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Relative Assessment of Tectonic Activity along the Seismically Active Katrol Hill Fault, Kachchh, Western India

Archana Das[1], S. P. Prizomwala[1]*, Tarun Solanki[1], Gaurav Chauhan[2], M. G. Thakkar[2] and Nilesh Bhatt[3]

[1]Active Tectonics Group, Institute of Seismological Research, Gandhinagar – 382009, India
[2]Department of Earth and Environmental Science, K.S.K.V. Kachchh University, Bhuj, Kachchh - 370001, India
[3]Department of Geology, The M. S. University of Baroda, Vadodara – 390002, India
E-mail: *siddharth_prizomwala@yahoo.co.in; prizomwala@isr.res.in*

ABSTRACT

The Katrol hill fault (KHF) is a 71 km long fault, striking E-W in the Kachchh intraplate region, western India which is moderately active, seismically, but exhibit high strain rate with considerable vertical deformation. It is dissected by several young transverse faults. Based on these transverse faults, KHF is longitudinally, divided into five segments. Even though there are evidences of its active nature during the Holocene Period, no studies have been carried out for quantifying the spatial variation in relative tectonic activity along the KHF, which is vital for assessing a more realistic seismic hazard potential of the fault. Quantitative geomorphic indices are employed to evaluate the 'Relative Index of Tectonic Activity (RITA)'. It has been observed that the central part (segment 2 & 3) is the most active segment, which covers an aerial extent of 38% of total KHF (class 1), compared to the eastern (segment 4 & 5) and the western segments (segment 1), which are moderately active (class 2). Interestingly none of the segments of the KHF, corresponded to class 3 of RITA i.e. least active/inactive class. The study highlights the important role of transverse faults, which cut across the major E-W faults in the Kachchh, and may regulate the relative activity and the earthquake potential of an individual segment. The study thus, hints the KHF as an under-rated source for future seismic hazard for the Kachchh and western India region.

INTRODUCTION

In tectonically active regions, the present-day topography results from the interplay of erosional and tectonic processes (Bishop, 2007, Jayangondaperumal et al., 2018). The fault generated mountain fronts are major tectonic landforms, where active tectonics and surface processes coexist (Mayer 1986; Bull 2008). Such landforms are very responsive to rates of active tectonics, surface processes and rock strength (Bull and McFadden, 1977; Silva et al. 2003). Spatial and temporal variations in rate of active tectonics, surface processes and rock strength lead to the development of mountain fronts of characteristics shapes and sizes. In alluvial setting, V-shaped valleys along with steep and straight mountain fronts are usually generated when tectonic processes are dominant, whereas sinuous and gentle mountain fronts are produced along with U-shaped valleys where tectonic processes are no longer active (Keller and Pinter, 2002; Silva et al., 2003; Yildirim, 2014; Prizomwala et al., 2016). The geomorphic indices have been widely used as a reconnaissance tool to differentiate zones influenced by active tectonics and landform responses to active deformation processes. Therefore, the steepness of mountain fronts, shape of valleys, gradient of stream channel and relief that provides vital information about archived tectonic activity, can be used to access the tectonic activity along the fault segments. The advantage in employing these indices is that they are robust and they allow to evaluate relative tectonic activity and illustrate the pattern of deformation associated with a long term slip of faults (Rockwell et al., 1985; Keller and Pinter, 2002; Kumar et al., 2006; Yildirim, 2014). The combination of these indices also allow to assign individual mountain fronts or segments of collective fronts to different classes of tectonic activity (i.e. Class 1 to Class 3) in the order of decreasing uplift rates (Bull and McFadden, 1977; Rockwell et al., 1985; Silva et al., 2003; El Hamdouni et al., 2007; Yildirim, 2014).

Kachchh region, a pericratonic Mesozoic palaeorift basin, situated in the western most part of India is an example of intraplate seismicity and has experienced four major earthquakes (*M*w > 6) in the last 200 years (i.e. 1819 Allah bund ~ *M*w 7.8, 1845 Lakhpat ~ *M*w 6.0, 1956 Anjar ~ *M*w 6.0 and 2001 Bhuj Earthquake ~ *M*w 7.7) (Mathew et al., 2006; Rastogi et al., 2012). The region has a high strain rate with small earthquake reoccurrence intervals and there exists a limited understanding of slip rates due to lack of palaeoseismological study, which makes the assessment of seismic hazard a difficult task (Malik et al., 2008; Morino et al., 2008; Patidar et al., 2008; Kundu et al., 2010; Mohan, 2014). Quantitative geomorphology provides auxiliary information to help overcome this issue in assessing the seismic hazard of the region (Bull and McFadden, 1977, Rockwell et al., 1985; Silva et al., 2003; Yildirim, 2014; Prizomwala et al., 2016).

Katrol hill fault (KHF) is a 71 km long E-W trending fault in the central Kachchh Mainland, is one of the major tectonic elements in the Kachchh and is considered as a source for seismic hazards in the western India (Fig.1) (Patidar et al., 2007; 2008; Morino et al., 2008; Kundu et al., 2010; Chopra et al., 2012; Rastogi et al., 2013; Mohan 2014). The Holocene reactivation of KHF has already been demonstrated by means of palaeoseismological study in central KHF (Patidar et al., 2008; Morino et al., 2008; Kundu et al., 2010). Despite this localized evidence of active deformation, the activity along the entire length of KHF has not been quantified, which makes the efforts to estimate seismic hazard more difficult. Due to the arid/semi-arid climate the Kachchh region lacks vegetation and it beholds good exposures of surface morphology making the conditions favorable for accessing the shape of mountain fronts, valley shapes and channel gradient. These information can be evaluated and linked to short and long term tectonic deformation of the KHF during late Quaternary period. Similar study employing geomorphometry were carried out previously in the same region (Thakkar et al., 1999; Sohoni et al., 1999), however, they were focused on the central segment of Kachchh and there has been no study pertaining to relative tectonic activity along the seismically active KHF.

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The primary aim of this paper is to study the morphology of various landforms along the KHF, which would enable us to assign relative degree of tectonic deformation (i.e. spatial variation in tectonic activity) undergone by various segments compared to one another, and would be helpful in assessing the realistic seismic hazard of this fault.

