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Morphotectonic of Sabarmati-Cambay basin, Gujarat, Western India

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ABSTRACT
The study area is a part of the peri-cratonic Sabarmati-Cambay rift basin of western Peninsular India, which has experienced in the historical past four earthquakes of about six magnitude located at Mt. Abu, Paliyad, Tarapur and Gogha. Earthquakes occurred not only along the two major rift boundary faults but also on the smaller longitudinal as well as transverse faults. Active tectonics is the major controlling factor of landform development, and it has been significantly affected by the fluvial system in the Sabarmati-Cambay basin. Using the valley morphology and longitudinal river profile of the Sabarmati River and adjoining trunk streams, the study area is divided into two broad tectono-morphic zones, namely Zone-1 and Zone-2. We computed stream length gradient index (SL) and steepness index (Ks) to validate these zones. The study suggests that the above mentioned structures exert significant influence on the evolution of fluvial landforms, thus suggesting tectonically active nature of the terrain. Based on integration of the morphometry and geomorphic expressions of tectonic instability, it is suggested that Zone-2 is tectonically more active as compared to Zone-1. The results obtained from morphotectonic studies are verified during the field work and validated with the present seismicity pattern.

Key words: Morphometric analysis, Sabarmati-Cambay basin, Western India.

INTRODUCTION

The Sabarmati river originates from the southern slope of the Aravalli Hills, crosses a large alluvial plain and flows into the Gulf of Cambay (GOC) (Figure 1a). The Sabarmati basin covers nearly 21477 km^2 area. It is divided into four major stratigraphic divisions namely, Waghpur, Mahesana, Akhaj and Sabarmati formations (Tandon et al., 1997; Jain et al., 2004). Lineament studies (Sareen et al., 1993) indicate that the regional drainage in the Gujarat alluvial plain follows the NE-SW to NNE-SSW trend of topography sloping towards southwest. The region comprises of three distinct geomorphic surfaces, (i) the upland terraces and associated fossil dunes; (ii) the river valley terraces and scroll plain; and (iii) the eastern piedmont plain (Raj et al., 1999; Srivastava et al., 2001; Juyal et al., 2003). In the central portion of the basin near Mahudi the land cover has been modified as a result of tectonic movement (Srivastava et al., 2001). Morphometric analysis is presently one of the emerging disciplines in Earth Sciences. Recent development of new geochronological and geodetic tools enables estimating precise rates of tectonic and morphological events (uplift rates, incision rates, erosion rates, slip rates on faults, etc.) at variable (10^3–10^6 years) time-scales (Burbank and Anderson, 2001; Keller and Pinter, 2002). Thus quantitative analysis has regional importance in evaluating the tectonic activity and mitigation planning of natural hazards (Cloetingh and Cornu, 2005). Studies of active tectonics follow a multi-disciplinary approach, which includes integration of data from structural geology, geomorphology, stratigraphy, geochronology, seismology and geodesy (Pérez-Peña et al., 2010). The drainage pattern of active regions is very sensitive towards tectonic perturbations (Burbank and Anderson, 2001). Active processes such as folding and faulting are responsible for accelerated river incision, asymmetries of the basins, offset of channel, and diversions (e.g., Cox, 1994; Clark et al., 2004; Salvany, 2004; Kothyari et al., 2016). These studies are important in evaluating earthquake hazards, particularly in areas which have experienced relatively high activity in the Holocene and Late Pleistocene times (Keller and Pinter, 2002). Therefore, such multidisciplinary studies are necessary for understanding the role of active tectonics and geomorphic evolutions in active terrains. A quantitative morphometric analysis of Sabarmati-Cambay River basin has been presently taken up to evaluate the tectonic activity in the region.

The tectonic activity in the Sabarmati basin during Holocene is evaluated by a representation of geomorphic indices and drainage pattern analysis. We try to present a conventional morphometric method (Bull and McFadden, 1977; Keller and Pinter, 2002) for evaluating active tectonics based on geomorphic indices of five southwest flowing river basins in the Sabarmati-Cambay basins viz.

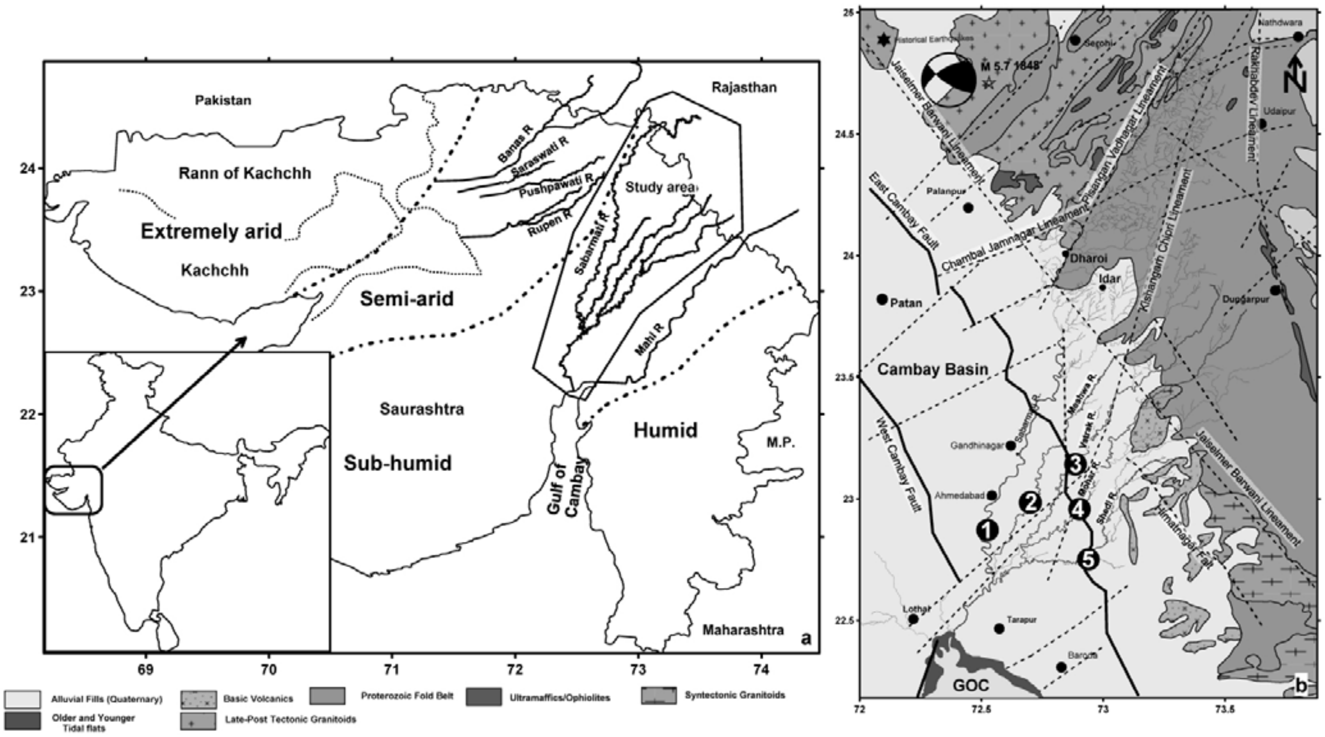

Figure 1. (a) Location map of the study area shows broad climatic zones of Gujarat (Juyal, et al., 2006) (b) Geological map of the study area showing position of major lineaments (after GSI.2000) and Cambay basin (Wani and Kundu, 1995) (Note: Numbers 1, 2, 3, 4, and 5 represent five basins).

