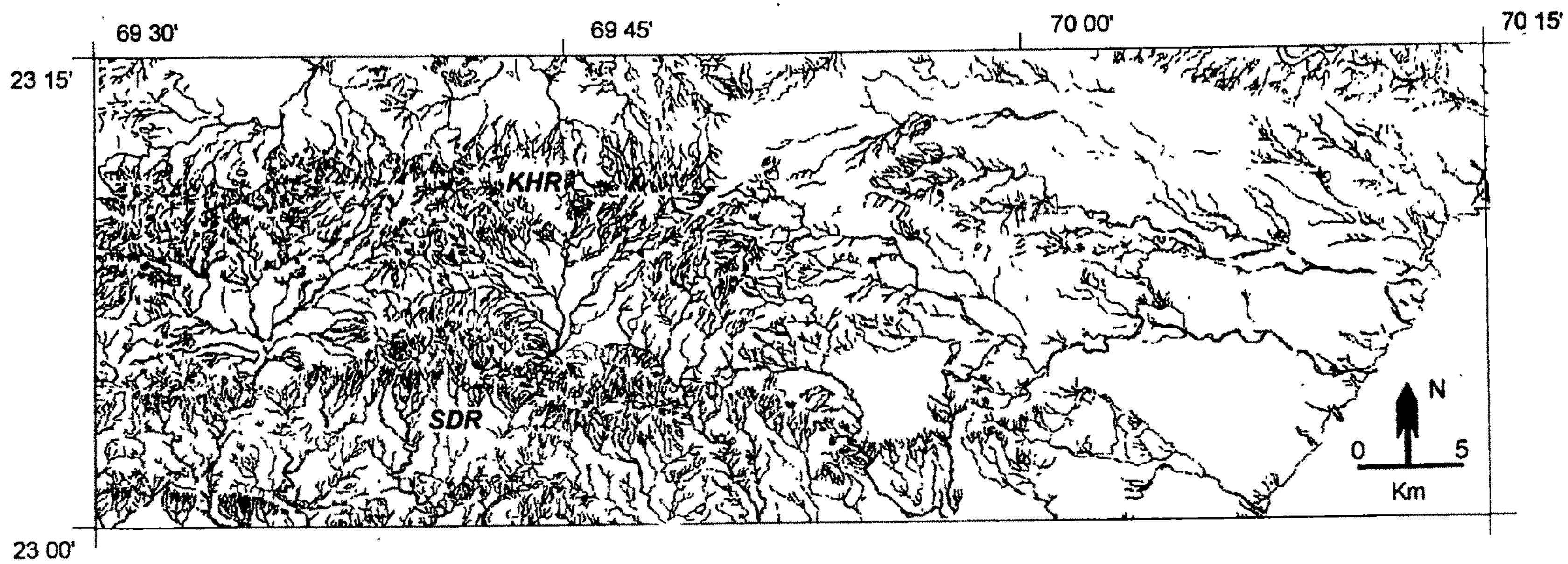


Fig 5.2 Drainage map of Central Kachchh Mainland

Various other features such as drainage reversal on local and regional scale and conspicuous terracing were observed which signify the active tectonism in Central Kachchh Mainland.

5.2.1 Drainage reversal

The most striking and conspicuous effect of KHR uplift is seen in the phenomenon of drainage reversal. Current directions in the exposed fluvial sequences along various south and north flowing rivers provide a more or less conclusive evidence of this phenomenon of drainage reversal. Envisaging the drainage prior to Katrol uplift that streams flowed from north to south, it is logical to expect continued southward paleo-flow directions in the south flowing streams originating from KHR, whereas those flowing due north would provide an almost total reversal of flow and associated current directions. Pre-uplift fluvial sediment record, mainly trough and planar cross-stratified gravely lithofacies representing the south flowing streams, show paleo-flow trends due south and southwest suggesting that upto the close of Tertiary there existed a drainage network flowing southward and meeting the Gulf of Kachchh and the Arabian Sea (Fig. 5.3a&b). On the basis of this evidence it is envisaged that the existence of southward flowing streams existed in Kachchh mainland originating from the elevated hill range in the north (NHR) till the reversal event. Subsequent to the KHR uplift the streams to the south continued their original path of journey; they, however, show increased fluvial activity. On the other hand, those flowing due north point to uplift related valley incision and an almost 180° swing in the current direction. The streams that started flowing due north after reversal flowed across the NHR through the gaps in the range and debouched into the Banni-Great Rann depression and have developed large (fan deposits) alluvial fans (Fig. 5.3b). Interestingly, the fans at the base of the NHR are seen incised by the same streams (that deposited them), marked by 20-25 m high cliffs.

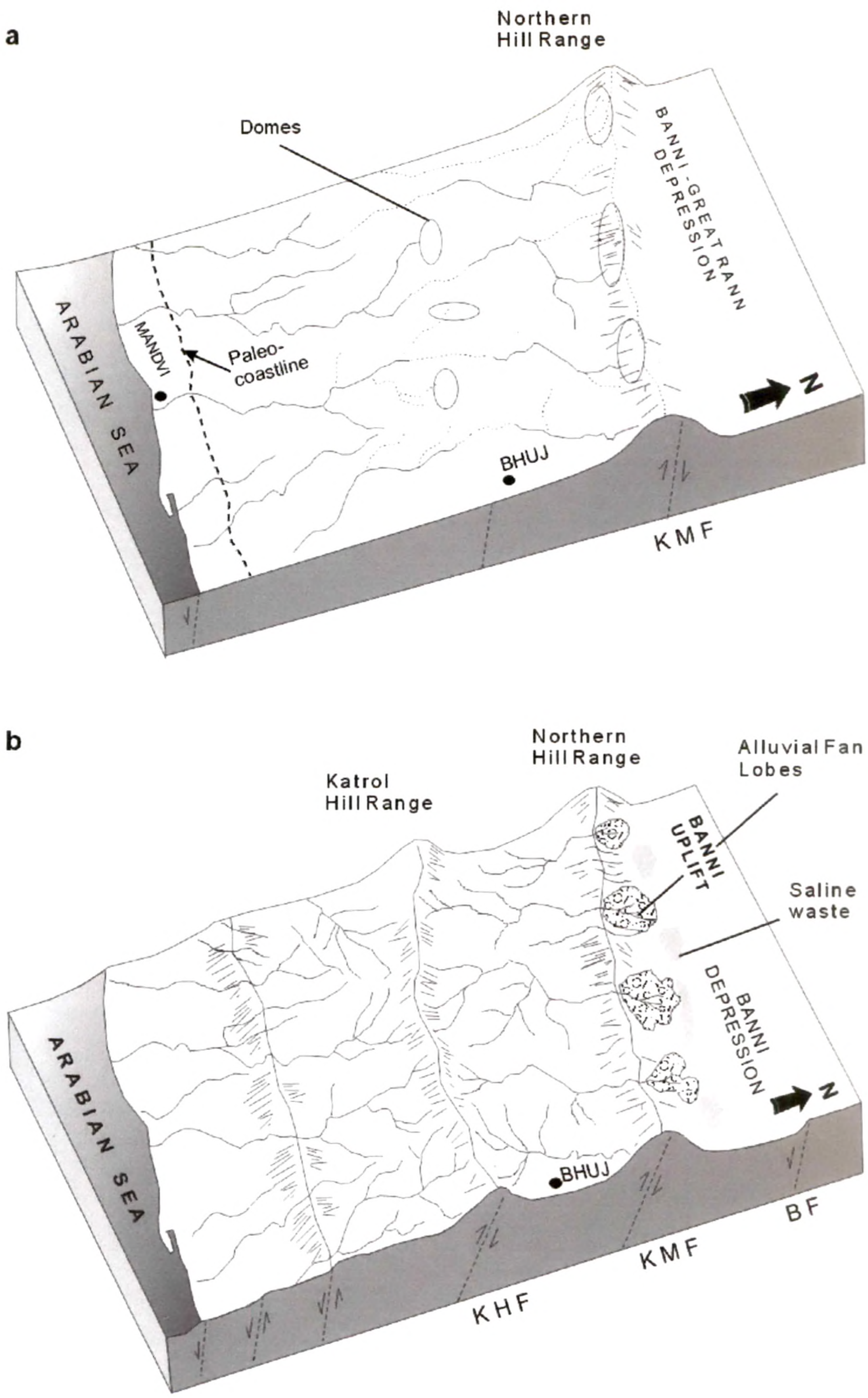


Fig 5.3 a). Earlier drainage that existed before the major uplift event, b) The post uplift scenario of the drainage behaviour of Central Kachchh Mainland

Subsequent to the major episode of drainage diversion, the mainland experienced several successive events of deformational upheavals along major as well as subordinate faults (Sohoni et al, 1999; Malik et al, 2000). Apart from various other evidences of uplifts along river valleys, an important manifestation is that of small-scale flexuring, thereby causing drainage changes at local scale. However, the response of smaller streams to the phenomenon of flexuring is variable. In some cases where the rate of flexuring related uplift has been out-paced by the cutting power of the streams, vertical cliffs with height upto 45 m are seen to have developed locally. Whereas, the streams with sluggish flow regime have been so affected that they show flexure related stream diversion.

Fig 5.4 a. Photograph showing the ponding condition to the north of Bhuj in the Khari river channel

It is also observed that at places in the lower order streams fault-related flexuring have caused local reversal of flow resulting into formation of small local ponds along their channels. Two good examples of flexuring related reversed flow directions and ponding conditions, have been observed; one along the north flowing Khari Channel near Bhuj and other along a lower order tributary of south flowing Nagavanti river near Godpar (Fig. 5.4a & 5.4b). This tributary originates from the southern flank of KHR flows due ESE and joins Nagavanti river in the downstream. Here flexuring has resulted the stream water to flow locally in reversed direction, i.e. due NW. Instances of similar local reversals are quite common in the streams of Bhuj lowland and in the area south of Katrol Hill.

Fig 5.4 b. The conditions of flow diversion observed near Godpar in a small tributary of Nagavanti river

5.2.2 Stream entrenchment and Terracing

Stream entrenchment is another prominent tectonism-related geomorphic element and is seen in rocky as well as in unconsolidated alluvial terrain. Various north and south flowing rivers originating from the KHR show rather steep cliffy channels and incised paired terraces. This points to following sequence of events, a) An initial stream flowing in any particular direction eroding in the upper and depositing in the lower reaches, b) Entrenchment of the stream due to downcutting caused by an event of uplift, c) Cessation of downcutting and a period of lateral erosion of valley sides, thereby broadening of the channel floor; flood plain deposition in the widened valley, d) Renewed uplift, and stream rejuvenation causing another event of channel incision; downcutting of the channel fill deposits as well as the underlying rocky portions and e) Repetition of these processes on account of the stream response to several successive events of uplifts. A summarised picture of the stream terracing is presented in Table. 5.1.

Table 5.1. Terracing sequence of Central Kachchh Mainland, note the more number of terraces within the Katrol Hill Zone indicating the highest amount of tectonic instability within this zone as compared to the north and south of it.

Distribution of Terraces	Number of Terraces	Type of Terraces	Lithological and Morphological Description	Height in Meters	Probable Cause
Katrol Hill Range (Zone)	3	One Paired Strath Terrace and Two Paired Alluvial-Fill Terrace	Strath Terrace – forming the oldest rocky paired surface comprising Mesozoic sediment succession	Cliff height ranges from 25 to 35 m	Periodic uplifts related to Katrol Hill Fault
			Second Alluvial-Fill Terrace – Comprise valley fill miliolitic deposit	Cliff height ranges from 10 to 15 m	
			Lower most Younger Alluvial-Fill Terrace - comprise coarser colluvial material made up of angular to sub-angular boulders and cobbles representing tectonically generated fragments during strong seismic shaking	Cliff height ranges from 1.5 to 3 m	
North of Katrol Hill Range – Bhuj lowland	2	Paired Strath Terrace and Paired Alluvial Fill Terrace	Strath Terrace – comprise Mesozoic sediment succession, at places show capping of 2.0 to 3.0 m thick Quaternary fluvial sediment.	Cliff height ranges from 8 to 20 m	Incised due to uplift along fault-bounded blocks or due to fault related flexuring. These terraces are the manifestation of two individual event of uplift related down-cutting
			Alluvial fill Terrace – made up of trough to planar cross-stratified gravel facies along with silty and clayey litho units	Cliff height ranges from 1.5 to 3 m	
North of Katrol Hill Range – Along the Northern Hill Range	1	Paired Alluvial Fan Surfaces	Dissected alluvial fan surface comprising debris flow facies, high-density traction carpet deposits, trough cross-stratified gravel and sand facies representing channel-fill deposits and sheet flood deposits.	Cliff height ranges from 20 to 25 m	Uplift along Kachchh Mainland Fault (KMF) was responsible for formation and incision of the alluvial fan lobes by the same newly developed north flowing streams originating from KHR after the main episode of drainage reversal
South of Katrol Hill Range	1	Paired Rocky Strath Terrace	The terraces in the central and lower segment consists Tertiary succession, at places capped by 3-4 m thick unconsolidated Quaternary fluvial material	Cliff height ranges from 20 to 35 m in upper reaches, 20 m in central and 5 m in lower reaches	Strath terrace along KHR is a result of KHF related flexuring, whereas terraces in central and lower portions represent younger tectonic event of fault related flexuring

5.2.2.1 *Terraces within Katrol Hill Range*

A detailed study was undertaken for two major north-flowing rivers viz. Kaila and Khari and have revealed many tectono-geomorphic features. In the upper reaches within the KHR, the channels of both rivers show three distinct sets of paired terraces (Fig. 5.5; Fig. 5.6) in the bedrock as well as in alluvial deposits.

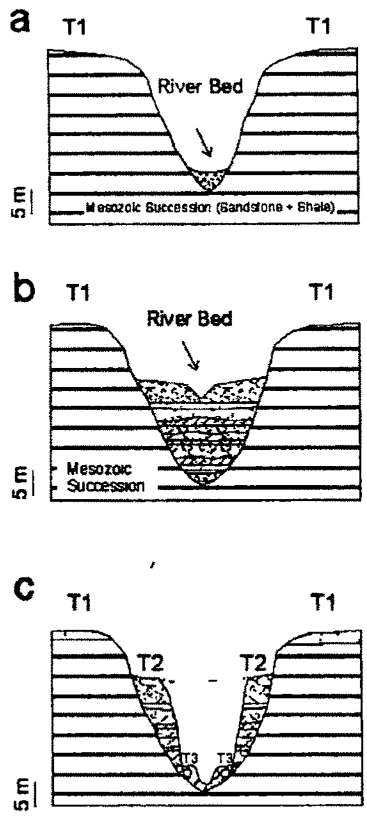


Fig 5.5 The Sketch showing the development of successive terraces exposed within the Katrol Hill Zone (T1- Strath Terrace, T2- Alluvial fill Terrace, T3-Alluvial fill Terrace)

Of these, the uppermost, a strath terrace forming the oldest rocky surface, is marked by a vertical cliff ranging from 25 to 35 m in height, cutting a Mesozoic sediment succession (sandstone-shale). Whereas, the other two terraces are exclusively developed in unconsolidated Quaternary material. The middle terrace is an incised valley-fill comprising fluvio-aeolian (miliolitic) deposits of Middle Pleistocene age with cliff height varying between 10 and 15 m. The lowermost surface represents younger alluvial fill terrace, cliff height being 1.5-3 m. Significantly, this youngest terrace is seen incising a colluvial deposits consisting of angular to sub-angular bouldery-cobbly material, in all probabilities representing tectonically generated fragments/KHF related landslide accumulations.

Fig 5.6 Three paired terraces within the Katrol Hill Zone (Loc. 6 km south of Bhuj, along the Bhuj-Mandvi Road)

Obviously, the three sets of paired terrace are the manifestation of successive events of uplift-related incision along the KHR. The uppermost rocky strath terrace formed during the main uplift along the KHR. that caused the main drainage reversal. This uplift along KHF, was followed by two other uplifts, to which are attributed the younger terraces.

5.2.2.2 *Terraces north of the Katrol Hill Range*

Streams originating from the northern flank of KHR flow across the Bhuj lowland and debouch into the Banni depression after crossing NHR. Nature and distribution of terraces in these north flowing streams with reversed flow directions differ from those of the terraces recorded along KHR. Within the *Bhuj lowland*, two sets of paired terraces are observed (Fig. 5.7). The upper one represents older strath terrace cutting Mesozoic bedrock.