REGIONAL SETTING

The Kachchh rift is evolved during drifting of the Indian plate around late Triassic - early Jurassic (Biswas, 1987). The basin is bounded by the Nagar Parkar block in the north, Saurashtra block in the south, Radhanpur-Barmer arc in the east and it merges with the continental shelf in the west (Biswas, 1987, 2005, 2014). The Kachchh basin is sliced by many E-W oriented faults viz. Nagar Parkar fault (NPF), Allah Bund fault (ABF), Kachchh Mainland fault (KMF), Katrol hill fault (KHF), South Wagad fault (SWF), Gedi fault (GF) and Island Belt fault (IBF) (Fig. 1b). The KHF is situated in the central Kachchh Mainland and it divides the Mainland into two tilted blocks (Biswas, 2005). (i) the rugged hills of Katrol hill range in the south (up-thrown block), and (ii) rocky plain of Bhuj Low to the north (down-thrown block). The KHF is well defined by a single fault plane having sharp contact between Jurassic (Jumara) to the south and Cretaceous (Bhuj) Formation in the north. The strike of fault plane of KHF is E-W with local variation NWW-SEE caused by influence of oblique transverse faults. The fault plane of KHF is South dipping having dip amount ranging from 50°-80°. The KHR acts as a drainage divide for the fluvial systems of the Kachchh mainland, where all northerly and southerly flowing rivers originate. All north flowing rivers originate from KHR, eventually cuts through the northern hill range and debouch in the Banni plains/Great Rann of Kachchh forming alluvial fans (Maurya et al., 2003), whereas all south flowing rivers passes through all the geological formations and debouch into the Arabian sea (Maurya et al., 2003; Patidar et al., 2007).

The KHF zone is characterized by several small magnitude earthquakes (M_w< 4.0) and infrequent large earthquakes (M_w> 6.0) (Fig. 1c) (Rastogi et al. 2013). The most recent large earthquake along the KHF was 21[st] July, 1956 Anjar earthquake of *Mw* ~ 6.0 (Chung and Gao, 1995). The focal mechanism of earthquakes in and around KHF and a palaeoseismological study indicated that KHF is a 'low angle reverse fault' dipping towards south (Chung and Gao, 1995; Morino et al. 2008; Singh et al. 2014). The KHF is dissected at many places and laterally displaced by younger NW-SE, NNE-SSW and NE-SW trending transverse faults (Fig. 1c) (Maurya et al., 2003; Patidar et al., 2007; Maurya et al., 2016). The geological evidences of these transverse faults like sag ponds, deflected streams, displaced shutter ridges/mountain fronts and offset channels, have been reported earlier (Thakkar et al., 1999; Sohoni et al., 1999; Maurya et al., 2003; Patidar et al., 2007). Earlier studies suggested that on the E-W trending faults, a part of the stresses being build up is probably transferred to the NW- SE to NE- SW transverse faults, which may be responsible for the present day seismic activity. The formation of the transverse faults is linked with the pre–Deccan trap phase of dyke replacement (Maurya et al., 2003, 2016). Biswas and Deshpande (1973) suggested that the emplacement of the intrusive bodies and dykes are syn-tectonic.