(1) Sabarmati river (basin-1), (2) Khari river (basin-2), (3) Meshwa river (basin-3), (4) Majham river (basin-4) and (5) Vatrak river (basin-5) (Figure 1a). These indices include: stream length-gradient index (SL), hypsometric integral (HI), drainage basin asymmetry (AF), and drainage basin shape (Bs) index. Presently, the Sabarmati-Cambay basin has huge oil deposits and the region is under enormous industrial growth and hence has high population density compared to the rest of Gujarat. As such it is important to understand the tectonically active regions by correlating morphology and seismicity with the active faults. Thus for the first time the details of the morphotectonics of Sabarmati-Cambay basin, supported by field evidences, are reported in this paper.

General Geology and Structural Framework

The N-S to NNW-SSE trending intercratonic Cambay basin is bounded along east and west by discontinuous en-echelon step faults (Biswas, 1982; Wani and Kundu, 1995). The basin is characterized by hilly areas of southeastern Rajasthan to the north and alluvial terrain of Gujarat to the south (Merh, 1995; Maurya et al., 1995; 2000; Merh and Chamyal, 1997). Wide spectrum of lithological units is exposed in the study area from north to south (Merh, 1995). Towards north of the basin Archean rocks are exposed, whereas the central and southern parts comprise of Quaternary alluvial sediments. At a few places disseminated outcrops of Deccan Traps, of Proterozoic to Cenezoic Era are located (Anon, 1980; 1999). The structural framework of the basin is controlled by the interplay of two major NNW-SSE and ENE-WSW Precambrian trends represented by several faults and lineaments (Chandra and Chowdhary, 1969; Wani and Kundu, 1995; Mathur et al., 1968).

The geological history of the study area, in the recent past, indicates a sequential reactivation of these faults/ lineaments. The NW-SE trending Jaisalmer-Barwani lineament (JBL) is marked as a boundary between Archean rocks of the Aravalli and the Quaternary alluvial cover of Gujarat (Figure 1b). Rakhabdev lineament (RL) has a NNE-SSW curvilinear trend passing through Udaipur-Dungarpur area of Rajasthan and is marked by a linear alignment of ultramafic rocks (Anon, 1980) (Figure 1b). The NE-SW trending Chambal-Jamnagar lineament (CJL) cuts across all the lithosequences of the region. The NNE-SSW trending Kishangarh-Chipri Lineament (KCL) passes through the lithological contacts of Proterozoics and crosses through the vast alluvial plains (Figure 1b). The NNE-SSW trending Pisangan-Vadhanagar Lineament (PVL) is marked by the boundary between Archean and Proterozoic rocks of the Aravalli belt. Few patches of ultramafic rocks occur in close proximity to this lineament. The NW-SE trending Himatnagar Fault (HnF) passes through the alluvial plain and syntectonic granites of the Aravalli belt (Anon, 1980).

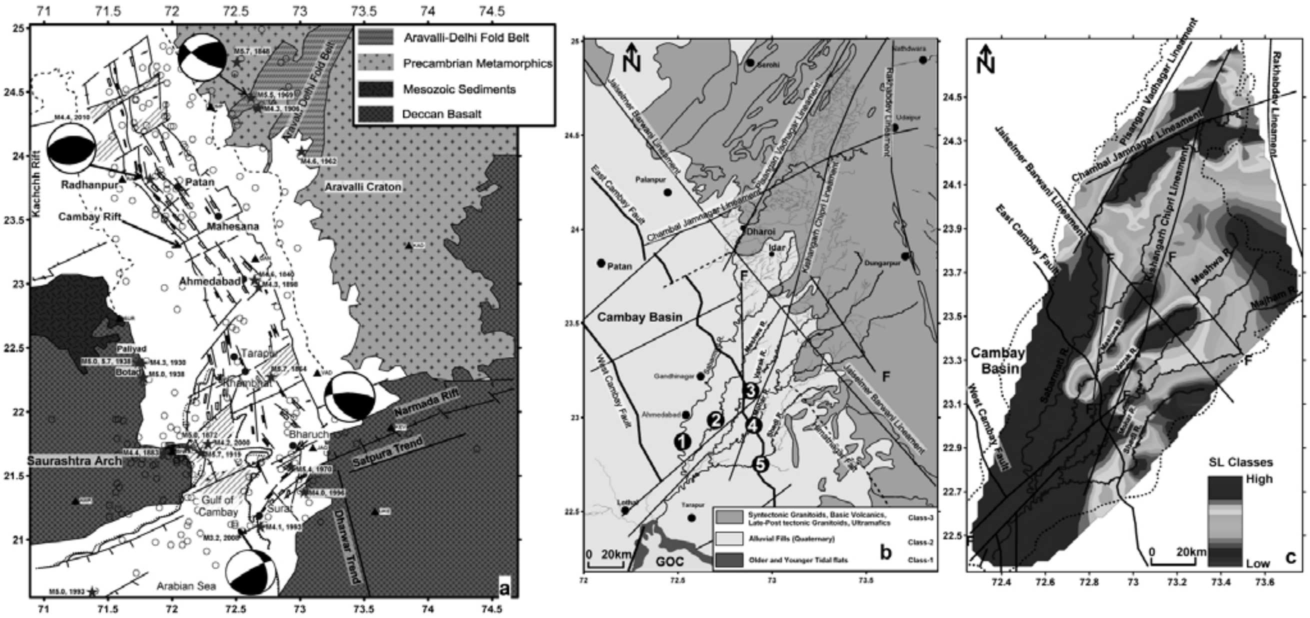

Figure 2. (a) Seismotectonic map of Cambay Basin (modified from Wani and Kundu, 1995). Stars show pre-2006 earthquake locations while circles show post-2006 epicenters. Triangles show seismograph stations. The focal mechanism from north to south, (i) Mt. Abu 1969 M5.5, (Chandra, 1977), (ii) Patan, 2010 M 4.4 MTS, ISR, (iii) Bharuch, 1970, M 5.4 (Gupta et al., 1972), (iv) Surat, 2008, M 3.2, from 1st motion directions, ISR. A total of 43 pre-2001 and 114 post-2001 earthquakes of M ≥ 2 are plotted. Shocks of M ≥ 4 are shown as stars, (b) Relative rock strength (RRS) map of study area, (c) Contour map shows plot of SL class values along the major rivers. Note: the higher values of SL represent relative higher tectonic activity.

Southern and central parts of the Sabarmati basin is controlled on the east and west by NNW-SSW trending marginal faults(named ESF and WSF) of Cambay (Figure 1b; Wani and Kundu, 1995).

Seismicity of the Area

The Sabarmati River basin has experienced five earthquakes of magnitude (M) about 6 on Richter scale in the historical past (near Mt. Abu, Paliyad, Tarapur and Ghogha) (Figure 2a). Until the year 2000, locations of 43 (M ≥ 4) earthquakes are available based on field reports and limited instrumental data (Rastogi et al., 2012). Most of the epicenters were confined to south of Ahmedabad (south of 24.5^{0}N latitude) and some in Mt. Abu area (around 24.5^{0}N 72.5^{0}E). Most of these events are associated with the East (ECF) and West (WCF) Cambay Faults while some of them may be with the Neogene Boundary Faults and lineaments like Paliyad and Mt. Abu earthquakes (Gupta et al., 1972). Epicenters of earthquakes in and around the Cambay basin are shown in Figure 2a. Seismicity of the study area is described in two periods i.e. pre- and post - 2006. A network of broadband seismic stations was established in starting mid-2006, as shown by black triangles (Figure 2a). A large number of earthquakes of M ≥ 2 (Maximum 4.4) from 2006 to 2012 are found located in and around the Cambay Basin. No shock is reported during 2001 to 2005 in the region. During the period from mid- 2006 to 2014 nearly 625 earthquakes of magnitude ~1 to 4.4 were recorded in the Cambay rift region by the Gujarat state seismic network. Figure 2a shows the locations of earthquakes of M $\geq$ 2in the Sabarmati-Cambay basin. Earthquake epicenters are located using data of 4 to 11 broadband seismic stations (Figure 2a). Annually some 10-20 shocks of M= 2-2.9 and 2-3 shocks of M ≥ 3 are being recorded. Entire spread of the basin seems to be active seismically. Based on recent seismicity pattern it appears that the ~50km long stretch in the central portion of the basin between Ahmedabad and Mehsana is relatively less active (Figure 2a).