Fig 5.7 Terracing sequence to the north of Katrol Hill Fault

The terrace height varies from 8 to 20m and at places shows a capping of 2-3m thick Quaternary material deposited prior to the incision. The lower terrace with height ranging between 1.5 and 3 m marks the younger valley fill terrace confined within the older rocky channel. Occurrence of small folding and pseudo-nodules are common within the alluvial succession. Development of this terrace is consistently seen to occur in the major trunk streams as well as in the lower order tributaries. Northward, where these rivers flow across the Mesozoics of the NHR before crossing the KMF show the usual upper strath terrace and the lower one incising its own deposit. Significantly, after crossing the KMF the streams have incised their own alluvial fan lobes. Terraces in north flowing streams are the manifestation of two tectonic episodes subsequent to the event of reversal, vertical uplifts due to fault or fault propagated flexuring within the fault-bound blocks. Successive uplifts along the regional E-W trending faults as well as associated smaller faults during the late Quaternary were the major factors for (i) generating the colluvial debris in the catchment areas of north flowing rivers, (ii) controlling the northward flow of the streams and (iii) causing formation and subsequent incision of the alluvial fan lobes. The incision of alluvial fan lobes by the same river channels points to post-fan aggradation uplift along the KMF.

5.2.2.3 ***Terraces South of Katrol Hill Range***

South flowing streams originating from the KHR show marked differences in their channel morphology and valley incision as compared to their north-flowing counterparts. Three major valleys viz. those of Rukmawati, Nagavanti and Bhukhi, have been studied (Fig. 5.9 & 5.13). These rivers follow more or less parallel courses, and all through their journey, exhibit only one set of paired terrace with entrenchment upto 20-35m in the upper reaches and upto 20m in the central; and 5m in the lower reaches. Terrace pairs in the upper reaches and confined within KHR dissect the rocky Mesozoics with a thin veneer of alluvial material. In the central segments, the river valleys show a terrace comprising Tertiary bedrock with overlying 3-4m of Quaternary sediments. In the distant ends, the terraces are seen dissecting only the Quaternary deposits.

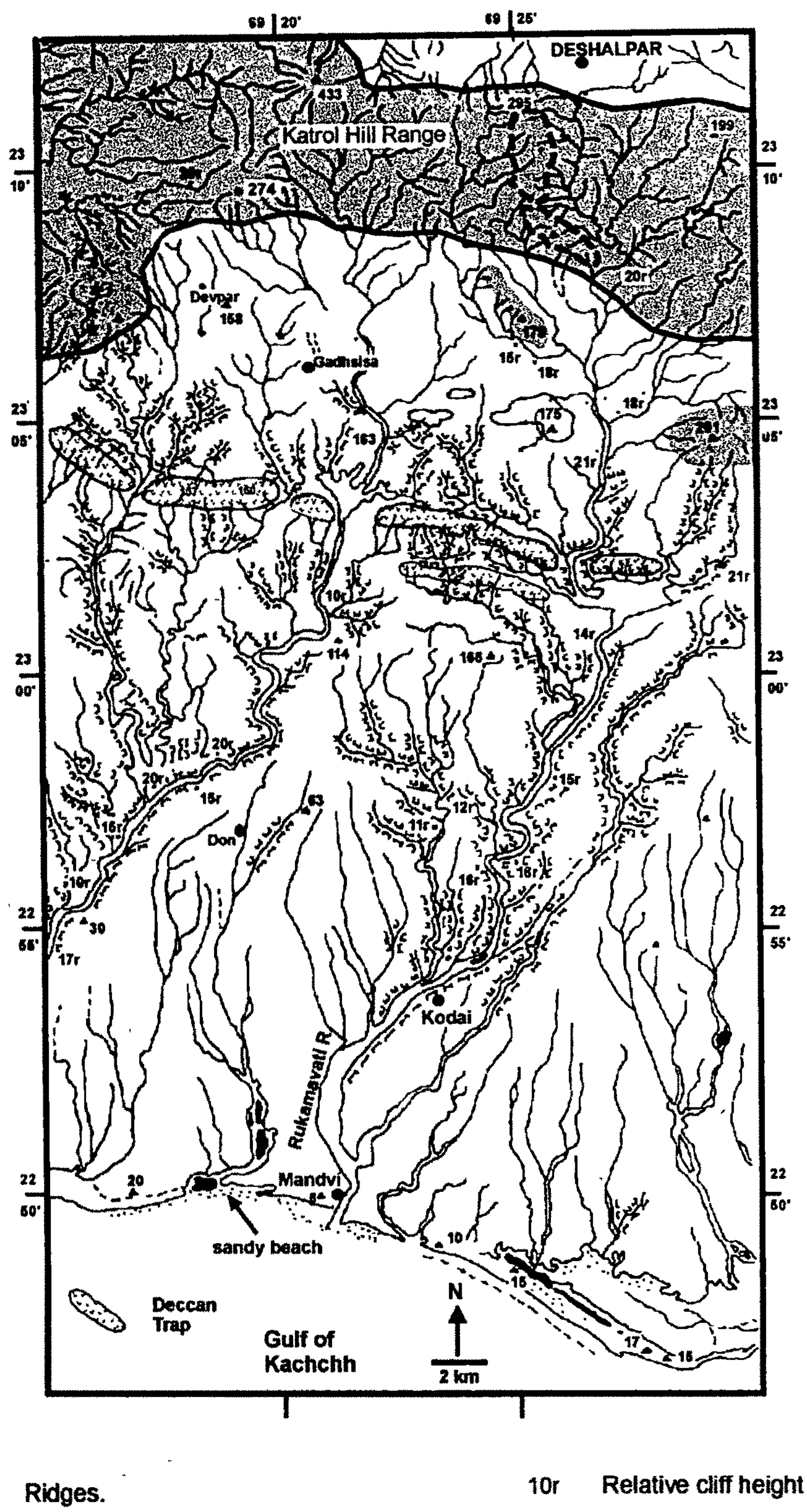
Obviously, the older strath terrace, confined along the southern margin of KHR is a result of uplift related to KHF. It is reasonable to presume that the fluvial Quaternaries resting over rocky surface in KHR and to its immediately south represented vestiges of the pre-reversal fluvial material, deposited by the original south flowing streams and thus represent the oldest fluvial material. The terraces in central and lower segments are the manifestation of younger events that followed the main Katrol uplift.

Even the coastline exhibits feature of active tectonism. The area between Suthri in the west and Mundra in the east is marked by a sandy beach, whereas, the region beyond their either flank is muddy and occupied by recent tidal flats. The sandy beach is an indication of uplift with mud flats forming subsided areas. Within the sandy coastal zone between Mandvi and Mundra near the mouths of these rivers raised beaches, rising 2-2.5m above the High Water Line (Fig. 5.8) are clear indications of an uplift that took place sometime around late Holocene.

Fig 5.8 Raised beach along Mandvi coast

5.2.3 Evidences of active tectonism in channel morphologies

Channels of most streams show typical narrowing and broadening, local development of tight meanders, braided pattern and development of localised ponds (Fig. 5.9, 5.10 & 5.13). These features along the valleys are good indicators of active tectonic control (Schumm, 1986). Kaila, Khari, Nirona and Kaswali rivers flowing due north and several streams flowing south including Rukmawati, Phot, Nagavanti and Bhukhi were studied. In the north flowing rivers, channel width ranges between 8 and 250m in the upper (KHR) and central reaches (Bhuj lowland). Within the Bhuj lowland, the NNE-SSW trending lineaments have controlled the channel courses of the trunk streams and their tributaries.



Ridges.

Deeply incised channels marked by narrow valleys, steep verticalcliffs resulting into development of paired terraces.

10r Relative cliff height in meter

▲125 Elevation in meter

Major and minorfaults

Fig 5.9. Drainage morphology of south flowing Rukmavati and Kharod rivers originating from southern flank of Katrol Hill. Note the intense gully erosion marking the course of the channels

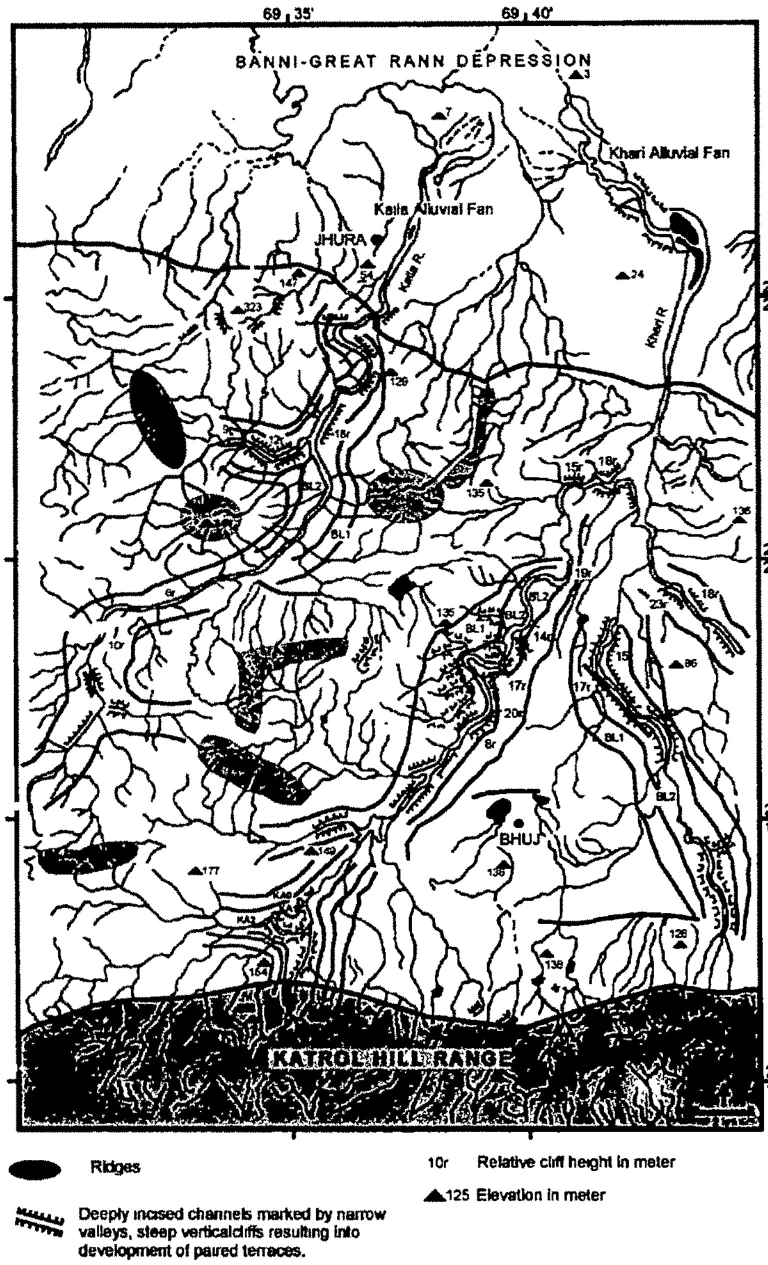


Fig 5.10 Morphological drainage network of north flowing streams marked by their structure controlled deeply entrenched courses and sudden high angle deflections

Of the various northern streams, Khari river valley is the most prominent and revealing. Its channel characteristics show very clear evidences of tectonic uplift. This stream in Bhuj lowland forms a narrow channel with a width of 8-12m; it has vertically cut the Mesozoic bedrock (sandstone-shale) giving rise to 20-25m deep gorges (Fig. 5.11).

Within the lowland, the channel follows a straight course NNE ward for about 3-km, flowing along a NNE-SSW trending fracture.

Fig 5.11 Formation of Gorge along the Khari river near Kodki (Loc: 9 km west of Bhuj)

In the extreme downstream on crossing the NHR, where the streams cut the alluvial fan lobes, entrenched valleys are however broad, being as wide as 200-350m, and are marked by distributary networks (Fig. 5.10), a feature indicative of a sudden steepening of gradient caused by a renewed uplift along KMF subsequent to the formation of lobes.

An example of control of tectonic lineament over channel trend is ideally illustrated in the Khari river valley just north of Bhuj. Here Khari channel shows a sudden high angle deflection due NNE and flows straight for about 1.5 km, with vertical entrenchment of about 20-25m. The exposed succession has preserved the relicts of the earlier channel along which the stream was originally flowing eastward (Fig 5.12). The palaeo-channel is clearly recognised, as a perched trough 10-12m above the streambed. This filled up channel 7 to 8m thick and 50m wide shows an erosive contact with respect to the underlying Mesozoic succession. Obviously, the younger channel that formed due to the development of a NNE-SSW fracture disrupted the older easterly channel course.

Fig 5.12 Palaeochannel observed in the Khari river channel, north of Bhuj

More or less identical phenomenon is observed in the south flowing rivers. These also show tectonism-related variable channel morphology. The rivers drain through a terrain of variable lithology. In their downstream portion they have significantly incised into the Mesozoic (sandstone -shale), Deccan basalts (Upper Cretaceous-Lower Palaeocene), Tertiary sequence and Late Quaternary sediments (Biswas, 1971). In their upper headwater areas near the southern margin of KHR, incised channels have given rise to 35-m deep gorges. Even the smaller tributaries here show entrenchment upto 15m in their upper and central reaches. While the trunk streams show conspicuous cliffy banks, the lower order streams and major tributaries are marked by a badland topography characterised by incision related ravines (Fig. 5.9 & 5.13). Channels follow straight courses with high angle deflections suggestive of tectonic lineament control. Two prominent fracture trends, NNE-SSW and WNW-ESE, seem to have influenced the channel courses.

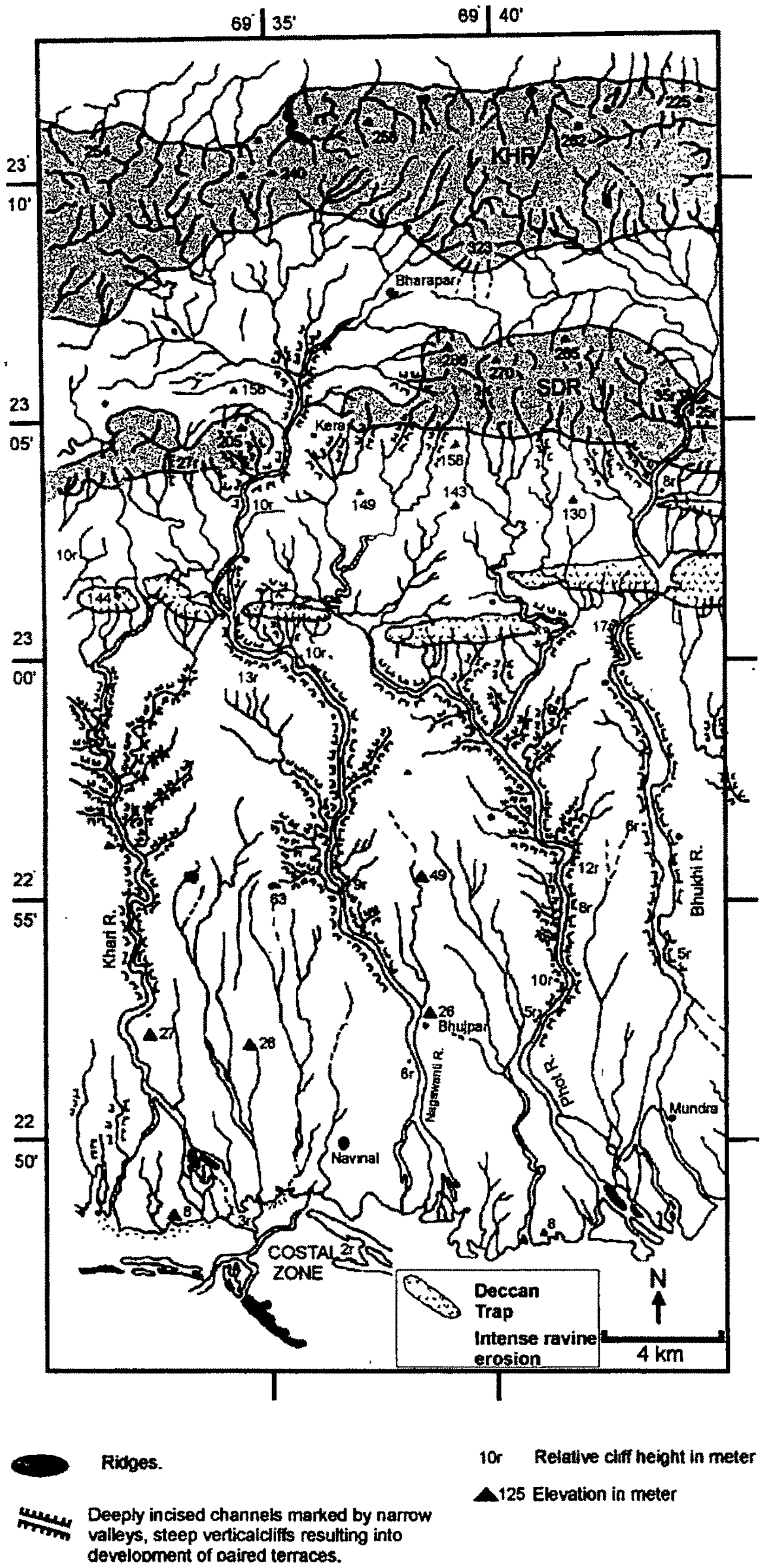


Fig 5.13 Mo rphological map of the south flowing rivers showing intensive ravine erosion