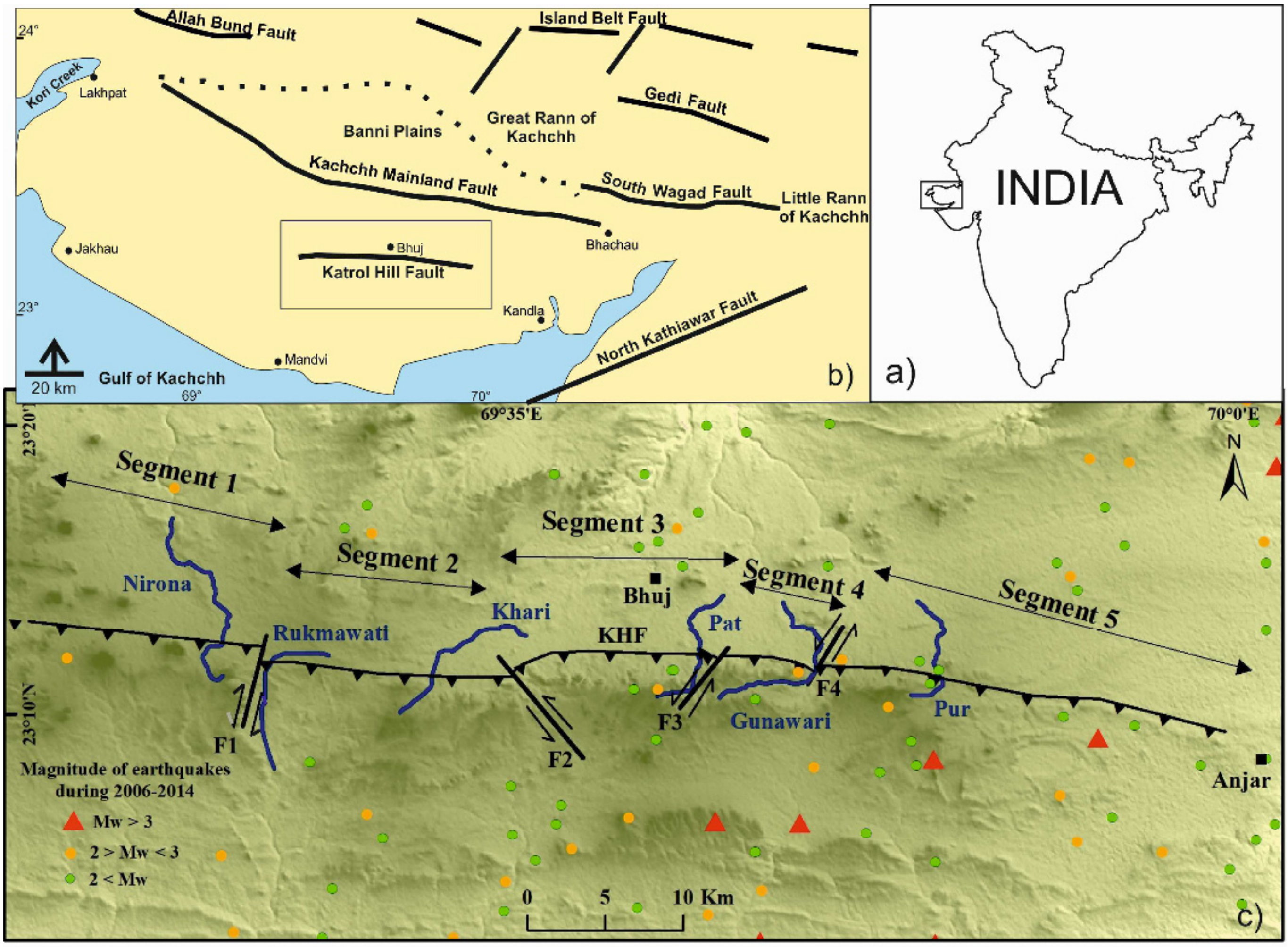

Fig.1. (a) Key map of India showing Kachchh. **(b)** Seismo-tectonic map of Kachchh showing major faults along with study area and **(c)** DEM of study area along with major faults segments, drainages and seismicity during the period 2006 to 2014 (ISR earthquake catalogue).

These deep seated plutonic bodies are close to major faults which are main source for stress barriers and potential zone for earthquake generation (Biswas, 2005, 2014; Mandal and Chadha, 2008). Based on this information along with presence of transverse elements that cut across the KHF (Maurya et al., 2003; Biswas, 2005, 2014; Mandal and Chadha, 2008), the KHF is divided into five segments from west to east with lengths of approximately 14, 15, 12, 6 and 24 km respectively (Fig. 1c). The length of each segment is defined by a delimiting transverse fault, lying on its eastern and western sides (Maurya et al., 2003; Patidar et al., 2007; Maurya et al., 2016).

MATERIALS AND METHODS

In the present study, six major streams cutting the KHF and flowing northward (five) and southward (one) from the KHR is investigated for assessing the spatial variability of tectonic activity along the KHF. The application of the quantitative geomorphology in assessing relative degree of tectonic deformation has been successfully demonstrated in the Garlock fault, California, USA (Bull and McFadden, 1977), South Mountain-Oak ridge anticline, Ventura basin, southern California, USA (Azor et al., 2002), fault-generated mountain fronts in southeast Spain (Silva et al., 2003), Sierra Nevada Mountain range, Spain (El Hamdouni et al., 2007; Pérez-Peña et al., 2010), Normandy intraplate area, France (Font et al., 2010), Tuz Golu fault zone, Central Anatolia, Turkey (Yildirim, 2014) and Kachchh Mainland fault (KMF) zone, Kachchh, India (Prizomwala et al., 2016). Quantitative geomorphic indices ~ mountain front sinuosity (S_{mf}), valley floor width to height ratios (V_f), stream length gradient index (*SL* index), drainage basin asymmetry factor (A_f) and hypsometric integral (*HI*) along with rock strength index were employed to assess the spatial variation in tectonic activity along the KHF (Strahler, 1952; Bull and McFadden, 1977; Keller and Pinter, 2002). Use of these specific parameters were based on understanding that these parameters respond to basins scale differential uplift and lithology changes (Keller and Pinter, 2002; El Hamdouni et al., 2008). As the objective was to assess the spatial variability in the tectonic activity along the individual fault segments of the KHF, the study focussed on the stretch of streams, beginning from its origin till it crosses the KHF instead of entire length of the streams. This is primarily done because of the knowledge that KHF is a reverse fault (Chung and Gao, 1995; Maurya et al., 2003; Patidar et al., 2007) and hence signatures of its tectonic activity will be archived in its hanging wall. A 30 m resolution of ASTER data to generate Digital Elevation Model (DEM) of the study area was used. The DEM was used to extract drainage network and 10 m interval contour maps were generated to evaluate the different geomorphic parameters mentioned previously.

Rock Strength

Various parameters of geomorphic indices are controlled by the combination of structure (tectonics) and lithological contrast. However, when it comes to classifying the degree of erodabililty, the lithological variability can be used as a first order approximation. Thus, based on spatial variability in the rock strength, the studied basin can be divided into three classes following El Hamdouni et al. (2008) to define rock strength: low (Quaternary unconsolidated alluvium), moderate (Khari and Madh series Tertiary limestones and clays), high (Jhurio, Jhuran, Jumara, Bhuj Formations -Mesozoic shale - sandstone; and Deccan Trap Formation - basalt) (Fig 2).

Mountain Front Sinuosity (S_{mf})

The mountain front sinuosity represents the relationship between stream erosion processes, that tends to cut some parts of a mountain front, and vertical tectonics, that tends to produce straight mountain fronts (Dehbogorzi et al, 2010). It is defined (Bull and McFadden, 1977; Keller and Pinter, 2002; Silva et al., 2003) as

$$S_{mf} = L_{mf}/L_s$$

Where, L_{mf} is the length of a mountain front along the foot of the mountain and L_s is a straight line length of the mountain front. The degree of active tectonic shapes the mountain fronts, viz., active vertical tectonics usually produces straight mountain fronts, normally associated with active faults or folds (Bull and McFadden, 1977; Jayangondaperumal et al., 2017) and similarly on account of cessation of tectonics, laterally sinuous mountain fronts are produced. Low S_{mf} value indicates youthfulness of mountain fronts due to continued neotectonic activity (Bull and McFadden, 1977). If the rate of the uplift is reduced, then erosional processes carve a more irregular mountain front and the S_{mf} value will increase. In the present study, the entire main front of the Katrol Hill Range was focused for calculating the S_{mf}. A total of five mountain fronts, $S_{mf}1$ to $S_{mf}5$ were studied (Fig. 3).