Method and Material

Presently several relevant morphometric indices were computed and a relative index of active tectonics (RIAT) was calculated from the five indices for every catchment. Some of these indices relate to the morphology of drainage basin and river channel. The 30 m SRTM data set and WGS 84 datum were used to generate a digital elevation model (DEM) which was ultimately used to extract drainage basins from the Sabarmati River basin. All morphometric parameters were computed in GIS platform on the DEM extracted drainage basin. In the present study, the Relative level of Rock Strength (RRS) resistance has also been

Table 1. Geomorphic indices of active tectonics and their calculations.

SI No.	Indices	Formula	Variables	References
1	Steepness Index (K_s)	$S = K_s A^{-□}$	S = local channel slope A = is the stream drainage area K_s = is the steepness index □ = is the concavity	Goldrick and Bishop (2007) Whipple et al., (2013)
2	Stream length Gradient Index (SL)	SL = $(\Delta H/\Delta L)$ L	$\Delta H/\Delta L$ = channel slope or gradient of the reach ΔH = is the change in elevation ΔL = is the length of the reach L = is the total channel length from the point of interest	Hack, 1973 Bull 2009
3	Hypsometric Integral (HI)	HI = $(E_m - E_{min}) / (E_{max} - E_{min})$	E_m = Mean elevation E_{min} = Maximum elevation E_{min} = Minimum elecation	Hack, 1973 Keller and Pinter, 2002, Bull and Mc Fadden, 1977
4	Basin Asymmetry (AF)	AF = $A_R/A_T \times 100$	A_R = area of the basin to the right of the trunk stream A_T =is the total area of the drainage basin	Hare and Gardner, 1985 Keller and Pinter, 2002
5	valley floor width ratio (Vf)	Vf = 2Vfw/[(Eld-Esc)+(Erd-Esc)]	Vf = valley-floor width to height ratio Vfw = width of the valley floor Eld = Elevation of the left divide Erd = Elevations of the left and right valley divides and Esc is the elevation of valley floor	Bull and Mcfadden, 1977
6	Basin shape (Bs)	$B_s = B_l/B_w$	B_l = length of the basin measured from the headwaters to the mouth B_w = is the width of the basin measured at its widest point	Cannon, 1976

categorized on the basis of regional geology as was done earlier by El Hamouni et al., (2007) from other parts of world and by Kothyari et al., 2016 for Wagad area of Kachchh region. The results of RRS for the study area have been presented in Figure 2b. The study is based on the calculation of six conventional geomorphic indices of active tectonics such as steepness index (K_s), stream length gradient index (SL), hypsometric integral (HI), basin asymmetry (AF), valley floor width and height ratio (Vf), and Basin shape (B_s). The procedure used to calculate geomorphic indices is summarized in table 1.

Results of Morphometric Analysis

The River Sabarmati originates from the Aravalli Hills at an elevation of 738 m and flows across the major fault/ lineaments namely the KCL; CJL; PVL/ The JBL lineaments in upper reaches and through Cambay basin in the lower reaches controlled by several intra-basin faults. The longitudinal river profile shows normal river slope (33.53°) from source to mouth of the river (Figure 3). The computed SL value along the longitudinal length of river varies from place to place. In the central and lower reaches, the values are increasing abnormally; where the higher values in the region are associated with the PVL, JBL, ECF lineaments and several other faults (Figure 4b). Toward the upper reaches, the low SL values may be because of presence of lithological contacts. The River Meshwa originates from frontal zone of the Aravalli Hill at an elevation of 162 m and flows across the KCL, JBL, ECF lineaments and other subsidiary faults and merges with the River Sabarmati at Versing locality. Normal river slope is 30° from source to mouth. Towards the upper reaches, the SL value along the river profiles ranges between 11 and 300. The variation (high and low) in SL values of upper reaches could be owing to lithological variations. Towards the central and lower reaches, the values are relatively on the higher side, which correspond to the presence of faults passing through the Cambay basin and also controlling river gradient in the region (Figure 3).

River Vatrak originates from southern extension of the Aravalli Hill at an elevation of 392 m and flows through JBL, KCL, ECF lineaments and the associated Cambay basinal faults (Figure 2b). In the whole stretch of 262 km the river has a general slope of 35.1° towards SW direction. The river has knick points and shows higher rate of elevation drop in 100 km stretch out of the total 262 km course (Figure 3) before entering into the Cambay basin. In the central portion of the river SL values are abruptly increasing, which correspond to JBL, KCL, ECF in the area. Towards the lower reaches, the SL values are very high which may be due to presence of intra-basinal faults of the Cambay basin. River Mohar originates from the Aravalli Hill at an elevation of 354 m and flows through JBL, HnF, ECF and associated transverse faults (Figure 2b). In the