Behaviour of Bhukhi and Rukmawati River channels among the south flowing streams needs a special mention. Channel widths of other rivers like Nagavanti, Khari and Phot range between 150 and 300m, but that of Bhukhi river shows a significant range of width variation from 50-800m, which is seen all along its course (Fig. 5.9). The channel of Rukmawati river on the other hand, shows a marked channel widening only in its lower part in the downstream. As it approaches the coast it suddenly shows a broadening from 250-800m (Fig. 5.9). The broadening and narrowing of the channels are indicative of changes in base level of channels caused by uplift and subsequent subsidence in the area. Amongst the south flowing streams, it is observed that incision and concentration of ravinous area is more along the Khari and Rukmawati river basins as compared to the Nagavanti, Phot and Bhukhi (Fig. 5.9 & 5.13). These two rivers are located within the *"Median High"* of Biswas(1970), and perhaps form an area of relatively higher tectonic activity. It is relevant to mention that active tectonism along this median high is also manifested by a linear clustering of earthquakes (Malik et al, 1999).

5.3 MORPHOMETRY

In the last two decades, the emphasis has been on quantification of different morphologic parameters to support and enhance the qualitative inferences made in the field and laboratory. The author has carried out studies on individual longitudinal profiles of several streams draining north as well as south of KHF, essentially with a view to identify river response to active tectonism. Various morphometric parameters viz. Pseudo Hypsometric Integral (PHI), Sinuosity Fractal Dimension (*SFD*), Gradient Index (GI) and Gradient (Slope) were studied to estimate the role of active tectonics on river channel morphology. Table 5.2a & b summarise different parameters calculated. Along with this, a relatively new approach suggested by Hovius (1996) and Talling et al, (1997) to study the drainage behaviour on individual fault blocks has also been followed.

Table 5.2a Morphometric data for different streams flowing north of Katrol Hill Fault

River		Length (km)	Elevation (m)	Slope (m/km)	Gradient index	PHI	SFD
1	Khari Nadi	42.5	200	4.4	61.16	.438	.958
2	Kaila Nadi	39	200	8.6	82.72	.462	.923
3	Kaswali Nadi	20	240	7.5	73.16	.309	-
4	Ratiya Nala	17	200	5.07	35.93	.5	-
5	Hamadra	10	220	24.07	29.96	.309	-
6	Padhar	9.25	200	25.49	26.27	.343	-
7	Gunawari	12	200	7.37	34.87	.538	-
8	Pur	7.5	200	18.18	26.41	.395	-
9	Khatrod	7.5	200	12.61	25.74	.359	-
10	Mochirai	8.5	180	11.38	23.03	.426	-

Table 5.2b Morphometric data for different streams flowing south of Katrol Hill Fault

River		Length (km)	Elevation (m)	Slope (m/km)	Gradient Index	PHI	SFD
A	Phot Nadi	43.25	240	11.04	63.25	.26	.995
B	Sarkari Nadi	42.5	200	4.96	62.14	.5	-
C	Song Nadi	50.5	200	7.7	55.69	.425	-
D	Nagavanti Nadi	51	260	5.57	71.69	.37	-
E	Babia Nadi	27	180	7.61	60.05	.443	-
F	Bhukhi Nadi	48	240	5.6	69.42	.35	1.11
G	Lerakh Nadi	47	140	2.6	40.22	.44	-
H	Rukmavati Nadi	58	200	4.09	89.97	.39	-
I	Khari Nadi	37.5	160	6.17	35.84	.26	.908
J	Kirigiya	13.25	220	9.26	44.71	.483	-
K	Sanosra	6.5	220	21.99	48.04	.478	-
L	Kanjhara	10.75	220	16.51	35.02	.337	-
M	Surai Nadi	12.5	220	20.03	42.11	.345	-

5.3.1 Longitudinal Profiles

Longitudinal profile is a graphical representation of the relationship between river elevation and river length.

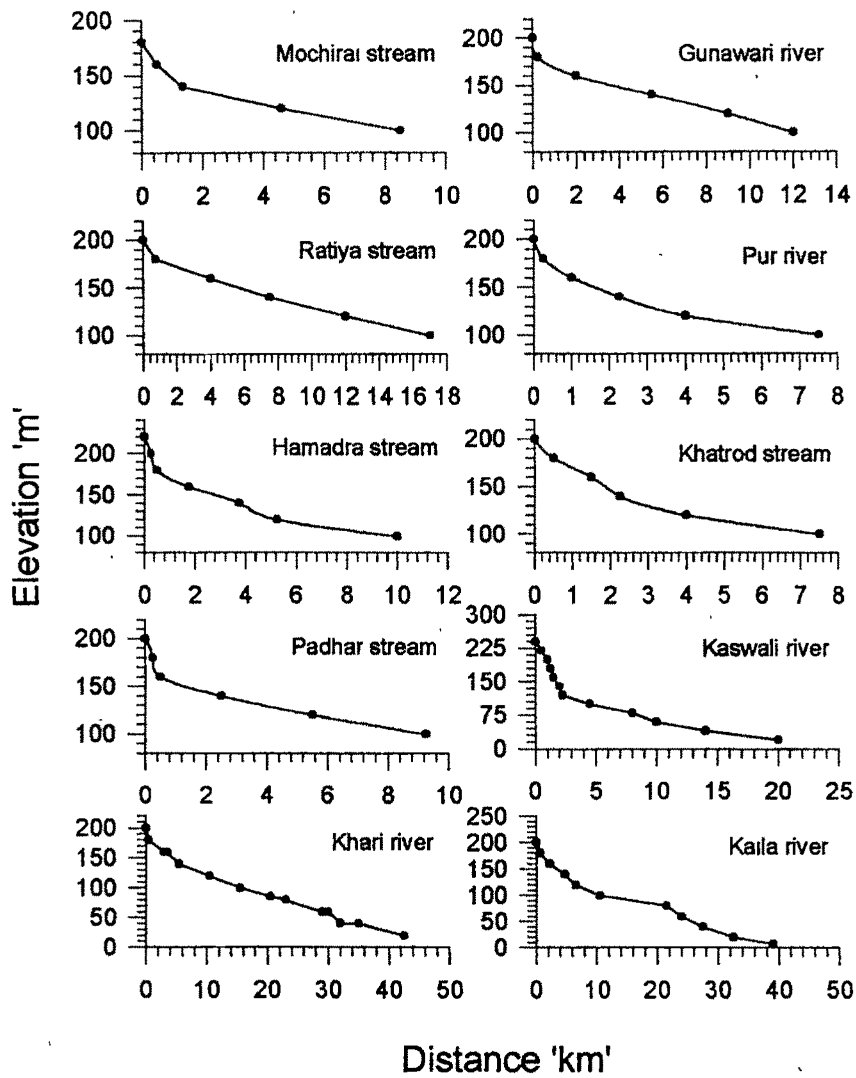


Fig 5.14a Longitudinal profiles for different north flowing rivers

There has been a varied degree of approach as far as the scale used to graph the river channel. Many workers, viz. Shepherd (1979), Wells et al, (1988) normalized the long profiles by graphing vertical and horizontal scales at 100% elevation versus 100% length to notice the scale independent pattern. Langbein and Leopold (1962) discussed the theoretical end members of profile evolution, from least work to equally distributed work.

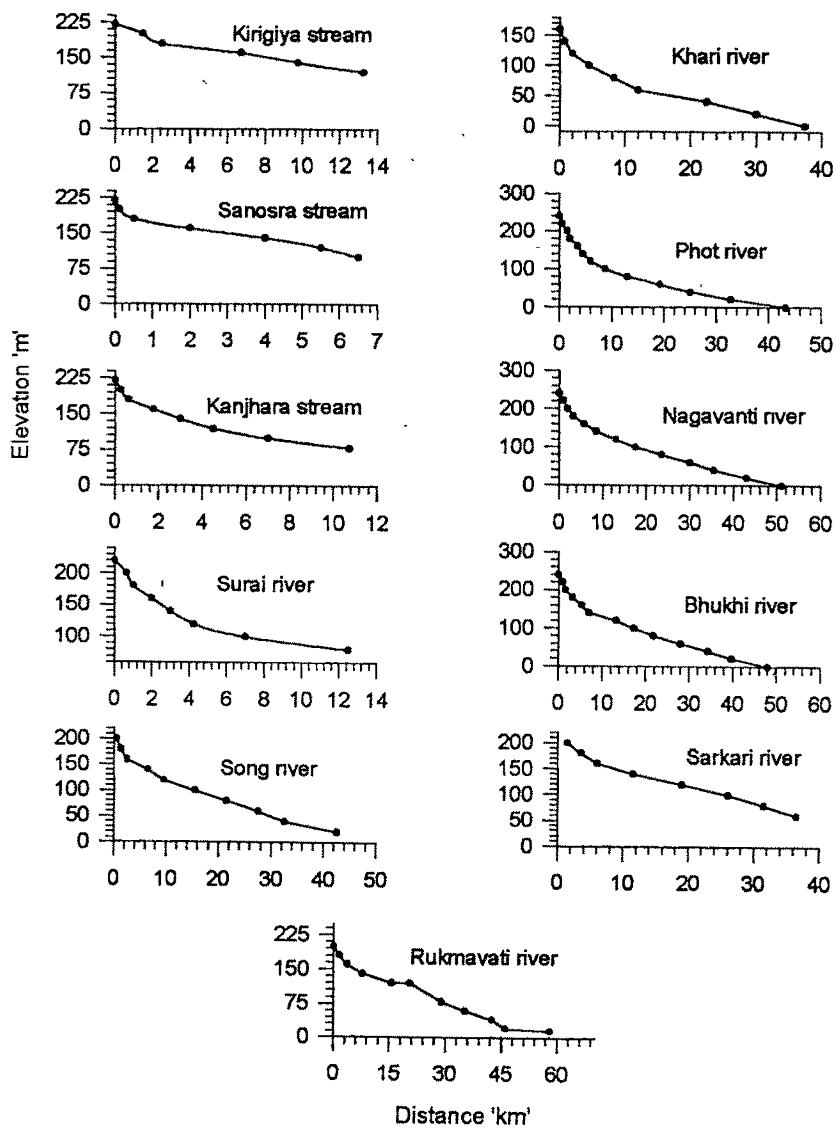


Fig 5.14b Longitudinal profiles for different south flowing rivers

The least work profile is thought to be more common in humid regions (Shephard, 1979) but from this investigation also appears to be common in areas that have experienced periodic uplifts. Rhea (1993) chose to significantly exaggerate the profiles vertically to emulate the normalized profile. For the present purpose the method of Rhea (1993) has been adopted.

To deduce different morphometric parameters, longitudinal profiles were plotted for various north and the south flowing streams. Many of the north (Fig. 5.14a) and south (Fig. 5.14b) flowing streams show the concave-up profiles pointing towards the active tectonic influence on the river channel morphology.

5.3.2 Pseudo Hypsometric Integral

Pseudo Hypsometric Integral (*PHI*) is the numerical means to describe overall shape of the long profile. It reflects the relative amount of deformational and/or degradational influence on a river channel (Rhea, 1993). The PHI has been calculated for the whole river from the area under the long profile and the area defined by the elevation and length of the profile. Tables 5.2a & b list the calculated PHIs for several north and south flowing streams. The values are listed in stream order from West to East. The western part primarily consists of complex Mesozoic sedimentary rocks and eastern part mainly comprises Tertiary and Quaternary rocks. It is observed that there is a significant variation in the range of PHI values for the streams draining south of Katrol Hill Fault (Fig 5.15). The values range from 0.26 to 0.5. Variations for the north flowing rivers are minimal, ranging from 0.309 to 0.538.

According to Rhea (1993) the anomalies for the rivers flowing through identical lithologies and not too far from each other point to differential block movements. The Katrol Hill Fault (KHF) is cut by several transverse faults (Sohoni et al, 1999) and the area to the south of it (KHR) shows striking amount of differential uplift dividing the area into small discrete blocks.

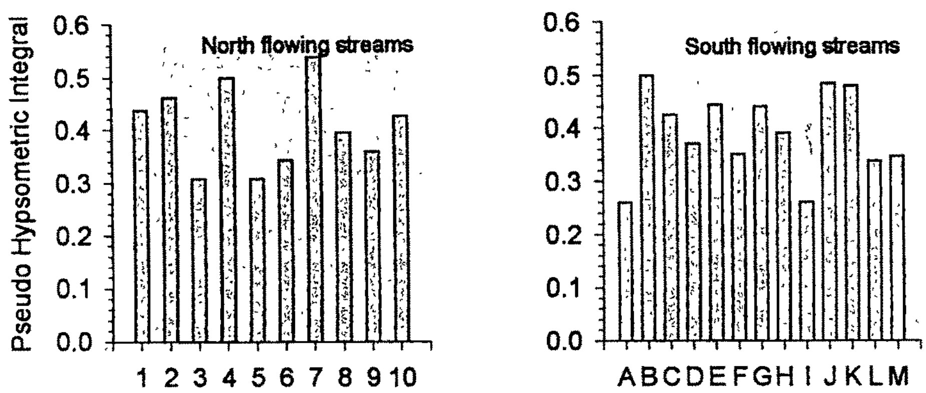


Fig. 5.15 Univariate plot showing Pseudo Hypsometric Integral values for different north and south flowing streams (label of each bar in the figure represents the river as in Table 5.2)

The striking variations of PHI values for the rivers draining south of KHF appear be on account of the differential response of major E-W faults (i.e. KHF & SDF) to repetitive tectonic activity.

5.3.3 Gradient and Gradient Index

The Gradient and Gradient Index (*GI*) are commonly used to measure river slope, and can be effectively used to know relative differences in uplifts (Meritts and Vincent, 1989; Rhea, 1993) and erosion (Hack, 1973).