Valley Floor Width to Height Ratio (V_f)

Valley floor width-height ratio is a sensitive tool that responds to the vertical uplift and is dependent on the time of uplift, as newly uplifted/uplifting valleys show deeper and narrower valleys and these valleys gets broader after cessation of the uplift in the course

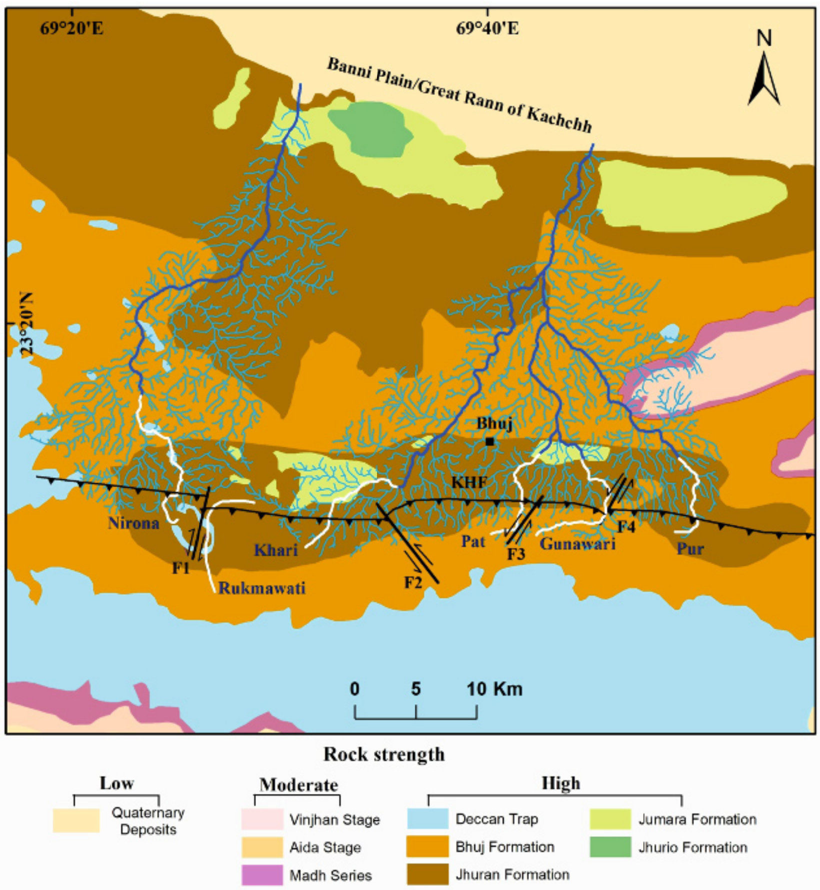

Fig.2. Geological map, drainage network and studied segment of the streams (after Biswas and Despnande, 1970)

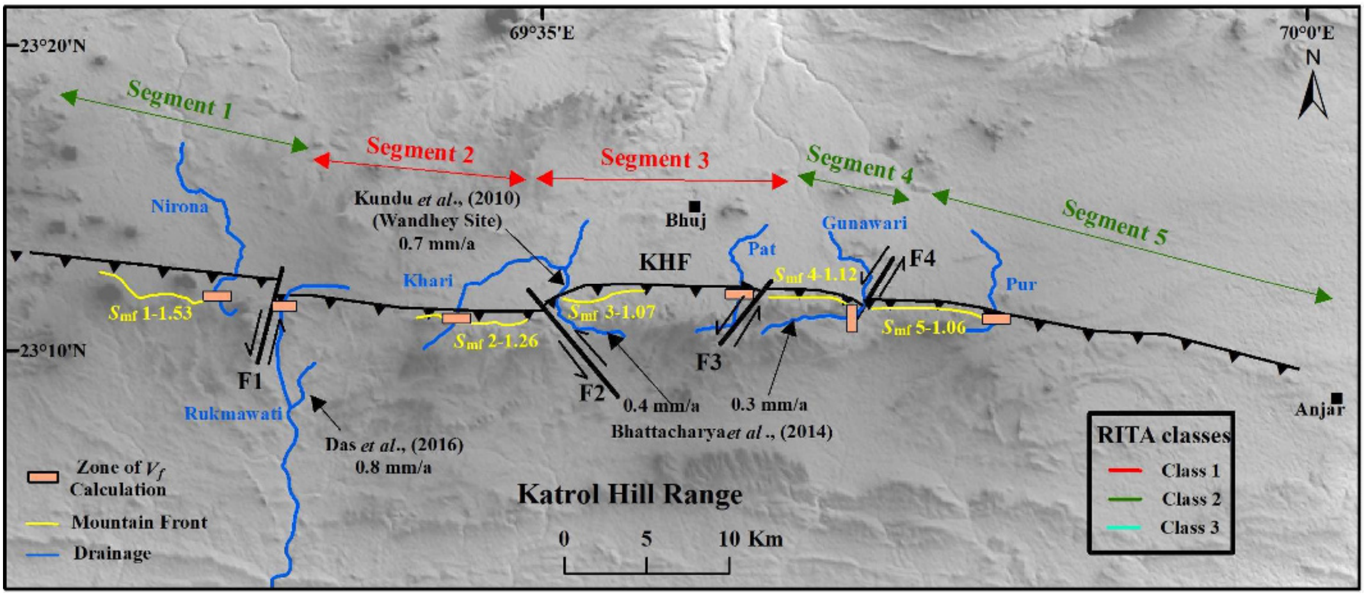

Fig.3. Mountain front sinuosity (S_{mf}) values, zone of V_f calculations along the rivers cutting the KHF and RITA classification of segments of KHF.

of time (Bull, 2008). The valley floor width-height ratio is defined as (Bull and McFadden, 1977)

$$V_f = 2V_{fw} / [(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})] \quad (2)$$

Where, V_{fw} is width of the valley floor, E_{sc} is elevation of the valley floor with respect to the mean sea level, E_{ld} and E_{rd} are the elevations of the left and the right side of the valley with respect to the mean sea level, respectively. Bull and McFadden (1977) found significant differences in the V_f values due to the tectonically active and inactive mountain fronts, as valley floor is narrowed down due to the rapid stream down-cutting, associated with active tectonics. The V_f index is used to differentiate between the "U" shaped valley, related to the inactive mountain fronts, and "V" shaped valleys related to the tectonically active mountain fronts. The higher values of the V_f are associated with the "U" shaped valleys, indicative of the lower rate of the uplift and the incision, whereas lower V_f values are associated with the "V" shaped valleys, hinting at higher uplift rates and the incision in fluvial environments (Bull and McFadden, 1977). Usually, in an active mountain fronts, the V_f values < 1.0 are considered as indicative of tectonically active segments (Bull and McFadden 1977; Silva et al. 2003; El Hamdouni et al. 2008). In intraplate regions, where tectonic quiescence is longer, the river channels are broader and V_f ratio usually shows higher values, even if the area is tectonically active (Raj et al., 1999; Kale et al., 2014). In this study, the V_f values were calculated at 4-5 positions, approximately at 1 - 1.5 km upstream of the respective mountain fronts as suggested by Silva et al. (2003) (Fig. 3).