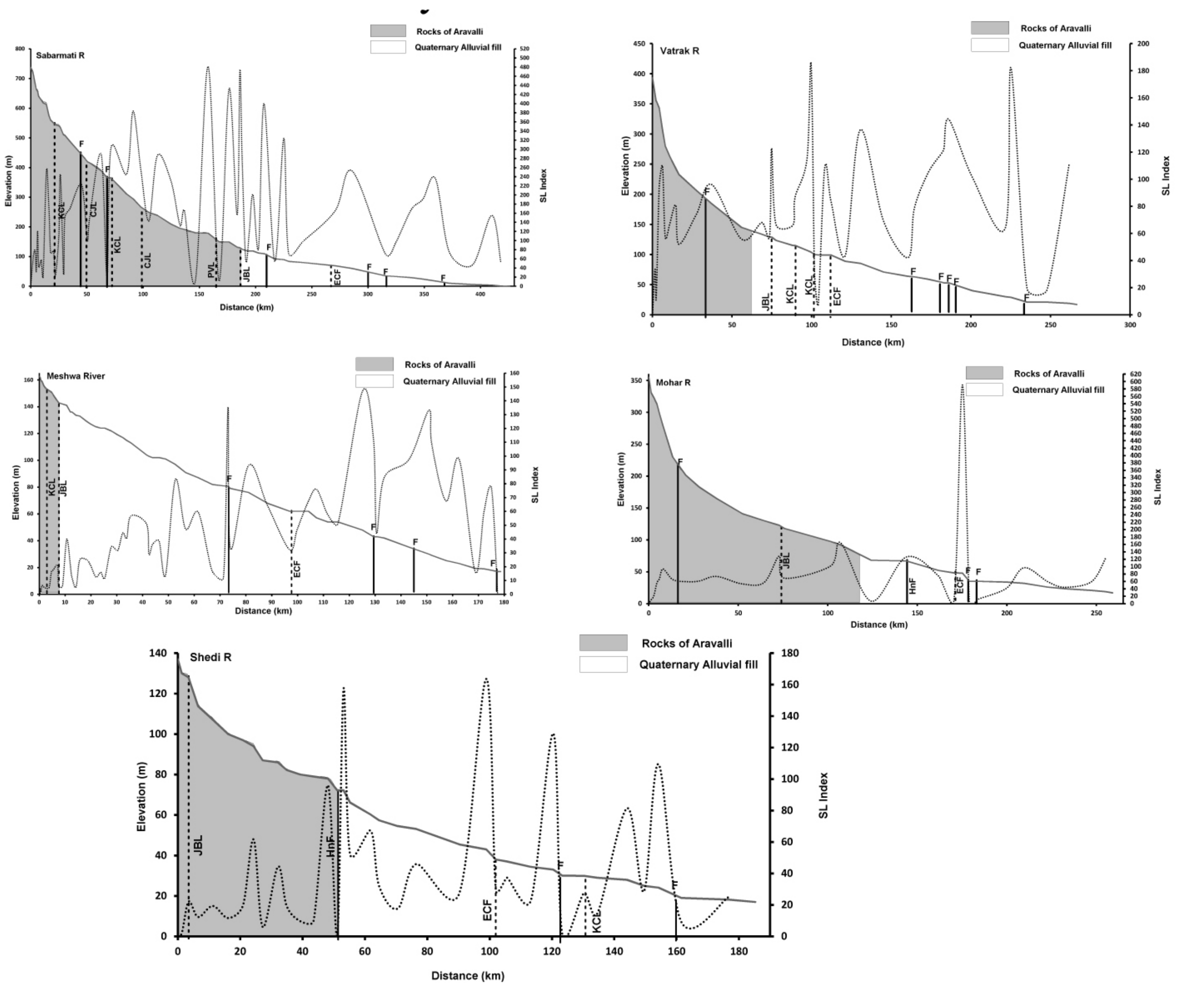

Figure 3. Longitudinal river profiles of the Sabarmati, Meshwa, Vatrak, Mohar and Shedi rivers SL index values plotted along the longitudinal profiles using dotted line.

longitudinal river profile, several knick points have been observed near/along the flank of lineaments/faults. The SL values are very low towards the upper reaches, whereas in the central portion and lower reaches the values are comparatively high. The value of SL becomes very high as the river crosses the ECF and other intrabasinal faults of the Cambay basin (Figure 3). The higher values along the river profile are compared with tectonic uplift in the central and lower reaches. The SW flowing Shedi river originates from the Aravalli hill at an elevation of 136 m and crosses through JBL, HnF, KCL, ECF and associated basinal faults showing a normal river slope of 36.85° towards southwest. Several knick points have been observed along the length of River Shedi. The SL values towards the central and lower reaches are relatively higher (Figure 3). These values are corresponding to the tectonic movement along the KCL, ECF and HnF and intrabasinal faults in the Cambay basin. However, towards the upper reaches high and low values are possibly due to changes in lithology (Figure 2). The SL values along Sabarmati River range from 11 to 481. The SL values of the Meshwa River ranges between 1 and 146, for the Vatrak River these values vary from 8 to 184, and for the Mohar River SL ranges from 9 to 590. However, the computed values of SL for the Shedi River range between 1 and 164 (Figure 3). Figures 2c to 3 represent plots of computed SL values from the longitudinal profile for all five rivers. The SL values are ranging from $\leq$10 SL $\geq$500 (Figure 3). These values are grouped into five classes: class-1 (lesser activity: SL $\leq$10), class-2 (active: SL 10-70), class-3 (moderately active: 70-140), class-4 (high active: 140-210) and class-5 (very active: $\geq$210) (Table 2, Figure 2c). The SL classes for all the rivers show high values towards lower reaches. The higher SL values towards the lower reaches are compared with the reactivation of intrabasinal faults of

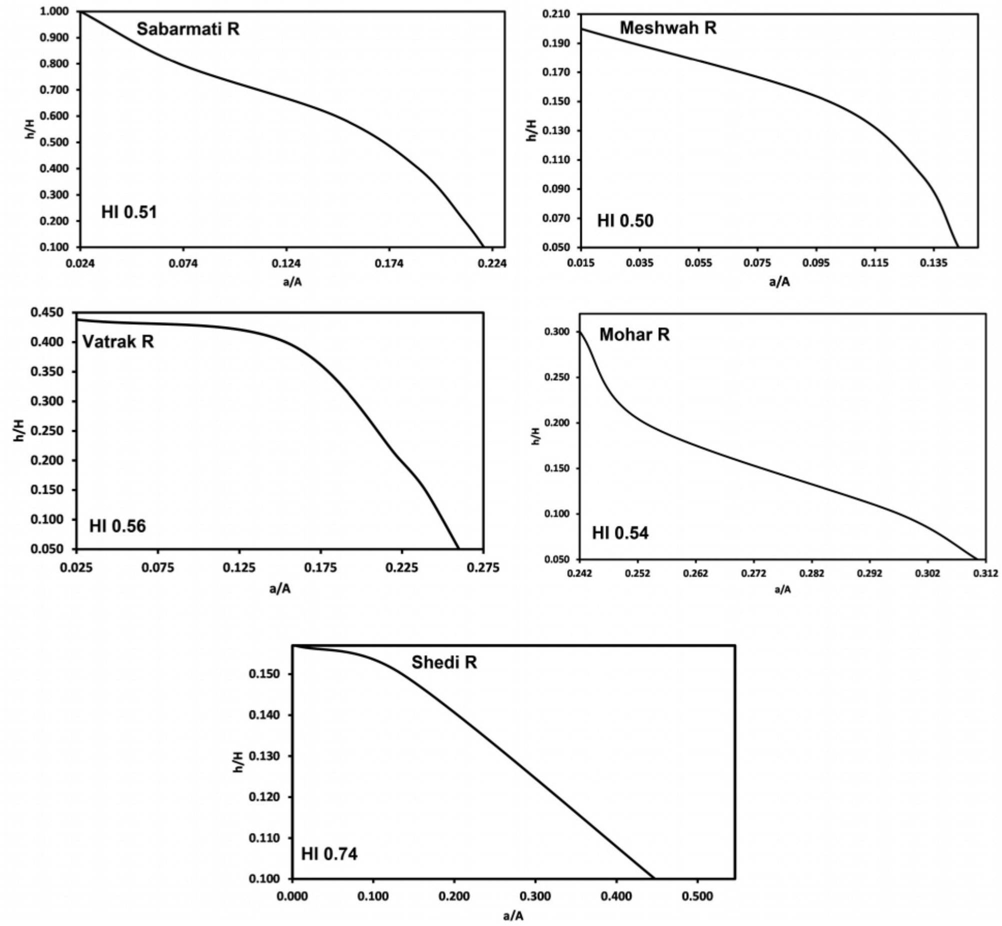

Figure 4. Hypsometry curves of fiver sub basins.

Cambay. In the middle part of River Sabarmati the activity is associated with the PVL, JBL, and ECF lineaments. The SL values are characterized by class-1 and class-2 for all the river basins and may be due to changes in lithology (Figure 2b and 2c).

Similarly, the SL values increase abruptly as they cross the KCL, CJL, PVL, JBP and HnF lineaments and associated faults, which suggest that they are controlled most likely by tectonics rather than lithological heterogeneity (Figure 2b). In the present investigation three types of profile curves have been observed, concave, convex and convex-concave (Figure 4). The computed value of HI (0.51) is observed for Sabarmati river basin, (HI 0.50) for the Meshwa River basin, (HI 0.56) for Vatrak river basin, (HI 0.54) for the Mohar river basin and (HI 0.74) for Shedi river basin (Table 2). These values are further classified into four classes: class-1 (lesser activity: HI $\leq$0.50), class-2 (active: HI 0.50-0.55), class-3 (moderately active: HI 0.55-0.60) and class-4 (highly active HI $\geq$ 0.60) (Figure 4). The convex nature of all the profiles in central part and lower reaches may indicate higher tectonic activity compared to other regions which is more likely to be related with the activity along intrabasinal faults of the Cambay basin.