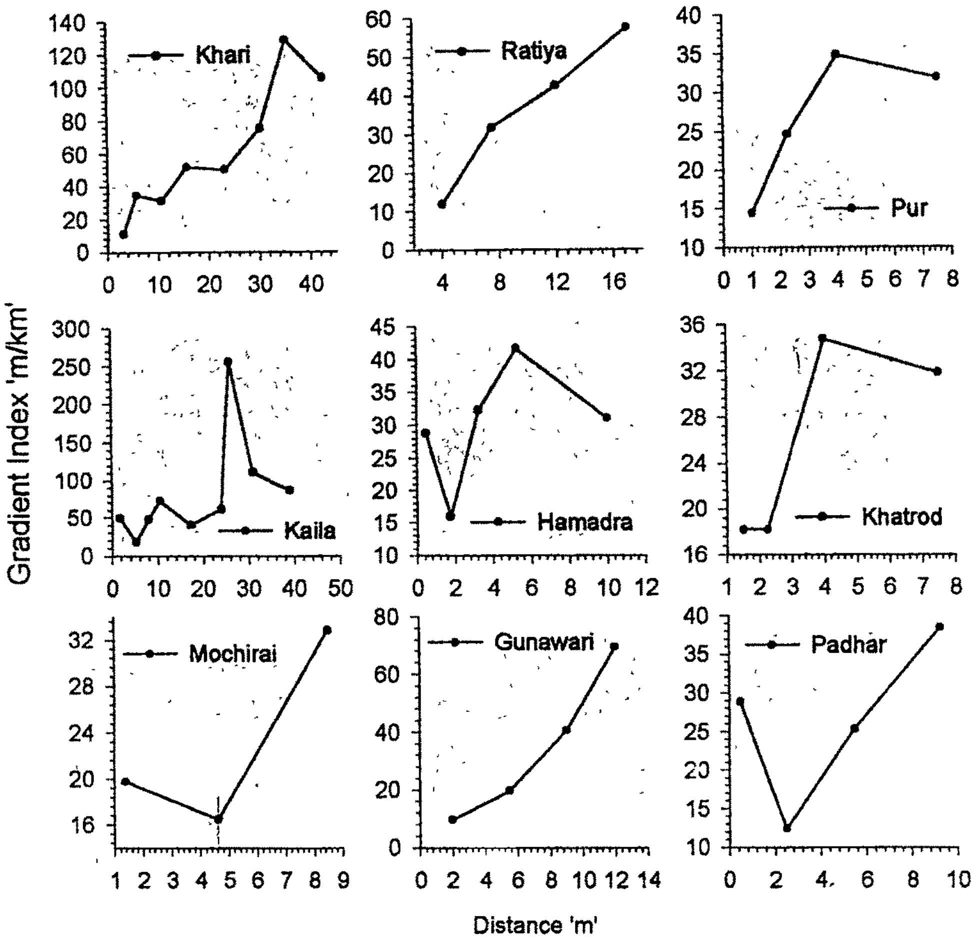


Fig 5.16a Gradient index for different north flowing streams

Generally, the gradient of a river channel is steeper near the headwaters with decrease in slope downstream. If the upstream part of an alluvial system is elevated under the influence of tectonic activity, the stream would try to acquire its natural gradient by incising, aggrading or altering its sinuosity (Ouchi, 1985). However, such a process takes time and thereby deviations of streams from their natural gradients could indicate recent tectonic deformation (Hesterberg and Merritts, 1995). Gradient and Gradient Index (GI) can be calculated from the measurements done on the longitudinal stream profiles. GI is the elevation change over logarithmically normalized distance and can be more useful for comparing slope changes over similar nearby lengths (Rhea, 1993). Both of these parameters are found to be very useful for the present studies. Tables 5.2a & b provide the mean Gradient and Gradient Index for several north and south flowing streams.

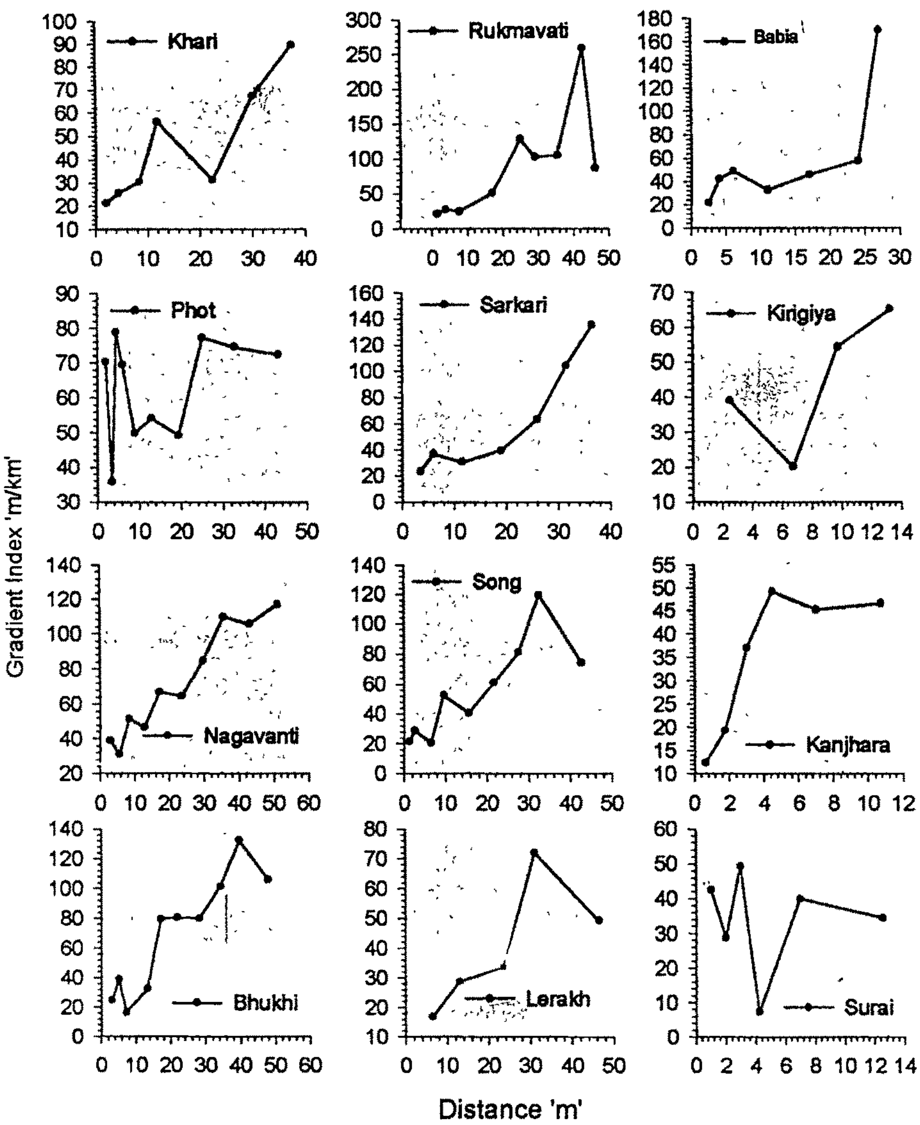


Fig 5.16b Gradient index of different south flowing streams

As has been stated earlier, although the rivers draining Central Kachchh Mainland flow through identical lithologies, the Gradient and Gradient Index for different close by streams show striking variation over the same distances. Fig. 5.16b shows higher degree of fluctuations in GI's of the individual streams draining south of KHF. Most of these streams show striking incision (upto 35m at places) throughout most of their course. The variation in GI indicates a recent uplift in Katrol Hill Zone and although the rivers are incising they have not acquired their natural course yet; which again could be on account of continuous uplift within the KHZ.

5.3.4 Sinuosity Fractal Dimension

Sinuosity Fractal Dimension (*SFD*) is a measure to quantify the degree of river curvature, which is independent of valley length. It was calculated for several streams following the method described by Snow (1989). *SFD* can be used to quantitatively characterize the river meandering. The higher *SFD* indicates a more sinuous course whereas the lower value indicates a less sinuous course.

SFD was calculated for rivers flowing north and south of KHF (Fig 5.17), this was done by progressively increasing ruler length; from 0.5km to 3.5km in most cases. Using the shorter ruler length more precise information about river curvature can be obtained, and therefore longer calculation of length whereas long ruler generates more general, and therefore shorter calculation of length. Although limiting values for both exist, but there is a linear relationship between calculated lengths and the ruler. Sinuosity Fractal Dimension was calculated from the slope of linear regressions, which mostly had R^2 values ranging between 92% to 99%. Tables 5.2a & b give the calculated *SFD* values for different rivers. It is observed that there are not much statistical differences in *SFD* values for rivers draining north and south of KHF except for the Bhukhi river which has a value of 1.11.

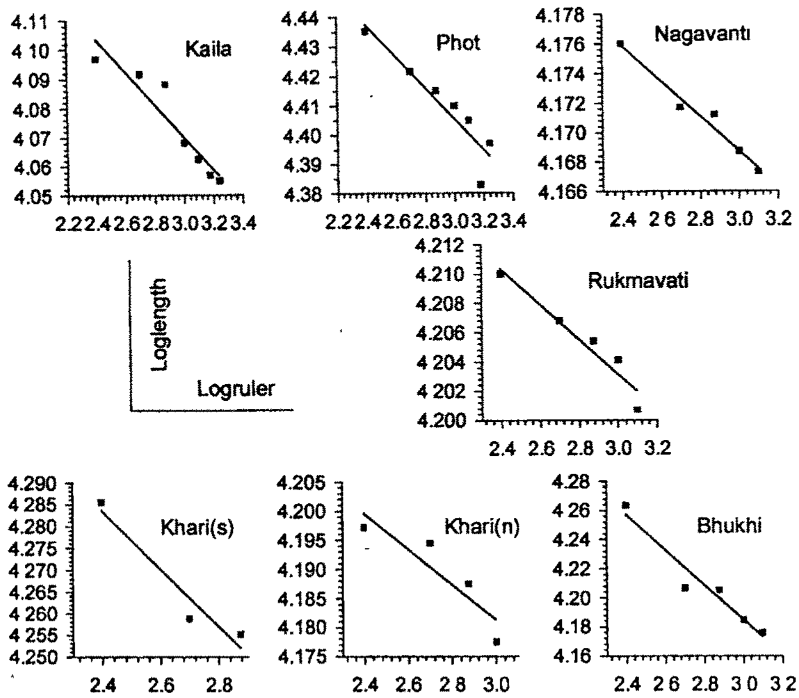


Fig 5.17 Sinuosity fractal dimensions for different rivers studied within Kachchh Mainland

5.3.5 Drainage Spacing Ratio

Drainage pattern of many young actively uplifting mountain belts is simple and is transverse to their main structural trend (Hovius, 1996). The origin of such a transverse drainage pattern has been discussed by a number of workers (e.g. Seeber and Gorintz, 1987). Recently, some workers (e.g. Talling et al, 1997; Hovius, 1996) have shown that many young mountain chains around the world show seemingly regular drainage spacing at the base of mountain fronts. Talling et al (1997), on the studies based on individual linear fault blocks have demonstrated the spatial behavioural pattern of streams at the base of the escarpment. The complex interactions between the valley formation and mountain building has prompted the observations on very small scale (e.g. Talling et al, 1997).

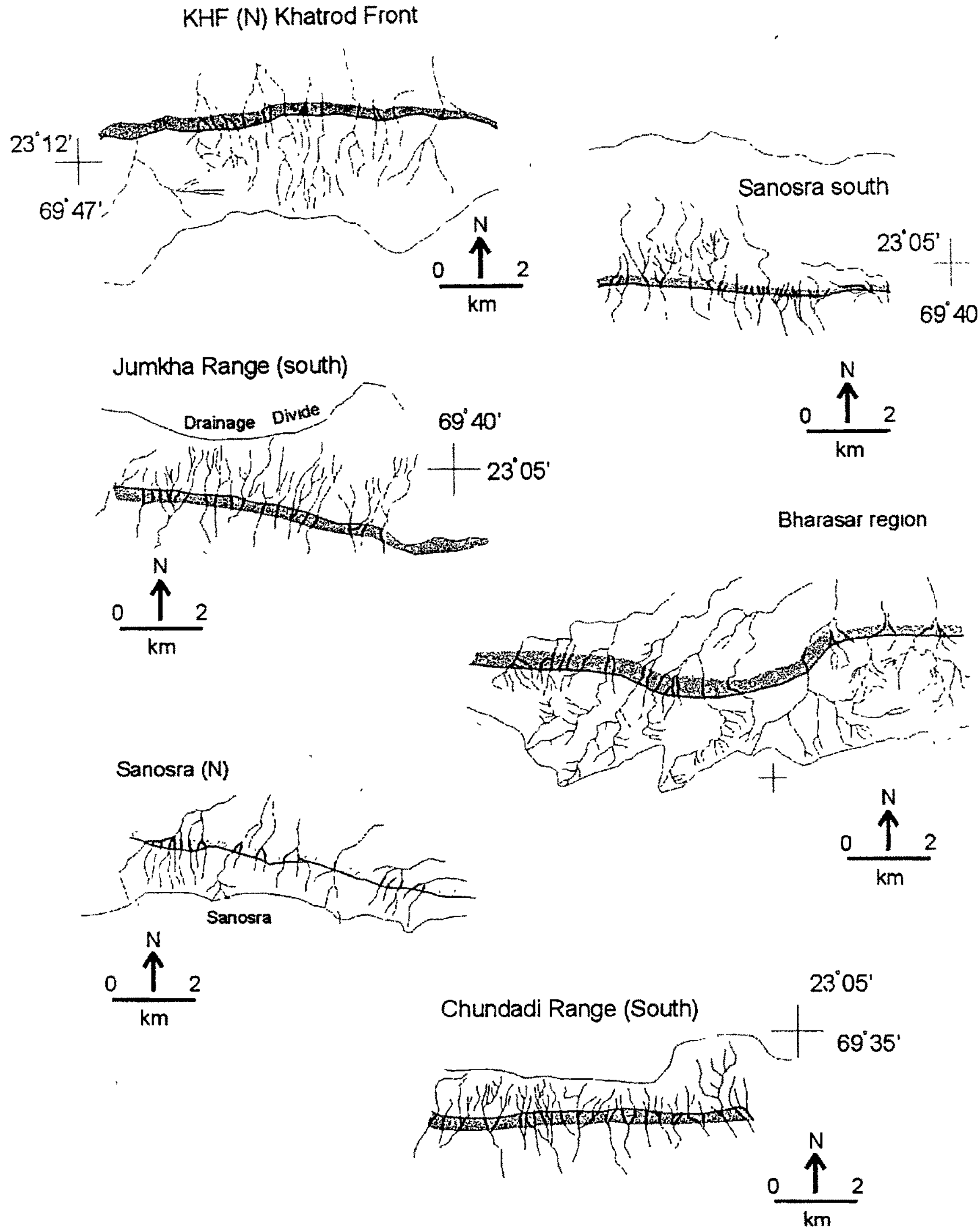


Fig 5.18 Drainage pattern on individual fault blocks studied

Central Kachchh Mainland is characterised by many anticlinal ridges with one steep front resulting on account of slip on related faults (Fig. 5.1). Katrol Hill Range along with several others is one of the most prominent ridges of Central Kachchh Mainland. The present study lays emphasis on determining the drainage spacing ratios for individual fault blocks (anticlines) and thereby support the results and observations made in the field. The studies were carried out for a) Bharasar Dome region, b) Tapka Devi range, c) Khatrod front, d) Sanosra Dungar range, e) Jumkha range and f) Chundadi hills (Fig 5.18).

The procedure followed was after Hovius (1996). The topographic maps on the scale of 1:50,000 were used to determine the drainage network and measure the characteristic morphometric parameters. Only suspected segments of the hill ranges with linear topography generated by presently active faults were selected. The linearity of segments in the present case although not very ideal (i.e. the sinuosity of the front is less than 1.09 as defined by Keller and Pinter, 1996) is in the range from 1 to 1.2. Streams with confluence less than 3% from the mountain front are treated as separate drainage basins. Moreover, a very little ambiguity exists in measuring the drainage outlet spacing as it is a unique element within each catchment (Hovius, 1996). The lengths of the measured mountain fronts vary between 10 and 25km and all segments considered are drained by substantial number of transverse streams.

The base of the mountain front is defined as the boundary between the structure and the flanking recent foreland sediments/pediment. The outlet of the catchment is at the junction of trunk stream and base. Fig. 5.19 shows the different parameters used in this study.

In Fig. 5.18 the individual ridges studied are shown. The resulting data (Table. 5.3) shows that there is a considerable regularity in the drainage outlet spacings of linear fault blocks. In all the seven fault blocks studied the standard deviation of the outlet spacing is less than 50% of the mean spacing.