Stream Length Gradient Index (SL Index)

Hack (1973) defined stream length gradient index (*SL* Index) as a tool to changes in channel slope with respect to upstream length. It is used to evaluate the possible effects of tectonic activity and differential rock resistance along the river channel (Keller and Pinter, 2002). In tectonically active areas SL peaks are used as an indicator of uplifted zones within the drainage basin (Merritts and Vincent, 1989; El Hamdouni et al., 2008; Troiani and Della Seta, 2008). It is expressed as

$$SL = (\Delta h / \Delta l)\, l$$

Where $\Delta h/\Delta l$ is slope of the reach which is studied and l is channel length from divide to midpoint of reach which is studied. The higher SL index values are frequently associated with tectonically active and uplifting segments, while lower values are associated with inactive faults and in some cases with strike-slip faults (Dehbozorgi et al., 2010). Additionally, one more factor influencing the SL values is rock resistance (Pérez-Peña et al., 2010). However, rock resistance did not affect the present study since; SL changes in the same lithology only, have been interpreted as signal of tectonic forcings.

Longitudinal river profile of all six drainages were studied and superimposed on the lithology along with the SL index variations, to assess the zones of uplift within the drainage basins (Fig 4).

Hypsometric Curve and Hypsometric Integral (HI)

Hypsometric curve is an expression of relative distribution of elevation in a drainage basin (Strahler 1952; Keller and Pinter, 2002; Mahmood and Gloaguen, 2012), hence indicating an area that has not been eroded so far.

These curves are useful when comparing different basins of varying sizes for evaluating relative amount of deformation undergone by them (Keller and Pinter 2002). Convex shaped hypsometric curves with value of hypsometric integral nearing 1 indicate a 'weakly eroded' regions and concave hypsometric curves with value of hypsometric integral nearing 0 indicate 'highly eroded' regions.

The hypsometric integral can be calculated by a simple expression,

$$HI = \frac{(\text{Average elevation} - \text{Minimum elevation})}{(\text{Highest elevation} - \text{Minimum elevation})}$$

Hypsometric integral produces curve with typical convex, convex to concave and concave shape.

The convex shape is associated with HI value greater than 0.5, similarly convex to concave curves have HI values between 0.4 to 0.5 and concave curves have HI value less than 0.4. Higher value generally indicates not much of the upland is eroded and hence is a younger landscape, probably produced due to active tectonics (Keller and Pinter 2002; El Hamdouni et al. 2007; Perez-Pena et al. 2010; Mahmood and Gloaguen, 2012).

Drainage Basin Asymmetry Factor (Af)

The drainage basin asymmetric factor (*Af*) reflects the existence of tectonic tilting at the scale of a drainage basin. The evaluation of

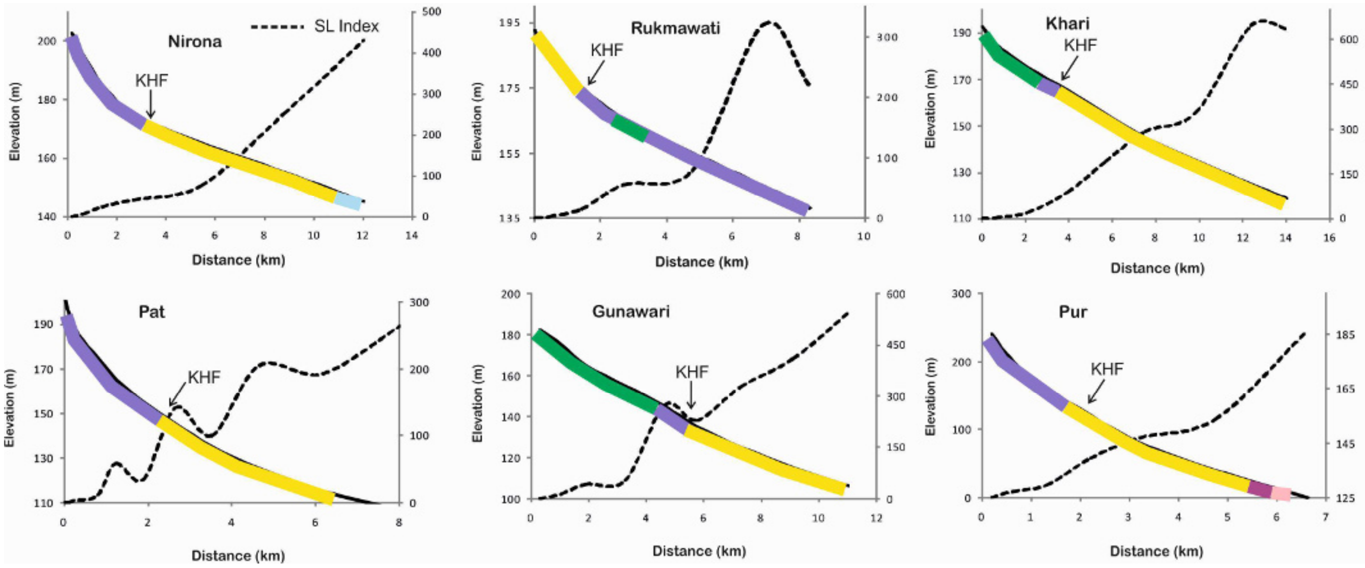

Fig.4. Longitudinal river profile and SL index values super imposed on lithology in the studied drainages.

the tilting within the different sub-basins, gives an idea about the lateral migration of the river basin and the direction of possible tilting. The asymmetry factor is expressed as (Hare and Gardner, 1985):

$$Af = 100\ (Ar / At)$$

where A_r is the area of the basin to the right of the trunk stream, and A_t is the total area of the drainage basin. Values of A_f above or below 50 indicate that the basin is asymmetric. If the basin demonstrates stable conditions with little or no tilting, A_f is close to 50. If AF is significantly greater or smaller than 50, then it indicates that the basin has developed under the effects of active tectonics and/or strong lithological control. In order to evaluate the relative extent of degree of tilting, undergone by each basin, we have subtracted the value of A_f by 50.