In this study huge variations have been observed in AF viz. basin-1 (7.91), basin-2 (59.92), basin-3 (41.61), basin-4 (18.23) and basin-5 (33.17) (Table 2, Figure 5a). We have divided observed absolute values of AF into four classes: class-1 (AF<1; symmetric basins), class-2 (1<AF<10; gently asymmetric basins), class-3 (10<AF<20; moderately asymmetric basins), and class-4 (AF>20; strongly asymmetric basins) (Table 2, Figure 5a). These AF classes reveal that the Sabarmati, Mohar river basins are strongly asymmetric, the Shedi river basin is moderately asymmetric, the Meshwa river basin is gently asymmetric and the Khari river basin is symmetric in nature (Figure 5a).

In this work Vf has been analyzed for various places along the lengths (courses) of all the five rivers (Figure 5b). In the lower reaches (near the Gulf of Cambay) low Vf value (1.48) has been observed. The Vf value of this region is compared with eustatic changes along the coastal region rather than tectonic. In the middle part of the River Sabarmati values range from 2 to 4. In this part river flows

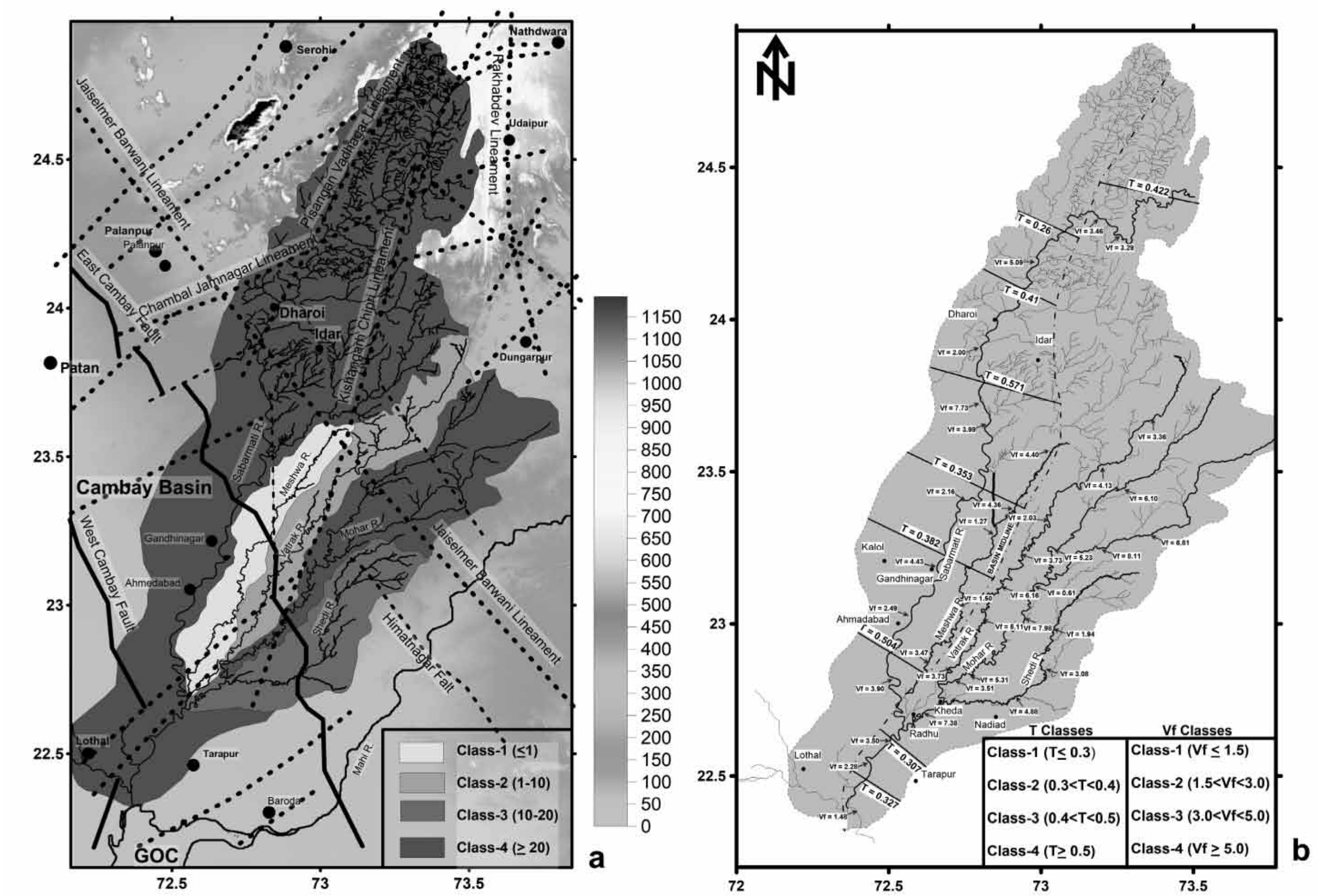

Figure 5. (a) Basin asymmetry, (AF) class map of study area, (b) Map showing topographic symmetric factor (T), ratio of valley floor width to height (VF) classes of the study area.

through the Cambay basin and incised into the sediments. Towards the upper reaches the valley become comparatively wider showing less amount of incision. In this region values of Vf range between 3 and 7 (Figure 5b). The Vf values are for Sabarmati River (1.2 to 4.3), Meshwa, River (2 to 8), Vatrak River (0.61 to 7.98), River Mohar (1.9 to 4.8) and River Shedi (0.61 to 7.98) respectively (Figure 9b). The observed values of Vf from all these basins were grouped into four classes: class-1 (very active; Vf≤1.5), class-2 (moderately active; 1.5<Vf<3.0), class-3 (active; 3.0<Vf<5.0) and class-4 (less active; Vf≥5.0) (Table 2, Figure 5b).

The valley floor width increased with watershed size, erodibility of rock type and with the decrease of uplift rate (Bull, 2009). High values (>1) of B_s are associated with elongated basins, generally with relatively higher tectonic activity. Low values (<1) of B_s indicate a more circular-shaped basin, generally associated with low tectonic activity. Though the river crosses through major lineaments of the Aravalli and Cambay rift basins, those have been considered to be rapidly uplifted along various lineaments and faults thus producing higher values of B_S. The Bs has been calculated for 5 river basins in the study area showing the values as 4.50 (basin-1), 7.19 (basin-2), 10.57 (basin-3), 7.8 (basin-4) and 6.81 (basin-5) respectively (Table 2). Further the computed Bs values are divided into four active classes to define degree of tectonic activity: class-1 (less active Bs<1.5), class-2 (active 1.5<Bs<4), class-3 (moderately active 4<Bs<6) and class-4 (very active, Bs >6) (Table 2). The observed values and activity classes of all the basins indicate that these basins are elongated during recent time due to reactivation of faults within the Cambay basin and movement along the KCL, CJL, JBL, PVL, HnF lineaments and associated faults.