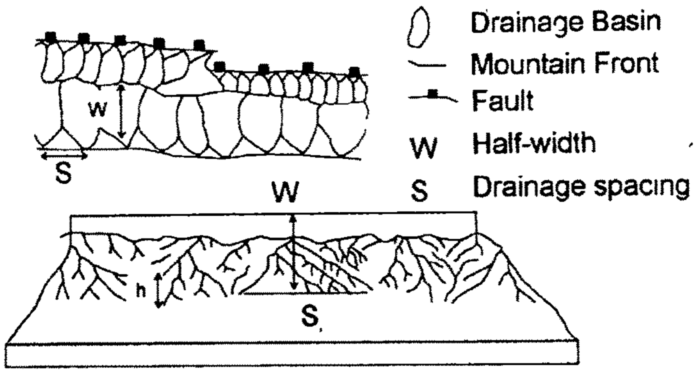


Fig 5.19 Line drawing showing the methodology used for calculating different parameters (after Talling et al, 1996)

Table 5.3 Morphometric data showing different parameters calculated

Hill Range		Topographic half width (W)		Drainage outlet spacing (*s*)		Relief (H) in 'm'	Standard deviation(σ) in km	Spacing Ratio (S)
		Mean	σ	Mean	σ			
Katrol Hill Range	Bharasar dome range	2.27	.8	.87	.21	60	1.17	2.79
Katrol Hill Range	Tapka devi range	2.35	.9	.79	.36	75	1.5	3.27
Katrol Hill Range	Khatrod range	2.40	.4	.58	.22	75	1.95	4.62
Sanosra Dungar Range	Sanosra dungar range (N)	.73	.10	.2827	.12	80	1.36	2.9
Sanosra Dungar Range	Sanosra dungar range (S)	3.425	.118	.4876	.14	80	1.66	5.9
Sanosra Dungar Range	Chundadi range (S)	.825	.29	.32	.15	80	1.14	2.81
Sanosra Dungar Range	Junkha range	1.33	.1	.3	.1	75	1.12	4.5

The number of drainage outlets measured along each mountain front varied between 6 and 20 (Fig 5.20); there is no significant correlation between a lower number of outlets and a higher standard deviation, as has been observed by Talling et al (1996), however it is seen that as the oulet spacing increases the topographic half width also increases to a certain extent and then is constant (Fig 5.21b). According to these workers the drainage outlets were less regularly spaced on fault blocks with a sinuosity greater than 1.09, however, from this study it is evident that the regularity is not affected much even for the sinuosity values upto 1.20.

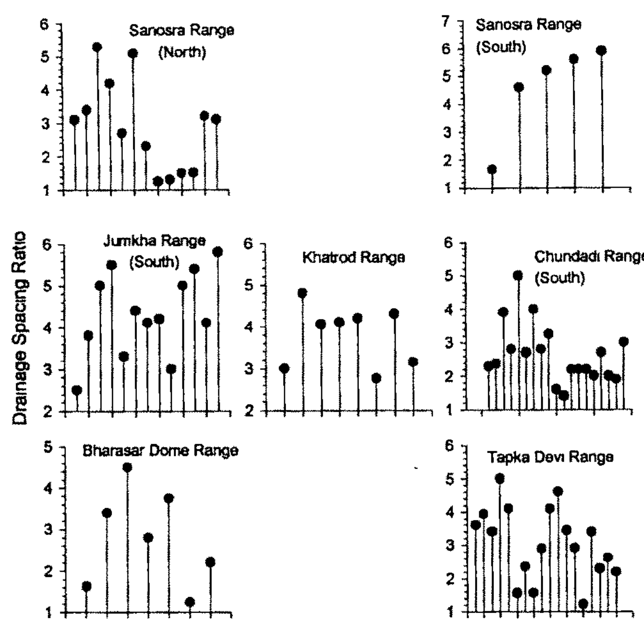


Fig 5.20 Univariate plot showing the Drainage spacing ratio for different fault blocks studied

This is envisaged on the basis of the standard deviation characteristics, i.e. in none of the fault blocks studied, the standard deviation is more than 50% of the mean outlet spacing. This observation slightly differs from that of Talling et al (1996) that the standard deviation increases between 48% and 97% of the mean outlet spacing for the fronts having sinuosity greater than 1.09.

Also, in the present case there is not much variation in spacing ratio (i.e. the ratios range between 2.81 and 4.5) as noticed by Talling et al (1996). This may be on account of the calculations made on the blocks of the same system of faults, which is not the case with the earlier work.

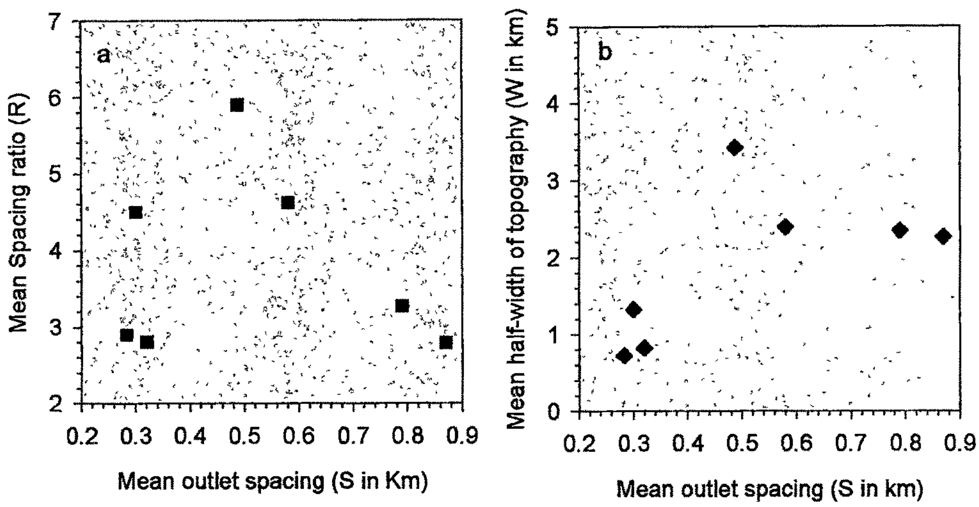


Fig 5.21 a) Plot showing the relationship between the Mean spacing and Mean outlet spacing, b) Plot showing the relationship between Mean topographic half width and Mean outlet spacing

5.2.6 Drainage Basin Elongation Ratio

Drainage Basin Elongation Ratio (R_e) is a parameter that describes tectonic activity of the mountain fronts. Basins in areas under the influence of active tectonic activity are predominantly elongated (i.e. ratio < 0.5), whereas more circular basins (i.e. ratio > 0.75) are apparently associated with tectonically inactive areas (Bull and Macfadden, 1977; Krzyszkowski et al, 1995). The ratio is derived using the formula.

It is seen that the drainage basins of the rivers draining south of KHF are relatively more elongated then the north flowing streams (Fig. 5.22a & b). The R_e values for south flowing streams range from .157 to .335, whereas for the north flowing streams range from .339 to .482 (Fig 5.23). It is very clear from the values that the drainage basins to the south of KHF must not have had enough time for lateral planation on account of continuous tectonic activity.

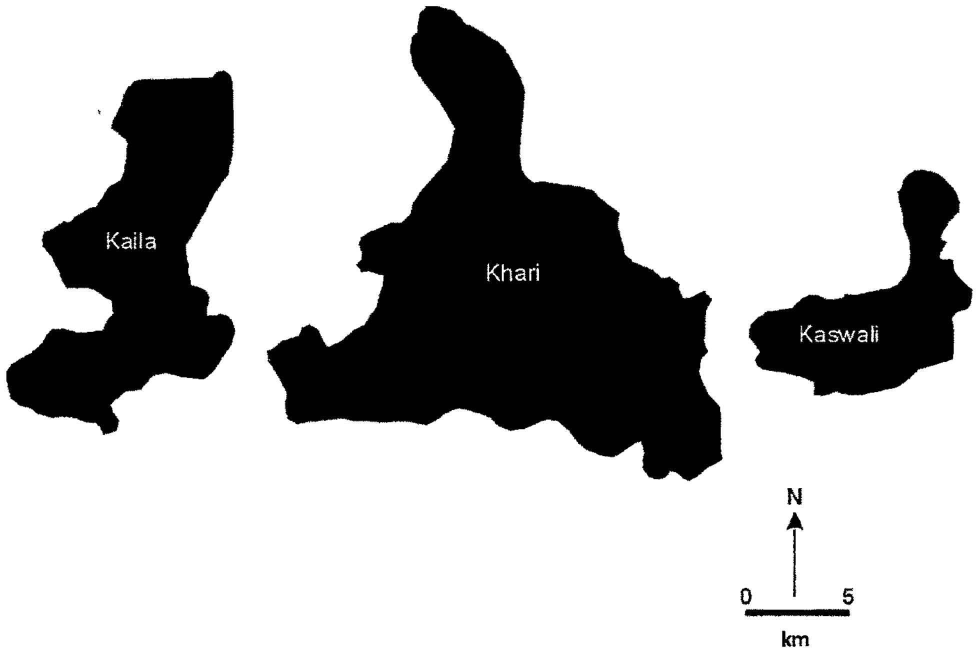


Fig 5.22a Drainage basins of some of the north flowing streams

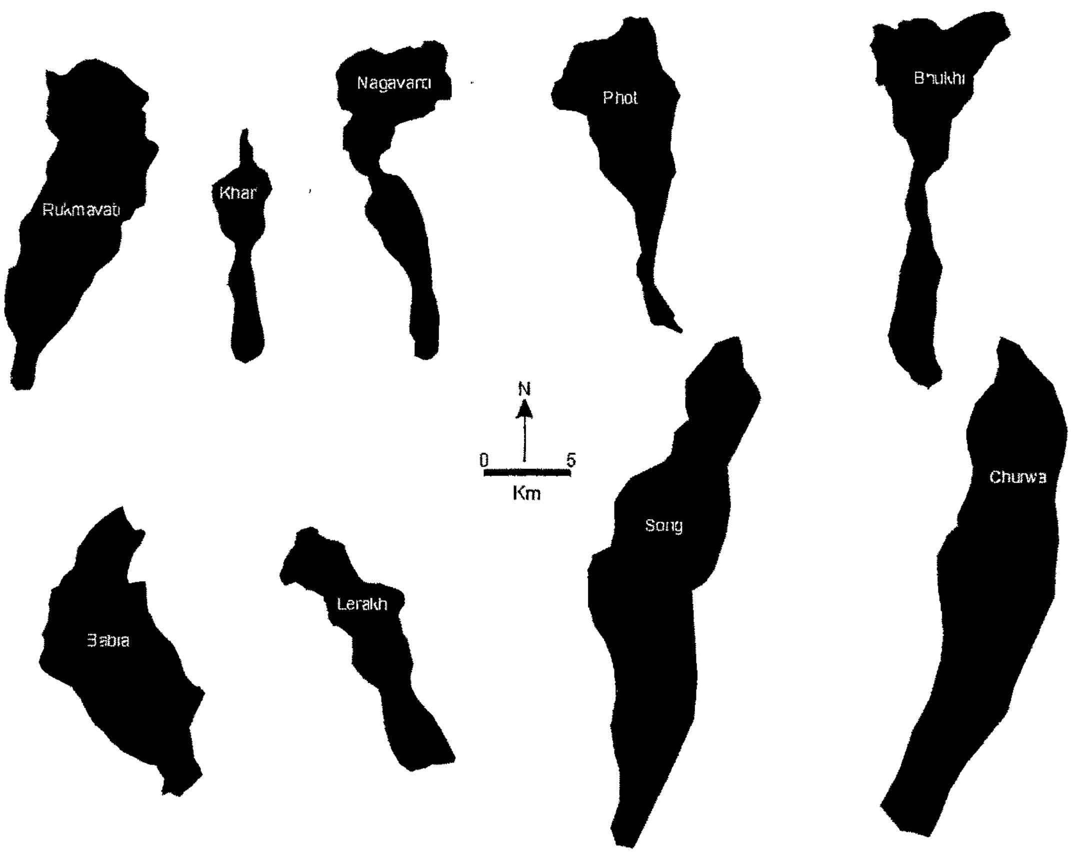


Fig 5.22b Drainage basins of some of the south flowing streams

The relatively higher values for Babia and Churwa rivers could be attributed to differential block movements in the sense that these blocks were relatively less active. The north flowing streams on the other hand have comparatively higher R_e values, but it has to be noted that the values are less than 0.5, again indicating a fair amount of active tectonic movement at Kachchh Mainland Fault front.

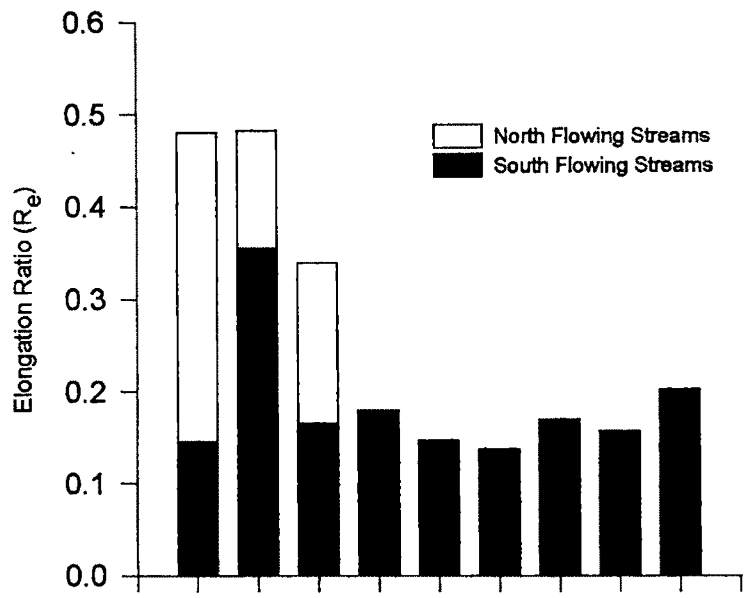


Fig 5.23 Univariate plot showing the Drainage basin elongation ratio for different north and south flowing rivers, note that the ratio for south flowing rivers is in between 0.1 and 0.35 indicative of active influence of deformational movements on these drainage basins

5.3.7 Valley Floor to Valley Height Ratio

Valley Floor to Valley Height Ratio (V_f) is a parameter, which provides an opportunity to estimate whether the stream is actively downcutting (Bull, 1978, 1984). According to Bull and Macfadden (1977) values < 1.0 indicate higher tectonic activity of mountain fronts, whereas values of 1.0 to 3.5 and above characterise weak or moderate activity. The stream reaches with low V_f values are dominated by downcutting in response to local base level fall, whereas those with high V_f values are characterised by more lateral planation. In the present study, this parameter has been emphasised because of the fact that the rivers in the region drain through identical lithologies thereby negating the influence of lithologic control on the parameter. The data obtained (Fig. 5.18) from the study indicate that V_f values for the central Kachchh Mainland vary between 0.05 and 0.75. This, when combined with other parameters and field perceptions suggest localized differential uplift within the Katrol Hill zone.

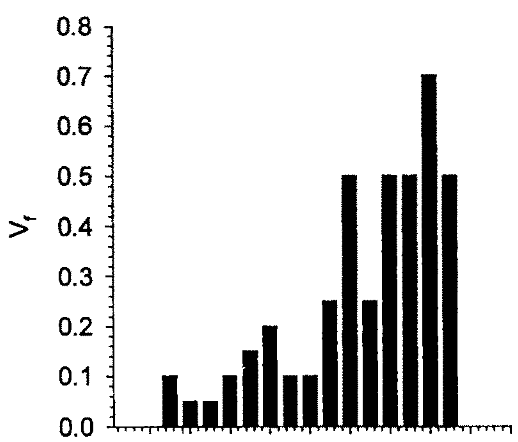
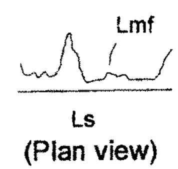
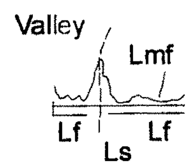
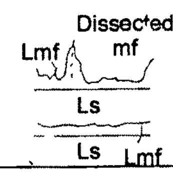
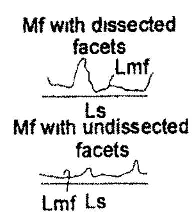


Fig 5.24 Univariate plot showing the valley floor to valley height ratios indicating the general shape of the valleys (i.e. U shape or V shape), note that all the values are below 1 indicative of V shape valleys

5.4 MOUNTAIN FRONT SINUOSITY

Major fault-bound topographic escarpments with measurable relief exceeding 20m have been referred to as *mountain fronts*. These fronts can be either linear or irregular, depending on the degree of continued tectonism along fault scarps. Degree of sinuosity of the fronts provides an authentic and dependable evidence of active tectonism in arid and semi-arid areas (Wells et al., 1988).