RESULTS

Rock Strength

The northern Katrol Hill mountain front and its footwall consist of sandstones and shales of Bhuj and Juran Formation (Fig. 2), associated with high rock strength level. The major part of the drainages in the Western and Central segments pass through high rock strength level rock types. Only the lower part of drainages in eastern segment cuts through the moderate rock strength level.

Mountain Front Sinuosity (S_{mf})

In the northern Katrol Hill range, five mountain fronts are marked, using 30m ASTER DEM data, having maximum elevation difference of 100m with respect to the mountain front and the piedmont zone. The S_{mf} values ranged from 1.06 to 1.53 (Supplementary Table 1). In order to access the spatial variability in the mountain front sinuosity, we have classified the S_{mf} values in three classes; Class 1: very active (S_{mf}<1.1), Class 2: moderately active (1.1 <S_{mf}< 1.5), Class 3: least active (S_{mf}> 1.5). It has been observed that the lowest S_{mf} values are associated with the segment 3 and 5 from the KHR mountain fronts (i.e. Pat and Pur River).

Valley floor width-height ratio (V_f)

In the northern Katrol Hill Range mountain fronts, the V_f values range from 1.23 (i.e. Gunawari) to 6.06 (i.e. Pur) (Table 2). This implies that the valleys along the KHR are in transition between 'V' and 'U' shaped valleys. We have classified the V_f values in three classes: Class 1 (very active: V_f< 1), Class 2 (moderately Active 1<V_f<5) and Class 3 (least Active: V_f>5) of varying degree of activity (Supply Table 1).

Stream Length-Gradient Index (SL Index)

Figure 4 shows longitudinal river profile and *SL* index variations in all the 6 rivers. The result suggests that the increase in *SL* index values within the same rock unit can be considered as a manifestation of active tectonics. The longitudinal river profile shows convex nature at KHF with associated zone of SL index peak, however as the position of KHF is a contact between litho-units of varying strength; hence we do not consider this anomaly being 'solely' due to tectonic activity along KHF. The rivers Pur, Gunawari and Pat in eastern and central segments show presence of a knick points and associated SL peak upstream of KHF (i.e. on the hanging wall block) (Fig. 4). In order to ascertain the spatial variation in the *SL* index values within the individual channels, we have classified the *SL* index values in three classes: class 1 (*SL* > 500), class 2 (300 < *SL* < 500) and class 3 (*SL*<300) (Dehbozorgi et al., 2010).

Hypsometric Curve and Hypsometric Integral

Figure 5 shows hypsometric curves and hypsometric integral values for all six drainage basins along the KHF. The hypsometric curves range from convex, convex-concave shape to convex shape. The HI values ranges from 0.43 (i.e. Pat) to 0.57 (i.e. Pur) (Fig. 5). As the KHF is located in the upstream portion of all the basins, we assume that the convex upper portion in hypsometric curve points to an uplift along the KHF. We have divided the *HI* values in three classes; class 1 (very active *HI* > 0.50, convex), class 2 (moderately active, 0.45 < *HI* < 0.50, convex to concave), class 3 (least active, *HI* < 0.40, concave) (El Hamdouni et al., 2008).

Drainage Basin Asymmetry (A_f)

Absolute values of A_f for our study area range from 7.41 (Nirona) to 31.50 (Rukmawati). The absolute A_f values has divided into three classes: Class 1: A_f > 15 (strongly asymmetric basins), Class 2: 7 < A_f < 15 (moderately asymmetric basins) and Class 3: A_f < 5 (symmetric basins) for assessing the relative degree of tilting in the respective basins (Supplementary Table 1). Nirona and Pat shows value less than 50 pointing towards tilting of their basins towards right side of the downstream i.e. westward tilting while the remaining rivers show values more than 50, i.e., eastward tilting.

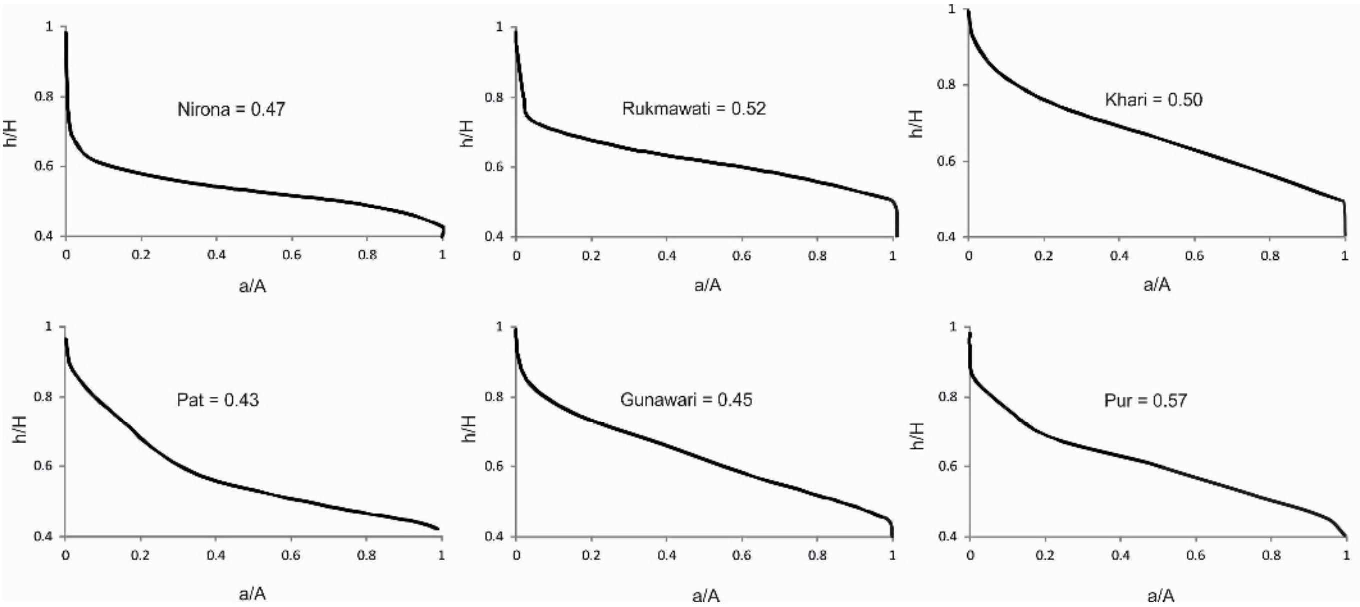

Fig.5. Hypsometric integral (HI) curve and values for all the six studied drainages.