Geomorphic Evidences of Tectonic Activities

The upper reaches of the Sabarmati river basin consists of Aravalli Group of rocks of Archean age and flows across the JBL, RL, CJL, KCL, and PVL lineaments of the Delhi-Aravalli belt. River offset is one of the most remarkable geomorphic expressions that have been observed towards the upper reaches (Figure 6e). The SSW flowing rivers cross

Table 2. Activity classes of SL (stream-gradient index), AF (drainage basin asymmetry), T (topographic symmetric factor), Vf (valley floor width–valley height ratio), Bs (drainage basin shape) and classes of RIAT (relative index of active tectonics).

Basin Name	Area (Sq Km)	Area%	Hypsometric Integral (HI)	BASIN SHAPE (BS)			Basin Asymmetry			Activity classes						
				L (km)	W (km)	(BS)	Ar	AF	AF class	SL	AF	T	Vf	BS	RIAT Value	RIAT
Sabarmati	12677	67.2	0.51	90.11	20	4.50	1003.5	7.91	42.09	5	4	4	3	3	3	2
Meshwa	1483.7	7.86	0.50	151	21	7.19	883.17	59.92	-9.92	4	1	-	2	4	2.2	1
Vatrak	1922.5	10.2	0.56	148	14	10.57	800	41.61	8.39	5	2	-	3	4	2.8	2
Mohar	2962.1	15.70	0.54	117	15	7.8	540	18.23	31.77	5	4	-	4	4	3.4	3
Sheid	1741.7	9.23	0.74	300	44	6.81	577.7	33.17	16.83	4	3	-	3	4	2.8	2

the Cambay basin in the central and lower reaches (Figure 1b) and flow through normal topographic-tilt and finally disappear in the GOC. The longitudinal river profiles of all the SSW flowing rivers in the study area show major knick-points when they cross major faults/lineaments and various lithounits (low to highly resistive) as illustrated in Figure 2b. Near Aspa locality in zone-1, south of Dharoi the southward flowing stream suddenly turns eastward and again takes a 90° turn to the north when it passes through a NE-SW trending transverse fault and forms box shape meander (Figure 6a,b). The middle reaches of the basin are controlled by intrabasinal faults of the Cambay basin. Seismic events in the recent past and geomorphic evidences suggest that the region is one of the most active segments of the Sabarmati-Cambay basin. The geomorphic features like deep incised ravine surfaces, fluvial strath terraces, fault scarp, paleo channel, wind gaps, and uplifted scroll plains (Figures 6 and 7) suggest recent tectonic activities. Ravine surfaces are the youngest remarkable geomorphic expressions observed in zone-2 (Figure 7a, b). These ravine surfaces are incised by ~40 m owing to vertical tectonic forcing associated with the intrabasial Cambay Fault. Two to three levels of 10 to 45 m thick well-developed unpaired fluvial strath terraces have been observed in this segment (Figure 7c-f). Near Mahudi, around 20 km long abandoned channel of the Sabarmati River has been observed. At this location approximately 44m high two levels of terraces were well preserved in the area. These terraces were resting over a 2m thick conglomerate. The upper fluvial terraces are mainly composed of greyish yellow fine sand and silt with alternate bands of calcrete covered by red brown clay. These units are overlain by ~ 3 m thick aeolian sand. Based on OSL chronology Srivastava et al., (2001) suggest that the aggradation of upper fluvial sequence started around 55 ka and continued until 12 ka. These terraces were incised after 12 ka. Due to uplift along the N-S oriented fault River Sabarmati gradually migrated towards west. Continuous migration of river followed by progressive incision of present day river channel has exposed nearly ~40 m thick sedimentary sequence in this region and three levels of 7 m high scroll plains that have developed near Mahudi area with a vertical offset of 2-3 m (Figure 7g). These scroll plains got developed during terminal bar aggradation between 3 and 0.3 ka when a major phase of tectonic activity took place in this region (Srivastava et al., 2001; Figure 6c). Further a N-S oriented paleochannel is observed along the trace of Bok Fault (Figures 6c and 7h). Presence of paleochannel and wind gap near the confluence of the Sabarmati and Hathmati rivers suggest that the area is rejuvenated during late Holocene around 0.4ka and 3ka. Furthermore, towards south between Kheda and Ahmedabad localities all the rivers are flowing across the ECF in zone-2. The region is dominated by a zone of compressed entrenched meandering where the river assumed its course to the present day channel (Figure 6d). Henceforth the compressed meandering and incision of river in this region have been correlated with tectonic event. Towards the upper reaches (zone-1) near Kot area River Sabarmati incised into the bedrock of the Aravalli Group. This area is dominated by several NNE-SSW trending lineaments (PVL and KCL), where southwest flowing rivers (tributaries of River Sabarmati) show prominent linear alignment along these lineaments (Figure 6e). The reactivation of these lineaments in the area causes offset of these streams. North of Nadiad the SSE flowing River Shedi suddenly changed its course and diverted towards west (Figure 6a). A course of abandoned Shedi River channel has been observed near Aljada locality. In this area the river gradually migrated towards N and gave rise to a ~6 km long paleochannel (Figure 6f). Diversion and shifting of Shedi river channel in zone-2 could be associated with the tectonic activity along KCL and ECF lineaments in the area. Similarly, between Malpur-Modasa-Idar areas a prominent NW-SE trending deflection has been observed along all SW flowing rivers as illustrated in Figure 10a, correlated with the tectonic activity associated with newly reactivated fault. One to two levels of fluvial strath terraces were observed along the Meshwa and Vatrak rivers (Figures