Table 5.4a Table showing different morphometric parameters calculated for the individual mountain fronts

Morphometric parameter	Definition	Mathematical Derivation	Measurement procedure	Purpose	Potential Difficulties	Source
S	Sinuosity of Topographic Mountain fronts	Lmf/Ls		Define the degree of topographic modification (embayment and/or pediment) of mountain front from the position of possible controlling tectonically active structures.	Define actual topographic junction. Definition of discrete mountain front segment.	Bull, 1978 Bull and McFadden, 1977
Facet (%)	Percent faceting along mountain fronts	Lf/Ls		Define the percentage of given mountain front with well-defined triangular facets, using the ratio of cumulative of facets to length of overall mountain front	Systematic definition of individual facet.	Wells et al, 1988
Fd	Percent dissected mountain fronts (in a given region)	# of dissected MF/ total # MF (in a given region)		Define the percentage of total mountain fronts that have been dissected by large drainage basins into distinct facets	Systematic definition of mountain front dissection.	Wells et al, 1988
FfD	Percent dissected facets (on mountain fronts in a given region)	# of MF, with dissected facets/ total # MF (in a given region)		Define the percentage of mountain front that contain facets with significant internal dissection (as indicated by degree of contour crenulation along facet base	Systematic identification of dissected vs undissected facets.	Wells et al, 1988

Mountain front sinuosity is an index of the degree of irregularity along the base of a topographic escarpment. Usage of this parameter takes into account the tendency of the tectonically active structures to maintain straight or curvilinear profiles in plan view in contrast to more irregular ones produced due to erosional activities. *Mountain front sinuosity* (*S*) is therefore, defined as the *ratio of observed length along the margin of physiographic divide* (L_{mf}) *to the overall mountain length* (L_s) *of mountain front* or [$S= L_{mf}/L_s$] (Wells et al., 1988, Bull, 1984). The *S* value approaches 1 on the most active fronts. These fronts can be classified as external or internal, depending upon their occurrences i.e. whether they lie within the mountainous terrain or form a part of the physiographic boundary between mountain chain and adjoining lowland. On the basis of the geomorphic characteristics individual sub-areas of fronts were identified using 1:50,000 scale topographical maps.

In the present study, emphasis is given to external fronts of the Northern Hill Range (NHR) and the Katrol Hill Range (KHR) of the Kachchh mainland. Sinuosity index has been found very useful and relevant in establishing the continued uplift along the Kachchh Mainland Fault Zone (KMFZ) and along the Katrol Hill Fault Zone (KHFZ). Morphometric analyses of 80 fronts along KMFZ and 62 fronts along KHFZ were carried out. The details of morphometric data are shown in Table. 5.4a.

5.4.1 Kachchh Mainland Fault Zone

The Kachchh Mainland Fault Zone forms the northern part of Kachchh Mainland. Along this, two sub-areas were selected for detailed study. Mountain front characteristics of about 80 fronts were studied within two subareas i.e. Kas Front and Habo Front. The general drainage characteristics, topographic variations and size of the channel networks were taken into consideration to categorise the subareas. The fronts in both the subareas are marked by well-defined triangular facets (triangular or polyhedral shaped hill slope areas that lie between adjacent drainage outlets for a given mountain front) and are internally less dissected.

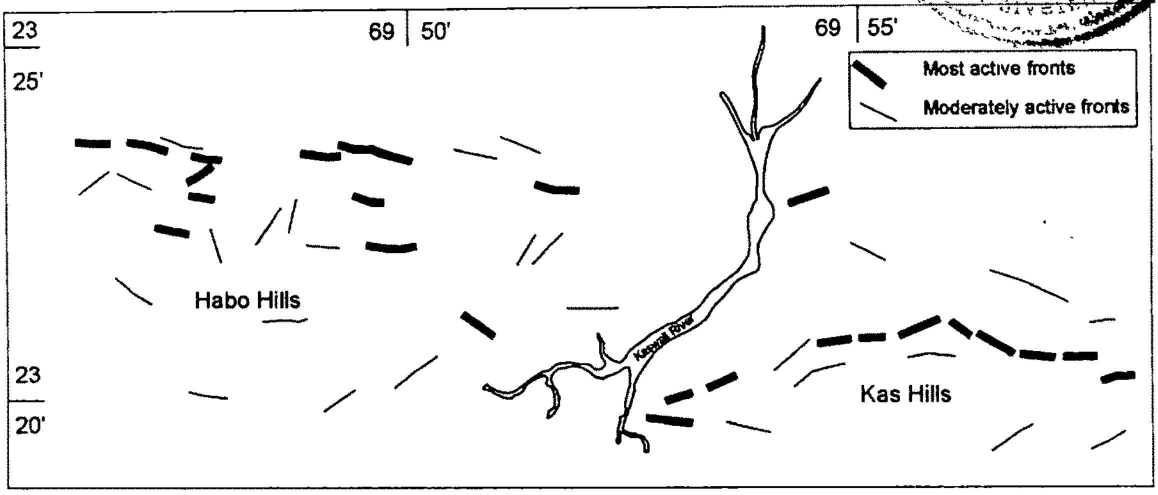


Fig 5.25 Mountain front characteristics of Habo and Kas Hills

Both external and internal fronts were studied for both the regions. The fronts studied along the Kas Hii zone/range show *S* values ranging between 1.07 and 1.3 with mean value of 1.2 and 86% of faceting with mean facet dissection percentage of 48% and about 40 fronts along Habo front show the values of *S* ranging in between 1.05 to 3.7 with mean value of 1.72. The faceting percentage for this area is 69% with mean facet dissection percentage of 67% (Table. 5.4b, Fig 5.20).

The observed values along both the subareas show marked variations in the mountain front sinuosity characteristics. The Kas Front has mean *S* value of about 1.2 whereas for that of Habo Front is of 1.72. The Faceting percentage for Kas front is more than that of Habo Front (i.e. 86% for Kas Front and 69% for Habo Front); also the facet dissection percentage of Kas Front is much lower than that of Habo front.

Table 5.4b: Mountain front characteristics of Kachchh Mainland Front

SUBAREA		KAS FRONT		HABO FRONT	
Number of Mountain fronts		40		40	
Faceting %		NF	Faceting %	NF	Faceting %
		23	>80%	11	>80%
		17	50-80%	29	50-80%
Mountain front Dissection %		42%		57%	
Facet Dissection %		58%		67%	
Sinuosity Ratio (SR)	1-1.5	23		16	
	1.5-2	10		8	
	2-2.5	7		10	
	2.5-3	-		6	
Mean SR		1.2		1.72	
Sinuosity Ratio %	1-1.5	57		40	
	1-2	87.5		60	

Such differences in the parameters of both fronts suggest that the Kas Front is comparatively more active than the Habo Front. Several other field evidences discussed elsewhere in the text also support this inference.

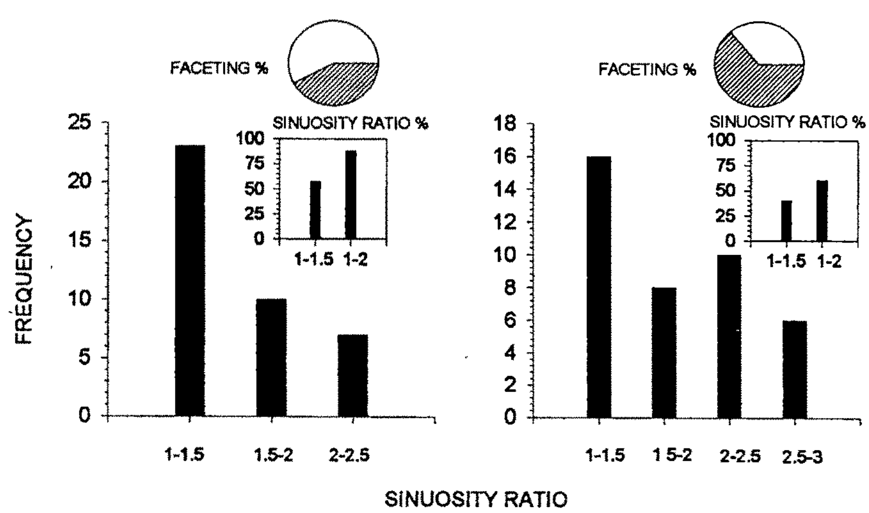


Fig 5.26 Figure showing the calculated parameters for the two subareas along the Kachchh Mainalnd Fault

5.4.2 Katrol Hill Zone

Sinuosity characteristics of 62-mountain front segments (Fig 5.27) falling within two subareas along the Katrol hill escarpment have been analysed.

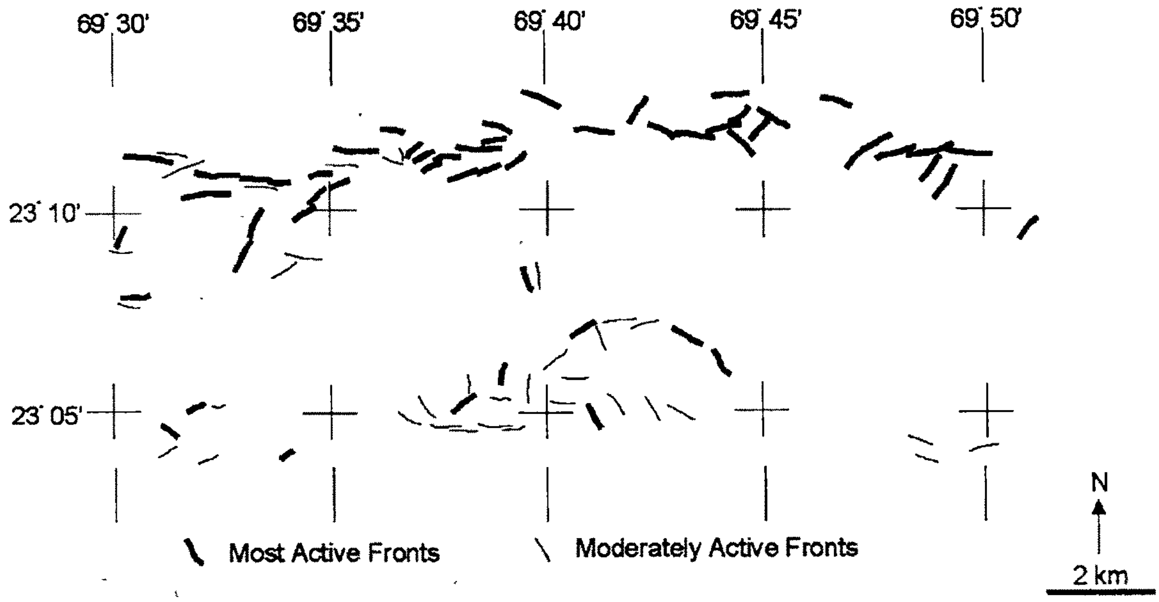


Fig 5.27 Mountain front characteristics along Katrol Hill Zone

The subareas (Fig. 5.1) were categorised on the basis of the general nature of the topography of mountains and the variations in size and patterns of channel networks. Mountain fronts in both sub-areas show well-defined facets. Results of the analysis show that in general, sinuosity is low in both the subareas, 62% of the total mountain front segments falling in the range of S values 1 to 1.5 and 88% in the range of 1 to 2. *S* values range from 1 to 3 with mean values of 1.45 and 1.6 for subareas A and B respectively; data suggests that S values or sinuosity is relatively higher in subarea B (Fig. 5.28). Although, there is some statistical difference in sinuosity values of the two sub-areas, the combined morphometric data as a whole clearly imply that mountain fronts of both the subareas are influenced by tectonic activity (Table. 5.4c).

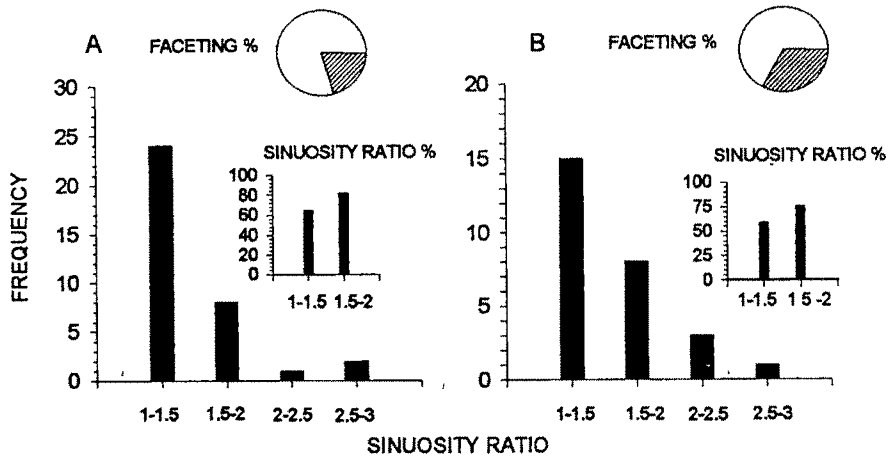


Fig 5.28 Mountain front sinousity of 62 Mountain fronts in two sub areas along the Katrol Hill Zone

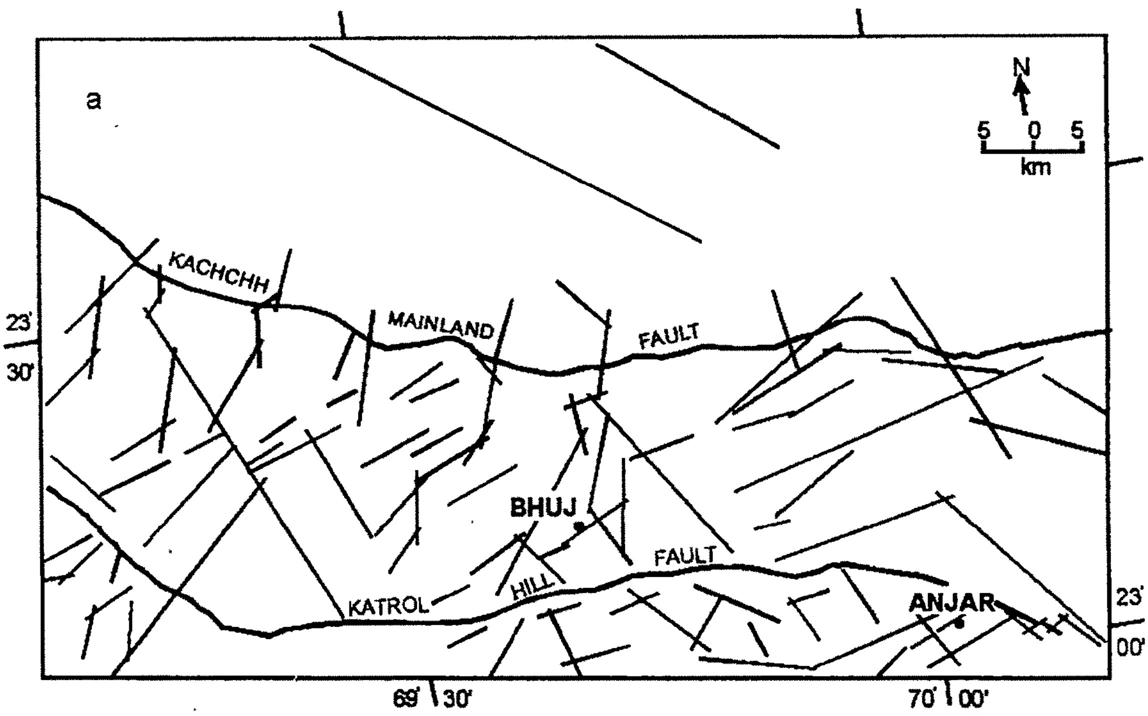
Table 5.4c: Mountain front characteristics of Katrol Hill Zone

SUBAREA		A		B	
Number of Mountain fronts		35		27	
FACETING %		NF %	Faceting	NF	Faceting %
		27 08	>80% 50-80%	18 09	>80% 50-80%
Mountain front Dissection %		40%		45%	
Facet Dissection %		59%		62%	
Sinuosity Ratio (SR)	1-1.5	24		15	
	1.5-2	8		8	
	2-2.5	1		3	
	2.5-3	2		1	
Mean SR		1.45		1.6	
Sinuosity Ratio %	1-1.5	68		56	
	1-2	91		85	

5.5 ALLUVIAL FANS

Kachchh region in western India is marked by areas of uplift (e.g. Kachchh mainland and Wagad uplift) and residual depression (Great Rann-Banni plains). Uplifts are oriented along and related to major sub-parallel E-W trending longitudinal faults, e.g. Katrol Hill Fault, Kachchh Mainland Fault, Banni Fault and Allah Band Fault (Biswas & Deshpande 1970, Biswas 1980). The landscape provides a good example of a terrain with neotectonically influenced landscape evolution and fluvial regime. The landforms reflect both uplift and subsidence along well-defined major faults, and the stream courses flow along the fault related fractures and joints trending NNE-SSW, ENE-WSW, N-S and WNW-ESE (Fig. 5.29a & b) This structural control is reflected in their unusually straight courses, narrow deeply incised valleys and sharp high angle channel deflections.