DISCUSSION

Classification of Relative Tectonic Activity based on Geomorphic Indices

In order to ascertain the relative tectonic activity along five segments of KHF, the data of the geomorphic indices that have been proven successful in various parts of the world, for assessing relative index of tectonic activity (RITA) viz., SL, $S_{mf,}$ HI, A_f and V_f have been synthesized and assigned classes to the computed geomorphic indices as described earlier, with Class 1 being most active and Class 3 being least active (Silva et al.. 2003, El Hamdouni et al., 2008; Dehbozorgi et al., 2010; Mahmood and Gloaguen, 2012). All the three classes were combined and their average values were obtained which is termed as *'Relative Index of Tectonic Activity (RITA)'*. RITA is an index obtained by combining all the classes of various computed geomorphic parameters (Table 1). The RITA values were then classified as, Class 1 <2.0, very active; 2.0 ≤ Class 2 < 2.5, moderately active and Class 3 ≥ 2.5, least active (Table 1). In general, tectonically active mountain fronts of Class 1 are characterized by low values of Smf and Vf indexes and inactive mountain fronts of Class 3 show normally high values (Silva et al., 2003) of both (Smf and Vf) indices. However, it is an opposite case in HI and AF indices, where low values indicate inactive basin and higher values indicate active basin (Dehbozorgi et al., 2010; Pérez-Peña et al., 2010). In the present study, the segment 2 and 3 (i.e. western and central segment covering Rukmawati, Khari and Pat Rivers) hosts uniform lithology and are found to be the most active segment with RITA values corresponding to Class 1 (Fig. 3). The moderately active part of the KHF comprises of segments 1, 4 and 5 (i.e. westernmost segment Nirona and easternmost segment of the KHF covering Gunawari and Pur River), with RITA values corresponding to Class 2 (Fig. 3). Interestingly, no segment along the KHF, shows presence of inactive class (i.e. class 3) in the KHF zone.

Table 1. Classes of various geomorphic parameters and classification of Relative Index of Tectonic Activity (RITA) along the KHF

River	A_f class	HI class	V_f class	SL class	S_{mf} class	RIAT	RIAT class
Nirona	2	2	2	2	3	2.2	2
Rukmawati	1	1	2	2	-	1.5	1
Khari	2	1	2	1	2	1.6	1
Pat	1	2	2	3	1	1.8	1
Gunawari	2	2	2	2	2	2	2
Pur	2	1	3	3	1	2	2

Implications of RITA along the KHF

Limited palaeoseismological and chronologically supported neotectonic studies have explored the KHF zone for assessing its tectonic history during the late Quaternary period (Patidar et al., 2008; Morino et al., 2008; Kundu et al., 2010; Bhattacharya et al., 2013, 2014; Das et al., 2016). A minimum long term uplift rate of 0.8 mm/a for Rukmawati (Das et al., 2016) (present study: segment 2), 0.3 mm/a for Gunawari (present study : segment 4), 0.4 mm/a for Khari river (Bhattacharya et al., 2014) (present study : segment 3) and 0.7 mm/a for Khari trench site (Kundu et al., 2010) (present study: segment 3) has been reported. Similarly, the slip rate along KHF is estimated as > 0.23 mm/a for last 30 ka at Wandhey section (present study : segment 3) based on palaeoseismological trench investigation (Patidar et al., 2008; Morino et al., 2008; Kundu et al., 2010). All these investigations have been limited to segment 2 to segment 4 i.e. central part of KHF (Fig. 3). The westernmost (segment 1) and eastern KHF (segment 5) have not been explored adequately; one of the reasons for this being the lack of preservation of Quaternary sediments in the river valley of these segments. Interestingly, KHF during the last decade has witnessed low to moderate seismicity, restricted only to its central and eastern segments (Fig 1c: ISR earthquake catalogue).

The geomorphic indices computed in the present study shows that the central (segment 2 and 3) KHF is relatively more active than the eastern (segments 4 and 5) and the western segments (segment 1). This is also corroborated by the formation of steep fronts, narrow valleys, and gorges along the central segment of KHF. Some of the field evidences that depict the tectonic activity along the KHF in recent times are triangular facets, free face, colluvial fans and alluvial fans developed along with the youthful scarp of KHF (Fig. 6a). It has been observed that triangular facets are signatures of the youthful nature of the scarp in tectonically active terrains (Keller and Pinter, 2002; Bull, 2008). Similarly, the development of narrow gorges in the hanging wall block of the KHF zone, like in Gunawari River (Fig. 6b), is also manifestation of the uplifts along the KHF. It has been noticed that most of the north flowing drainages forms gorges of variable sizes just before they cut across the KHF scarp.