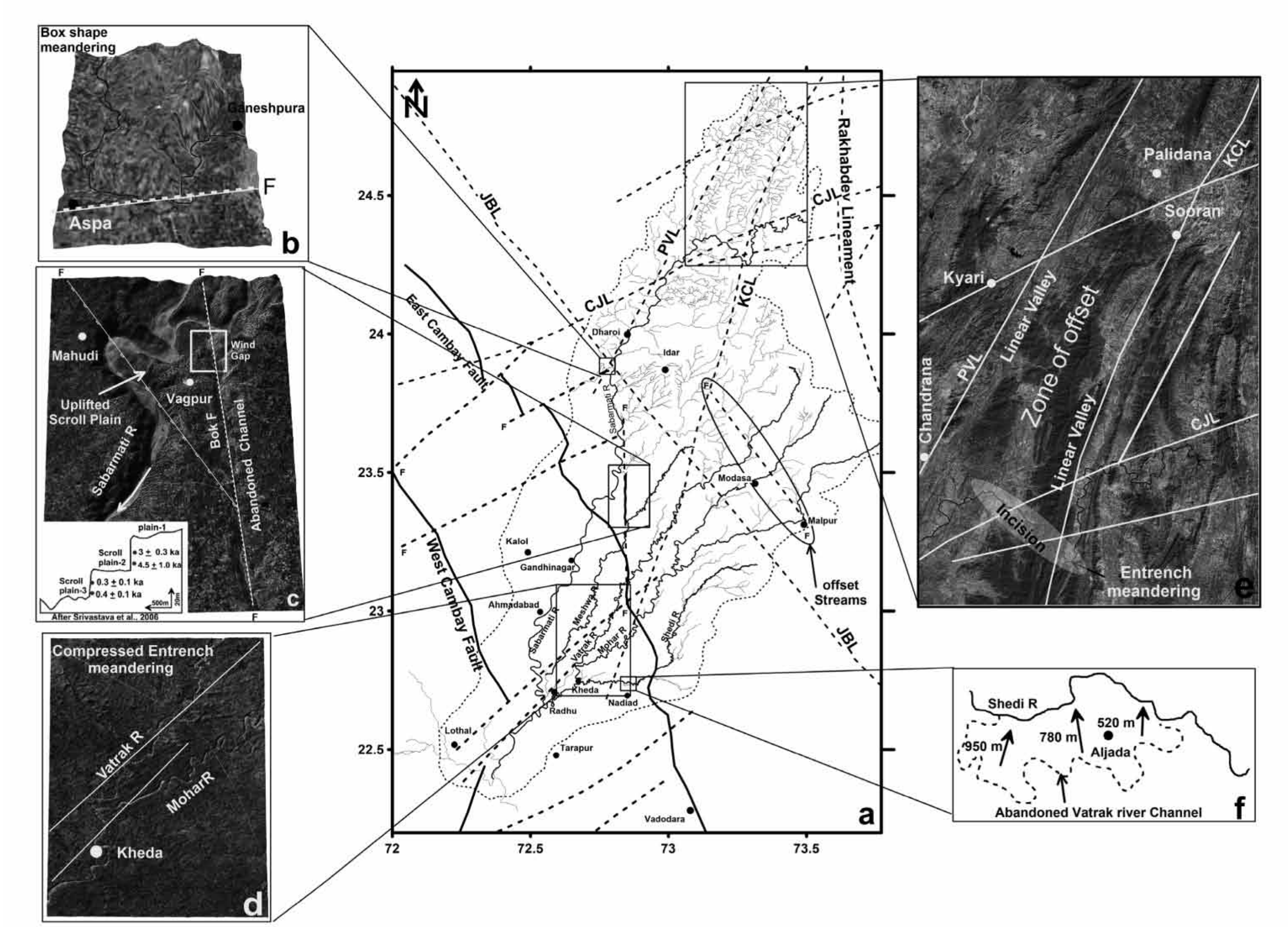

Figure 6. (a) Drainage map of study area shows distribution of various morphotectonic features (b) box shape meandering, (c) abandoned Sabarmati river channel and development of three levels of scroll plains (Note: arrow indicates migration direction of river, sketch (after Srivastava et al., 2001), (d) compressed entrenched meandering of rivers, (e) formation of linear valley and offset of river channel along the PVL and KCL, and (f) northward shifting of River Vatrak.

7e and f). The leading side of these terraces are truncated along a NW-SE oriented fault, led to development of a prominent fault scarp in the area.

The southern end of the Sabarmati-Cambay basin near Bhavnagar / Narmada basin and the northern end near Mehasana-Patan are seismically more active than the central part near Ahmedabad (Figure 2a). Three shocks of magnitude M 5.7 have been cataloged in and around the Cambay rift basin. Earthquakes occur not only along the two major rift boundary faults but also along smaller longitudinal as well as transverse faults (Figure 2b). Thrust mechanism along an E-W fault indicates tectonic inversion as observed in other rifts of India like Kachchh, Narmada and Koyna-Kurdwadi (Chandra, 1977; Gupta et al., 1972).

In Gujarat alluvial plains the River Sabarmati flows through the N-S oriented Cambay basin instead of flowing through SW tilted topography. This tectonic forcing of the Sabarmati River is interpreted to be an adjustment of neotectonics (Sareen et al., 1993; Tandon et al., 1997, Raj, 2004, 2007, 2012; Raj et al., 1998, 2015 and 2016). The OSL chronology from limited areas of River Sabarmati suggests that the river adjusted to its present course as a result of active tectonics prevailing in the region between 12–4.5 ka (Srivastava et al., 2001; Juyal et al., 2006), whereas incision began around the Last Glacial Maximum (LGM) and was accentuated as the monsoon strengthened (Juyal et al., 2006). This incision was predominantly governed by (a) increased fluvial activity in response to enhanced monsoon and was aided by a lower sea level (Srivastava et al., 2001). Incision of sediment after 4.5 ka is correlated with enhanced tectonic uplift during Mid-Late Holocene 3 and 0.3 ka as observed from the central part of the basin (Srivastava et al., 2001).

The uplift and incision of central part of the Sabarmati-Cambay basin is validated by our incision parameter SL that is of class-5 (very active). A comparison of morphological observations of the active tectonics from the Sabarmati-Cambay basin clearly corresponds with

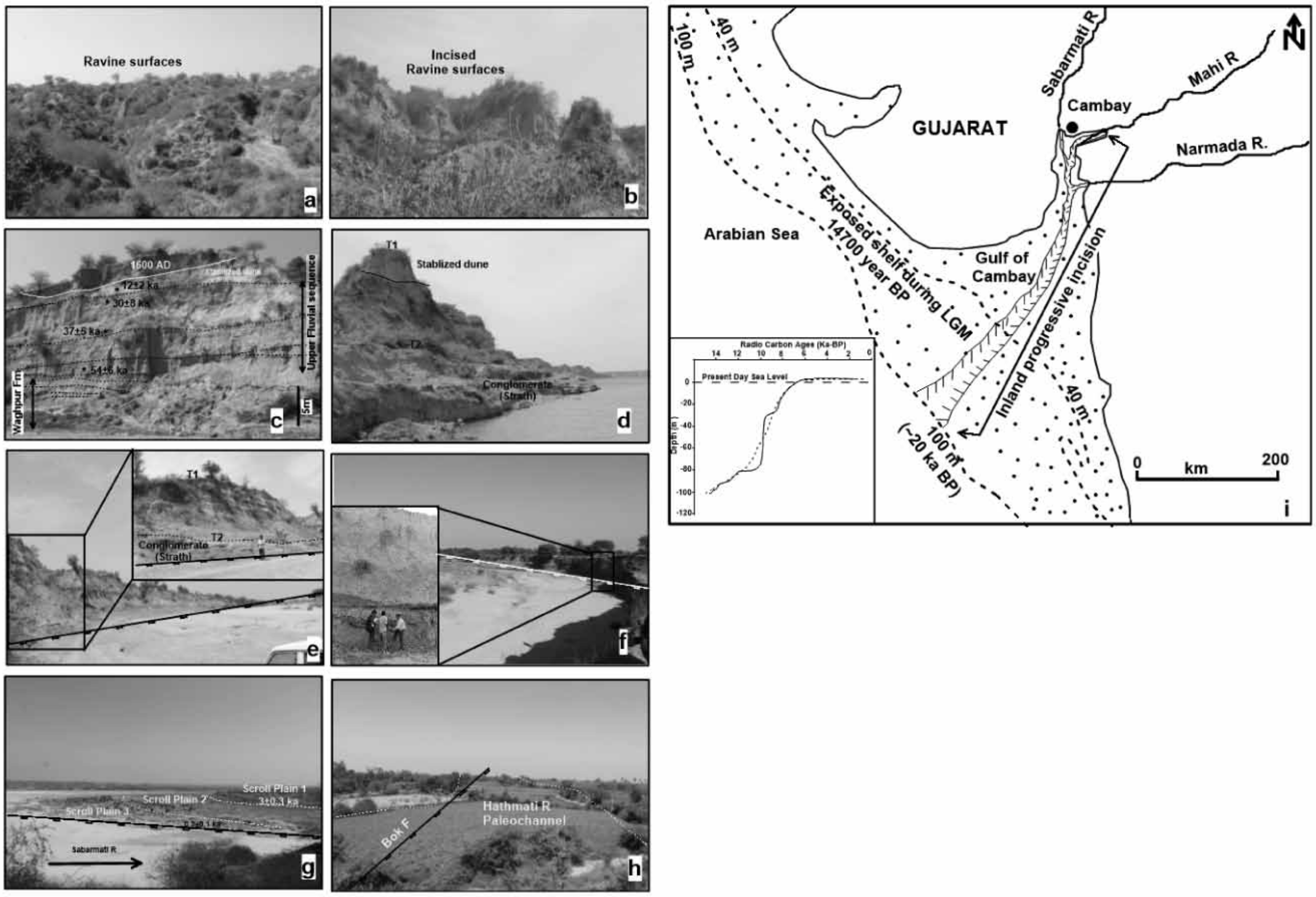

Figure 7. Photoplate shows (a and b) incised ravine surfaces, (c, d and e) show development of two levels of strath terrace along Sabarmati river, (f) development of fault scarp toward the leading edge of terraces, (g) three levels of scroll plains, and (h) Paleochannel of Hathmati river. (i) Map showing the progression of coastline during the Last Glacial Maxima. The desert Margin Rivers extended their course into the exposed shelf. Incision progressed from the shelf to the land (Juyal et al., 2006). Inset shows Holocene sea level curve of western India relative to present day sea level (Hashimi et al., 1995).