Katrol Hill Range forms the major drainage divide of the rocky mainland, and is characterised by numerous south and north flowing rivers. Various north flowing rivers on crossing the Kachchh Mainland Fault and debouching into the Great Rann-Banni depression have given rise to conspicuous alluvial fans. These fans comprise an important geomorphic element of the Great Rann-Banni area. The Banni depression is hypothesised to have come into existence with a concomitant uplift of the mainland, around 2.5 ka when the northern Rann delta complex was partly destroyed (Malik et al. 1999). As the outer fringes of the fans are seen to overlie the sediments of the depression that occurs between the mainland uplift and the Banni plains, these fans must have been deposited during the late Holocene after the formation of the depression. These fans point to an initial depositional phase followed by that of incision by the same rivers. Although, these alluvial fans occurring at the base of Northern Hill Range have so far received little attention, except for a passing reference made by Kar (1993a). The fans are unique in the sense that both their deposition and incision, are manifestations of a series of uplifts at successive stages of their deposition.



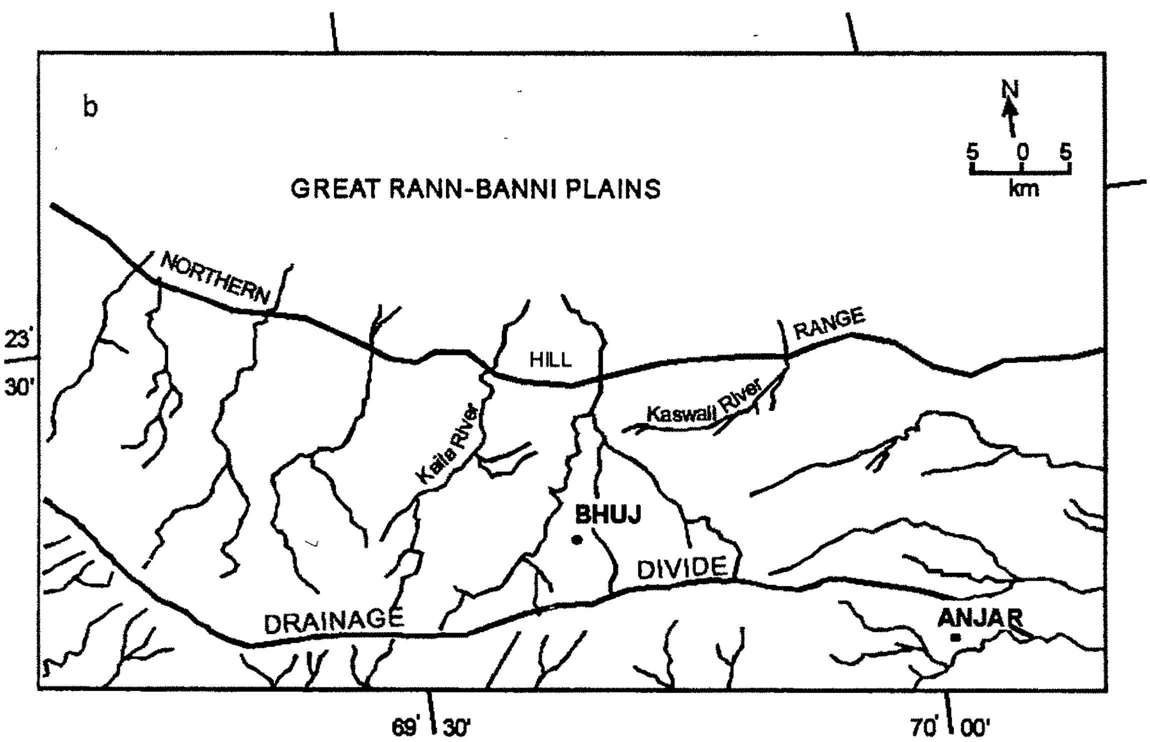


Fig 5. 29 a) Figure showing the drainage along the Kachchh Mainland Fault, b) the lineaments along that influence the drainage of the area

Formation of an alluvial fan is dependent on several essential conditions of which, the most important one being an abrupt change in geomorphic setting so that a river emerging from uplands is suddenly unconfined over a relatively flat lowland (Bull 1977, Blair & McPherson 1994 a, b). The Kachchh Mainland Fault that lies at the northern fringe of Kachchh mainland has provided such a physiographic setting. The primary processes involved in building up of the fan include rock falls, rock avalanches, gravity slides, debris flow, sheet flows and incised channel flows. The former four processes commonly produce angular to sub-angular fragments (Larsen & Steel 1978, Blair 1987, Beaty 1990, Blair & McPherson 1992, Brierley et al. 1993).

Even though tectonism was the dominant factor, climate too has played its due role in the formation of fans. Kachchh region falls under arid to semi-arid climatic zone with a mean annual rainfall of 300 to 400 mm (Merh, 1995). Its ephemeral rivers often experience flash floods during monsoon, and such high magnitude floods of the past appear to have controlled the transportation and deposition of voluminous debris with large clasts. The incised fan successions provide an opportunity in understanding the role of tectonic activity and climate in the formation and denudation of these fans.

As a case study Kaswali and the Kaila alluvial fans were taken (Fig. 5.30) and the scope of investigation aims at deciphering the distinctive morphometric elements of the two fans. The role of active tectonism that controlled the formation of the fans has been highlighted. The sedimentary facies, related fluvial processes and clast composition (size variations), length of the river channel and individual catchment and fan areas have also been described and estimated. Fan lobes along Kachchh Mainland Fault are the most striking and prominent geomorphic features of active tectonism-related fluvial processes.

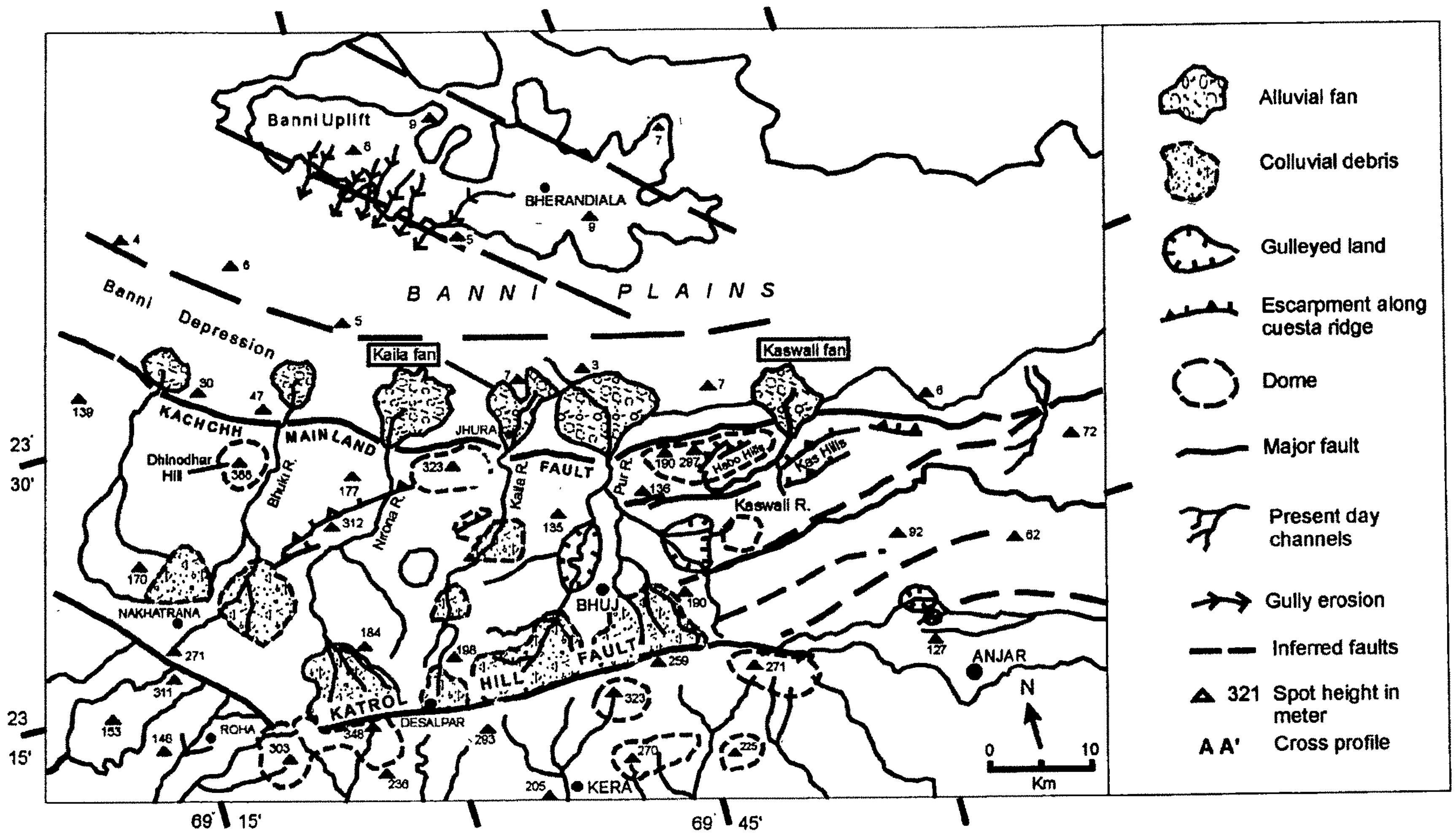


Fig 5.30 Figure showing the general morphology of alluvial and colluvial fans along the Kachchh Mainland Fault and Katrol Hill Fault

So are the colluvial debris accumulations in Bhuj lowland (Fig. 5.30). Interestingly, a significant portion of the fan material is made up of the transported colluvial debris derived from Katrol Hill Range as well as that from numerous smaller fault escarpments that are found in Bhuj lowland.

5.5.1 Morphology of Kaila and Kaswali alluvial fans

On crossing the Northern Hill Range, the rivers change their gradient and have built up fan lobes, where they end in the saline wasteland of Great Rann-Banni depression. Respective streams are dissecting the fans themselves.

Kaswali river emerges from an altitude of 298m north of Baladia and flows along a NNE-SSW trending fracture for 7km (Fig. 5.31), after which its channel is abruptly gets deflected northward along a N-S lineament. Total length of the channel upto its mouth is about 20km, and the stream has a drainage basin area of 66sq.km. It flows across a terrain made up of sandstone, shale and limestone of Mesozoic and Tertiary ages. The trunk channel is fed by several 1st and 2nd order streams originating from Kas hill range and from the southern flank of Habo anticline. The main river, a 3rd order stream forms a prominent channel with a varying width of 100 to 600m. The river flowing across the Northern Hill Range not only shows a sudden change in the gradient but also bifurcates into several distributary channels. This feature is well reflected in the longitudinal profile. Kaswali fan has a radial length of 7km and a maximum width of 6km. It covers an area of about 35sq km. Elevation of the fan lobe at the proximal end is 30 m near the base of Kachchh Mainland Fault scarp and it decreases to as less as 5m at the distal of its long axis where it merges with the surrounding saline wasteland of the Great Rann-Banni depression. Flowing northward across the fan, the trunk channel near the apex is 250m wide and 8 to 9m deep. Further north in the medial part of the fan, the channel is more than 150m wide, and between 2m and 5 m in depth. Here that the river shows the maximum width of 600m.

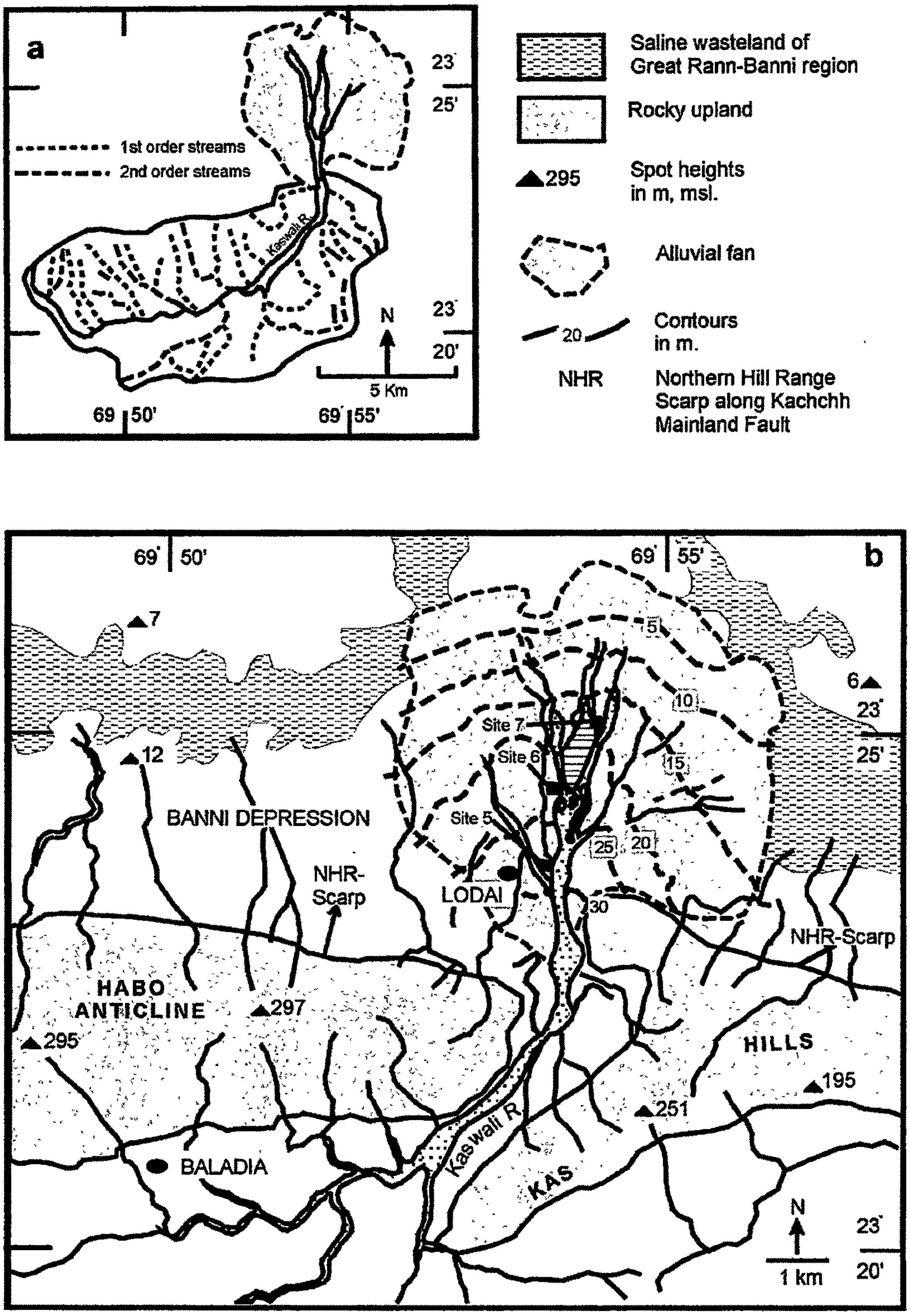


Fig 5.31 Morphology of Kaswali fan showing the drainage configuration of Kaswali river and the sites studied along the exposed succession of the fan

The fan is considerably incised and cliffs mark the channel walls. The lobe surface near the fringe is characterised by numerous dry streams that appear to have been detached in the past from their major trunk channel, in all probability due to tectonic activity.