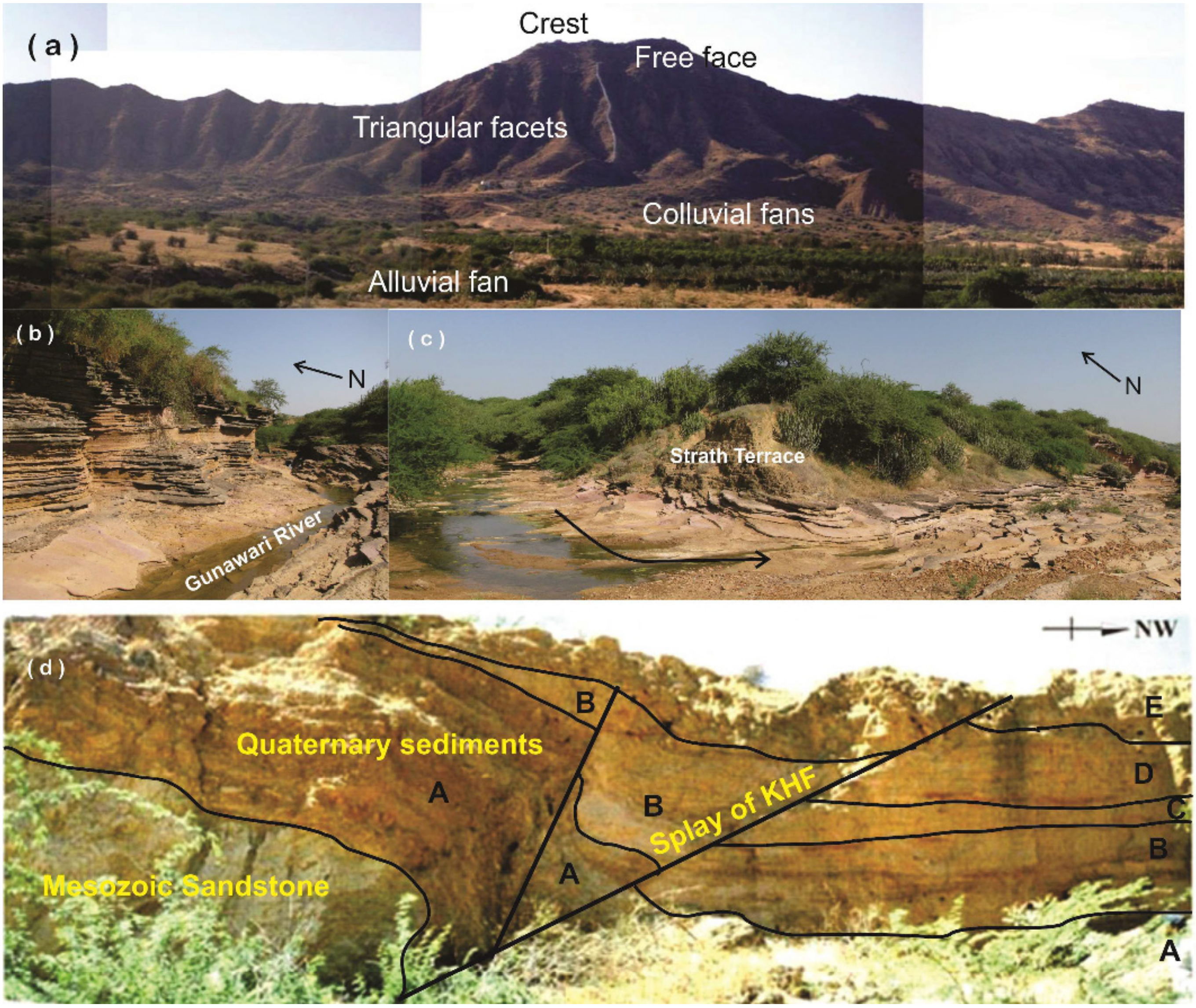

Fig.6. Field evidences of tectonic activity in Northern Hill Range. **(a)** Neotectonic features along north facing scarp of KHF near Kukma village (view of photograph is south facing), **(b)** East-West trending Gunawari river gorge, **(c)** Strath terrace on the hanging wall block of KHF zone and **(d)** Signature of KHF reactivation in late Quaternary sediments (after Patidar et al., 2008).

Some of the rivers in the studied region showed formation of 'strath terraces' in the hanging wall block of the KHF (Fig. 6c). Strath terraces are formed when a river incises the Quaternary sediment cover and the underlying bedrock to a considerable extent (Gilbert, 1877; Mackin, 1937). Bedrock incision requires very high stream power and Kachchh being an arid region, may not have potential for such high degree of stream power, which can lead to incision of the bedrock. Another driver for the bedrock incision has often been sea level change. However, the distance of the KHF from the present day sea stand (> 50 km), which was even at further distance during the late Quaternary period due to low sea stand (Das et al., 2016), rules out the sea level change to be primary cause for bedrock incision. Hence, it is postulated that bedrock incision during the Quaternary period near the fault segments in the Kachchh is a manifestation of tectonic activity (Das et al., 2016; Bhattacharya et al., 2013, 2014; Prizomwala et al., 2016).

One of the direct evidences of the active tectonics, is the deformation in the Quaternary sediments. Three events of active faulting during the late Quaternary have been suggested based on the offsetting in the Quaternary sediments across the KHF (Patidar et al., 2008; Morino et al., 2008). However, other than Wandhey site, there are no evidences of surface faulting / deformation along the KHF so far (Maurya et al., 2016). Figure 6d shows the deformation in the Quaternary sediments by splay of KHF at Wandhey site (Morino et al., 2008; Patidar et al., 2008; Kundu et al., 2010). The extension of splay of KHF in the late Holocene (< 3 ka) sediments again testifies the active nature of the KHF (Kundu et al., 2010). The results of the geomorphometric parameters of the five studied streams also accords well with the field evidences and scantily available long-term incision rates from the studied stretch of the KHF, however does not permit us to draw a comparison of the segments on relative deformation apart from quantitative geomorphic parameters.

CONCLUSION

Based on quantitative geomorphology with an aid of field evidences of active tectonics along the Katrol Hill Fault (KHF), we summarize the following

1. Quantitative geomorphic parameters in conjucation with the field evidences of active tectonics suggest that the segments 2 and 3 (i.e. central KHF) is relatively more active segments compared with segments 1, 4 and 5 (i.e. western most and eastern most KHF).
2. Based on the assessment, a total of 38% (27 km of total of

71 Km) of length of KHF zone falls under highest tectonically active class 1 (central i.e. segment 2 and 3).

3. Despite limited seismicity of higher magnitude earthquakes along the KHF, none of the segments show low class (class 3) of tectonic activity.

The study highlights the important role of transverse faults, which cut across the major E-W faults in Kachchh, and may regulate the relative activity and earthquake potential of the individual segment. The study also hints the KHF being an under-rated source of future seismic hazard for the Kachchh and western Indian region.

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