the recent seismicity pattern, classes of active tectonics indices and with the overall RIAT index (Table 2). The activity classes of all the parameters with moderate to high RIAT correspond with intrabasinal faults of the Cambay basin and reactivated very old geological structures such as the JBL, CJL, PVL, KCL, RL and HnF lineaments. The river has deeply incised the Quaternary sediments at many places, as observed in our incision parameter (high SL values). The river originates from the Aravalli hills and traverses through several E-W to NE-SW trending fractures and step faults (Maurya et al., 1995; Juyal et al., 2006). Merh and Chamyal (1997) believe that the region has experienced a phase of major tectonic activity. The Aravalli hills have risen up to ~700 m between Tertiary and Late Holocene and, the region experienced continued tectonic activity (Ahmed, 1986) Morphotectonic features suggest the reactivation of the pre-Quaternary faults. The geomorphological study associated with geological and seismo-tectonic data allowed us to distinguish the faults/lineaments within the Sabarmati river basin.

The hydrographic network of basins has provided information about possible tectonic modifications. The present study further highlights the regional-scale evidence of late Quaternary tectonic activities within the whole Sabarmati basin. The regional slope and knick points developed within the valley have formed as a tectonic adjustment along major faults. Based on values of the SL, Af, HI, T, Vf, and Bs an overall index (RIAT) has been developed, which is a combination of the other indices that divide the landscape into four classes of relative index of active tectonics. The lowest class-1 of RIAT is mainly observed for the SSW flowing Meshwa river basin which shows relatively less amount of tectonic activity, while RIAT of Sabarmati, Vatrak, Mohar and Shedi falls in class-2 and class-3, indicating moderate to high active tectonics (Table 2). The higher class values of SL index of all the basins are due to varying relative rock strength (i.e. change in lithology) and presence of several faults/lineaments (Figures 2b). However, the variation of SL in the lower reaches near GOC indicates a manifestation of eustatic factor during the Last Glacial Maximum (LGM).

The sea level curve in the west coast of India suggests a ~100 m fall in sea level during LGM (~20 ka) (Hashmi et al., 1995; Figure 7i). In case of such enormously lowered sea level the rivers would have incised their channel to attain equilibrium. Several studies have documented LGM driven incision in the fluvial sequence of west coast of India (Hashmi et al., 1995; Rao and Wagle, 1997; Juyal et al., 2006). During this period, rivers draining into the Cambay basin would have had an extended trajectory across the continental shelf. Bathymetric contours in the Gulf of Cambay show that inner shelf (~100 m water depth) was located at a distance of 175 km from the Cambay (Juyal et al., 2006) (Figure 7i). Presence of submarine terraces and terrigenous sediments at depths of 35 and 140 m suggests presence of palaeo coastlines during low sea stand (Rao and Wagle, 1997; Juyal et al., 2006). In case of tectonic uplift, incision is restricted to the lower reaches of river with an increasing trend in upstream direction, whereas in case of eustatic driven the incision shall be maximum at coastline with a reducing trend of incision in upstream direction. The evidence of progressive inland incision can be seen by the presence of a drowned valley around the Mahi estuary proximal to the Gulf of Cambay (Juyal et al., 2006; Raj et al., 1999) (Figure 7i). Our incision parameter (SL index) of Sabarmati basin shows increasing trend of incision in the lower reaches of River Sabarmati near the GOC. The higher SL value towards lower reaches (GOC) attributes that the incision is associated with eustatic forcing. The Sabarmati-Cambay basin needed special attention especially on active fault studies, neotectonics and past climatic changes. In the central portion, the River Sabarmati follows a regional slope-deviatory course interpreted previously to be a neotectonic adjustment within the intrabasinal fault of the Cambay basin. The Sabarmati-Cambay basin gives an insight into the climatic forcing and the varied semi-arid-sub-humid fluvial response (Juyal, et al., 2006). The fluvial pattern of Sabarmati river basin can be explained in terms of changes in discharge and sediment supply which were forced by changes in the monsoonal strength. In River Sabarmati these studies have been done only in central part of the basin. However, lower reaches of the basin should be studied to link the past climatic record during LGM (Tandon et al., 1997; Juyal et al., 2006).

CONCLUSIONS

1. On the basis of results obtained from morphometric analysis and field observations, the following conclusions have been drawn.
2. Analysis of the geomorphic features reveals that the area is tectonically active.
3. The SL, HI, and Bs values were found to be high along major faults and lineaments. The AF values show SSW oriented drainage basin asymmetry related to tectonic tilting. The low values of VF show that many valleys are narrow and deep, suggesting a high rate of incision associated with tectonic uplift.
4. About one-third of the study area (76.44%) has RIAT values of class-2 and class-3, indicating moderate to highly active tectonics. Only 7.86% area lies in the class-1 of RIAT, indicative of tectonically less active area.
5. The class-2 and class-3 of RIAT corresponding to moderate to highly active tectonics occur mainly in the JBL, RL, CJL, KCL, PVL, and HnF lineaments and newly reactivated intrabasinal faults of the Cambay basin.
6. From the RIAT classes and past and present seismicity pattern it is inferred that the central and lower reaches of basin area are the most active parts of the Sabarmati-Cambay basin.
7. At present the central and lower reaches of the Sabarmati-Cambay region have huge oil deposits, and is under enormous industrial growth and hence has high population density compared to rest of Gujarat region. So it is important to understand the earthquake hazard assessment in the region by correlating seismicity with active faults. Industrial development has to take care about active faults and seismic safety factor and follow building codes available for India.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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The Future of Earth Looks Drier…but Just How Dry?

As global warming progresses, factors that promote drought and aridity will outweigh a gentle rise in precipitation, scientists predict, leading to a net increase in aridity over Earth's landmasses. However, recent research suggests that the calculations behind these predictions may overestimate future dryness because they rely too much on indirect atmospheric factors.

Instead, some scientists have called for predictions based directly on projected changes in the water cycle itself, such as changes in runoff and soil moisture. To help resolve this issue a research team recently analyzed the future of soil moisture. Although previous studies have focused mostly on soil moisture down to a depth of 10 cm, researchers note that such analyses may be incomplete because many plants soak up water at depths of 2–3 meters. For a more comprehensive analysis, they examined previously simulated soil moisture at different depths down to 3 meters. The researchers used data from such prior simulations of monthly changes in soil moisture around the world between 1976–2005 and 2070–2099. They found that soil moisture changes in the modelled data followed a vertical gradient, with surface layers losing more moisture than deeper layers. The scientists interpret the vertical gradient seen in the models as a reflection of seasonal factors. The results highlight the importance of considering vertical water transport in soil when predicting the effects of global warming on water resources, agriculture, and ecosystems. (**Source:** Geophysical Research Letters, https://doi.org/10.1002/2016GL071921, 2017)