The Kaila river has built a similar fan. The river originates at an altitude of 198m near Desalpar (Fig. 5.32) from the northern slopes of the Katrol Hill Range and flows in NNE direction. The total length of the channel and the drainage basin area are about 40km and 180sq km respectively. It flows across the rocky uplands of Mesozoic and Tertiary rocks. The trunk channel is of 4th order, and is joined by numerous tributaries emerging from the surrounding higher domes and ridges. In the southern upper reaches, where it flows in a rocky terrain, the channel is 50 to 100m wide and shows entrenchment cutting across upwarps, flexures, half domes and fault related uplifts giving rise to 10 to 18m steep rocky paired terraces. The nature of channel flowing across upwarps and downwarps is well indicated in the longitudinal profile. At places the main channel as well as some of its tributaries flow along straight fracture-controlled courses and also show frequent high angle deflections in NNE-SSW, N-S and WNW-ESE directions. Just before crossing the Kachchh Mainland Fault scarp, the river turns sharply, with a 30m steep escarpment indicative of tectonic uplift. The Kaila fan located at the base of the escarpment has an average elevation from 20 to 25m near the proximal end. The thickness reduces to almost 4 to 5m at the distal end, gradually merging with the saline wasteland. The fan lobe covers an area of about 39sqkm and has a radial length of 9km and maximum width of 8km. The channel near the fan apex is 50m wide and has incised not only the fan material but also the underlying bedrock. Its forms steep banks range between 15 and 25 m in height. The streams follow a straight course flowing along a NNE-SSW fracture. In the medial part of the fan the channel width is 250m, but the main channel becomes narrower further downstream where it divides into multiple distributaries.

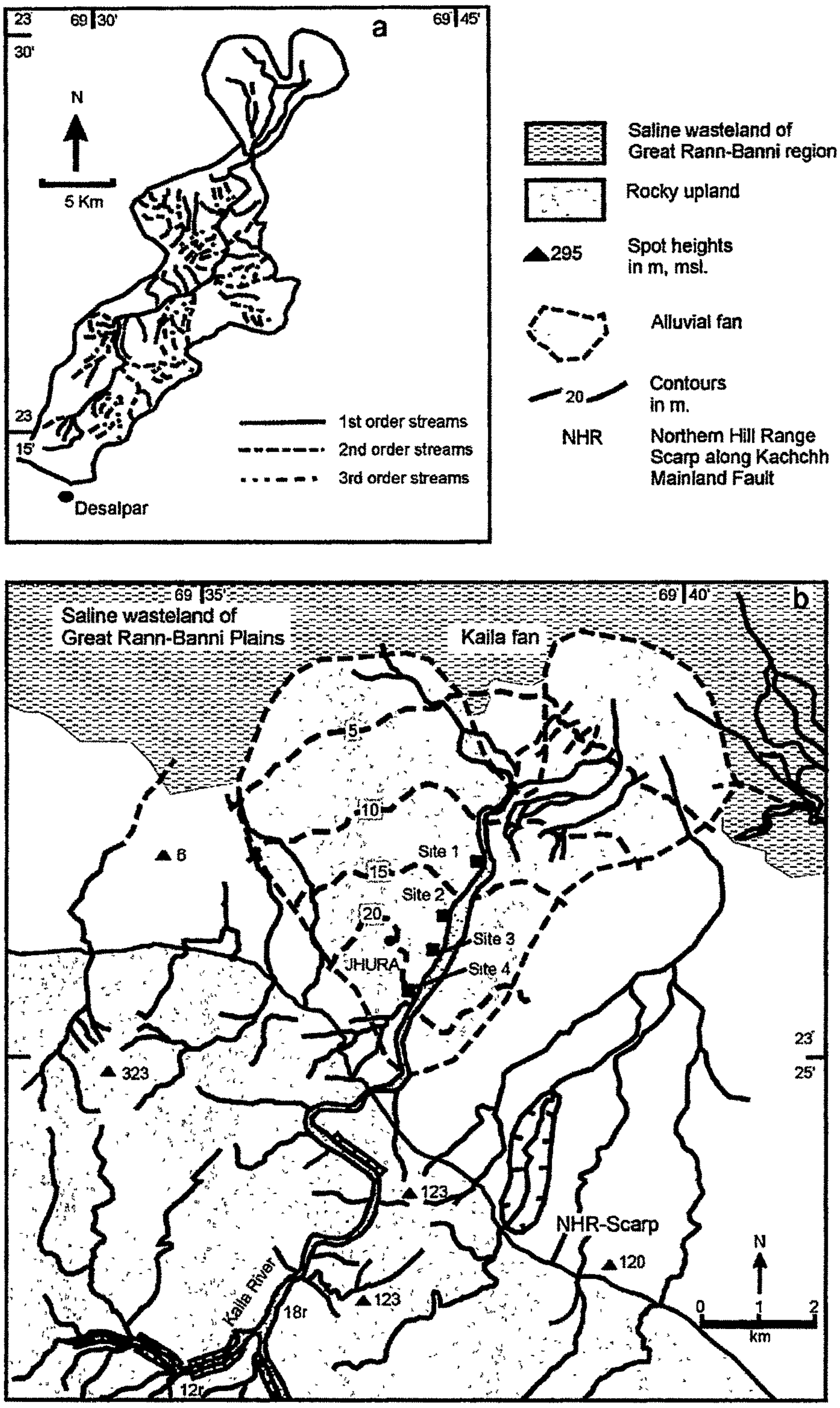


Fig 5.32 Figure showing morphology of Kaila fan alongwith the drainage basin configuration of Kaila river and sites studied along the exposed alluvial succession along the fan

Sudden uplifts thus provided essential geomorphic setting for the formation of alluvial fans along the Northern Hill Range. Also, incision of the two fan sequences point to successive differential uplift along Kachchh Mainland Fault during Late Holocene.

5.5.2 Sedimentary facies of the fan lobes

Architecture of exposed alluvial fan along Kaila and Kaswali rivers indicate various processes involved in building up of these fans. Four sites (1 to 4) along Kaila river and three sites (5 to 7) along Kaswali river were logged (Fig. 5.33). Plausible interpretations regarding their mode of deposition were made on the basis of categorisation of lithounits as per lithofacies code scheme of Miall (1985). Five major sedimentary facies make up Kaila and Kaswali fans and they include (i) debris-flow deposits (Gms), (ii) massive clast supported planar bedded gravel facies (Gm), (iii) trough cross-stratified gravel facies (Gt), (iv) trough cross-stratified sand facies (St) and (v) horizontally stratified sand facies (Sh) (Table. 5.5).

The constituent clastics, a heterogeneous assemblage of the larger angular fragments and smaller rounded grains, typically point to a combination of transported sediments representing two distinct sources - Primary colluvial material mixed up with reworked older sandstone fragments.

On the basis of the detritus characteristics, two categories of the constituents have been recognised: One comprises unsorted, angular to sub-angular bouldery clasts having maximum size of 75cm in Kaswali fan and 150cm in Kaila fan with a variety of rock types, represent tectonically-generated stream-transported colluvial material. This material was later subjected to a debris-flow process during heavy rain and flash floods, a phenomenon typical of ephemeral streams in arid to semi-arid regions (Costa 1984). The associated sub-rounded to rounded pebbles-cobbles are possibly the released clasts derived from the weathering and erosion of the pre-existing conglomeratic bedrock of Mesozoic age. Looking to the structural framework and history of active tectonism, the two aggradational events seen in the fan lobes reflect sudden uplifts in the provenance area. However, the role of flash floods in the development of fans cannot be completely ruled out. In this region, tectonism dominated over climate. The other category consists of coarse to fine sand grains, mainly quartz, well sorted and well rounded. In all probabilities it represents reworked material i.e. sand particles released due to denudation of the Mesozoic sandstones of Bhuj lowland. Such a high degree of rounding cannot be achieved when transported over a short distance by rivers with rather small catchment areas.

Successive uplifts along the various regional as well as local faults during the late Quaternary (i) generated the colluvial debris in the catchment areas, (ii) controlled the northward flow of rivers, and (iii) caused formation and subsequent incision of alluvial fan lobes. It is envisaged that of the two factors (tectonic adjustment and climate) responsible for the formation and incision of the Kaila and Kaswali alluvial fans, tectonism predominated. The uplift of Katrol Hill Range was responsible for the evolution of north-flowing rivers, which drained Central Kachchh Mainland. The Kachchh Mainland Fault related Northern Hill Range demarcating the northern fringe of Kachchh mainland provided ideal geomorphic setting for the development of alluvial fans. The north flowing rivers emerging from the upland in south after crossing Northern Hill Range became unconfined over flat low-lying Banni Plains and deposited semi-conical shaped alluvial fans at the base.

Various sediment-gravity and fluid-gravity processes, along with intervening channelized flows (Table. 5.5) built the fans. In the Kaila fan debris-flow facies is identified at two distinct stratigraphic levels, whereas in the Kaswali fan only one such unit is observed. Gt, Sh and St lithofacies separate the Gms-facies at different levels in Kaila fan indicating intervening channelized flows followed by each debris-flow event. This is in contrast to Kaswali fan deposition, where only one debris-flow event is recorded, the Kaila, thus point to two fan aggradational phases.

Kachchh mainland is characterised by ephemeral rivers that currently carry only sand and gravel as bedload, and have incised the older (? late Quaternary) fan deposits forming steep banks ranging in height from 10 to25 m along their valleys in the lower reaches in fan lobe areas.

NNE-SSW, ENE-WSW, N-S and WNW-ESE trending fractures that are periodically activated control the present day channel courses of the Kachchh mainland. These features are reflected in their straight courses and entrenched valleys, widening and narrowing of channels and valleys, and abrupt high angle deflections in the channel courses. Incision of Mesozoic and Tertiary sedimentary succession in the rocky upland along the trunk streams giving rise to 5 to 10 m wide and 20 to 25 m deep gorges or narrow valleys. Incision of the Quaternary sediment succession along with the bedrock resulting into formation of paired terraces (10-25 m high) suggest, uplifts in region during early and late Quaternary. The uplifts (vertical slips along the fractures as well as flexuring of fault-bounded blocks) are associated with the E-W trending major Katrol Hill Fault and Kachchh Mainland Fault and along minor faults (NNE-SSW, ENE-WSW, N-S and WNW-ESE) during late Quaternary. Continued tectonism is reflected in the dissection of fan lobes. Conspicuous local braiding of the trunk channels within fan lobes also indicates post-depositional tectonism.

Abundance of large angular to sub-angular cobbly-bouldery fragments in Kaswali and Kaila fans suggests very high energy carrying capacity, in contrast to present-day conditions prevailing in the two rivers. At present, the Kaila and Kaswali are ephemeral streams and is limited to bedload size of sand and gravel (4 to 20 cm) even during the periods of peak floods.

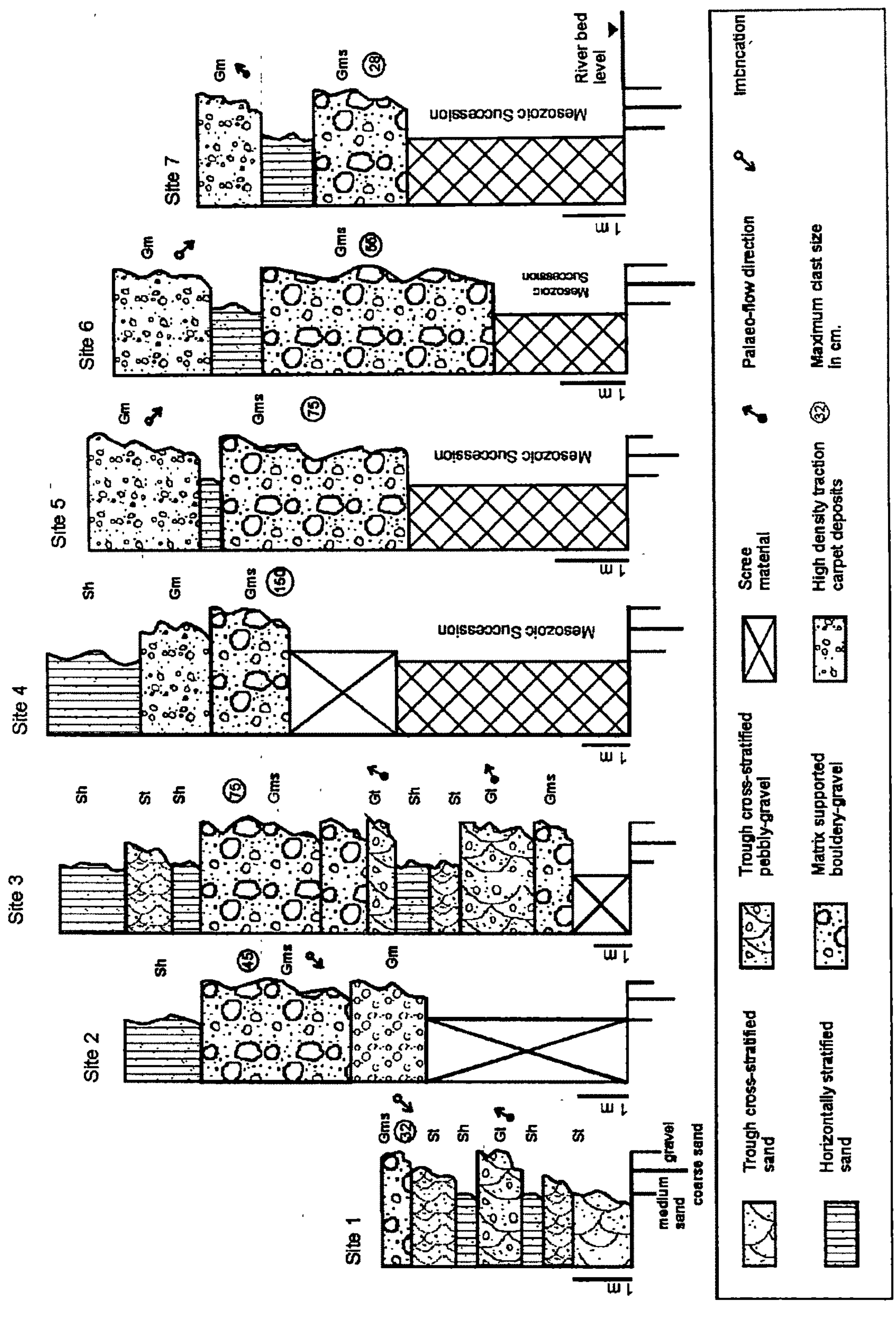


Fig 5.33 Sedimentary successions studied at various sites along the Kaswali and Kaila fans (for locations please refer Fig Nos. 5.24 and 5.25

The author therefore is of the view that major movements along the faults could have probably caused sudden change in gradient resulting flows of magnitude higher than that occurring at present in order to explain the transportation and deposition of the colluvial debris comprising large angular fragments. Thus, the large remnant clasts reflect the net response of the fault generated topographic displacement. Seismic events of late Quaternary played important role in producing sandstone cobbles and boulders along the faults, fractures and joints. Even today, the major fault zones are seismically active. Finer sediments, sub-rounded to rounded grains within the succession on the other hand are released material derived from the weathering of older sedimentary deposits.

One fact that needs to be highlighted is that whereas the fan areas of both rivers are similar (i.e. the Kaswali fan, 35sq.km and the Kaila fan, 39sq.km), although the drainage basin area of Kaila river (180 sq.km) is almost three times larger than that of the Kaswali river (66 sq.km) and the rivers flow across identical terrains made up of Mesozoic and Tertiary rocks. It is likely that Kaswali fan was produced by a bigger river with a catchment further south, quite close to Katrol Hill Range, and the present day Kaswali river is a truncated remnant of this older channel which stands obliterated today on account of tectonic movements. Both Kaila and Kaswali fans are comparable to the other fans occurring at the base of Northern Hill Range in Kachchh region. Uplift along Kachchh Mainland Fault was the common factor that provided unconfinement to all north flowing rivers over the low-lying Banni Plains and controlled the alluvial fan architecture. The alluvial fans of Kachchh are thus typical example of fans that are reported from the tectonically active regions with arid to semi-arid climatic conditions.